COMPREHENSIVE STUDIES ON FAST SETTING EARLY STRENGTH HYBRID FIBRE REINFORCED SELF COMPACTING CONCRETE

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Civil Engineering

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2026

DECLARATION

"I, Pavan Kumar D, hereby state that the proposal of this research is submitted in accomplishment of the requirements for the award of Doctor of Philosophy, in the School of Civil Engineering, Lovely Professional University, Punjab, is entirely my own work excluding the part which is referenced or accredited".

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CERTIFICATE

"I certify that **Mr. Pavan Kumar D** bearing Registration Number **41800133** has prepared his thesis entitled **"Comprehensive Studies on Fast Setting Early Strength Hybrid Fibre Reinforced Self Compacting Concrete"** for the honour of Ph.D in Civil Engineering, doctoral degree of Lovely Professional University**,** under my supervision. He has conceded out the work at the School of Civil Engineering, Lovely Professional University. This thesis report has never ever been submitted earlier in any institution. So this is the first time work ever".

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ACKNOWLEDGEMENTS

I sculpt to express my earnest gratitude and insightful sense of thankfulness to my supervisor Dr. Pushpendra Kumar Sharma, Professor, School of Civil Engineering, Lovely Professional University for his gifted guidance, inspiration and subjective concern during the course. His prosperity of understanding and enthusiasm towards work is greatly appreciable. I am really humbled for his guidance.

I express my heartily thanks to Dr.Amit Srivastava, for co-guiding me and motivated me to carry the experimental research.

I am extremely thankful to Dr. Sri Rama Chand for co-guiding and encouraging me to do Ph.D and to have focus on research.

I am exceedingly obliged to my organization, National Council for Cement and Building Materials(NCB), to all my senior officials and colleagues for inspiring and motivating me to carry the research.

I am humbly grateful to Sh.E.Srinivas Reddy, Director, Hyderabad Test Laboratory, Hyderabad and all the Staff of the Laboratory to help me in attaining all my research objectives with ease and providing expert results, well in time, without which it was not possible to complete the research.

I am humbly grateful to Head of School, Civil Engineering, LPU, entire Staff of Civil Engineering, LPU and all other officials of LPU to help me to complete the research.

I sincerely acknowledge my mother, my father, my wife, my children, all my beloved family members, friends, mentors and well-wishers for constantly providing me the support and encouragement throughout my thesis which kept me highly motivated to keep on working and to complete the research work earnestly which kept me concentrated to complete the research.

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ABSTRACT

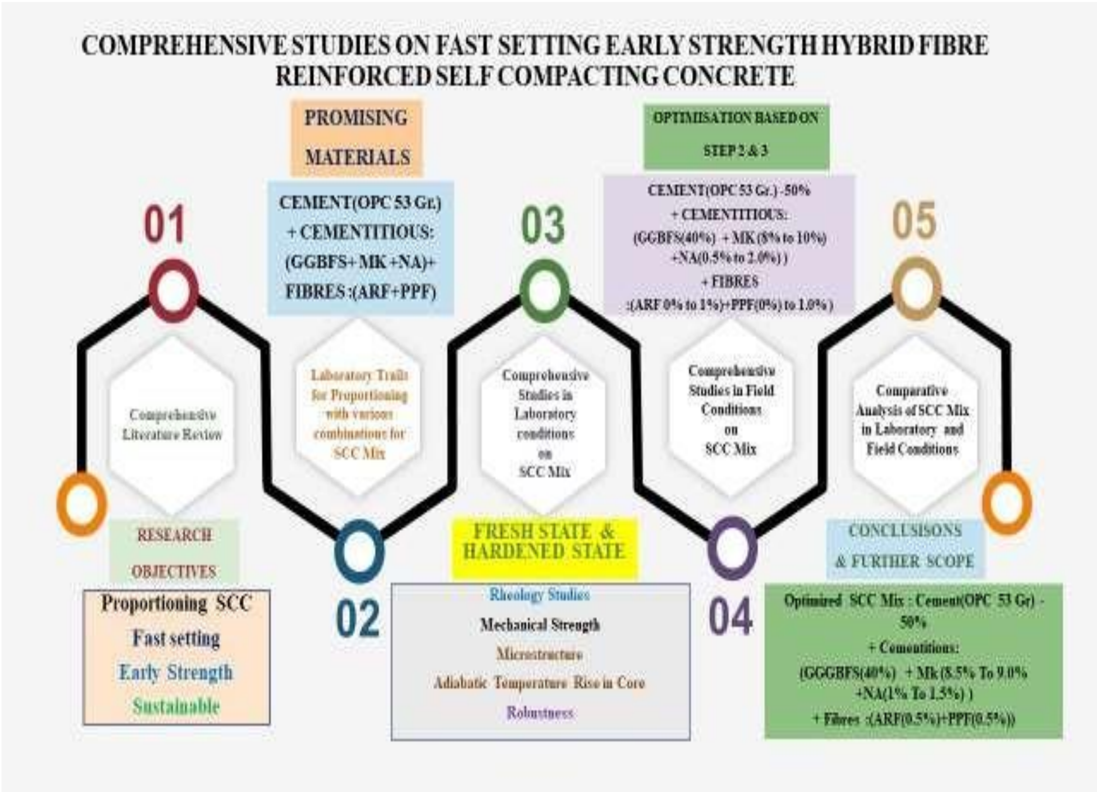
Ordinary Portland Cement (OPC), the most important building material worldwide, used for the past few decades for fashioning various infrastructure made up of concrete. It is evident that the production of OPC, involves enormous quantities of raw-materials, processing, energy requirements etc., thus, discharges approximately 7% of the world's greenhouse gas emissions into the atmosphere. Also, the industrial revolution happened worldwide, few decades ago and continuing, has resulted into accumulation of huge quantities of waste by-products like flyash(FA), granulated slags, silica fume(SF) etc., Research on these industrial wastes has established that they possess some qualities, as desired, of pozzolanic materials, popularly called as supplementary cementing materials(SCM), capable to partially replace the OPC in the production of concrete. In order to achieve sustainability in construction activities using concrete, it is a challenge to use blends of different by- products of SCM nature, as resulted from various industries, possessing various degrees of reactivity like highly reactive, reactive, and moderately reactive, as part replacement of OPC for desired characteristics of concrete. Moreover, as a measure towards achieving sustainability besides reducing the carbon footprint related to the construction industry -the use of above types of SCMs, as partial replacement of OPC, to be encouraged as much as possible. It is evident that the consumption of conventional Cement i.e. OPC has greatly expanded worldwide due to the construction of massive infrastructure facilities to meet the ever increasing demands of public amenities like housing, transport, energy etc. In order to achieve sustainability in concrete construction activities, it is a challenge to use combinations of different industrial by-products with highly reactive, reactive, and moderately reactive class, as partial substitution of OPC, to cut green-house gas discharges however meeting the target times of fast-track construction. Furthermore, the venerable infrastructure, constructed decades ago, necessitates care and conservations, which has additionally driven up the demand for OPC. Therefore, researches, around the world, are attempting investigations for reducing the carbon footprints however sustaining the demands of faster constructions, in finding out appropriate groupings of various proportions of

materials, such as finer -SCMs and ultrafine-SCMs, that are being investigated along with different types of fibre to produce fibre reinforced self compacting concrete(FRSCC) for use in fast-track constructions. The development of fibre reinforced concrete (FRC) as a result of research on the integration of disjointed short-length fibres like polypropylene (PP-F), alkali resistant fibre (AR-F), and others gave a significant boost to the use of this concrete for contraction resistance, cracks bridging, and controlling the tensile load carrying flexibility. The performance of FRC is continually being researched by combining alternative groupings of similar fibre materials or fibre groupings of distinct materials. SCMs are highly required for proportioning self-compacting concrete (SCC), since they provide greater quantities of the powder size (0.125 mm size), as necessary to achieve the requisite properties of SCC. Diverse reactive materials being added to the SCC to achieve fast-setting and early-strength as well as the combination of various fibres to give the SCC resistance to shrinkage, crack formation, and the improvement of adequate flexure strength in early-age for early opening of structures. These innovations being made in order to improve the SCC for use in fast-track construction and repair projects. Therefore, this study was based on using total cementitious materials, which include OPC as the main binder, GGBFS as a moderately reactive SCM, MK as a reactive SCM, and NA as a highly reactive SCM, with groups of synthetic fibres AR-F and PP-F, with natural aggregates, and determining the best mix proportions for creating a fast-setting, early-strength SCC recipes. In order to arrive at a proper recipe of fibre reinforced and hybrid fibre reinforced SCC, extensive experiments on various OPC + SCMs + Synthetic Fibre groupings were conducted. SCC characteristics, such as Slump-Flow, 'V'-Funnel $_{\text{Flow Time}}$, L-Box $_{\text{Flow Ratio}}$, Segregation- Resistance, Test to determine time for hardening, and Adiabatic rise temperature studies, were carried out on the proportioned recipes to understand the influence of different combinations of cementitious materials and synthetic fibres, including water demand and chemical admixture demand, for maintaining the desired rheological properties and for achieving the targeted setting time of SCC. Casting cubes, beams, and cylinders allowed for the evaluation of the compressive-strength and split-tensile strength of SCC. On the cast specimen under laboratory conditions, durability tests such as shrinkage, permeability, and resistance to ingression of Cl^- and $SO_3{}^-$ Ions into the body of concrete were also conducted. Beginning with a thorough analysis of two series of SCM mix proportion in a single series of SCC mix (referred to as the SCC_{GMK} series), part replacement of OPC was carried out with 2.50%, 5.00%, 7.50%, 10.00%, 12.50%, 15.00%, 17.50%, and 20.00% of MK and GGBFS fixed at 25.00%.A portion of the OPC in the second series of SCC mix (also known as the SCC_{FMK} series) OPC was replaced by 2.50%, 5.00%, 7.50%, 10.00%, 12.50%, 15.00%, 17.50%, and 20.00% of MK ,flyash(FA) was fixed at 25%. In order to comprehend the synergistic effects of MK with GGBFS and FA, the performance of the SCC_{GMK} series and SCC_{FMK} series were assessed. Based on the findings of this initial investigations, it was determined that the combination of MK+GGBFS is more synergetic than MK+FA. In the second stage of this investigation, OPC was kept at 50% and GGBFS was used for the remaining 50% of the cementitious material in SCC mix (known as SCC_{GM}) in order to determine the ideal % replacement of OPC with combinations of GGBFS+MK, from 5% to 20% of the GGBFS was substituted with MK, and the resulting SCC mix was referred to as SCC_{GM5}, SCC_{GM10}, SCC_{GM15}, and SCC_{GM20}. In this second stage investigation, it was found that combinations of 40% GGBFS+10% MK were more successful at developing SCC mixes with early-strength gaining and fast-setting characteristics in addition maintaining sustainability. In the third stage of the research, 1.00% mono-fibres (AR-F/PP-F) and 1.00% hybrid fibre combinations (AR-F+PP-F) were tested in the optimal blend of 50.00% OPC+40.00% GGBFS+10.00%MK to see how the recipes of AR-F and PP-F affected the attributes of early-strength SCC. $Hy_{FSCCType-1}$ and $Hy_{FSCCType-2}$ are two different varieties of hybrid fibre reinforced SCC (Hy_{FSCC}) mixtures were examined in this third stage research project. The PPF and ARF fibre combinations of 1.00% PP-F+0.00%AR-F, 0.70% PP-F+0.30%AR-F, 0.60% PP-F+0.40%AR-F, and 0.50% PP-F+0.50%AR-F were tested with $Hy_{FSCCType1}$. $Hy_{FSCCType1-A}$, $Hy_{FSCCType1-B}$, $Hy_{FSCCType1-C}$, and $Hy_{FSCCType1-D}$ are the names given to these mixtures. $Hy_{FSCCType2}$ was tried with using PP-F and AR-F fibre combinations like 1.00% AR-F+0.00%PPF, 0.70%ARF+0.30%PPF, and 0.60%ARF+0.40%PPF. $Hy_{FSCCType2-A}$, $Hy_{FSCCType2-B}$, and $Hy_{FSCCType2-C}$ are the names given to these mixtures. This third investigation proved that, in addition to the enhancement in tensile strength at young ages, the optimum mix combinations of 50.00% OPC+40.00% GGBFS+10.00%MK, 0.50% AR-

F+0.5%PP-F, gave good SCC properties The above-mentioned optimum mix combinations were examined further in the fourth stage of the research study by replacing MK with NA in amounts ranging from 0.50% to 3.00% in reverse order, with the goal of maintaining the combined proportion of MK+NA at 10.00%. As a result, six different SCC_{HyFRNA} mixes were created and coded as $SCC_{HyFR-NA0.50}$, $SCC_{HyFR-NA1.00}$, $SCC_{HyFR-NA1.50}$, $SCC_{HyFR-NA2.00}$, $SCC_{HyFR-NA2.50}$, and $SCC_{HyFR-NA3.00}$, respectively, based on the varied NA content as mentioned in the subscript MK with NA in nominal ranges of 0.50% – 3.00% in order to further improve the quickness in reactions for further optimizing the blend. It was determined that the mix failed to function as SCC after adding 2.00% of NA as a partial replacement of MK. The blend $SCC_{HyFR-NA1.00}$, $SCC_{HyFR-NA1.50}$ performed well in lab settings, according to this fourth stage investigation. Accordingly, the mix $SCC_{HyFR-NA1.00}$, $SCC_{HyFR-NA1.50}$ were further studied in field circumstances for durability features including restrained shrinkage, sorptivity, bond strength, abrasion resistance, etc. based on the findings of the fourth stage research study.

Optimised mixture of $SCC_{HyFR-NA1.00}$ and $SCC_{HyFR-NA1.50}$, as well as control SCC, were subjected to XRD, SEM, photomicrographs, and FTIR analyses. The SCC mixes that were optimized, SCCHyFR-$NA_{1.00}$ and $SCC_{HyFR-NA1.50}$, provided better early age strength, elasticity, composite behaviour, impermeability, and robustness. Thus, the mix $SCC_{HyFR-NA1.00}$, $SCC_{HyFR-NA1.50}$ can be employed easily in quick building and maintenance projects where both users and construction organizations value early operating time significantly.

Keywords: MK, NA, AR-F,PP-F, Fast-setting, Early-Strength, XRD, SEM,.


COMPREHENSIVE STUDIES ON FAST SETTING EARLY STRENGTH HYBRID FIBRE REINFORCED SELF COMPACTING CONCRETE
PROMISING MATERIALS
CEMENT(OPC 53 Gr.) + CEMENTITIOUS: (GGBFS+ MK +NA)+ FIBRES :(ARF+PPF)
OPTIMISATION BASED ON STEP 2 & 3
CEMENT(OPC 53 Gr.) -50% + CEMENTITIOUS: (GGBFS(40%) + MK (8% to 10%) +NA(0.5% to 2.0%)) + FIBRES :(ARF 0% to 1%)+PPF(0%) to 1.0%)
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Optimized SCC Mix : Cement(OPC 53 Gr) - 50%
+ Cementitions:
(GGGBFS(40%) + Mk (8.5% To 9.0% +NA(1% To 1.5%))
+ Fibres :(ARF(0.5%)+PPF(0.5%))

TERMINOLOGY

BFS	Blast furnace slag
ITZ	Inter transition zone
GGBFS	Ground granulated blast furnace slag
SiF	Silica fume
CSH	Calcium silicate hydrate
EA	Early age
OPC	Ordinary portland cement
MK	Metakaolin
FY	Financial year
PPF	Poly propylene fibres
MOE	Modulus of elasticity
StF	Steel fibres
MPC	Magnesium phosphate cement
SCC	Self-compacting concrete
CSA	Calcium Sulfo alumina
PCE	Poly carboxylic ether
FSHC	Fast setting high strength concrete
%	Percentage
ASTM	American society for testing materials
CO_2	Carbon dioxide
FWHA	Federal highway administration
<	Less than
ESHPC	Early strength high performance concrete
Al_2O_3	Alumina
SCM	Supplementary cementitious materials
SiO_2	Silica
MAPC	Magnesium ammonium phosphate cement

$CaOH_2$ /CH	Calcium hydroxide
FA	Fly ash
>	Greater than
CAH	Calcium alumino hydrate
RCC	Reinforced concrete
UGGBFS	Ultra fine GROUND GRANULATED BLAST FURNACE SLAG
µm	Micro meter
Fe_3O_4	Ferric oxide
TiO_2	Titanium oxide
nm	Mille meter
C_3S	Tricalcium silicate
FRC	Fibre reinforced concrete
PVAF	Poly vinyl acetate fibre
LSP	Lime stone powder
w/b ratio	Water/binder
RHA	Rice husk ash
HRWRCA	High range water reducing chemical admixtures
LOI	Loss on ignition
$MgSO_4$	Magnesium sulphate
PSD	Particle size distribution
Cl^-	Chloride ion
NVC	Normally vibrated concrete
AW	Alumina waste
$CaCO_3$	Calcium carbonate
NC	Nano-$caco_3$
CNT	Carbon nano tube
CNF	Carbon nano Fibre
CS	Colloidal silica

NS	Nano silica
NF	Nano-ferric oxide
NMK	Nano metakaolin
NM	Nano MGO
StF	Steel fibres
SyF	Synthetic fibres
Gr	Grade
SEM	Scanning electron microscope
M40	Concrete Grade 40 N/mm2
M50	Concrete Grade 50 N/mm2
M60	Concrete Grade 60 N/mm2
MSA	Maximum Size of Aggregate
NC	Standard consistency
IST	Initial setting time
FST	, Final setting time,
IS	Indian standard
Cl.	Clause
CaO	Calcium oxide
SO_3	Sulphur tri oxide
Fe_2O_3	Ferrous oxide
D_{10}	10% diameter size
D_{50}	50% diameter size
D_{90}	90% diameter size
MnO	Manganese oxide
MgO	Magnesium oxide
S	Sulphide sulphur
IR	Insoluble residue
RMC	Ready mix concrete

Na_2O	Sodium oxide
CA	Calcium aluminate
NaOH	Sodium hydroxide
N	Normality
mg	Milligram
ml	Mille litre
Max.	Maximum
Min.	Minimum
DMC	Dry material content
T	Tested value
XRD	X-ray diffraction
Ɵ	Theta
FTIR	Fourier transform infrared spectroscopy
FSESHFRSCC	Fast setting early strength hybrid fibre reinforced self-compacting concrete
SF1	Slump flow category 1
SF2	Slump flow category 2
SF3	Slump flow category 3
cm	Centimetre
SR	Segregation ratio
EFNARC	European federation of national trade associations
MPa	Mega Pascal
MR	Moment of Resistance
MoE	Modulus of Elasticity
EN	European nations
°C	Degree centigrade
g	Grams
kg	Kilo grams
VMA	Viscosity modifying admixture

SSD	Saturated surface dry conditions
NA	Natural aggregates
f_{ck}	Characteristic compressive strength
σ	Stress
GMK	GGBFS+MK
FMK	FA+MK

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CHAPTER 1
INTRODUCTION

1.0 General

This section compacts and outlines the entire intention of thesis featuring the apprehensive problem addressed, requirement for exploration and challenges encountered throughout the research advancement. This research study was focused towards utilisation of larger quantities of industrial waste co-product materials from steel manufacturing industry i.e. blast furnace slag(BFS) which after mechanical processing by grinding, in ball mills, turns in to powder form known as pulverized blast furnace slag (popularly known as GGBFS). Such types of industrial co-products depending upon its chemical nature ,will exhibit moderate pozzolonic reaction properties i.e. reasonably reacts with cement hydration products to form secondary CSH gel(binding media) and proved to improve durability in addition to yield sustainable concrete,when incorporated in ordinary portland cement(OPC) as limited addition. There occur other fine sized potential materials like metakaolin, ultrafine slags, silica fume etc., which possessing high pozzolonic properties and can contribute a definite role when blended with moderately reactive materials like GGBFS in formulating tailor made concrete recipes for use in fast track concrete construction activities as well as for speedy repair of aged and distressed concrete structures. Lacs of tonnes of such moderately reactive pozzolonic materials is lying in huge mounds in the vicinity of steel manufacturing plants and other such vicinities all over the world which, otherwise if unutilised properly, can pose challenges to the environment.

1.1 Research Background

Over the previous time spans, infrastructure expansion accomplishments have charted the use of huge quantities of the popular construction material 'concrete'. India retains second position in production of cement, amongst all the global producers of Cement. India's Cement production during year 2022 increased by approximately 20.30% as compared to the cement production during the year 2021[1-2].This surge in cement consumption has established ample intensification for required sustainable observances for producing concrete for various construction infrastructures thus triggering the need for more customised concrete recipes to style the concrete as sustainable as practicable for various uses including for the fast track construction ,early opening to users for functionalising the constructed infrastructure as well as the rehabilitation projects to continue all such infrastructure in a serviceable form. Individualities of concrete material-like feasible mouldable form for easy management, constructability, effortlessness production using nearby accessible local constituents, development of sufficient mechanical strength, elastic properties (MoE)etc., has securely augmented per capita consumption of concrete material over past half century. Plea for swift construction solutions from infrastructure construction related agencies, motivated the existing exploration steadily pointing from performance oriented concrete recipe to tailor made concrete recipe yielding quick hardening, strength gaining- at early ages and consequential for early utilisation of infrastructure viz. air field pavements, highways, bridges, repaired stretches etc., among other things, in order to make them functional at the earliest time.

This is due to logical factors such as competency, user convenience, socio-economic considerations and others. Constant advances in concrete material technologies and building procedures ensuring responsiveness for meeting the demands of the construction sector like quick hardening strength gaining at early ages resulting timely utilisation of infrastructure facilities by the users. It is well known that during the first 3 days of time, after casting of concrete ,traditional concrete recipe prepared only with OPC accomplishes about 50% of the intended strength, relying on the resourceful of construction and operational curing practices, whereas blended concrete mix recipes incorporating the presence of moderately reactive mineral admixtures like flyash, GGBFS etc., requires, a little longer time of curing as it proceeds, seven to fourteen days to reach the same strength as OPC concrete reaches in three days. These practices of deferments in obtaining strengths of concrete in the initial ages in concrete are regarded as a stumbling block for realising the building evolution due to less use of repletion cycles formworks- affecting economy, thereby delaying the operation of the infrastructure to users, precast construction industries, and so on. As a result, several researchers have concentrated their efforts on novelties and enhancements to material knowledge in all spheres of suitable materials like exploring promising industrial wastes –as mineral additives and fine-tuned chemistry of chemical additives, stretching from the micro scale to the nano-scales in order to fashion concrete recipe meeting set economic criteria of construction industry for satisfying age related strength and long lasting nature of construction projects [3-6].

It was highlighted in many of the reports that projects which were built, all over the world, over the last half-century are deteriorating for a variety of reasons, necessitating high stakes for individual maintenance such as surface repairs, partial depth remedies, rehabilitation, renovation, restoration, and so on, in order to sphere them in extendable service life conditions. As a result, rehabilitation of projects- a critical motivator for economical reuse of distressed projects,emphasizing preservation, roaring dependable repairs to prolong the serviceable life of buildings while minimizing costs and time delays [7]. As evident from various literatures, with the passage of age, concrete material deteriorates -when exposed to various environmental elements such as weather and rolling loads, making restoration difficult for early openings and shortening closure durations while maintenance of air field pavements, highways, bridges, repaired stretches which necessitates planned repair strategies to eliminate movement barriers and slowdowns or total obstructions. Figures 1.1–1.4 depict typical CC Pavement failures.

It was determined that though the patented or commercial swift strength developing repair materials available, but these materials fail to provide durability of repaired elements. Economising the cost of materials, intended for repair, has been the subject of on-going research. Revolutionary materials like Magnesium Phosphate Cement (MPC), Calcium Sulpho Aluminate Cement (CSAC), and others have been thoroughly investigated over the time with the hope of exploring their characteristics and performances as fast setting early strength gaining repair materials[8].In a bid to improve the durability of concrete mixes incorporated with the above said revolutionary materials, research has looked at various conceptions such as: use of fibre reinforcements, the assimilation of nano-sized materials to strengthen the microstructure of compounds based on cementitious properties, the assimilation of microorganisms as self-healing of cracks, creating mechanisms for interior hydration needs - avoiding conventional curing practices for concrete elements , quick strength yielding alumina rich materials[9].

Figures showing the failure of Concrete Pavements

Fig.1.1 Cracking and Failure of CC Pavement at Bust Terminal

Fig.1.2 Failure of CC Pavement at Toll Plaza

Fig.1.3 Failure of CC Pavement in a National Highway

Fig.1.4 Failure of CC Pavement in urban area

From the considerations presented above, it is clear that delays in the repair of CC roadways becoming less and less accepted due to the ever-increasing traffic volume, and the obligation to carry out early repair sections becoming greater and greater, as in the case of user fee collecting road stretches, busy urban roads, etc., Thus there required a mandate for concrete able to result a compressive strength of > 15 N/mm^2 and a tensile strength of > 1.8 N/mm^2 in the first 24 hours after adding water to the cement, the qualification standard set by the FWHA in 2003 [10], for the quality of the building concrete, when buildings are opened so early. Concrete for rapid repair work should meet the mandatory minimum strength requirements so that it can be opened to the user group early before being used to reopen the structures, e.g. such as buildings for public use, sidewalks, bridges for road traffic, etc., This has become an essential inspiration for the selection of repair materials. Therefore, a systematic understanding of perceptible influencing factors such as the nature of Cement, Water/Cement or Water/Cementitious material (cm), type of additives, pozzolonic material additives required. To verify the attainment of strength at nascent ages after concrete pouring, literature has demonstrated that alumina rich cements has the advantages of high early strength, short setting time, impermeability, resistance to sulphate, chloride penetration and corrosion formation as compared with ordinary Portland Cement (OPC). Higher cost, not readily availability in open markets and failing to yield durable repairs observed to be the obvious disadvantage of this type of trademarked materials. This has led researchers to explore new alternative materials, either as partial or complete replacements for these more expensive products.

There are increasingly higher requirements for the economic viability of investments made in construction of infrastructure projects and thus the demand for high strength and robustness of concrete when positioning modern infrastructures, a vital life line for the economic prosperity of society. However, the control concrete made only with OPC proved to be difficult for meeting these requirements. Compared to the control concrete innovative material proportions were advocated for meeting the speedy construction activities[11].Exploration of new types of potential highly reactive additional cementitious materials (SCMs) for incorporation into concrete systems has confidence in these materials and hence materials such as metakaolin, ultrafine ground granulated blast furnace slag, microsilica, Nano- mineral additives such as nano-alumina, nano-clay etc. are becoming more and more popular[12].Refinement of concrete microstructure using nanoparticles and other potential materials revealed the development of a densified material. Over the past several years, with the expansion of research, the nanomaterial cost decreased and the market availability of the same has prompted the use of nano material based cement composites in the construction field. Incorporating various materials ,as partial replacement in OPC, such as metakaolin, ultra-fine ground blast furnace slag, microsilica, nano-mineral admixtures such as nano-alumina, nano-clay into conventional, binary blended, ternary blended cements like MAPC etc., proved to yield recipe of concrete for meeting strengths at nascent ages after pouring of concrete [13]. Previous studies have also shown that the use of polypropylene fibres, glass fibres and steel fibres in either mono-combinations or hybrid combinations as elastic concrete components and the use of these fibres results in an increase in concrete tensile strength [14–15]. Therefore, taking into account the above, the research on quick-setting concrete for rapid track construction of structures and repair of CC pavements, bridge structures, etc. is formulated with the following research objectives:

1.2 Scope of Research Work

To improve the early age properties of concrete in a sustainable way through partial replacement of OPC by blends of moderately reactive SCMs such as GGBFS, Flyash; Highly reactive SCMs such as metakaolin, ultrafine ground granulated blast furnace slag, microsilica, superfine SCMs such as Nano- mineral admixtures such as nano-alumina, nano-clay, as well as the use of polypropylene fibres and alkali-resistant glass fibres in either mono-combinations or hybrid combinations- wherein synergy amongst the material combinations,can be investigated. One of the greatest challenges of our civilization today is protecting the environment and adhering to sustainable guidelines in the construction, rehabilitation and maintenance of infrastructure facilities for their robustness [16–18]. Key features of this award include reducing energy consumption, using industrial by-products as sustainable building materials and using self-compacting concrete (SCC) wherever practical and feasible. Industrial by-products such as moderately reactive SCMs, i.e. GGBFS, fly ash etc., highly reactive SCMs viz. Metakaolin, ultrafine GGBFS, etc. have so far been used as partial replacements in various SCC blend formulations. However, though the behaviour of the above SCM types has been studied by various researchers in the past,their combined effect on SCC has not been studied in detail.

Therefore, in this research work is endeavoured:

1) To develop fast-setting, early-strength SCC recipe with the combinations of OPC in the order of 50-75%, Moderately reactive SCMs in higher proportions in the order of 25-40%, Highly reactive SCMs in the order of 5-25%, nano-alumina in the order of 0.5-3% and hybrid combinations of fibres in the order of 0.5-3%.

2) Evaluate fresh state properties of SCC as prepared by (1) above.

3) Evaluate properties of above SCC in the cured state such as compressive strength, splitting tensile strength etc.,

4) Evaluate durability properties of above SCC

1.3 Research Objectives

1. Development of mix ratios of fast-setting, early-strength, hybrid fibre-reinforced, self-compacting concrete mix for fast track construction works like repair of CC pavements and bridge decks.

2. To investigate the mechanical properties of fast-setting, early-strength, hybrid fibre-reinforced, self-compacting concrete for fast track construction works like repair of CC pavements and bridge decks.

3. To determine the durability properties of fast-setting, early-strength, hybrid-fibre-reinforced, self-compacting concrete.

4. To conduct field studies on a fast-setting, early-strength, hybrid fibre-reinforced, self-compacting concrete mix

1.4 Proposed Methodology:

Taking into account the objectives set out in 1.3 above, the present research was divided into four phases as listed below.

Phase I: Formulation of recipe for fast setting early-strength self compacting concrete improved by hybrid combinations of fibres.

Phase II: Investigation of the characteristics of recipe derived in Phase I above.

Phase III: Conduct durability studies of recipe derived in Phase I above.

Phase IV: Conducting field studies of recipe derived in Phase I above

1.5 Outline of Chapters

This thesis comprises of 9 (nine) Chapters and the same has been drafted to fulfil the major objectives of research. The chapter contents are summarized in the paragraphs given below.

Chapter 2 consist a detailed literature study on the research that has been done on the influence of various materials and combinations on various fresh state and hardened state properties of SCC mix upon incorporation of various types of SCMs like moderately reactive SCMs, high reactive SCMs, super fine SCMs and also due to the integration of different types of fibres into SCC. The research has been reckoned in consecutive direction captivating the up-to-date outcomes first and a comprehensive summary has been organized after analysing the inclinations which were majorly perceptible.

Chapter 3 consists of various materials identified for the envisioned research study and their characteristics using relevant Indian standards and other International standards.

Chapter 4 emphasises on the methodology that being used in accomplishment of the comprehensive research study arrangements and the various Indian standards, ASTM standards and other International standards being used for completion of the experiments under standard methodology.

Chapter 5 consists of various experiments carried out in this research in laboratory, with experimental study values observed, and discussions on the consequences as observed in various investigations in laboratory tests like fresh state properties, mechanical strength, robustness i.e. durability studies and microstructure study and for arriving to the mix proportions for carrying field investigations.

Chapter 6 consists of various experiments carried out in this research in filed and discussions on the consequences as observed in various field investigations like bond strength, shrinkage, durability studies.

Chapter 7 recapitulates the entire research study into definite opinions and provisions on the findings.

Chapter 8 presents outcome of study and conclusions drawn from the study.

Chapter 9 includes impending opportunity of further study that means the auxiliary research that can be carried by other interested researchers.

CHAPTER 2

LITERATURE REVIEW

2.0 General

In the last few decades, infrastructure development measures have taken place around the world, which has led to an enormous use of cement concrete(CC) which has good compressive strength, but weak tensile strength and therefore cracks whenever its tensile strength exceeds the specified tensile loads. Additionally, there are numerous explanations that can lead to cracks in concrete. Cracking in concrete therefore an issue of great concern in infrastructure construction. Apart from the natural disasters that affect the lifespan of concrete, the corrosion induced distress, different modes of shrinkage, freeze-thaw cycles, poor workmanship, construction practices, etc. also affect the durability and thereby shorten the lifespan of concrete [19]. Such a decrease in concrete durability often requires repair of damaged sections [20]. The increasing renovation, retrofitting and repair costs of aged concrete structures are a matter of concern for all stakeholders in the infrastructure sectors of highly developed, developing and underdeveloped countries around the world [21]. Therefore, this approach is long-lasting and exceptional. The performance of repair materials is particularly ensured for the sustainability of high traffic volumes with different structures such as bridges, sidewalks, toll booths, parking lots, airport taxiways, runways, etc.[22]. The basic requirement for a superlative repair material is therefore that it has properties such as free-flowing properties, which show self-compaction, show rapid setting and achieve high strength at a young age in heavily stressed structures with high traffic volumes [19,23], where the repair/maintenance is usually completed during the night time so that the structure/structures can be put back into use at rush hour the next morning, i.e. in less than 16 hours to 24 hours or so from the time the structure closed for guaranteed repairs/maintenance[24]. In addition, high early strength – a mandatory pre requisite material property for concrete repair, but leads to an increase in the elastic modulus and increasing the brittleness of the material, resulting in crack progression [25]. Repairs made with conservative materials are prone to cracking (virtually half of repeated concrete repairs fail due to this practice) [26]. In addition to premature crack formation in repair materials with high early strength, cracks also occur due to autogenous shrinkage [27]. Fluctuations in thermal gradients are one of the biggest problems for the robustness of repair materials [28]. Therefore, the crucial intent of Fast Track Concrete Construction and Repair Material remains essentially to have self-compaction to easily occupy every nook and corner of the formwork, even in the narrower places where the reinforcement obstructs concrete flow, and for betterment of age related mechanical properties at nascent age [29], showing sufficient flexural strength [30,31] and compensation for the development of cracks caused by the possession of different shrinkage mechanisms [32]. Furthermore, high early strength of concrete leads to a reduction in ductility due to altered paste maturity and its detrimental effects on the intermediate transition zone (ITZ)[33]. Furthermore, altered early compressive strength can lead to cracks caused by various types of shrinkage [34]. Therefore, over the years, several researchers motivated their research studies on fast-setting and high-strength concrete mix proportions for rapid track construction and repair and published vivid confirmations on the dosage of sustainable concrete/mortar matrix for rapid track construction and repair using numerous methods such as the partial replacement of OPC by medium to high fine SCMs such as fly ash (FA), GGBFS, silica fume (SiF)[35]. Besides this the combination of blends of flexible fibres, i.e. Hybrid fibres, admixed in CC or cement mortar(CM), noticeably advances structural behaviour against imposed loads [36]. Therefore, a comprehensive study of the previous scholarships of various researchers around the world was conducted and presented in this chapter. It was found that significant developments will occur in micro-scale in concrete during the hydration process, especially during the first 24 hours [37]and includes the changing phases from workable state to hard phase. Therefore, the properties of concrete in the immediate hard phase are now considered as a strategic point in the further development of cement-based materials, as they make it possible to predict the material effect in the hardened state and over long periods of time,when the concrete is properly cured [38-40]. Early properties of concrete to be modified experimentally through the inclusion of highly reactive SCMs coupled with moderately reactive SCMs ,as fractional substitution in OPC, are slowly gaining traction in the research community as the results of such inclusions have improved early aging performance of concrete in terms of on the performance of concrete containing only moderately reactive SCMs as a partial replacement of OPC. Therefore, motivation of researchers diverted towards the highly reactive SCM, Metakaolin (MK)- an industrial product prepared by thermal activation of clays, rich in aluminosilicates, ranging from 650^0–900^0C under certain conditions, yielding high pozzolonic potential material[41-43].Calcination of kaolinite clays(rich in aluminosilicates) helps breakdown the structure of clays, stripping away OH ions thus creating panes bearing Si-Al consequently resulting powdery material possessing high reactive characteristics ,known as MK [44]. Thus, due to it high reactiveness, MK steadily acquiring its place, in construction field, as a highly inventive pozzolana, as it reacts quickly with the excess calcium hydroxide that is a result of the hydration of Cement thereby causing advancement in the strength and densifying the interior microstructure of concrete[45]. The literature also illustrates that the use of nanoparticles in a small proportion of 1–5% of the cement weight in concrete densifies the concrete by occupying the pore spaces besides advancing the strengths. Nanoparticles have been proven to accelerate the hydration reactions due to its high surface area.[46]. It has also been found that the use of highly reactive SCMs such as metakaolin, ultrafine GGBFS, micro silica, etc. and various nano-sized materials such as nano-alumina, nano-silica, nano-clay, etc. results in long-lasting concrete[47].Improved results such as splitting tensile strength, shrinkage resistance and abrasion resistance have also been achieved by using various fibres such as alkali-resistant glass fibres(ARG-F), polypropylene fibres(PP-F) and steel fibres(St-F) in mono combinations or in hybrid combinations, from same fibres in different sizes or different fibres, in Concrete[48]. In the mid-1980s, self-compacting concrete (SCC), made from larger quantities of required cement and cementitious materials (binding materials), was developed in Japan to overcome the shortages in the availability of trained labour for concrete construction activities, using OPC as well as the SCMs as a partial replacement of OPC, low amount of coarse aggregates, high amount of fine aggregates and tailor-made chemical additives [49]. SCC's development has fashioned the concrete technology towards encouraging the use of higher quantities of fine sized industrial waste by products like fly ash, various slags etc., and indirectly ensuring low carbon footprint oriented sustainable constructions [50].The prospect of applying combinations of the above moderately reactive and highly reactive SCMs, nanomaterial and fibres in mono or hybrid combinations for improved performance of SCC in early life was identified through an extensive literature review on the subject. The above materials are presented below and discussed.

2.1 Literature review on the role of SCMs in concrete sustainability

All over the past century urbanization, constant population growth etc., has occasioned in the widely used promising construction material, concrete, for all types of infrastructure projects. There stands a constant demand from law enforcement agencies and environmental organizations to practice sustainable engineering in the production of cement, right from extraction of raw ingredients, preparation of raw meal (significant fossil fuel absorption),fashioning the production process ,lowering down the energy and resource materials needs etc.,[51]. It has been estimated that half of the cement produced used in concrete recipe and other half finds its consumption such as masonry mortars, producing masonry units, plastering, etc. It was predicted that by year 2030 the Global production of cement, annually, might reach approximately 5.00 billion tonnes[52], driven by the expansion of numerous concrete-related industries[53] and thus entails significant environmental impacts that need to be urgently mitigated [54].Since then, improving the sustainability of concrete has become a primary concern of researchers around the world. The majority of the binder components of concrete consist of OPC, production of which remains emitting significant greenhouse gases(CO_2 etc.,)in to the atmosphere. Across the world, current CO_2 emissions from cement production have been forecast to be in the region of 58% and are expected to increase in the near future due to a similar trend towards increased use of concrete in construction activities.Though ,over the recent decades, noticeable changes made towards the sustainable production process of Cement[55-58] stands yielding results towards sustainability but, the same is overtaken by the sharp increase in demand ,all over the world, of Cement for building various infrastructure projects. Further progress stands imperative to lessen the ecological influences and expenses associated with the use of OPC[59].There stands a critical need to evolve recipe of concrete with lower OPC to ensure eco-friendliness of building materials associating with OPC[60]. Recently, attempts have been made to achieve eco-friendliness in concrete through optimization by fashioning the concrete recipe incorporating tailor-made chemical additives[61].In addition, improvements through obvious admixture of appropriate potential materials SCMs such as slag, fly ash, etc. to partially replace the OPC. However, since these high-quality SCMs remain in-sufficient ,as they are not specifically manufactured, as they are only the by-products of the industry and their availability remains site-specific but not available worldwide [54,57]. The construction industry therefore remains faced with many problems arising from the harmfulness of released CO_2 discharges associated during the production of cement, mining of precious rare materials, depletion of the same with time, as well as the increased cost of production [62].Thus in order to have a brief account of SCMs role in concrete construction, summary of the literature review on the role of SCMs in sustainability in concrete construction is presented in Table 2.1.

2.2 Literature Review on role of popular SCMs –GGBFS and Flyash in Sustainable Concrete Practices

Continuing the ponderings of section 2.1 wherein, SCMs role in fashioning the concrete recipe discussed, a brief deliberations of popular SCMs i.e. GGBFS and Flyash towards ensuring the sustainability of constructions is presented in this section. GGBFS-a by-product of production of steel making industry, having appealing chemistry rich in calcium and aluminates [63]. Though, the reduction of strength at nascent age of concrete admixed partially with GGBFS ,its appealed result of less water demand for workable concrete as compared to OPC concrete, densification resulted through refined pore sizes fashioning impermeable concrete etc ,encourages its use widely in concrete construction in harsh environments like marine areas [64-65]. Fly ash (FA), an industrial byproduct derived from thermal power plants, has been used as SCM in various types of concrete in recent decades. Over the last three decades literature has revealed that the use of FAs as a partial replacement of OPC has been proven effective, in yielding sustainable solutions, to construction sector due to its chemical nature and refinement nature [66]. The incorporation of FA into SCC reduces the water requirement for processing due to its spherical shape, thus improving its rheological properties, reducing bleeding and also improving the curing properties [67], however the observed strength gain remains slower compared to control mixes prepared with OPC [51]. Thus in order to have a brief account of SCMs role in concrete , summary of the literature review on the role of popular SCMs i.e. GGBFS and FA in sustainability in concrete construction is presented in Table 2.2.

2.3 Literature review on the role of SCMs in self-compacting concrete (SCC)

Continuing the reflections of section 2.2, wherein GGBFS and FA's role in shaping the concrete recipe was discussed, a brief deliberations of significance of SCMs in nurturing the SCC made in this section. In the recent decades concrete technology has seen many significant changes right from conventional recipe to SCC recipe, which doesn't warrant any external vibration for compaction [68]. SCC results in an aesthetically pleasing surface finish that stands intended to increase both the speed of construction and the quality of the concrete [69]. SCC uses bulk powder materials (size < 125 microns) -industrial by-products such as FA, GGBFS, microsilica (MS), etc. with potential pozzolanic properties [70]. Addition of these pozzolanas as a fraction of OPC results not only sustainable concrete but also ensures durable concrete by advancing proper dispersion of fine sized pozzolana in the entire concrete uniformly ,refinement of ITZ, development of resistance against aggressive environments etc[71-75]. Thus in order to have a brief account of SCMs role in realisation of SCC recipe , a summary of the literature review on the role of SCMs in tailoring the concrete mix towards self compacting presented in Table 2.3.

2.4 Literature Review on Synergy of Metakaolin (MK) and Ultrafine slags (UFS) in early strength SCC

In continuation of the views as deliberated in section 2.3, where significance of SCMs in nurturing the SCC was briefed, a short discussion on the reactive SCMs like MK,UFS is discussed in this section. The availability of variety of alternative source materials for cement manufacturing as well as the increasing awareness and demand from regulators worldwide for reducing CO_2 emissions from cement manufacturing plants, forcing the cement manufacturing units to take appropriate actions towards reduced carbon footprints [76].As developing countries undergo rapid urbanization to meet the population's increasing need for basic amenities [77] the demand for concrete in turn increases and hence the consumption of the requirement more and more cement and thus an increase in CO_2 emissions into the environment [78]. The strength of concrete can be increased at early ages by tailormade recipe using the appropriate blends of SCMs and reactive SCMs to enable the concrete suitable for use in rapid construction and repair works[79] .Prompting economic efficiency in project related operations ,to achieve handsome gains on the invested financial resources in the construction of these infrastructure facilities in a short period of time etc are the reasons for early operation of projects [80].Accordingly, there remains an increasing inclination to treasure various part substitutions of OPC from domestic bases [81].Recently, it has been observed that clays, rich in alumino-silicates, gaining as promising a possibility for SCM due to its lower cost, more environmentally friendliness [80-85]. It was found that the hydration by-product $CaOH_2$ (referred to as CH) formed when cement reacts with water negatively effects the properties in long term. Silica and aluminium oxide react with such CH resulting in durable concrete [86]. Quite a few studies found a contrary relationship between the amount of CH and the degree of substitution of MK in relation to the curing time. The pozzolonic products of MK formed by partially substituted cement replacement depend on the reaction temperature, chemical composition of MK and its calcination method [87]. In relevant study on the effectiveness of MK over SiF, it was revealed that chemical nature of MK has prompted high reactiveness equivalent to that of SiF [88-89]. In addition, CO_2 emissions per ton of cement produced should decrease during manufacturing in various tolerable situations, especially in emerging countries, as concrete utilisation continues to increase [90]. Some of the proposed resolutions concerned the reduction of release of greenhouse gases into the atmosphere by admixing possible proportion of aluminosilicate rich clays whose reserves found to be abundant [91]. Increasing the durability of reinforced concrete structures (RCC) is being intensively researched worldwide. Despite all durability concerns, feasible mitigation of corrosion induced distress in RCC remains to be one of the greatest challenges to the researchers [92]. The integration of SCMs into concrete has been witnessed as the responses to improve the resistance against corrosion. In recent decades, synergistic influence of using highly reactive SCMs such as MK, SiF, etc. and other moderately reactive SCMs such as FA, GGBFS, etc. has been studied in numerous cases. Therefore, to counteract undesirable effects of integration of moderately reactive SCMs, higher reactive SCMs such as SiF and MK need to be used with combination of moderately reactive SCMs in a bid to compensate the demerits of moderately reactive SCMs [93]. Use of MK with FA etc other, not so expensive SCMs , reduces the cost of concrete mix while improving the properties [94]. Previous studies focused on ways to increase strength by means of ultrafine SCMs incorporation in formulating recipe [95-96] and similarly judged the durability against aggressive exposure conditions through a set of laboratory scale experiments[97].It was demonstrated that up to 1/5th replacement level OPC with MK, capillary rise ,a key durability index, of regular concrete increased against control samples. Similarly in line with the above observation another study[98] revealed that 1/10th level replacement of OPC with MK ,the sorptivity, permeation etc durability indices reduced as compared to control samples [99] but this outcome stands contradictory to the disclosure made vide study[100] wherein at the replacement level of 1/7th proportion of OPC with MK increased the sorptivity. Also, in another study it was declared that permeability reduced by 1/2 when 1/5th part of OPC was replaced with MK as judged against permeability of controlled samples[101], which again stands in difference to the consequences of a study[102] wherein the 1/7th level replacement of OPC with MK was mentioned as the maximum limit or threshold point for attaining advantageous durability results .Above all, these scholarships on the part insertion of MK in to the OPC exhibited an advancement in the seasoning behaviour of cementitious system at nascent ages[103], whereas MK in combination with the GGBFS insertion along with fly ash ,as part proportion of OPC ,displayed an upgrading in the rheological behaviour besides a constant strength advancement [104]. In former scholarships on replacement levels of GGBFS, FA, MK in OPC's cementitious systems, most scholars restricted their consideration to a partial number of test parameters [105] in freshly mixed state and hydration reactions stage. Besides MK, there also exists another capable ultrafine SCM material resulting from the fine grinding of GGBFS - known as ultrafine GGBFS (UGGBFS). UGGBFS has recently attracted the attention of various researchers because it develops early-strength concrete mixes and is slowly gaining importance in the construction field[106]. UGGBFS has similar chemical properties to GGBFS, but has a cumulative particle size (d_{80}) of 80% below 10microns, compared to d_{80} of conventional GGBFS, which is generally on the order of 60microns [107–109]. Through literature review, it was found that several research works were conducted to study the performance of MK,GGBFS in both conventional concrete and SCC, fresh state, cured state and durability properties[69,110] and found that the installation of MK is ultrafine. The material in the above-mentioned cementitious system was beneficial for shortening the setting time as well as improving the strength of concrete at early age [111–113]. Therefore, there is still a wide scope of research to fill the research gaps in the use of MK association with GGBFS or FA in SCC mixtures and also influence of MK in such SCC on rheological properties in fresh state, mechanical properties in cured state as well as durability properties in different environments, simulated at laboratory scale, to evaluate the role of MK in producing robust SCC mixtures. Thus in order to have a brief account of synergy of MK and UGGBFS on SCC recipe and its behaviour , a summary of the literature review displayed in Table 2.4.

2.5 Literature Review on Effect of Various Nano Materials in SCC

In extension of the interpretations as considered in section 2.4 ,where synergetic effects of MK and UGGBFS was discussed in influencing the SCC characteristics, a brief account is made in this section regarding the other promising materials which remains as the miniature forms of the materials reduced to nano-scale ,popularly called as nano materials . Continuous research on the integration of nano-mineral materials into concrete mixtures has created confidence in nano-materials and therefore in the use of nano sized materials, namely nano-silicon oxide, nanoalumina, nanotubes, nano sized limestone powder, nano sized Fe_3O_4, nano-sized TiO_2, nano sized Fly ash, nano sized metakaolin, etc. these days staying increasingly popular [114].Current research has shifted its focus towards nanotechnology due to great advancement of nano technology resulting the production of nano sized materials of the order 10^{-9} m wherein it was demonstrated thoroughly that as these reduced materials behaves differently to the advantage compared to the parent materials of micro scale or milli- scale. In this way, numerous industries could reengineer many prevailing goods and advance new and pioneering goods that accomplish at unparalleled echelons [115]. Nearly 5 decades past the innovation started to begin in the material science pioneering the size reduction of micro sized and milli sized materials to nano sized materials- which have great surface area compared to their parent materials [116] and thus attracted devotion of research fraternity significantly towards betterment of application based technologies [117]. In recent decades, nanomaterials focusing on their exceptional nanometre properties have shown promising performances in the fields of defence, electronics, industry, space technology etc[118].Nanoparticles of 4 nm demonstrates higher reactivity due to the availability , accounting to ½ of the total particles ,of the molecules in the outer region [119].In a study regarding the combinations of OPC+FA+Nano Silica, it was pragmatic that the available free water stands reduced, over control samples ,by the larger surface area of nano sized particles causing improved properties where acceleration of hydration reactions occurred[120-121]and these acceleration of hydration reactions are comparable to the study on 0.3% of CSH seeds incorporated fractional replacement of OPC[122].Microstructural development studies using the advance instrumentation techniques like SEM,EDAX etc proved to be handy for arriving to an agreeable conclusion for the acceleration effects of nano sized materials over the conventional blend as well as the binary and ternary blends using OPC+SCMs[123-124]. The market place availability of the nano sized materials, though in limited quantities, in the past decade due to the advent of newer material reduction technics has prompted the researchers to ponder for the various ways and means to improve the conventional concrete recipe advanced with these nano sized materials [125-126]. Accordingly in order to have an ephemeral account of influential advantages of nano sized material incorporation in concrete a summary of literature review of the same is presented in Table 2.5.

2.6 Literature Review on Effect of Various Fibres in SCC

In allowance of the elucidations as well-thought-out in section 2.5 ,where influential effects of various nano sized materials on the characteristics of concrete were revealed, a short-term justification made in this section concerning the effects of various fibres on the characteristics of concrete. Discrete reinforcement in the form of fibres when incorporated into the cementitious system, leading to fibre reinforced concrete(FRC), proved to improve the tensile properties which the conventional PCC couldn't alone demonstrate [127-129]. Besides steel fibres, other forms of synthetic fibres and natural fibres were also investigated for their influential effect upon incorporation in cementitious system and the results of the same demonstrated near equal influence on tensile properties of concrete when compared to the steel fibre incorporation [130-131] but due care to be taken to make the resulting concrete workable by using tailor-made super plasticising chemical additives. It was revealed in a study that long fibre, inclusion in concrete, somewhat improved the flexural strength and not the split tensile strength[132].This remains opposing to the results of studies [133-135] where split tensile strength was also observed to be increased. Beside this, it was also documented in a study [130-132] that superior performance noticed when hooked end steel fibres, admixing in concrete, as compared to typical steel fibres admixed concrete due to the anchorage effect exhibited by the hooked end steel fibres. It was also pronounced in literature that, volumetric ratio of fibre incorporation comparably advances the flexural behaviour of concrete [133]. It was also enunciated in corresponding literature that similar to the steel reinforcement corrosion ,discrete steel fibres in concrete also suffers the same distress[134]. Researchers were also turned their attention towards blending of long and short fibres for investigating the synergetic effect, of this hybrid blends of fibres, on flexural strength and shrinkage behaviour both in macro and micro scale [135-138]. Consequently to have a transient version of dominant recompenses of fibre inclusion in concrete system either in mono or hybrid blends an instantaneous equivalent briefing of literature review is presented in Table 2.6.

Table 2.1
Summary of Literature Review on role of SCMs in Sustainability of Concrete Constructions

Ref. No.	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[51]	2002	Mehta	Flyash (FA)	Quality of FA on concrete properties	• Urbanisation occurred during the past decades, around the world, depleted precious natural resources but resulted in mounds of industrial wastes like flyash. • Good quality fly ash acts as plasticizing admixture and hence reduces water demand for workable concrete mix	Spherical shape and the smooth surface of fly ash particles helps to lessens the inter-particle friction facilitating mobility in the mix
[52]	2014	Wongkeo, W et.al	Flyash (FA)	Workability, Early age strength development	Incorporation of FA in SCC improved the slump flow but no improvement in compressive strength.	For improvement in early age compressive strength of concrete consisting of moderately reactive SCMs viz. FA, other reactive SCMs, in lesser proportions, need to be incorporated along with moderately reactive SCMS.
[53] [54]	2016 2010	Castellano , C. et.al Khokhar, et.al	SCM	Proportion of Water/Binder effects on early age strength of concrete	For workable mixes ,the lower the w/b, the higher will be the early age strength	It is crucial to select compatible HRWRCA for achieving SCC mix characteristics.

Ref. No.	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[55]	2019	Tang, J et.al	LSP, MK	Effect of LSP on properties of concrete	MK particles of dia. 0.7 µm and LSP particles of dia. 3 µm were observed to play major role in early age reactions	10% of MK observed to be an optimum replacement of OPC for gaining early age strength
[56]	2019	Woodall, C. M et.al	Flyash (FA)	Effect of combination of FA and nano additives on properties of concrete	Part replacement of OPC with combination of fly ash and nano additives observed to improve the ecology by the way of saving the energy and consumption of industrial wastes in construction activities	Part replacement of OPC with SMCs results in decrease of the energy ingestion associated with production of concrete
[57]	2008	Safiuddin, M	Rice Husk Ash (RHA)	Workability, Compressive strength, W/b effects	RHA , Reactive SCM , integration up to 15% in SCC results in higher early age compressive strength as well as consequences improved durability by virtue due to higher fineness of RHA aiding pore refinement.	Low w/b ratio to the order of 0.30 to 0.35 to be maintained for achieving early strength as well as durability for SCMs incorporated SCC mix.
[58]	2014	Arivalagan, S et.al	GGBFS	Workability, nascent age strength, Durability	GGBFS addition level up to 40% does not significantly effects the strength at 28days with reference to concrete without any GGBFS.	Use of other reactive SCMs ,in lesser proportions, need to be incorporated along with moderately reactive SCMs viz. GGBFS.

Ref. No.	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[59]	2022	Tahwia, A. M et.al	GGBFS	Effect of GGBFS on concrete properties	Gaining of strength observed to be slow upon the integration of SCMs like GBFS, as part replacement of OPC in concrete	Activators like high reactive SCMs viz., MK,SF,RHA in combination of moderately reactive SCMs is the possible solution for gaining early strengths
[60]	2021	Amran, M et.al	Rice husk ash	Different types of shrinkages	SCMs assimilation in SCC in higher proportions prompts higher shrinkage compared to control SCC mix without any SCM.	In order to achieve sustainability in SCC mix, SCMs integration as part replacement of OPC is obligatory. Hence other shrinkage mitigating practices like inclusion of fibres /proper mix proportioning/lower w/b or a combination of same etc. to be implemented.
[61]	2012	Hannesson , G et.al	Flyash, slag	SCMs fineness and chemical composition	SCMs fineness and chemical composition are crucial for development of properties at early and later periods .	While using higher fineness of SCMs in SCC, HRWRCA be used for ensuring lower w/b, meeting SCC characteristics, eliminating segregation, bleeding and for ensuring durability of SCC.
[62]	2003	John, V. M	SCMs	OPC replacement, CO_2 emissions	For achieving sustainability in concrete, pozzolans i.e. SCMs to be used as part replacement of OPC.	For achieving higher early age compressive strengths in SCC mix, other reactive SCMs, in lesser proportions, need to be incorporated along with moderately reactive SCMs but still ensuring sustainability.

Ref. No.	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[63]	2011	Sajedi, F.,	GGBFS	Effect of GGBFS on concrete properties	Integration of GGBFS in concrete results in slow hydration effecting nascent age strength	Concrete for gaining early strength in a way as sustainable as possible, high reactive SCMs shall be used in combination with moderately reactive SCMs like FA ,GGBFS etc.,
[64]	2017	Samad, S et.al	SCM	SCM's reactivity	A higher loss on ignition(LOI) test values of pastes of SCMs blended binders hints to a higher amount of chemically bound water in the matrix and thus higher LOI values in such cases indirectly hints to higher reactive SCM.	Simple LOI test can be performed against costlier isothermal calorimetry tests.
[65]	2008	Zhang, J et.al	SCM	Maturity, MoE	MoE development can be predicted vide maturity concepts	MoE shall not be much higher than the substrate concrete while choosing early age strength concrete for repair
[66]	2018	Langaroudi, M. A. M.,	Clay	Effect of various clays on properties of concrete	Nano sized clay particle's admixing in cementitious system might prove advantageous for advancement of strength	Highly flocculated clay materials in concrete roots drop of flowability. Hence HRWRA chemical admixtures compatible with clay materials needs to be used for maintaining the required flow of concrete
[67]	2020,	Seifan,	Flyash	Combined effect of	Integration of high reactive SCMs	The combination of moderately reactive

Ref. No.	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[68]	2017	M., et.al, Kumar, R et.al	(FA)	moderately reactive FA with high reactive SCMs	like microsilica up to 10% as replacement of OPC improves the compressive strength by more than 30% and increase the flexural strength by around 20%	FA with high reactive SCMs like MK, Microsilica etc., advances early strength gain

Table 2.2
Summary of Literature Review on role of popular SCMs –GGBFS and Flyash in Sustainable Concrete Construction

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[69]	2014	Harison, A et.al	Flyash (FA)	Optimisation of part proportions of FA in OPC	40% -as part proportions of FA in OPC disclosed as optimal	Beyond 40% FA in OPC , strength observed to be decreased
[70]	2020	Qureshi, L. A et.al	SCMs	Fineness of SCMs	Fineness ,the most significant physical characteristic of material that controls the reactivity of SCMs and the subsequent strength development of blended binder	Finer SCMs significantly contribute to gaining of early strength in concrete
[71]	2015	Siad, H. et.al	SCMs	Resistance against sulphate attack in $MgSO_4$ environ	Resistance against sulphate attack improved due to the LSP and other SCMs	Denser microstructure resulting from SCM incorporation contributed to diminished transmission of aggressive ions

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[72]	2011	Khan, M. I et.al	Silica fume	Durability	Replacement of OPC with 15% of Silica fume results better durability	Laboratory scale permeation and capillary rise durability tests could be conducted on specimens for assessing the effectiveness of SCMs incorporation
[73]	2004	Nehdi, M et.al	Flyash (FA)	Particle size distribution [PSD]	Higher fineness OPC+ FA (Coarser nature) delivers early-age strengths enhancement	Blended cements usually requires less HRWR chemical admixtures for producing SCC compared to OPC SCC mixes
[74]	2010	Givi, A. N et.al	RHA	Resistance to Cl^- penetration	OPC partly replaced with RHA up to 20% observed to be effective in increased resistance to Cl^- penetration	Integration of RHA as part replacement of OPC improves durability
[75]	2021	Dai, X., Aydin et.al	LSP, FA,MK	Early age strength	A ternary blend combination resulting in 20% of LSP+FA/ MK attained high 1-day strength of 20 MPa and lowest calcium hydroxide content	Significant variations in the calorimetric reaction was detected when MK was used in conjunction with fine LSP
[76]	2018	Shon, C. S et.al	FA and MK	Resistance to ingress of Cl^- ions in concrete	The ternary combinations of OPC,FA and MK observed to be advantageous for early strength gaining sustainable concrete mix	Ternary combinations of OPC, FA and MK are advantageous in developing concrete mixes resistant to chloride ingress.
[77]	2015	Krishan, A et.al	SCMs	Long term durability of concrete	SCM's replacement levels for OPC depends on the requirement specifications of the projects and early age strength specifications	Long-term durability concept , the most fool-proof strategy for sustainable concretes

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[78]	2015	Arvaniti, E. C et.al	SCMs	PSD	Evidence acquired from sieve analysis of a fine powder is limited than that attained over sophisticated methods like PSD	PSD analysis of finer SCMs is an important tool for material charcaterisation
[79]	2018	Li, L. G et.al	FA and Silica fume	Water absorption	The effect of high reactive SCM i.e. Silica fume is much sophisticated than that of FA	Combined effect of moderately reactive and high reactive SCM is synergetic
[80]	2016	Santhanam, M et.al	Blended cements	Dimensional stability	Development of ettringite imperatively effected by permeation and enlargement	Sodium sulphate influences enlargement of samples whereas sulphates of magnesium leads to weight loss in samples
[81]	2017	Vivek, S. S et.al	GGBFS, Silica Fume, MK	Optimum replacement	Water absorption of SCC integrated with GGBFS was less compared to control SCC and NVC	If GGBFS present in proportion greater than 1/2 times of total cementitious materials in SCC, there occurs higher permeability

Table 2.3

Summary of Literature Review on role of SCMs in Densification of Self Compacting Concrete(SCC)

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/comments
[82]	2013	Sathawane, S. H et.al	RHA	Tensile Splitting Strength	15% of RHA as part replacement in OPC amended Tensile Splitting Strength	Tensile Splitting Strength of SCC at 7 days in the range 2.0 to 2.8 MPa, at 28 days in the range from 2.5 to 3.7 MPa, at 56 days in the range from 2.8 to 4.0 MPa

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/comments
[83]	2018	Djelloul, O. K et.al	SCM	SCC characteristics	SCMs improved rheology characteristics of SCC.	SCM included concretes increases T_{500} slump flow time
[84]	2007	Şahmaran, M et.al	Flyash (FA)	SCC characteristics	Particle size and shape effected the rheology of SCC	M30 and M40 grade SCC mix conveniently can be produced with up to 50% FA replacement
[85]	2021	Zhou, M., et.al	SCMs	Binder Index(B_i)	Binder Index per MPa strength was 5Kgs per Cubic metre for HPC_{SCC} where as for ordinary recipe the same was 10-20 Kgs Cubic metre	SCMs integration will aid in lowering water demand and results in high performance concrete
[86]	2019	Benli, A.	SCMs	SCC characteristics	Use of SCMs in SCC is a techno economical requirement	SCMs integration improves mix characteristics of SCC
[87]	2019	Bakera, A. T	MK	Durability characteristics	MK's optimum replacement level of $1/10^{th}$ part of OPC, for enhanced properties	For water /binder range 0.35-0.4, the optimum replacement range of MK in OPC was 10% -12.5%
[88]	2020	Mo, Z., Wang et.al	Flyash (FA), MK,Clay	SCC characteristics	Super plasticiser dosage inversely proportional to FA content in SCC	Super plasticiser dosage proportional to MK and Clay contents in SCC
[89]	2013	Sua-Iam, G et.al	RHA ,LSP	Workability	RHA incorporation requires higher water for ensuring the flowability of SCC	RHA+LSP combination demands additional water by approximately 30% for satisfying flowability of mix

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/comments
[90]	2017	Msinjili, N. S.,	LSP, FA	High compressive strength mix	LSP, FA in combination with RHA will yield SCC mix with high compressive strength.	LSP is a low reactive SCM, whereas Silica Fume, RHA, MK are reactive SCMs
[91]	2022	Al-Oran, A. A. A et.al	FA,GGBFS	SCC characteristics	Proportion of FA, GGBFS momentously influences rheology of mix	Combinations of FA+GGBFS improves rheology of mix
[92]	2015	Kostrzanowska-Siedlarz, A et.al	Silica Fume	Air content	As the slump flow of mix increases air content of the mix decreases	Air content will be <2% for SCC mix presenting slump flow > 650mm
[93]	2017	Gill, A. S	RHA, MK	Advancement of strength with time	Combinations of MK+RHA advanced the strength	10% MK +10% RHA as a part replacement of OPC continuously improves the strength
[94]	2007	Felekoglu, B.	SCMs	SCC Rheology	Rheology of SCC mix greatly depends on Cement physical and chemical properties	Decrease in workability observed with cement having high C_3A
[95]	2017	Sua-iam, G et.al	Flyash (FA),Alumina waste(AW)	SCC characteristics	Cementitious materials range from 500-600 Kg per cubic meter resulted proper SCC	40% FA + 50% AW found to be optimum for SCC mixes

Table 2.4
Summary of Literature Review on Synergy of Metakaolin and Ultrafine slags(UFS/UGGBFS) **in early strength SCC**

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/comments
[96]	2015	Sheen, Y. N et.al	MK, GGBFS	Workability	MK and UGGBFS forms secondary CSH causing advancement of properties	MK and UGGBFS enhanced consistency of the matrix
[97]	2020	Thankam, G. L et.al	MK	Autogenous Shrinkage	MK's incorporation as part replacement of OPC found to be very effective in reducing autogenous shrinkage	Upon incorporation of MK as part replacement of OPC, no overall expansion of pastes was observed at early ages
[98]	2021	Mo, Z et.al	MK	Early age mechanical properties	Early age strength advances with the presence of MK as part replacement in OPC	MK amends the pore arrangement in the paste pointedly causing decreased pores spaces
[99]	2022	Liang, G et.al	UGGBFS	Compressive strength, porosity and sorptivity	Due to finer particle size concrete made with UGGBFS performed well	Incorporation of UGGBFS in the concrete enhanced Compressive strength, porosity and sorptivity
[100]	2013	Dinakar, P et.al	MK	Compressive Strength	10% dosage of MK by weight of OPC observed to be optimum for advancement in strength	No advancements in strength beyond replacement level of 15% of MK in OPC
[101]	2016	Singh, S. P et.al	MK	Water Absorption	As the MK replacement increases, the total water absorption decreases w.r.t w/b ratio in both CC and SCC.	Integration of MK in SCC mix improved the densification and hence reduced pore sizes

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/comments
[102]	2010	Morsy, M. S	MK	Consistency	Normal consistency of cement partly replaced with MK was increased	MK's chemical composition, which generally have > 70% of silica, alumina and iron oxide, indicates highly Pozzolanicity
[103]	2002	Targan, Ş et.al	FA	Setting time and compressive strength	FA addition higher than 30% of total cementitious material resulted in reduction of early-strength gain property of the mixes.	FA addition higher than 30% caused reduction in the compressive strength at later ages
[104]	2018	Meddah, M. S et.al	MK	Durability	20% MK replacement to OPC improved resistance against Cl^- ion ingression	At 20% MK replacement level permeability of concrete decreased significantly
[105]	2017	Lenka, S et.al	MK	Flexural Strength	Continuous improvement in flexural strength occurred as replacement of MK ranges between of 5%-20%	10% MK replacement observed to be optimum and beyond this replacement level MK will act like a filler material only.
[106]	2015	Ahari, R. S et.al	MK, GGBFS	Cl^- ion penetration	Ternary concrete mixtures comprising of MK and GGBFS exhibited high resistance to chemical attack and very low Cl^- ion penetrability	Concrete mixtures integrated with MK as a replacement of OPC requires high dosage of superplasticizer
[107]	2013	Rashad, A. M	MK,UG GBFS	Mechanical characteristics	Addition of UGGBFS up to 15%, as partial replacement of MK has resulted in an increase in strength characteristics.	Beyond optimum content of 15% of UGGBFS has negatively affected the mechanical ,permeability characteristics.

Ref. No	Year of publication	Author/s	Type of SCM studied	Main characteristics studied	Main Observations /Conclusions	Remarks/comments
[108]	2018	Khatib, J. M et.al	MK	Setting time	MK incorporated mix exhibited a much shorter setting time than those obtained by control mix	MK presents accelerator effect on the hydration of the OPC.
[109]	2021	Homayoonmehr, R	MK, Silica fume	Strength and workability.	Optimum replacement level of 10% of MK in OPC advanced the strength	Reduction of workability of concrete blends prepared with OPC + Silica fume can be compensated by compatible HRWRA
[110]	2020	Amin, M et.al	MK,Silica Fume	Flexural strength	Initial flexural strength of Silica Fume incorporated concrete mix was higher but the same was reduced with an increase in % of Silica fume	MK supersedes Silica Fume in cost per m^3. Around 50% cost will be saved by using MK in place of Silica Fume .Hence MK's incorporation is economical compared to SiF
[111]	2021	Saba, A. M et.al	SiF, MK and GGBS	Split Tensile Strength	At 10% replacement level of SiF and MK separately,Flexural strength enhancement was marginally higher for SiF incorporated mix	Concrete mix having 10% SF replacement level, resulted better mechanical strengths compared to concrete comprising of 10% replacement level of MK

Table 2.5
Summary of Literature Review on Effect of Various Nano Materials in SCC

Ref. No	Year of publication	Author/s	Type of Nano material studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[112]	2021	Hosan,	Nano-	Compressive	NC's performance improved in	NC's addition as part replacement of OPC

Ref. No	Year of publication	Author/s	Type of Nano material studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
		A et.al	$CaCO_3$ (NC)	strength and microstructure	OPC+GGBFS+FA+NC mix than only OPC+NC mix	densified the microstructure compared to pastes without NC's addition
[113]	2014	Supit, S. W et.al	Nano-$CaCO_3$ (NC)	Rheology and Strength	NC accelerated the chemical reactions of cementitious system	Addition of 5% NC accelerated setting.
[114]	2014	Yazdani, N et.al	CNT and CNF	Compressive and flexural strength	CNT of 0.1% by OPC achieved 54% and 14% higher compressive and flexural strength than control cement mortar	CNF and CNT cement composites are promising material for the reinforcement of cement mortar.
[115]	2019	Gao, Y et.al	CNT	MoE	CNT incorporated samples exhibited higher MoE than control cement paste	Dosage of CNT inversely proportional to aspect ratio
[116]	2014	Chithra, S et.al	Colloidal Silica(CS)	Ductility	Up to 3% incorporation of CS improves the ductility	Water absorption slightly increases beyond 1.5% incorporation of CS
[117]	2016	Silvestre, J et.al	Nano Silica(NS), nano-ferric oxide(NF)	Early age mechanical properties	Addition of 1.5% of NS displayed a noteworthy effect on early age properties than control mix	0.5% each of NS and NF combinely integrated mix resulted reduced Sorptivity

Ref. No	Year of publication	Author/s	Type of Nano material studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[118]	2016	Meddah, M. S et.al	RHA, Nao alumina (NA)	Compressive and flexural strengths	NA's presence improved the strength of mixes containing 10%-20% RHA as part replacement of OPC	3% NA replacement of OPC observed to be optimum
[119]	2017	Adamu, M et.al	Nano Silica(NS)	Tensile and flexural strengths	Up to 3% incorporation of NS improves the tensile and flexural strengths of matrix	At early ages micro and nano filling ability of NS is advantageous for early strength development
[120]	2018	Zhan, P. M et.al	CNT, NMK	Compressive strength	Up to 20% of increase in strength resulted when 6% of NMK replaced in OPC	A fraction of 0.02%CNT by OPC content ,improved strength of OPC+MK +CNT mix
[121]	2020	Yao, K	Nano MgO(NM)	Compressive and flexural strengths	NM advanced the strength	1% NM's incorporation had resulted in increased compressive and flexural strengths
[122]	2019	Salemi, N et.al	Nao alumina (NA)	Hydration reactions	Acceleration of hydration reactions takes place in NA incorporated concretes due to chemical properties and particle size of the NA	NA promotes the hydration of C3A.
[123]	2021	Camiletti, J et.al	Nano-$CaCO_3$ (NC)	Rheology	Integration of 2.5% NC accelerated the reaction mechanism of cementitious system	NC's incorporation in OPC will accelerate the reaction mechanism

Ref. No	Year of publication	Author/s	Type of Nano material studied	Main characteristics studied	Main Observations /Conclusions	Remarks/ comments
[124]	2021	Jiao, D et.al	Nano Fe_3O_4 (NF)	Mechanical properties	Adding of (NF) to OPC and HSC improved mechanical properties	Incorporation of NF lead to quicken the rate of hydration

Table 2.6
Summary of Literature Review on Effect of Various Fibres in SCC

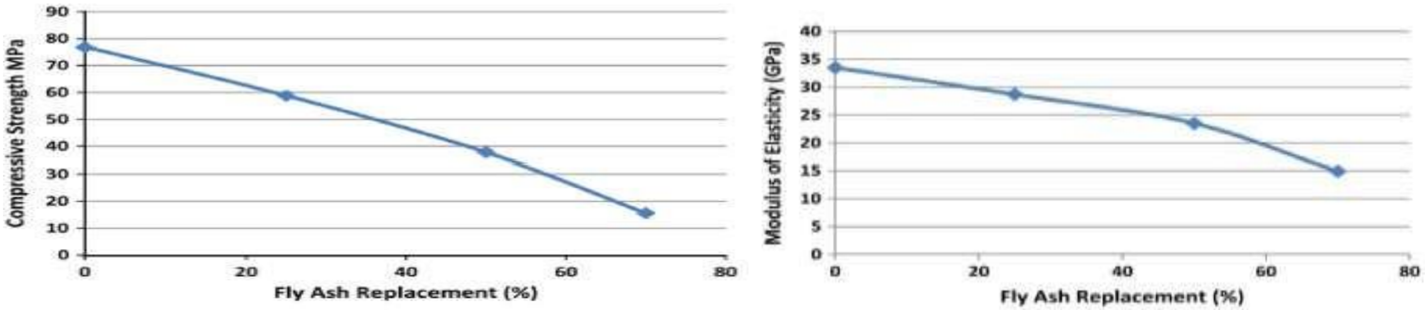
Ref. No	Year of publication	Author/s	Type of Fibres studied	Main characteristics studied	Main Observations /Conclusions/Remarks	Remarks/ comments
[125]	2009	Mohammadi, Y et.al	Steel fibres (STF)	Mechanical Strength, Durability	Fibres inclusion in concrete resulted in improvement of properties	Incorporation of fibres in to concrete also resulted in reduced shrinkage, cracking and permeability
[126]	2020	Hussain, I et.al	Steel fibres (STF) Polypropylene Fibres (PPF)	Compressive strength	Compressive strength was marginally increased upon incorporation of STF	Beyond 1% of PPF compressive strength effected negatively

Ref. No	Year of publication	Author/s	Type of Fibres studied	Main characteristics studied	Main Observations /Conclusions/Remarks	Remarks/ comments
[127]	2010	Huang, H et.al	Steel fibres (STF)	Flexural strength	Concrete with low yield stress lead to a good arrangement of the fibres displaying multiple cracking	Orientation of fibres and the rheology of mix greatly influences the flexural strength
[128]	2010	Teng, L et.al	Steel fibres (STF)	Fracture strength	Fibre addition in concrete plays an significant role in attainment a positive load bearing capacity of the concrete after fracture	Fibre orientation and embedded lengths in concrete are significant for the fracture strength.
[129]	2012	Usman, M et.al	Steel fibres (STF)	Workability ,toughness and ductility	Fibres presence in SCC reduced the flow nature	STF improved the ductile behaviour
[130]	2016	Yang, Y et.al	Hybrid fibre	Mechanical strength	Hybrid fibre incorporated concrete established superior properties over mono fibres	Incorporation of hybrid fibres than mono type fibres is advantageous for improved mechanical strength parameters
[131]	2019	Hari, R et.al	Sisal, Nylon fibres	Mechanical strength and performance of fibres	Natural fibres requires processing while using . Hybridisation with other fibres results into enhanced performance	Natural fibres inclusion in concrete has few disadvantages
[132]	2016	Danoglidis, P. A et.al	Synthetic fibres (SyF)	Mechanical strength and energy absorption capacity	Type of fibre, volume proportion and geometry are precarious factors effecting the performance of composites	Higher modulus of elasticity and strength of fibres crucial for improved properties
[134]	2015	Tian, H et.al	SyF and STF	Shrinkage, strength and durability.	Concrete integrated with long fibres resulted in higher shrinkage than the short fibres	Hybrid fibre combinations advanced strength as well as durability properties

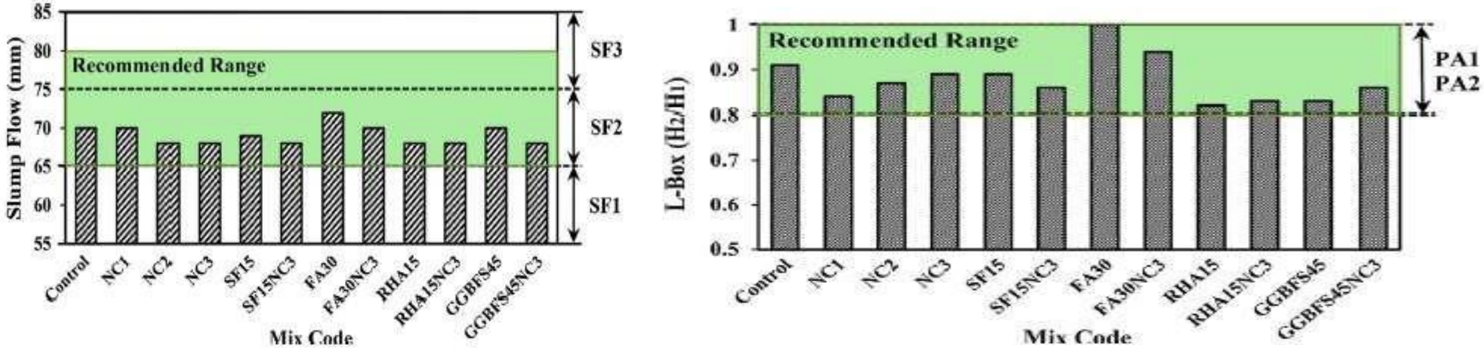
Ref. No	Year of publication	Author/s	Type of Fibres studied	Main characteristics studied	Main Observations /Conclusions/Remarks	Remarks/ comments
[135]	2021	Adesina, A	Basalt fibre	Split Tensile strength	0.5% to 2% volume fraction of Basalt fibre's incorporation in concrete augmented the peak flexural strength in a range of 15-75%.	At 2% of Basalt fibre incorporation resulted a 14% increase in splitting tensile strength
[136]	2007	Anandjiwala, R. D et.al	Natural and Synthetic fibres	Mechanical strength	Properly treated natural fibres can replace synthetic fibres without damaging the material's performance.	Techniques for fibre processing and treatment are essential for proper performance of natural fibres in concrete
[137]	2019	Al-Hadithi et.al	Coir fibres, nylon fibres	Mechanical and durability properties	Incorporation of natural or synthetic or the hybrid combination of both have resulted in higher mechanical and durability properties	Sustainable fibre reinforced SCC can be developed using hybrid combination of fibres
[138]	2020	Ganta, J. K	Polymer and Glass fibres	Mechanical and durability properties	PPF observed to be cost effective and reduces shrinkage in SCC	ARF due to high strength and stiffness notably improves concrete SCC performance

2.7 Influence of various materials on the properties of concrete

Influence of various materials on the properties of concrete is presented in the graphical forms Graph 2.1 to Graph 2.10 ,as under, which are extracted from various publications on concerned literature

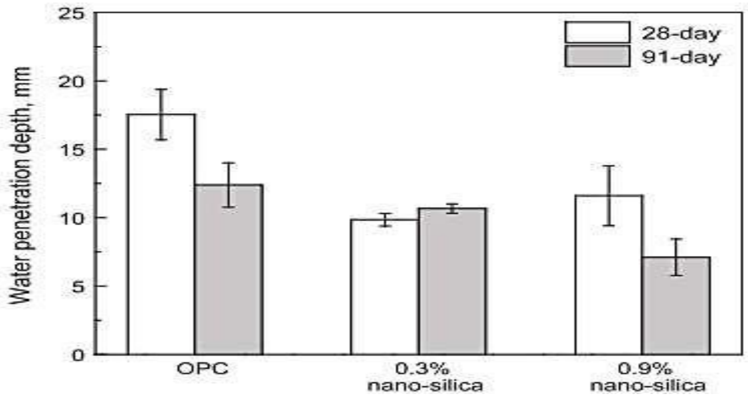


Graph 2.1 Effect of flyash on the compressive strength and MoE of concrete[Source[64]]

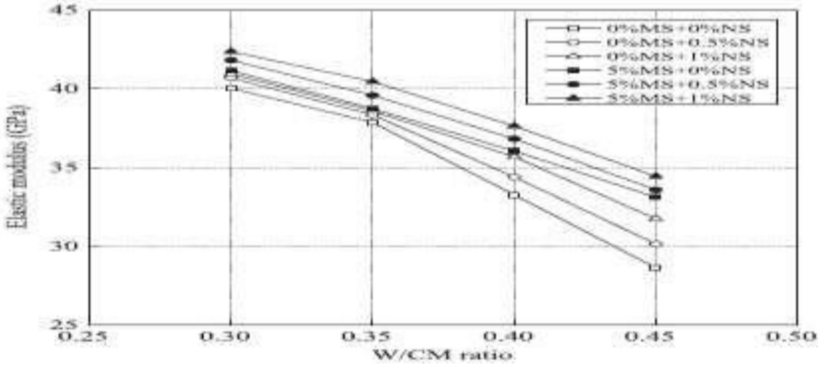


NC: Nano Clay(1% to 3%), SF: Silica Fume(15%), FA: Flyash(30%), RHA: Rice Husk Ash(15%)

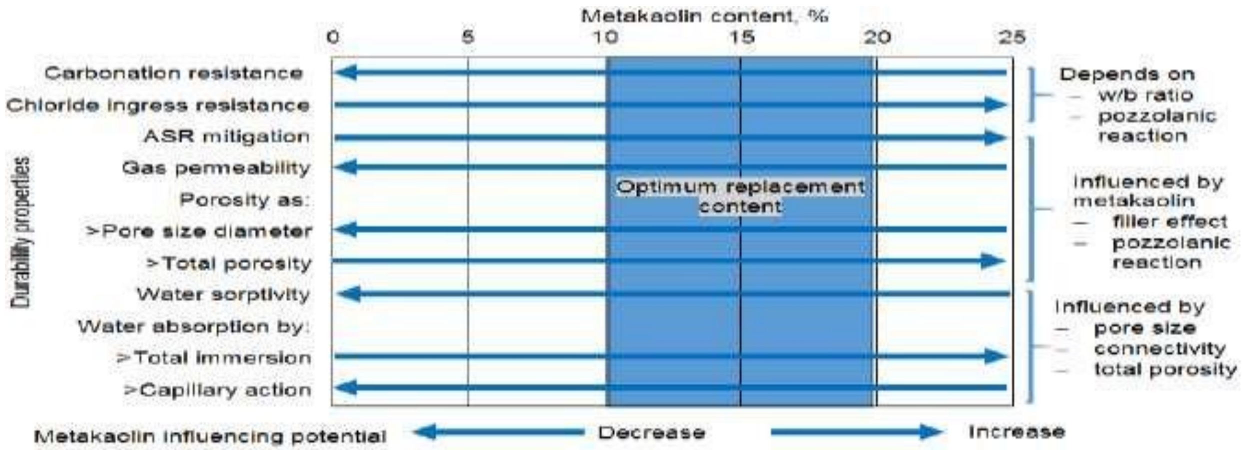
Graph 2.2 Slump-Flow and L Box flow obstruction ratio of SCC Mix[Source[66]]



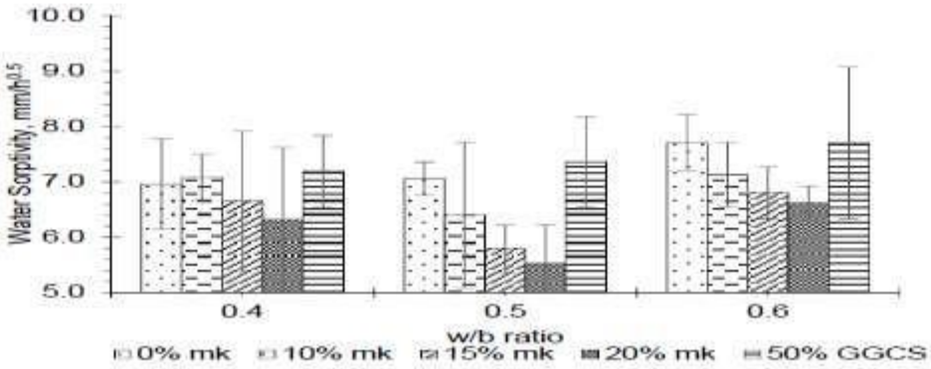
Graph 2.3 Effect of Nano Silica on Water penetration [Source[68]]



Graph 2.4 Effect of combinations of Micro Silica and Nano Silica on MoE [Source[79]]

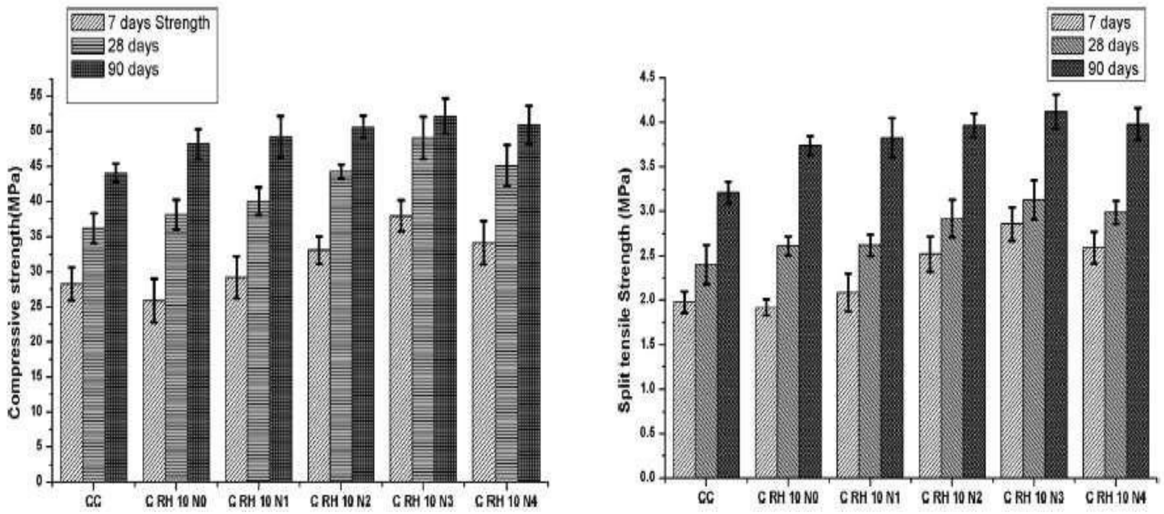


Graph 2.5 Effect of Metakaolin on various durability properties of concrete [Source[87]]



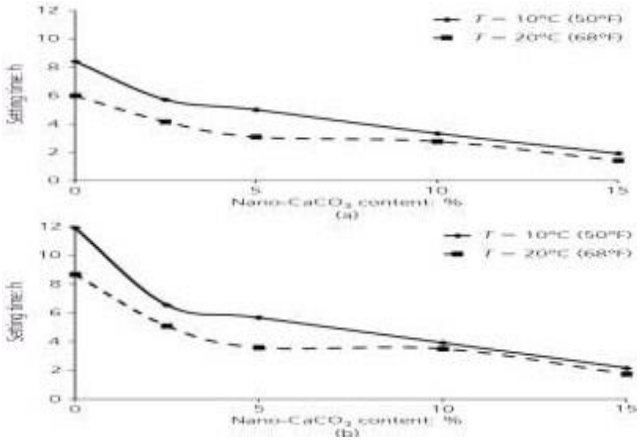
GGCS: Ground Granulated Cortex Slag

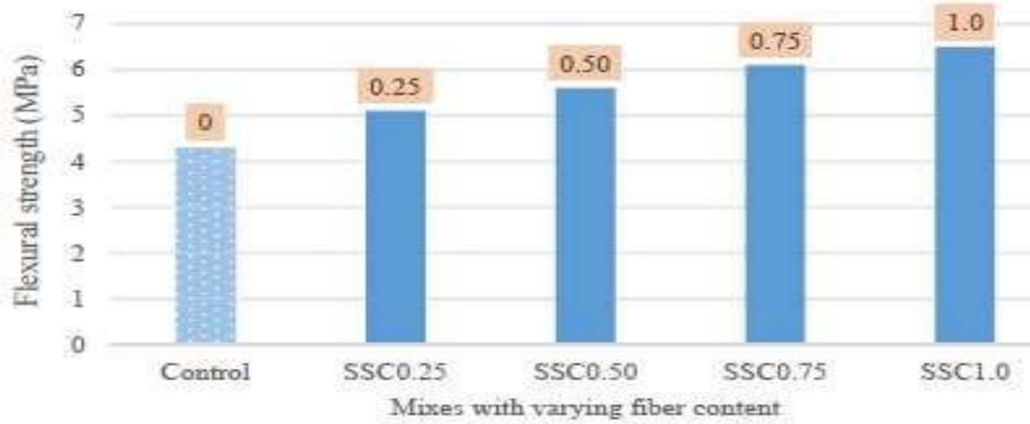
Graph 2.6 Effect of Metakaolin on water sorptivity of concrete [Source[87]]



RH 10: Rice Husk Ash 10%, N:Nanno Alumina(1% to 4%)

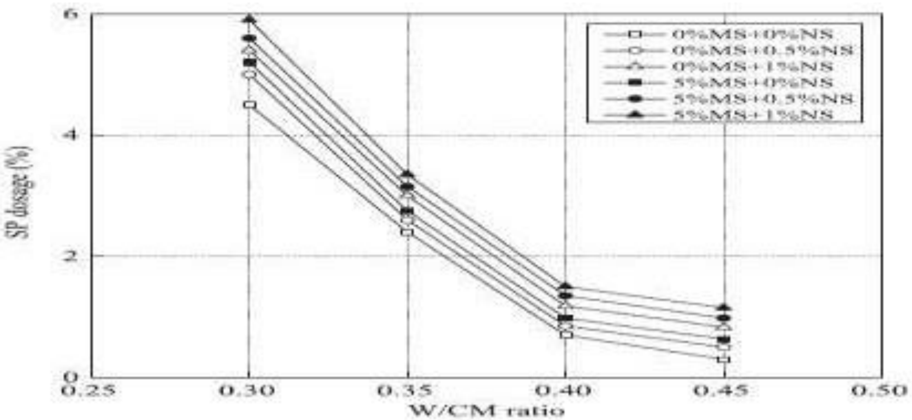
Graph 2.7 Effect of Nano Alumina and Rise Husk Ash on Compressive Strength and Tensile Strength of concrete [Source[118]]





Graph 2.8 Effect of Nano CaCO3 [Source[123]] on Setting Time of Concrete

Graph 2.9 Effect of Various Steel Fibre% on Flexural Strength of SCC [Source[111]]



Graph 2.10 Effect of combinations of Micro Silica and Nano Silica on Admixture Dosage [Source[79]]

2.8 Common summary of the literature review

After the above detailed literature review, it was concluded that using only OPC and other moderately reactive SCMs such as FA and GGBFS to produce SCC with fast setting early strength is neither practical nor feasible from a durability point of view. Therefore, a research idea was formulated to produce and carry out a comprehensive study on a quick setting early strength hybrid fibre reinforced self-compacting concrete that is as durable as possible by partially replacing OPC with SCMs of moderate reactivity, e.g. FA/GGBFS. Integration of highly reactive SCM such as MK/ultrafine slag with combinations (although in a lower proportion compared to moderately reactive SCMs), nano-materials such as nano-alumina/nano-silica etc. such as highly reactive nanofillers and incorporation of various hybrid fibre combinations to improve tensile properties of SCC, in both early and mature ages.

2.9 Deficiency of research and motivation to do research

After a comprehensive and narrow literature review of existing studies, research gaps related to area and thrust area were identified; a research idea was formulated for "comprehensive studies on the early strength of rapid healing hybrid fibre-reinforced self-compacting concrete". From the above literature studies, it has been determined that a maximum of 50-75% of OPC can be used with 100% binders and the remaining binders, i.e. 25-50%, are partially replaced by combinations of moderately reactive SCMs (for maximum possible substitutions), highly reactive SCMs (lower proportions compared to moderately reactive SCMs) and/or rapidly setting Nano fillers, in the development of early strength gaining SCC mixtures and also for attaining durability. However, the addition of fibres is also justified to improve the tensile properties, both in the early and maturing periods. The motivation to carry out the aforementioned research work arose from the nature of the research work on different early strength concrete mixes. Based on various relevant published research results, it is understood that moderately reactive SCMs such as Flyash/GGBFS can be advantageously used in combination with highly reactive SCMs such as metakaolin, ultrafine granulated slag, fumed silica and alumina powder etc. for rapid development. early treatment self-compacting concrete reinforced with hybrid fibres. Therefore, this idea naturally inspired and encouraged me to do research on the mentioned subject.

An additional incentive was the use of industrial by-products in SCC mixtures, which can help reduce the use of OPC and thus indirectly reduce carbon dioxide emissions from the use of such a mixture in rapid construction and repair work, as well as in achieving sustainable. development goals. such as environmental protection.

2.10 Research hypothesis

This study focuses on the mixing ratios of SCC mixtures containing hybrid combinations of synthetic fibres as they remain widely used in fast-track construction and repair applications. Therefore, the present study stands limited to the development of the aforementioned SCC recipe, mainly with locally available concrete production materials, and conducting extensive research on the same, mainly focusing on achieving rapid reactions and early strength, which is required for fast construction and repair works as well as for early opening of structures to users. The main hypothesis of this study is that moderately reactive SCMs such as FA/GGBFS can be combined with lower ratio reactive SCMs such as MK/UGGBFS to advance strengths and to reduce hardening time. In addition, the integration of hybrid combinations of fibres of PP-F and AR-F groups improves the early tensile properties of SCC. Another hypothesis was that the addition of nanoalumina at a lower ratio (compared to reactive SCMs) would further compact the above SCC mixtures and improves resistance to aggressive environments. The SCC recipe developed from this research expected to be used in accelerated construction and repair applications.

CHAPTER 3

CONSTITUENTS AND CHARACTERISATION

3.0 Early development

Based on extensive literature study conducted and examined within the Chapter 2 of this thesis, cement and cementitious materials like cement (OPC53Gr), moderately responsive cementitious materials- flyash, ground granulated blast furnace slag, exceedingly responsive cementitious materials metakaolin, ultrafine slag and alumina powder were chosen as noticeable , promising and potential materials for fashioning fast setting quick strength yielding SCC recipe. Separated from above potential binder materials, to upgrade the tensile strength of the fast setting, early strength SCC blend, fibres PP-F and ARG-F were chosen to further consolidate into the concrete blend. The so chosen materials have been characterised for physical properties, and chemical properties as per the relevant Indian Standards. Furthermore, the microstructure of the chosen materials was examined utilizing photo micrographs and Scanning Electron Microscope (SEM) images. Three grades of concrete blend of grades M40, M50 and M60 were developed utilizing different trial extents of the above-chosen materials and the optimum extents of the same were chosen to deliver the self-compacting concrete blend having characteristics of fast-setting nature and early strength developing capabilities for the intended application of fast track construction. Within the enhanced self-compacting concrete blend, to judge the consequence of inclusion of fibre strands over the behaviour regarding self-compacting recipe within fresh and solidified state, ARG-F and PP-F were utilized in mono combinations and crossover combinations in extents of 0.50%, 0.75%,1.00%,1.50%,2.00%2.50% and 3.00% by weight of cementitious materials. Crushed common coarse aggregate of 10mm MSA, natural fine aggregate-river sand had been sourced from local material suppliers and were appropriately tried as per the pertinent Indian Standards and utilized for preparing the self-compacting concrete blend specified over. A reputed brand of locally available high range water decreasing super plasticizing PCE based chemical admixture was sourced and appropriately tried as per the pertinent Indian Standards and has been utilized for preparing the self-compacting concrete. The following paragraphs briefly display an account of the nature and the characteristics of the selected materials.

3.1 Materials

3.1.1 Cement (OPC 53 Gr.)

Conventional Portland Cement OPC53 grade, manufactured by M/s Nuvoco Nuvista Constrained, with the brand name Double Bull, was secured from a nearby provider for utilization in all the concrete blends carried out in this study. Physical properties of OPC 53, i.e., NC, IST, FST, SG, specific surface area, calcium and magnesium soundness and strength developed with age were evaluated by the Indian Standard procedures of IS 4031. The chemical properties of OPC 53 were evaluated as per the Indian Standard procedures of IS 4032. OPC's specific gravity found to be 3.12 and whereas Blaine's fineness was found to be 350m^2/kg, IST and FST were 170 minutes and 280 minutes respectively. The particle size distribution (PSD) test of OPC was conducted utilizing the Laser diffraction method, and particle sizes were found to be as D_{10} = 6.9 microns, D_{50}= 28.2 microns and D_{90}= 61.6 microns. A photograph of OPC 53 Grade cement utilized in this study is presented in Fig. 3.1. Characteristics of Cement are presented in Table 3. Cement was observed to comply with the IS 269-2015.

Fig. 3.1 OPC 53 Grade Cement-Manufactured by M/s Nuvista Cement [Brand -Double Bull]

Table 3.1 Characteristics of OPC 53 Gr.

Particulars	Tested As per	Units	Test result	Requirement OPC 53 Gr as per IS 269:2015
I] Chemical Parameters	IS 4032			**Limits as per Table2of IS 269:2015**
$\frac{((CaO)-(0.7\ SO_3))}{((2.8\ SiO_2)+(1.2\ Al_2O_3)+(0.65Fe_2O_3))}$	Cl.4.4,4.5,4.6,4.9	%	0.89	0.80 Min. 1.02 Max.

Particulars	Tested As per	Units	Test result	Requirement OPC 53 Gr as per IS 269:2015
Al_2O_3/Fe_2O_3	Cl.4.5 and 4.6	%	1.17	0.66 Min.
Insoluble Residue	Cl.4.10	%	2.05	5.00 Max.
Magnesia	Cl.4.8	%	1.26	6.00 Max.
Sulphuric Anhydride	Cl.4.9	%	2.67	3.50 Max.
LOI	Cl.4.2	%	1.22	4.00 Max.
Total Chloride	Cl.4.10	%	0.004	0.10 Max.
Alkali Content	Cl.4.11	%	0.48	0.6 Max
II] Physical Parameters	IS 4031			**Limits as per Table3 of IS 269:2015**
Fineness	Part 2	m^2/Kg	350	225 Min.
Standard Consistency	Part 4	%	31.0	-----
Setting time IST FST	Part 5	Minutes	 170 280	 30 Min. 600 Max.
Soundness by le-chatlier expansion	Part 3	%	1.5	10.0 Max.
Autoclave expansion	Part 3	%	0.028	0.8 Max.
Specific Gravity	Part 13	-	3.12	-
Heat of Hydration @ 7Days	Part 9	KJ/Kg	255	-
Particle Size Distribution	By Laser Diffraction	microns		
D_{10}			6.9	-
D_{50}			28.2	-
D_{90}			61.6	-
Compressive Strength at 1 Day 3 Days 7 Days 28 Days 56 Days 3 Months 6 Months 1 year	Part 6	N/mm^2	 18.2 30.8 41.3 54.2 55.1 55.7 55.9 56.3	 - 27 Min. 37 Min. 53 Min. - - - -

3.1.2 GGBFS

GGBFS manufactured by M/s Tata Steel was secured from nearby provider for utilize in this study. GGBFS evaluated against the relevant parts of IS 4031, IS4032 and observed that the SG of GGBFS was 2.91 and specific surface area was 400m^2/Kg. Average particle diameter i.e. PSD test of same was conducted utilizing Laser diffraction method and particle sizes were observed to be as D_{10}=2.4 microns, D_{50}=106.5 microns and D_{90}=560.4 microns. Photograph of GGBFS utilized in this study is displayed in Fig.3.2. Characteristics of GGBFS are displayed in Table 3.2 and GGBFS was observed to be complying with the specifications of IS 16714:2018.

Table 3.2 Characteristics of GGBFS

Particulars	Tested As per	Units	Test result	Requirement GGBFS as per IS 16714:2018
I] Chemical Parameters	IS 4032			**Maximum Limits as per Table 1 of IS 16714:2018**
MnO		%	4.29	5.5
MgO		%	12.28	17.0
Sulphide Sulphur(S)		%	1.1	2.0
Sulphate(SO_3)		%	2.6	3.0
Insoluble Residue(IR)		%	2.81	3.0
Chloride Content		%	0.003	0.1
Loss on Ignition(LOI)		%	1.84	3.0
II] Physical Parameters	IS 4031			**Limits as per Table 2 of IS 16714:2018**
Fineness	Part 2	m^2/Kg	400	320 Min.
Specific Gravity	Part 13	-	2.91	-
Particle Size Distribution	By Laser Diffraction	microns		
D_{10}			2.4	
D_{50}			106.5	
D_{90}			560.4	
Slag Activity Index (%Ratio of strength of corresponding OPC 43 Gr control cement mortar cubes) Compressive Strength at	Table 2,Note 2 of IS 16714:2018 and IS 4031Part 6	%		
1 Day			36.4	-
3 Days			48.7	-
7 Days			68.2	60 Min.
28 Days			85.6	75 Min.
56 Days			86.1	-
3 Months			86.4	-
6 Months			86.5	-
1 year			86.8	-

Fig.3.2 GGBFS[Tata Steel] used in this study

3.1.3 Flyash(FlA)

Flyash utilized in this study was sourced from an adjacent thermal power plant and the same was obtained from nearby RMC plant. Flyash was evaluated following the relevant parts of IS 4031, IS4032 and IS 1727 and found that specific gravity of flyash as 2.08 and specific surface area as 330m^2/Kg. Average particle diameter i.e. PSD test of same was conducted utilizing Laser diffraction method and particle sizes of Flyash were observed to be as D_{10}=6.2 microns, D_{50}=45.2 microns and D_{90}=58.6 microns. Photograph of Flyash utilized in this study is presented in Fig.3.3. Characteristics of Flyash are presented in Table 3.3 and Flyash was observed to be complying with the specifications of IS 3812:2013.

Table 3.3 Characteristics of Flyash

Particulars	Tested As per	Units	Test result	Requirement Flyash as per IS 3182:2013
I] Chemical Parameters	IS 4032	**Limits as per Table 1 of IS 3182:2013**		
Silicon dioxide (SiO_2)		%	63.86	35 for Siliceous Fly Ash (Min.)25 for Calcareous Fly Ash (Min.)
Reactive silica		%	37.76	20 for FA- Siliceous and FA-Calcareous (Min)
Magnesium oxide (MgO)		%	0.19	5.0 for FA- Siliceous and FA-Calcareous (Max)
Total Sulphur as Sulphur trioxide (SO_3)		%	0.18	3.0 for FA- Siliceous and FA-Calcareous (Max)
Available alkalis as equivalent sodium oxide (Na_2O)		%	0.68	1.5 for FA- Siliceous and FA-Calcareous (Max)

Particulars	Tested As per	Units	Test result	Requirement Flyash as per IS 3182:2013
Total chlorides		%	0.007	0.05 for FA- Siliceous and FA-Calcareous (Max)
Loss on ignition		%	0.26	5.0 for FA- Siliceous and FA-Calcareous (Max)
II] Physical Parameters	IS 1727			**Limits as per Table 2 of IS 3182:2013**
Specific Gravity		-	2.08	-
Fineness — Specific surface		m^2/kg	330	320 Min.
Residue on 45 micron IS sieve (wet sieve analysis)		%	18	34 Max.
LR- Avg. CS		N/mm^2	5.2	4.5 Min
Soundness by autoclave test		%	0.3	0.8 Max.
Particle Size Distribution	By Laser Diffraction	microns		
D_{10}			6.2	-
D_{50}			45.2	-
D_{90}			58.6	-
Comparative Compressive strength (% strength of corresponding plain cement mortar cubes)	Table 2, IS 3182 and IS 4031 Part 6	%		
1 Day			28.2	-
3 Days			36.5	-
7 Days			59.4	-
28 Days			87.2	80 Min.
56 Days			87.4	-
3 Months			87.8	-
6 Months			88.9	-
1 year			89.2	-

Fig. 3.3 Flyash used in this study

3.1.4 Metakaolin(MK)

Metakaolin (MK) used in this study was procured from M/s Asttra Chemicals, Chennai. MK was evaluated as per relevant parts of IS 4031, IS4032 and IS 1727 and observed that specific gravity was 2.24. Average particle diameter i.e. PSD test of same was conducted using Laser diffraction method and particle sizes of MK were observed to be as D_{10} = 1.4 microns, D_{50}= 7.1 microns and D_{90}= 13.4 microns. Photograph of MK used in this study is presented in Fig.3.4. Characteristics of MK presented in Table 3.4 and MK was observed to be complying with the specifications of IS 16354:2015.

Fig.3.4 Metakaolin used in this study

Table 3.4
Characteristics of Metakaolin

Particulars	Tested As per	Units	Test result	Requirement Flyash as per IS 16354:2015
I] Chemical Parameters	IS 1727			**Limits as per Table1of IS 16354**
$SiO_2 + Al_2O_3$		%	95.5	94.0 Minimum
SiO_2 / Al_2O_3		%	1.26	1.15 Minimum
$Fe_2O_3 + TiO_2$		%	1.17	3.0 Maximum
Al_2O_3		%	42.1	40.0 Minimum
Moisture Content By mass		%	1.15	3.0 Maximum
Alkalies as Na_2O equivalent		%	0.9	1.5 Maximum
Loss on ignition		%	1.47	2.0 Maximum
Pozzolanicity by Modified Chappelle Test Mg CaO g$^-$ mK			880	800 Minimum
II] Physical Parameters	IS 1727			**Limits as per Table 2 of IS 16354**
Specific Gravity		-	2.24	-
Residue on 45 micron IS sieve (wet sieve analysis)		%	0.6	1.5 Max.
Particle Size Distribution	By Laser Diffraction	microns		
D_{10}			1.4	-
D_{50}			7.1	-
D_{90}			13.4	-
Compressive strength (% strength of corresponding plain cement mortar cubes)	Table 2, IS 16354 and IS 4031 Part 6	%		
1 Day			65.8	-
3 Days			86.2	-
7 Days				

Particulars	Tested As per	Units	Test result	Requirement Flyash as per IS 16354:2015
28 Days			105.6	100 Min.
56 Days			105.8	-
3 Months			106.1	-
6 Months			106.4	-
1 year			106.9	-
			107.3	-

3.1.5 Ultrafine Slag(UFS/UGGBFS)

UGGBFS used in this study was procured from a nearby grinding unit M/s Toshali with the brand name Toshali Nano. UGGBFS was evaluated as per relevant parts of IS 4031, IS4032, IS 1727 and found that the specific gravity of UGGBFS was 2.90. Particle size distribution test of UGGBFS was conducted using the Laser diffraction method and particle sizes of UGGBFS were observed to be as was D_{10} = 1 microns, D_{50}= 4 microns and D_{90}= 8 microns. A photograph of UGGBFS used in this study is presented in Fig. 3.5. Characteristics of UGGBFS are presented in Table 3.5 and UGGBFS was observed to be complying with the specifications of UGGBFS was complying with the specifications of IS 16715:2018.

Table 3.5 Characteristics of UFS/UGGBFS

Particulars	Tested As per	Units	Test result	Requirement GGBFS as per IS 16715:2018
I] Chemical Parameters	IS 4032	**Limits as per Table 1 of IS 16715:2018**		
MnO		%	4.31	5.5 Maximum
MgO		%	12.25	17.0 Maximum
Sulphide Sulphur(S)		%	1.2	2.0 Maximum
Sulphate(SO_3)		%	2.4	3.0 Maximum
Insoluble Residue(IR)		%	2.79	3.0 Maximum
Chloride Content		%	0.003	0.1 Maximum
Loss on Ignition(LOI)		%	1.82	3.0 Maximum
II] Physical Parameters	IS 4031			**Limits as per Table 2 of IS 16715:2018**
Specific Gravity	Part 13	-	2.90	-
Particle Size Distribution	By Laser Diffraction	microns		
D_{10}			1	

D_{50}			4	Maximum
D_{90}			8	15 Maximum (D_{95})
Slag Activity Index (%Ratio of the strength of corresponding OPC 43 Gr control cement mortar cubes)	Table 2, Note 2 of IS 16715:2018 and IS 4031Part 6	%		
1 Day			44.8	-
3 Days			56.2	-
7 Days			78.1	60 Min.
28 Days			95.4	75 Min.
56 Days			109.9	-
3 Months			110.2	-
6 Months			111.6	-
1 year			112.8	-

Fig.3.5 UFS/UGGBFS used in this study

3.1.6 Alumina Powder (NA)

NA used in this study was procured from M/s Asttra Chemicals, Chennai. NA was evaluated as per relevant parts of IS 4031, IS4032, IS 1727 and found that the specific gravity of NA was 3.82. % Al_2O_3 in the NA was 99.1%. Fig.3.6 represents the Alumina Powder (NA) used in this study.

Fig.3.6 Alumina Powder (NA) used in this study

3.1.7 FIBRE-ARG-F

ARGF procured from reputed manufacture from local suppliers. ARG-F observed to have the properties average diameter15 microns, length was 6mm and 12mm, Specific-Gravity = 2.4. Fig.3.7 represents the Fibre-ARG-F used in this study.

Fig.3.7 FIBRE-ARG-F used in this study

3.1.8 FIBRE- PP-F

PPF used in this study was procured locally.PPF observed to have the properties – average diameter 25 microns, length of fibres was 6mm and 12mm, Specific-Gravity= 0.9. Fig.3.7 represents the Fibre- PP-F used in this study

Fig.3.8 FIBRE-PP-F used in this study

3.1.9 Crushed Aggregate-Coarse

CA10 mm nominal size crushed aggregates was procured from a local RMC plant and used in this study and evaluated using relevant parts of IS 2386 and observed that Specific-Gravity =2.79, water absorption was 0.61%, AIV=17%, LAV=19%, Crushing Value=20%, FI &EI = 22%. Coarse aggregate sieve analysis was conducted as per IS 2386 Part 1 and the same is presented hereunder in Table 3.6. Coarse aggregate was confirmed to the requirements of IS 383:2016. Fig.3.9 represents the Coarse Aggregates (CA 10mm) used in this study.

Fig.3.9 Coarse Aggregates (CA 10mm) used in this study

Table 3.6
Sieve analysis of Coarse Aggregate CA(10mm) size

Mesh size of Sieves	Residue (Grams)	% Residue	Residue	Pass	Limits of Passing as per IS 383:2016 Table No.7
			Cumulative %		
12.5mm	0	0	0	100	100
10mm	450	9	9	91	85-100
4.75mm	4025	80	89	11	0-20
2.36mm	375	8	97	3	0-5
Pan	150	4	100	-	
Total	5000				

3.1.10 Fine Aggregate

Fine aggregate (natural river sand) was procured from local RMC Plant and used in this study and tested as per relevant parts of IS 2386. It was observed that sand was having passing average percentage through <125 Micron approximately 6.00%, specific gravity was 2.63, water absorption was 1.2%. Fine aggregate sieve analysis was conducted as per IS 2386 Part 1 and the same is presented hereunder in Table3.7. Sand was falling in Zone-III according the Zone classification spelt under IS 383:2016 and was complying with the requirements of IS 383:2016. Fig.3.10 represents the Fine Aggregates (River Sand) used in this study.

Fig.3.10 Fine Aggregate (River Sand) used in this study

3.1.11 Water

Tap water supplied by the municipality was used, as shown in Fig.3.11, for proportioning the self-compacting concrete mix. Water was tested as per relevant IS

3025 and the same is presented hereunder in Table 3.8. Water was confirming the requirements of IS 456:2000.

Fig.3.11 Tap Water(Municipal Supply) used in this study

Table 3.7
Sieve Analysis of Fine Aggregate(River Sand)

I.S. Sieves As per IS 460	Weight retained (Grams)	% Retained	Cumulative %				
			Retained	Passing	Limits spelt under IS 383:2016		
					Z-1	Z-2	Z-3
10.00 mm	0	0	0	100	100	100	100
4.75 mm	25	2.5	2.5	97.5	90-100	90-100	90-100
2.38 mm	65	6.5	9.0	91.0	60-95	75-100	85-100
1.18 mm	118	11.8	20.8	79.2	30-70	55-90	75-100
600 micron	82	8.2	29.0	**71.0**	15-34	35-59	**60-79**
300 micron	384	38.4	67.4	32.6	5-20	8-30	12-40
150 micron	237	23.7	91.1	8.9	0-10	0-10	0-10
75 micron	63	6.3	97.4	2.6	-	-	-
45 micron	18	1.8	99.2	0.8	-	-	-
Pan	8	0.8	100	-	-	-	-
Total	1000						

Table 3.8
Test results of Water(Tap Water-Municipal Supply)

Test Carried Out	Test Method	Result Obtained	Units	Specific Requirements As per IS 456:2000
P^H Value	IS 3025: Part 11	7.23	-	Not less than 6.0
Acidity Test using 0.0 Normality NaOH	IS 3025: Part 22	0.06	ml	5ml (Maximum)
Alkalinity Test using 0.2 Normality H_2SO_4	IS 3025: Part 23	21.69	ml	25ml(Maximum)
Total Organic Matter (Volatile residue)	IS 3025: Part 18	59.5	mg/ liter	200 mg/liter (Maximum)

Test Carried Out	Test Method	Result Obtained	Units	Specific Requirements As per IS 456:2000
Inorganic Solids (Fixed residue)	IS 3025: Part 18	502	mg/ liter	3000 mg/liter (Maximum)
Sulphates (as SO3)	IS 3025 : Part 24	65	mg/ liter	400 mg/liter (Maximum)
Chlorides (as Cl)	IS 3025 : Part 32 :	23	mg/ liter	2000 mg/liter (Maximum)
Suspended matter	IS 3025 : Part 17 :	Nil	mg/ liter	2000 mg/liter (Maximum)

3.1.12 Chemical Additives

PCE-based HRWRA, with a brand name PERMA PLAST, , as shown in Fig.3.12, capable to reduce 34% water quantity as against control sample was used. HRWRA used in this study is shown in Fig.3.6 and the same was tested as per relevant IS 9103. Test results of HRWA is presented hereunder in Table 3.9. HRWRA was confirming the requirements of IS 9103.

Fig.3.12 HRWR (PCE Based) Chemical Admixture used in this study

Table 3.9
Test results of HRWRA used in this study- Tested As per IS 9103, Annexure E

Parameters	Units	Observations (O)	Limits
Form	-	Liquid	Liquid/Powder
Shade	-	Dark brown	Light to dark brown
Solids percentage(S)	%	40.93	0.95*O< S<1.05*O
Ash percentage	%		$\pm$ 0.01 value mentioned in MTC
Chloride content	%	0.011	0.2%
P^H	-	7.29	Between 7-8
Specific Gravity	-	1.14	$\pm$ 0.2 value mentioned in MTC

3.2 Relative chemical composition of Cement and Cementitious materials used

Relative chemical composition of Cement and Cementitious materials used in this study is presented in Table 3.10.

Table 3.10

Relative chemical composition of OPC, Flyash ,GGBFS, MK

Chemical Compounds	OPC -53Gr	GGBFS	FA	MK
	%			
Lime(CaO)	63.10	32.10	5.10	-
SiO_2	22.39	30.77	63.82	53.40
Al_2O_3	4.48	16.61	22.51	42.10
MgO	4.15	12.28	0.17	0.79
Fe_2O_3	4.10	0.57	6.21	1.11
LOI	1.22	1.81	0.22	1.47
Insoluble Residue	3.10	2.13	22.65	1.94
Chloride content	0.003	0.004	0.009	0.071
Manganese Oxide	-	4.29	-	0.24
Relevant Specifications	IS 269-2015	IS16714-2018	IS3182-2013	IS16354-2015

3.3 Photo Micrographs of the materials at 1000x magnification

Photo Micrographs of the materials, at 1000x magnification, is presented hereunder in Fig.3.13.

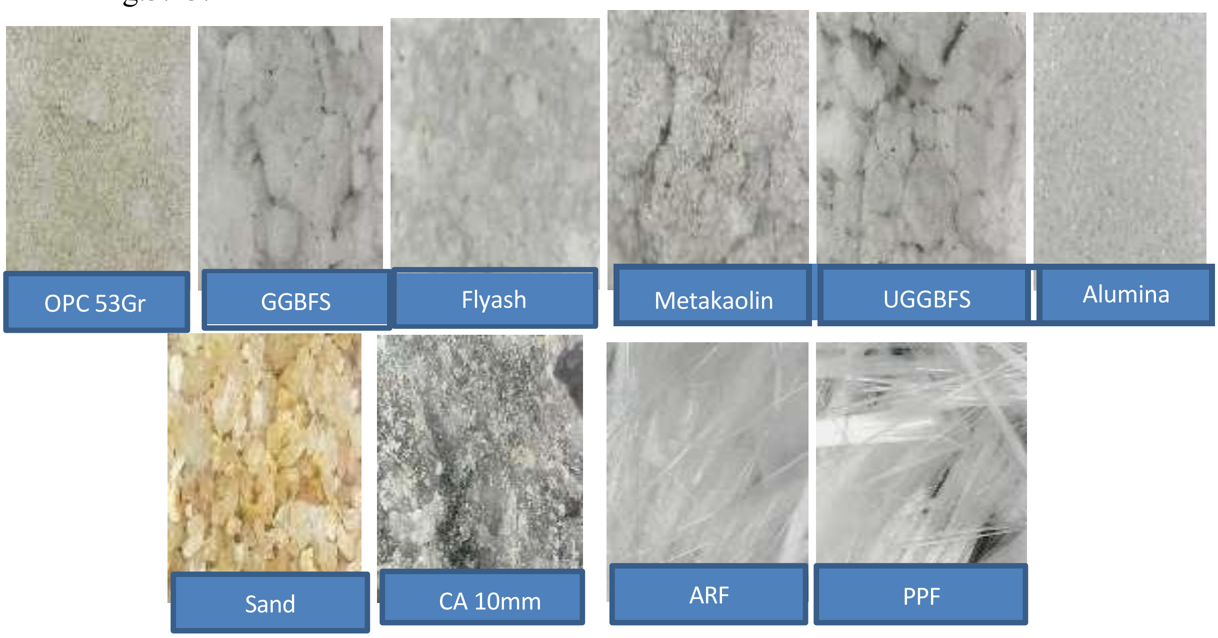


Fig. 3.13 Photomicrographs of OPC, GGBFS, Flyash , Metakaolin, UGGBFS, Nano Alumina, Sand, Coarse Aggregate(10mm), AR fibre and PP fibre (at 1000x magnification)

3.4 SEM images of cement and cementitious materials at 1 micrometre resolution

SEM images of cement and cementitious materials at 1 micrometre resolution presented in Fig.3.14

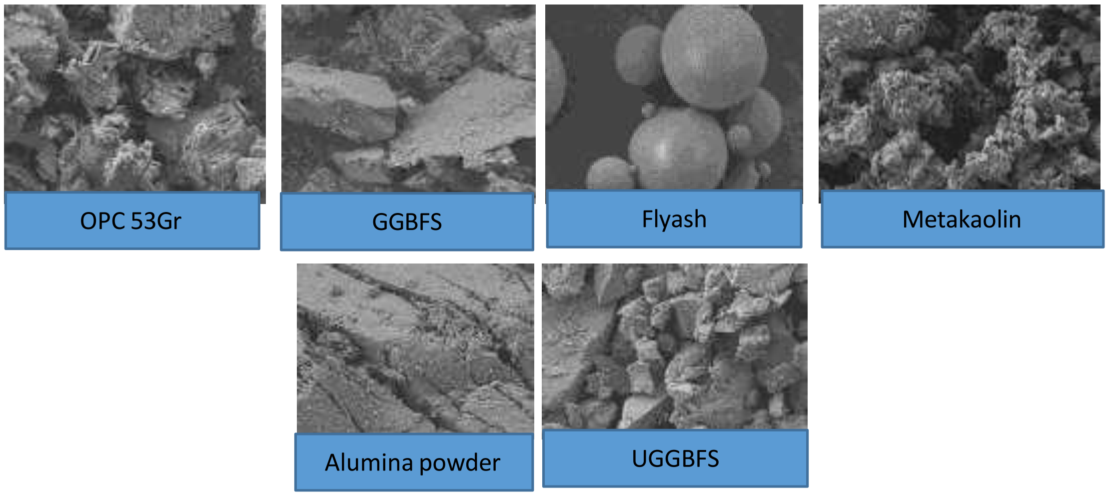


Fig.3.14. SEM images of cement and cementitious materials at 1 micrometre resolution (at 1000x magnification)

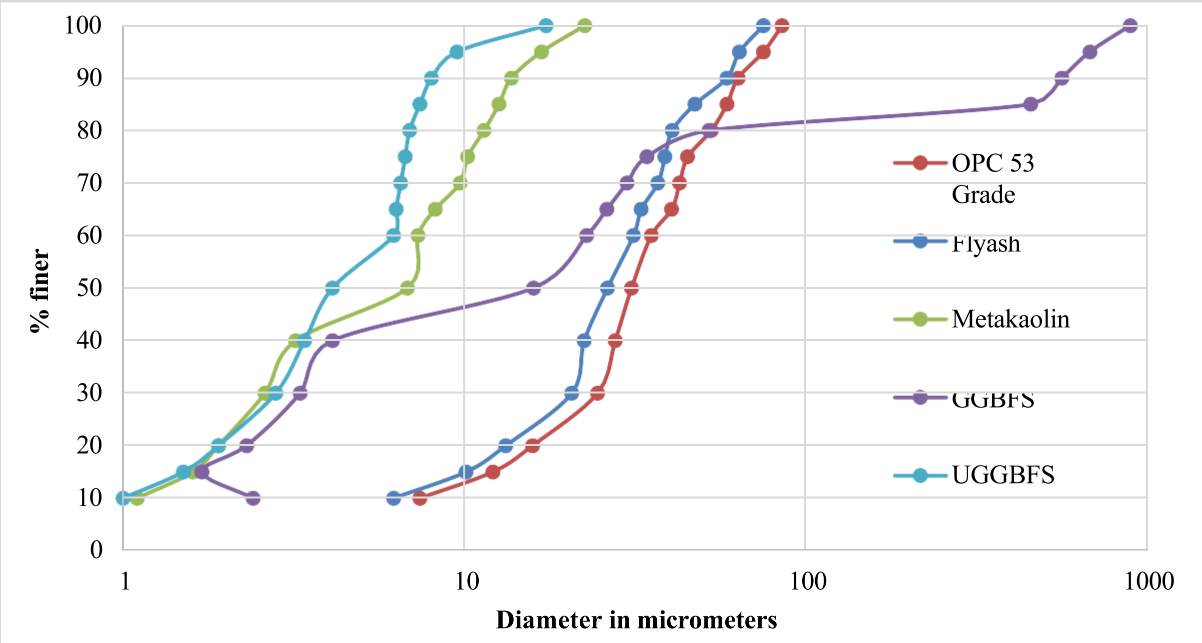
3.5 PSD Analysis of cement and cementitious materials

PSD Analysis of cement and cementitious materials reported in Table 3.11 . A graphical representation of the same is presented in Graph 3.1.

Table 3.11
PSD Analysis of OPC, Flyash ,GGBFS,UFS/UGGBFS, MK and NA

Sizes	Cement OPC 53	Flyash	MK	GGBFS	UFS/UGGBFS	Alumina Powder
	Diameter in 'Micro meter'					nm
D10	7.4	6.2	1.1	2.4	1	24.1
D15	12.1	10.1	1.6	1.7	1.5	28.4
D20	15.8	13.2	1.9	2.3	1.9	31.2
D30	24.5	20.6	2.6	3.3	2.8	40.1
D40	27.6	22.4	3.2	4.1	3.4	45.6
D50	30.8	26.2	6.8	15.9	4.1	53.9
D60	35.2	31.2	7.3	22.8	6.2	58.9
D65	40.4	32.9	8.2	26.1	6.3	64.3
D70	42.6	36.8	9.7	29.9	6.5	66.9
D75	45	38.6	10.2	34.2	6.7	76.2
D80	52.7	40.5	11.4	51.9	6.9	86.4
D85	58.6	47.2	12.6	455.1	7.4	93.5
D90	63.2	58.6	13.7	560.4	8	108.1

Sizes	Cement OPC 53	Flyash	MK	GGBFS	UFS/UGGBFS	Alumina Powder
	Diameter in 'Micro meter'					nm
D95	75	63.8	16.8	678.5	9.5	163.2
D100	85	75	22.5	890.1	17.3	168.2



Graph 3.1 PSD Graph of OPC, Flyash, GGBFS, UGGBFS, Metakaolin and Alumina Powder

3.6 XRD Analysis

XRD Investigation is carried to check out the minerals qualitatively. XRD was carried to verify the occurrence of 'glassy nature' and 'crystalline nature' material fractions. This method is opted by researches to quickly check the presence of above natured material fractions.

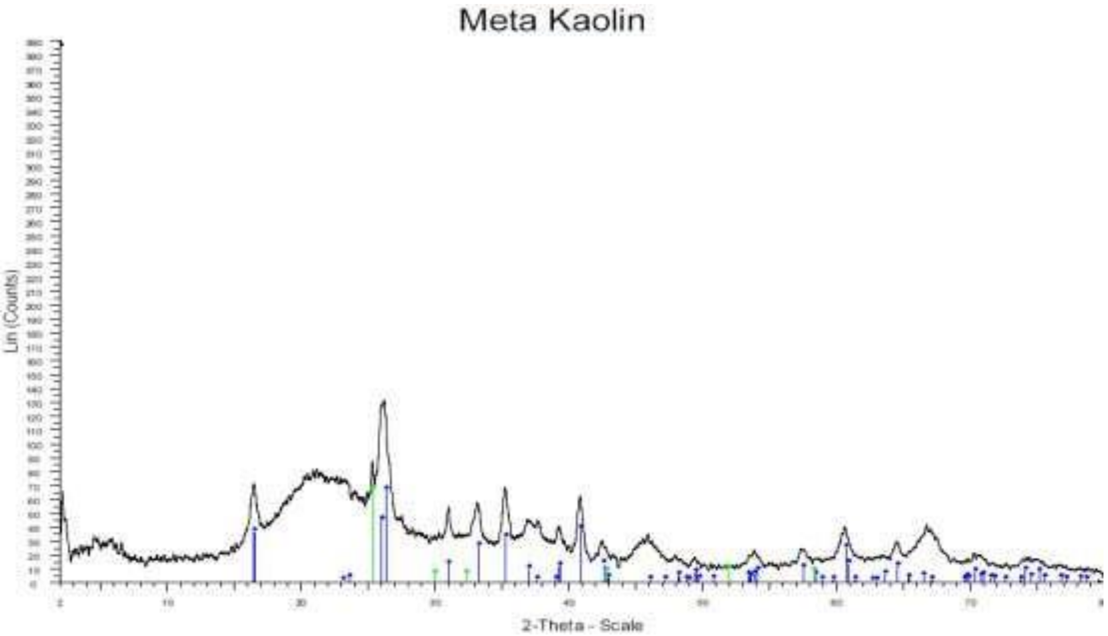
3.6.1 XRD Analysis of Reactive Cementitious Materials

3.6.1.1 Metakaolin

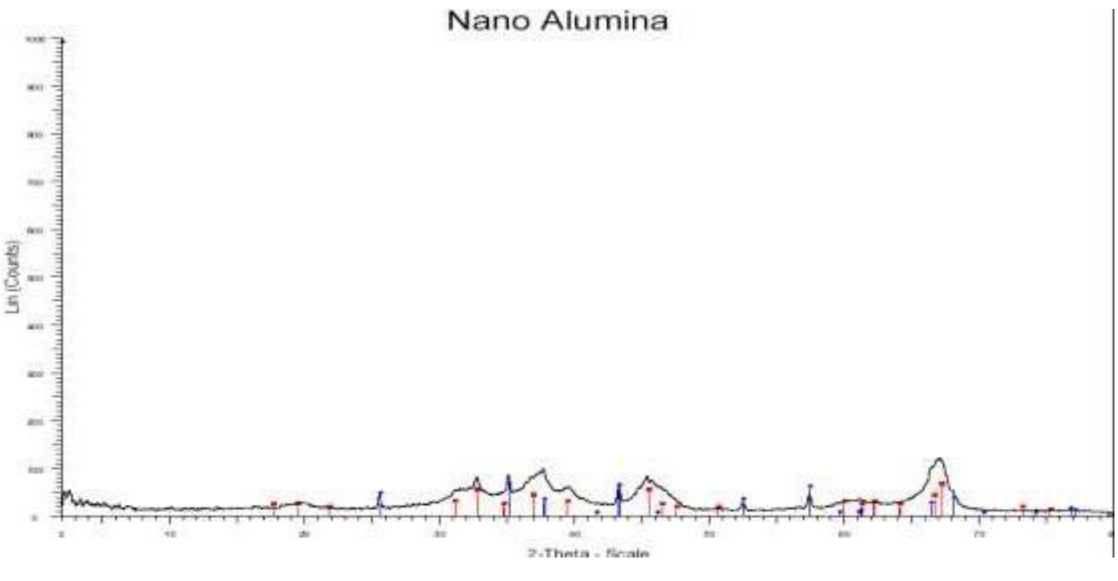
The XRD configuration of Metakaolin is shown in Graph 3.2. Presence of silica and alumina is observed in this analysis and the same corresponds to the chemical analysis carried using IS 4032. In the XRD of MK, the 1st highest point observed at '2ϴ' = 16.10 and 2nd highest point observed at '2ϴ' = 26.2.

3.6.1.2 Alumina Powder(NA)

Graph 3.3 represents the XRD outline of NA. XRD analysis confirmed the presence of alumina and the same is verified through chemical analysis carried as per IS 4032. In the XRD of NA, 1st highest point observed at '2Θ' = 19.26 and 2nd highest point observed at '2Θ' = 30.28.



Graph 3.2 XRD Pattern of Metakaolin



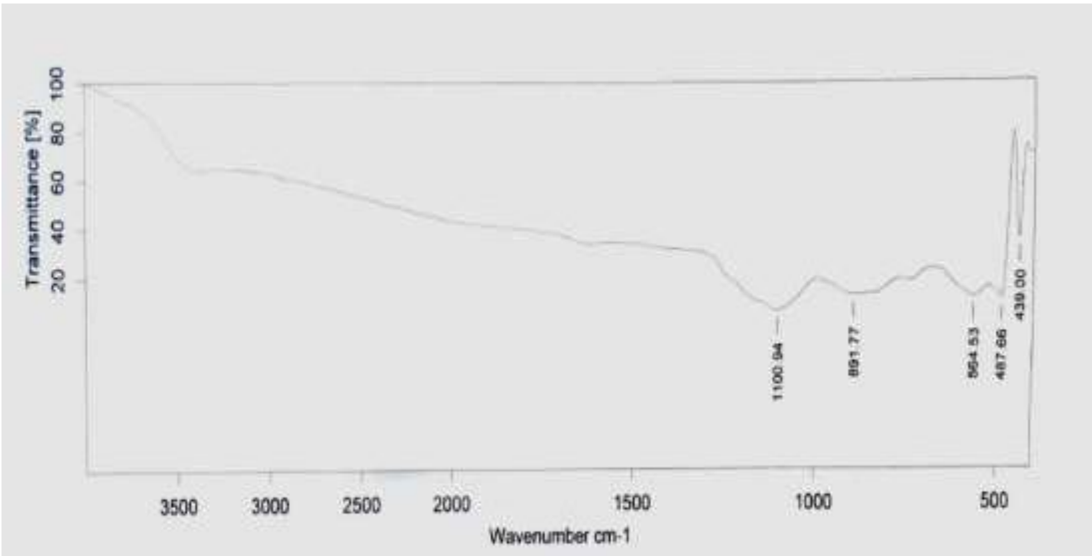
Graph 3.3 XRD Pattern of Alumina Powder(NA)

3.7 FTIR Analysis

FTIR -Analysis or FTIR- Spectroscopy, is an investigative procedure used to recognize carbon-based, polymeric-based and inert materials by subjecting the specimens under IR radiance ranging from 10^3 cm^{-1} to 10^2 cm^{-1} in which some part gets absorbed and remaining part passes through wherein the absorbed radiance part transforms to revolving energy form/shaking energy form or both types and the spectrum of the same appears in graphical form, naturally from $4*10^3$ cm^{-1} to $4*10^2$ cm^{-1}, and thus can be able to display chemical nature of the specimens under the test which is unique for each chemical compound.

3.7.1 FTIR spectrum of MK

FTIR spectra of pure Metakaolin samples in as shown in Graph 3.4. The spectrum of the pure Metakaolin sample shows that the OH stretching vibrations in the defined highest point at 3404 cm^{-1}. Furthermore, the highest points in the 1100cm^{-1} to 400cm^{-1} range are a confirmation of the presence of kaolinite in the sample.

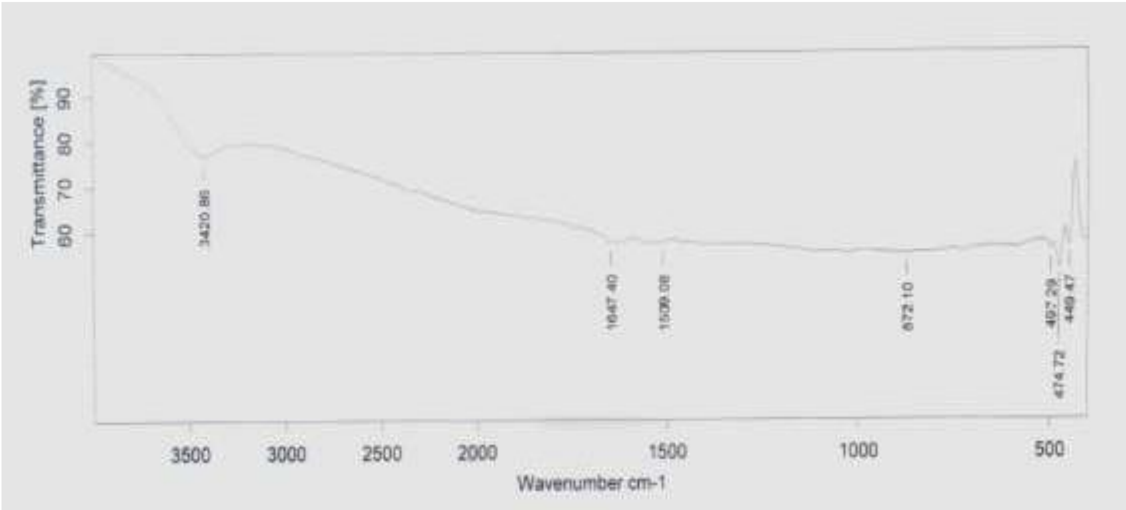


Graph 3.4 FTIR Pattern of Metakaolin

3.9.2 FTIR spectrum of NA

FTIR spectrum of NA is as shown in Graph 3.5. The FTIR spectra revealed that there are 449.47, 474.72, 479.29, 455.30, 489.15, 507.28, 570.93, cm^{-1} (O-Al-O) functional groups. A band cantered $34*10^2$ cm^{-1} and another around $15*10^2$ cm^{-1} was allotted to

O-H stretch and winding styles of water / alcohol molecules. The wide band appearing between $5*10^2$ cm^{-1} and $9*10^2$ cm^{-1} agrees to the shaking incidences of O-Al-O tie. The wide band is divided into two peaks. The peaks in the region $5*10^2$ – $7.5*10^2$ cm^{-1} were allocated as ϒ –AlO_6 and the other at $8*10^2$ cm-1 was assigned to ϒ – AlO_4 in 'Al_2O_3'. There are some widespread and high crests of Al–O stretching (AlO_4 /AlO_6 vibration) in the range of $5*10^2$ – $10*10^2$ cm^{-1} that relate to the in-between stages of 'Al_2O_3' and the steady stage of 'Al_2O_3'.



Graph 3.5 FTIR Pattern of Alumina Powder

CHAPTER 4

METHODOLOGY, MIX PROPORTIONING AND TESTS ON SCC

4.0 General

This chapter compacts with the explanation of methods used in experimentation of SCC and methods of various tests in fresh state, hardened state including microscopic analysis and durability tests as per relevant IS codes, IRC, ASTM etc.

4.1 Proposed Phases of Study:

4.1.1 Observance in sight of the ideas framed in this thesis, the research work was alienated into four segments/phases as comprehended below.

Phase-I : Mix Proportioning of fast setting early strength hybrid fibre reinforced self-compacting concrete(FSESHFRSCC)

Phase-II : Studying the mechanical properties of FSESHFRSCC

Phase-III : Conducting durability studies on FSESHFRSCC

Phase-IV : Carry out field studies on FSESHFRSCC.

4.2 Proposed Research Methodology

Proposed research methodology for the thesis is presented in flow chart here under in Fig.4.1.

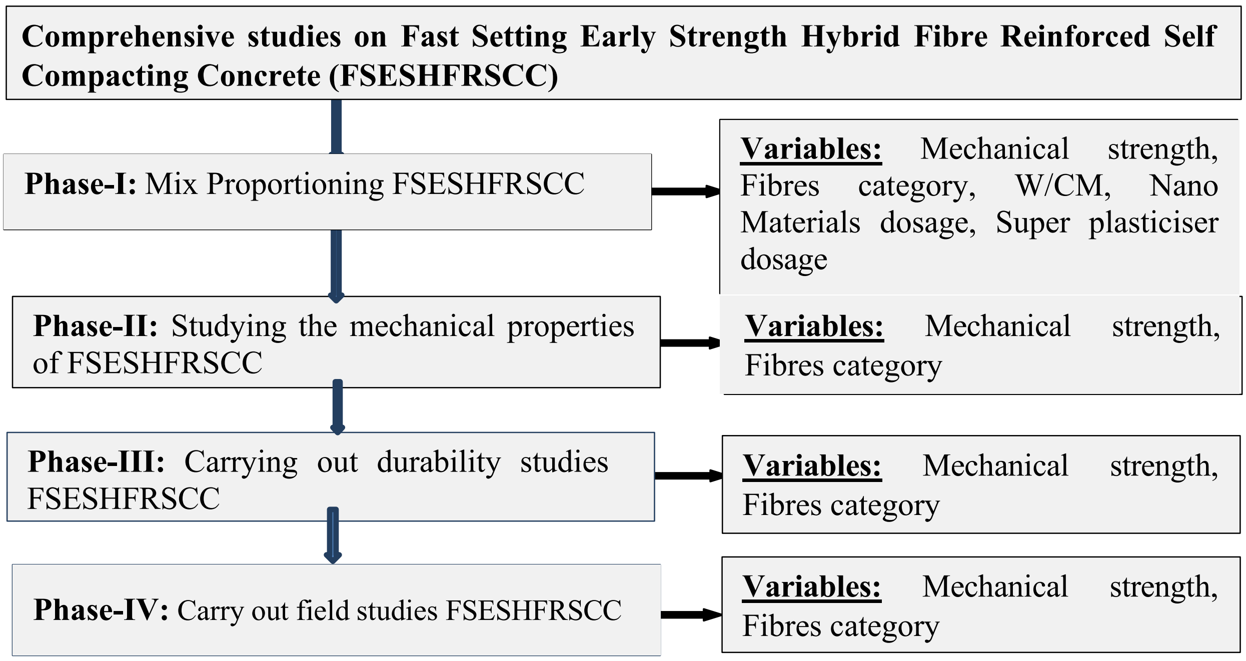


Fig.4.1 Flow Chart for studying Fast Setting Early Strength Hybrid Fibre Reinforced Self Compacting Concrete (FSESHFRSCC)

4.2.1 EXPECTED OUTPUT FROM STUDY

OUTPUT EXPECTED FROM THE STUDY

- Optimised FSESHFRSCC mix proportions for various depth of repair of CC Pavement and Bridge Decks
- Mechanical and Durability characteristics of FSESHFRSCC

4.3 Fast Setting Early Strength Hybrid Fibre Reinforced Self Compacting Concrete (FSESHFRSCC)- Proportioning and Studying

The following procedure, as presented in the flow chart in Fig.4.2 hereunder will be carried for arriving the proportions of **FSESHFRSCC**.

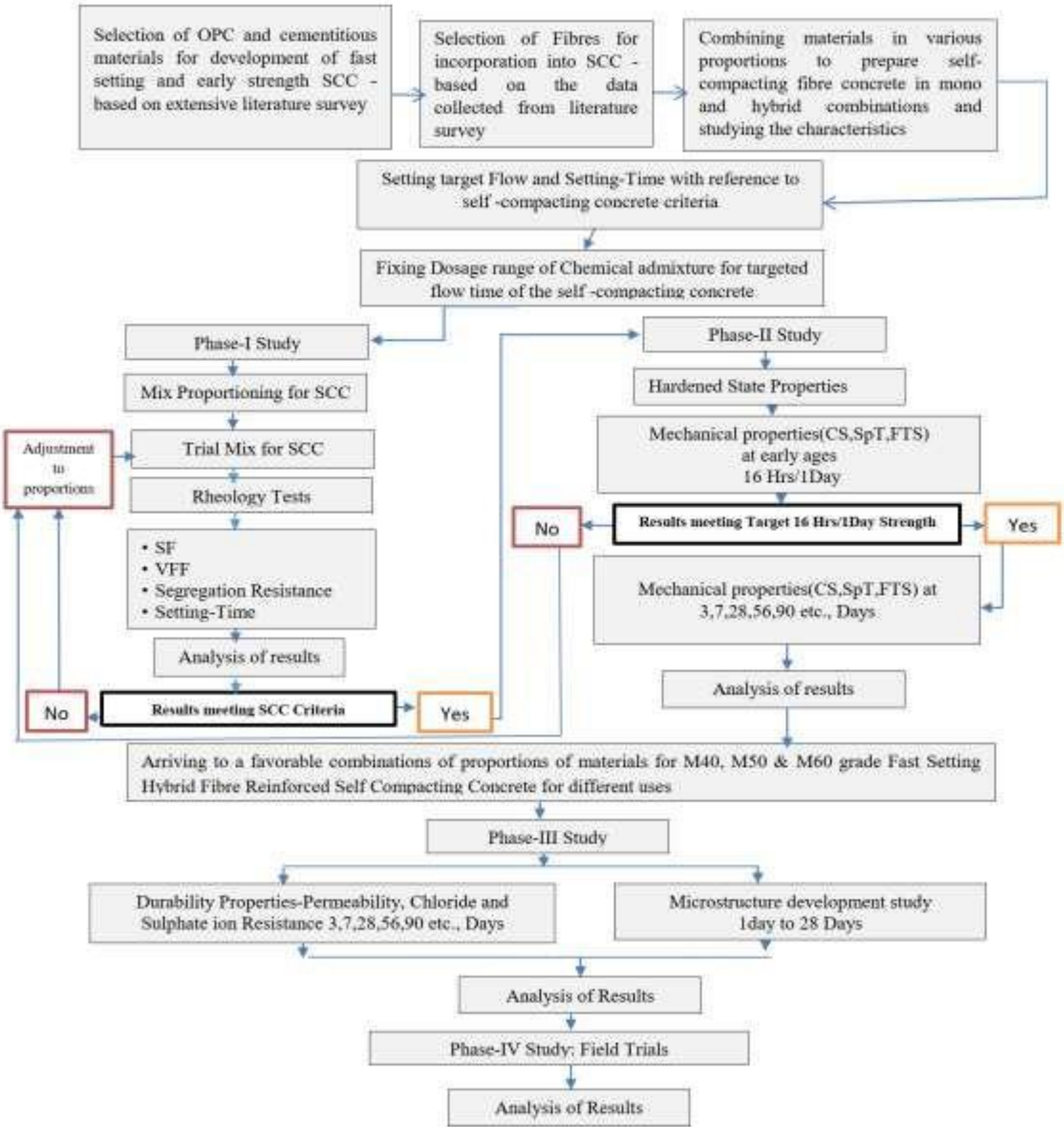


Fig.4.2 Flow Chart for Fast Setting Early Strength Hybrid Fibre Reinforced Self Compacting Concrete (FSESHFRSCC) - Proportioning and Analysis

4.4 Characteristics of SCC Mix

A recipe of concrete will be deemed to characterised as SCC Mix, when it satisfies minimum requirements of rheological parameters like SF,VFT etc tested as per provisions of IS 1199(Part 6) and the same tests as conducted in this research study are briefly discussed hereunder.

4.4.1 Slump- Flow(SF)

Slump-Flow is the average spread diameter of concrete under test and usually measured in 'mm'. This test can be conducted either in laboratory or filed conditions. Typical slump-flow classes of self- compacting concrete is provided in Table 4.1

Table 4.1
Typical slump-flow classes of self- compacting concrete

Class of SCC based on flowability	**Slump flow range**	**Equipment required for flow ability test**	**Method of test**	**View of slump flow equipment and test**	**Examples of usage of the SCC class**
SF_1	550mm to 650mm	Slump cone, steel scale 1000mm length, 3mm thick flat metal plate of dimensions of 1000 mm X 1000mm, container/can, cleaning cloth	IS 1199 (Part6)		SF1:Slabs, Tunnel lining, Piles and deep foundations etc.,
SF_2	660mm to 750mm				SF2:Walls, columns etc.,
SF_3	760mm to 850mm				SF3: Congested reinforcement areas, complex shapes etc.,

4.4.1.1 Slump –Flow(SF) Test Method

SF test performed using simple slump cone and a flat plate made up of non-absorbing materials of size 1000mmX1000mmX1mm thick. Concentric circles of suitable diameters like 200mm,400mm,500mm,600mm and 800mm are inscribed for easy measurement of spread of concrete under slump flow test upon lifting of the cone placed centrally and filled with concrete, without any tamping. The average spread diameter is considered as the flow of that particular recipe and visual observations like bleeding, segregation, obstruction, inertia to flow etc. can also be made on the concrete after spreading. If the concrete under test doesn't flow as desired correction or fine tuning the proportions to the recipe could be carried out

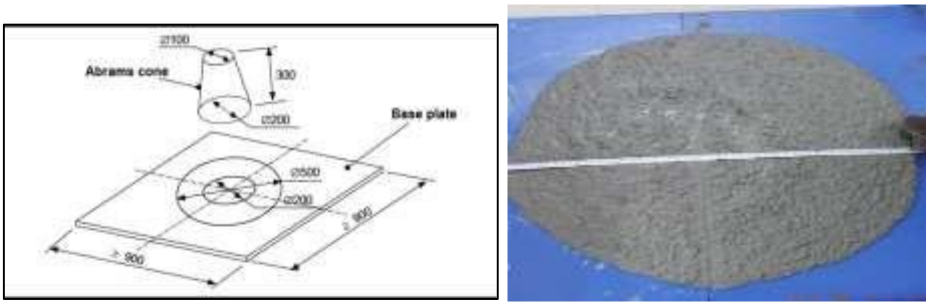


Fig.4.3 Accessories for carrying Slump-flow test [72]

4.1.1.2 Slump Flow Test Apparatus

The device is shown in Fig.4.3 and comprises of :

- Slump flow mould made up of mild steel, having the form tapered cone, will have 100mm top diameter,200mm bottom diameter and 300mm height
- Non-absorbent plate of 1000mmX1000mmX1mm thick inscribed with concentric circles of suitable diameters like 200mm,400mm,500mm,600mm and 800mm
- Other accessories like plastic container for keeping the sample, trowels, scoops, 1000mm Steel scale, spirit level, and stop watch, wiping cloths, sponge etc.,

4.1.1.3 Procedure and Measurement of Slump- Flow

The slump- flow measurement procedure briefed below

- ✓ Level the plate using spirit level
- ✓ Moisten the slump cone inside and plate with sponge or wiping cloth
- ✓ Take approximately 6.0 litters of freshly mixed concrete
- ✓ Place the slump cone concentrically over the plate and held it firmly
- ✓ Slowly and gently allow the concrete using the scoop to fill the slump cone, without any tamping and takeout gently the excess concrete from the cone
- ✓ Slowly lift the slump cone without any jerks or vibration and simultaneously start the stopwatch
- ✓ Observe the flow of concrete over the plate and stop the watch on reaching the spread concrete 500mm diameter mark. Record the time required for the concrete to reach 500mm diameter mark as Ti_{500}

✓ Measure the final diameter of the concrete in two perpendicular directions and take the average and record it as Slump-flow of the recipe

4.4.2 Obstruction to Flow - L shaped box flow test

In slump-flow test the concrete under test was free to flow without any hindrance to flow. But, this will not always be available for placements concrete at site conditions, since there will be obstructions in the forms of various shapes of reinforcement placed in the formwork for RCC works. To assess the capacity of concrete to pass through the simulated obstructions, the obstruction to flow test-L shaped box test is carried out. View of L shaped box device presented in the Fig.4.4 and L shaped box Flow ratio is measured as Flow ratio = $f/f_{end.}$ where f= depth in 'mm' of concrete near reinforcement and f_{end} is the depth of concrete at the end point of the L shaped box. For qualifying any recipe as SCC ,the Flow ratio = f/f_{end} ration shall be minimum 0.8

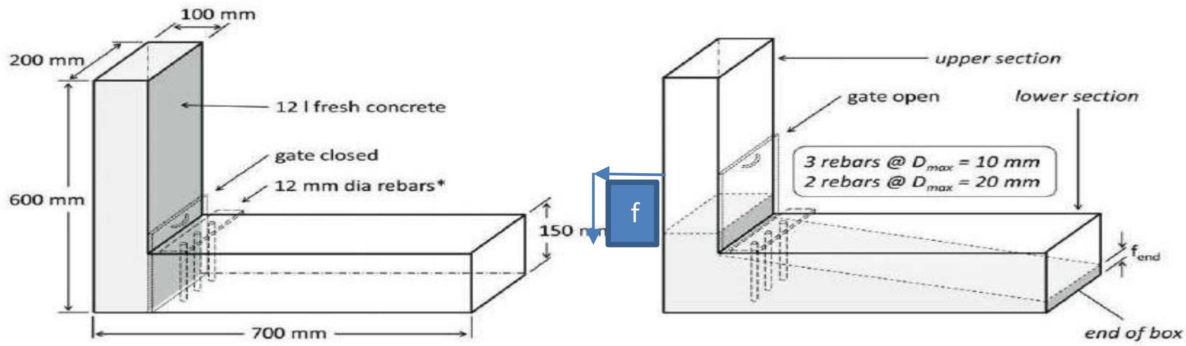


Fig. 4.4 View of L Box Flow measuring apparatus[81]

4.4.2.1 L shaped Box flow Test device and Test procedure

The dimensions of L shaped box test device is shown in Fig.4.4

4.4.2.2 Assessment of L shaped Box test

L shaped box test, a commonly used investigation technique, suitable for lab scale study on recipe's flow behaviour in case of reinforcement obstructions depicting the ability of recipe.

4.2.2.3 Equipment required for L shaped Box test

- L shaped box made , plastic container for keeping the sample, trowels, scoops, wiping cloth, sponge, plastic can etc.,
- Stopwatch

4.2.2.4 Flow through L shaped Box- test procedure

- ✓ L shaped box to be kept on firm level base ,moisten interior side slightly and ensure free movement of sliding gate
- ✓ Collect concrete sample about 14 litters, close the sliding gate properly and gently fill the concrete sample, under test, with the help of scoop in the vertical part of L shaped box
- ✓ Wipe-out the excess concrete/slurry if any and then slowly lift the sliding gate to permit the concrete to stream out into the straight part of the above device.
- ✓ On concrete attaining rest, measure the depths of concrete near the sliding gate (f) at and depth of concrete at the end point (f_{end}) and find out f / f_{end} , the blocking ratio
- ✓ Make visual observations of the mix in the L shaped box for hindering of coarse aggregate after the reinforcement at the gate, if any

4.4.3 Segregation Ratio (SR)

SR test determines the resistance of the concrete mix under test against separation of constituents. In this test the concrete sample under test, after separating bleeding water, if any, will be passed through IS 4.75mm sieve and the percentage proportion of passed down material in the total sample will be denoted as SR.

SR is categorized as SR1 class and SR2 class according to percentage proportion of passed down material through IS 4.75mm sieve in the total sample. If the percentage proportion is between 15% to 20%, then the mix is categorized as SR1 class and if it is <15% then the mix is categorized as SR2 class. Sieve segregation resistance test apparatus is presented in Fig.4.5.

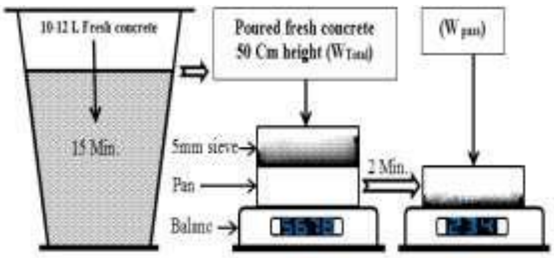


Fig.4.5 View of Sieve Segregation Resistance Test[81]

4.4.4 V-Funnel Tests (Viscosity Test)

Viscosity of SCC mix tested using V shaped funnel in which the time taken in ‘seconds’ by the mix, under test, will be measured and noted as the flow time. The recent revision of IS1199 under part 6 spells about the Viscosity test of SCC. Similar to the liquids, if the viscosity of the material is high, the time required for the same to pass through the V type funnel will take more time and if the viscosity of the material is less, the time required for the material to pass through the above funnel will be less. According to the viscosity i.e. the time required for the mix to pass through the V type funnel, the SCC is categorized as VF1 class, requiring time to pass as <8 seconds, and VF2 class requiring time to pass as 9seconds to 25 Seconds. V type funnel flow test apparatus is presented in Fig.4.6. In this test concrete sample under the test is poured into the V type funnel, ensure the closing of the hinged trapdoor provided at the square size outlet, after allowing the poured mix to settle, the trap door is opened, and simultaneously stopwatch started ,so that the mix will flow out from the funnel. The time required for the entire mix to flow out of the funnel is noted as V funnel flow time and accordingly the mix will be categorized as VF1 or VF2 as per the above criteria.

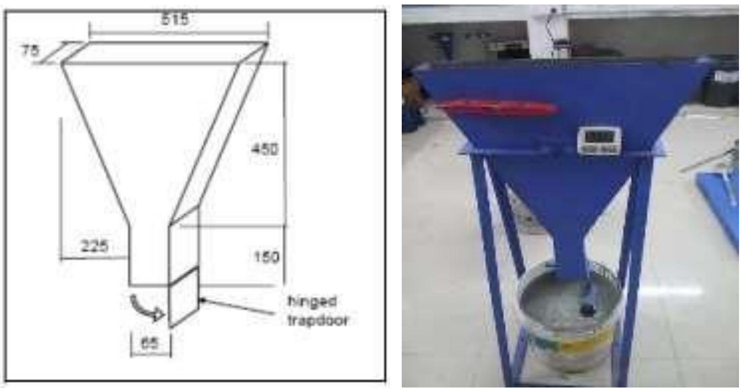


Fig.4.6 View of V Funnel Flow Test Apparatus [72]

4.4.5 Setting time test of Concrete Mix

Setting time test of concrete mix is carried out following the provisions of latest revised IS 1199 spelt under part 7. Calibrated equipment consisting of spring actuated plunger capable of measuring the resistance, in N/mm^2, against the penetration of plunger, head having various surface areas, to a depth of 25mm from the surface forced into the mix under test. The concrete mix whose setting time needs to be determined will be partitioned as mortar by passing the mix through IS 4.75 mm. The mortar collected in the pan will be poured in to 150mm size cube moulds filling up to 140mm.For SCC mix tamping of mortar is not required for other type of mix taming of mortar in layers will be required to be done for carrying the setting time test.

4.4.5.1 Procedure of Setting time test

a. The separated mortar fraction as done above will be subjected to at least six intermittent penetration resistance test determinations using various surface areas of plungers and the resistance exerted, in N/mm^2, against penetration depth of 25mm from surface is recorded and also the cumulative time, in minutes, elapsed from the time of adding water to cement or cementitious materials to the time of each intermittent test of penetration resistance.
b. A graph is plotted elapsed time of measurement Vs Penetration resistance
c. From the graph, Initial Setting Time of concrete is determined as that time elapsed from the time of adding water to cement or cementitious materials where the exerted penetration resistance is 3.43 N/mm^2.
d. From the graph, Initial Setting Time of concrete is determined as that time elapsed from the time of adding water to cement or cementitious materials where the exerted penetration resistance is 26.97 N/mm^2.

Equipment used for determination of concrete setting time and a typical graph of readings of the test is presented in Fig.4.7.

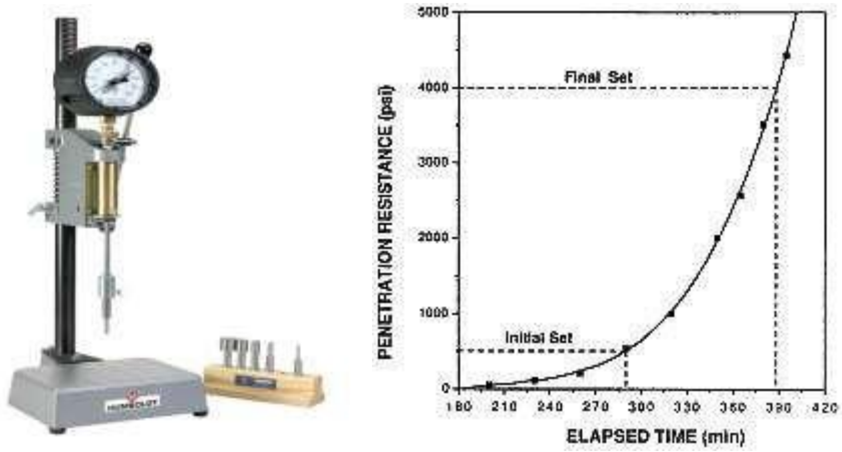


Fig. 4.7 (a)Penetration Resistance Apparatus (b) Setting time plot[88]

4.5 Tests on Hardened SCC

Various tests carried on hardened concrete in this research study are briefly discussed hereunder.

4.5.1 Test for determining compressive strength of concrete(CS)

Compressive strength of concrete measured in units N/mm^2 ,calculated using the formulae mentioned here under, was tested using compression testing machine(CTM) following the provision as spelt in latest revision of IS 516(Part1/Sec 1):2021

Formulae of Compressive Strength of Concrete :

Compressive Strength of Concrete = Load sustained by concrete specimen at failure(F)/ Surface area of concrete specimen(a)

Various SCC recipe intended to be tested for compressive strength was poured in the mould, without any tamping, marked with a unique ID and recorded accordingly. After the concrete specimen hardened, the specimens in the moulds were removed and specimens were placed in a controlled curing chamber maintained at 27 ± 2^0C till an intended age of test up to 28 days. For the concrete specimens intended to be tested beyond 28 days, the same specimens were taken out of curing tank, after 28 days curing and kept in a secured place in ambient conditions. For testing a concrete specimen, at any intended age, the specimens taken out from curing tank, if they were of less than 28 days age, and the surface of the same wiped with cloth to just make the surface to attain saturated surface dry condition, weight of the same recorded and securely placed between the platens of CTM and 14 N/mm^2/minute load applied gradually till the specimen fails. This load was recorded and upon division of the same with surface area was noted as compressive strength of the particular specimen.

4.5.2 Split Tensile Strength Test(STS)

STS of concrete measured in units N/mm^2 and calculated using the formulae mentioned here under, was tested following the provisions as spelt in IS 516 (Part 1/Sec 1) : 2021. This test can be performed in the CTM either on cube specimens or cylindrical specimens placed in the relevant jig. The environment conditions as well as the curing to be ensured will be the same as was followed for compressive strength test. The specimens ,in saturated surface dry conditions ,were weighed and applied with a 1.2 N/mm^2 /minute rate of loading till the specimen fails. Pictorial representation of split tensile strength test is presented in Fig.4.8.

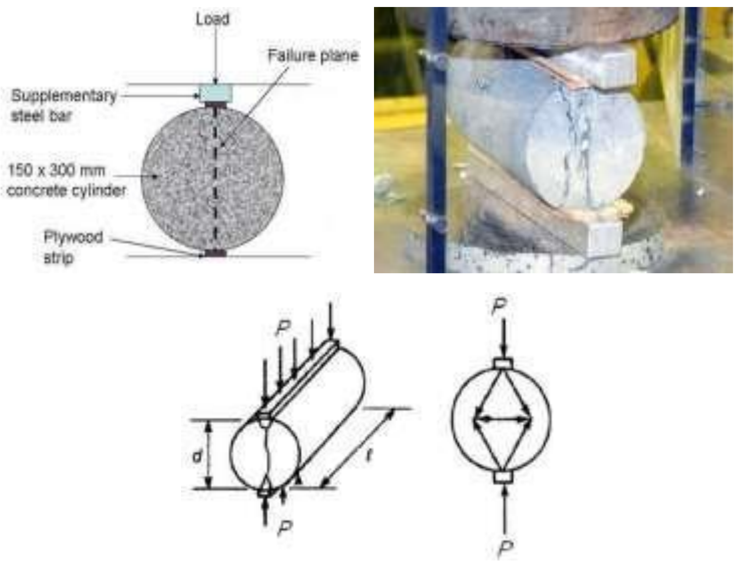


Fig. 4.8 General arrangement of Split Tensile Strength Test on Cylindrical Specimen[86]

Formulae for determining STS of the specimen

$$STS= 2*F/ (\pi* L*D)$$

Where F: Ultimate load sustained by specimen under STS test , units of load 'N'

D= Specimen Diameter in 'mm'

L= Specimen length in 'mm'

4.5.3 Modulus of Rupture (MR)

MR, also called popularly as flexure strength, measured in N/mm^2 and calculated using the formulae mentioned here under. Flexure strength of concrete carried on beam specimen of 500mmX50mmX100mm and carried in flexural strength testing machine, using four point bending method, duly following the procedures as spelt in IS 516 (Part 1/Sec 1) : 2021. The environment conditions as well as the curing to be ensured will be the same as was followed for compressive strength specimens. The specimens ,in saturated surface dry conditions ,were weighed and applied with a 1.8 KN /minute rate of loading till the failure .Pictorial representation of MR test , on concrete beam specimen, presented in Fig.4.9.

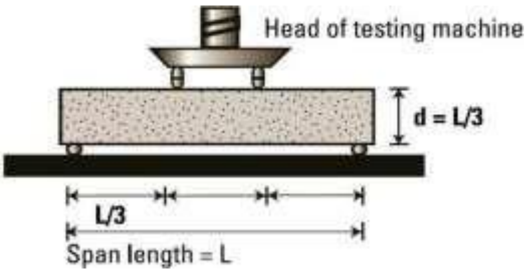


Fig. 4.9 General arrangement of specimen in MR test[88]

Formulae for MR is determined by the following formula.

$$\mathbf{MR = 3*F*L/2*b*d^2}$$

Where F = Ultimate load in 'KN', L= Specimen length in 'mm', b= specimen width in 'mm' and d= specimen depth in 'mm'.

4.5.4 Modulus of Elasticity(MoE)

MoE , also popularly known as Secant Modulus, measured in N/mm^2 and calculated using the formulae mentioned here under ,defined as the proportion of functional stress of the concrete specimen under test to the corresponding strain. MoE of concrete was tested on cylindrical specimen following the procedure as spelt in IS 516 (Part 8/Sec 1) : 2020. The environment conditions as well as the curing to be ensured will be the same as was followed for compressive strength specimens. CTM can be used to measure the MoE. The specimens ,in saturated surface dry conditions ,were weighed and secured in a special test accessory consisting of dial gauges positioned in horizontal and vertical directions to measure the strain . The specimens after securing under the platens were applied with a 14 N/mm^2 /minute rate of loading till the specimen fails. A graph needs to be drawn between stress Vs strain in order to calculate the MoE. Pictorial representation of MoE test of concrete presented in Fig.4.10.

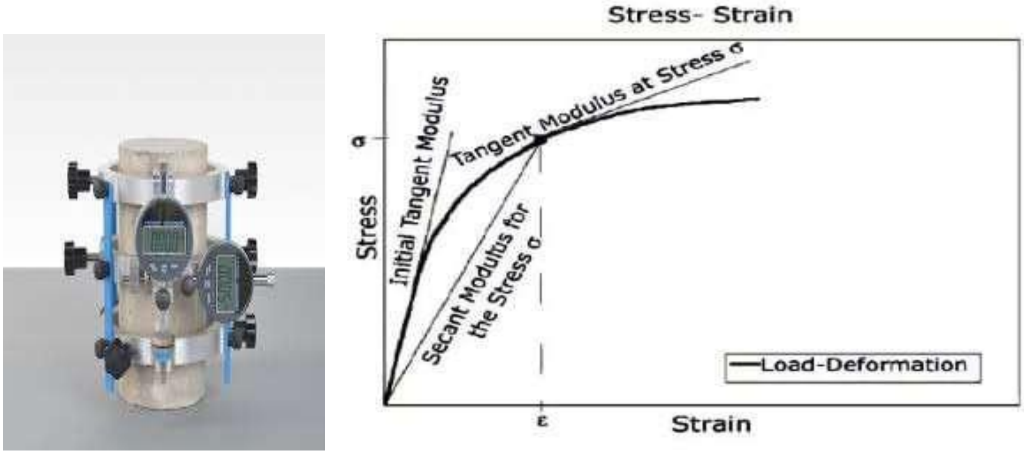


Fig.4.10. General Arrangements for MoE test and Pattern of Load-Deflection Graph in MoE test[48]

4.6 Durability Tests (conducted in laboratory)

4.6.1 Drying Shrinkage(DS)

DS of concrete is tested on cylindrical specimen or prismatic specimen and was tested as per the procedure as spelt in IS 516 (Part 6) : 2020. The dimensions of the mould used for casting specimens of drying shrinkage test will of be 75 × 75 × 300 mm. Measuring apparatus for drying shrinkage consists of a micrometre to read 1/1000 part of ‘ mm’. The gauge, firmly held in a measurement setting has a sunken end positioned upon a 6.5 mm diameter stainless steel ball or any other suitable non corroding locus point in the specimen or secured while preparing the specimens for shrinkage test. The further end point of the frame has an analogous sunken seat for placing the specimen. Standard reference bar meant for comparison the dimensions of specimens under shrinkage test will be made of a material characterized by an extremely low coefficient of thermal expansion such as invar or other material suitable for the purpose, shall be used with each comparator, and has at least 6 mm end diameter, and the overall length of the reference bar 300 ± 1.5 mm. The environment conditions as well as the curing to be ensured will be the same as was followed for compressive strength specimens. The specimens length initially after demoulding will be recorded as dry length and the same is used for comparison of change in length of each specimen at a particular age against the length of the same specimen in saturated surface dry conditions after subjecting the specimen to particular curing condition.

Pictorial representation of drying shrinkage test of concrete is presented in Fig.4.11

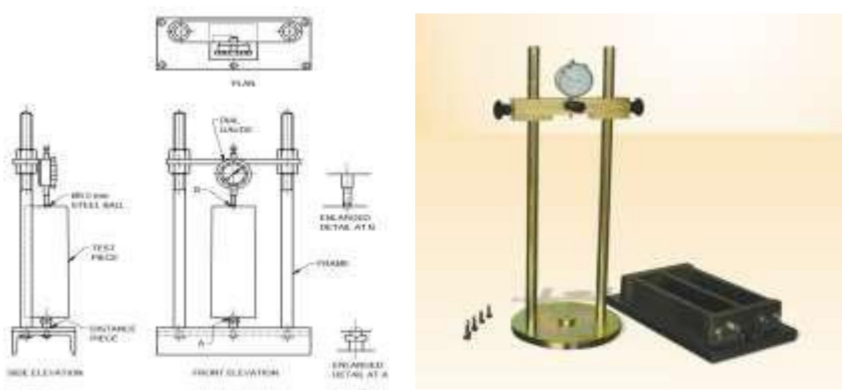


Fig. 4.11 Accessories for measurement of shrinkage[66]

Drying shrinkage = 100*[Length of specimen in wet condition – Length of specimen in dry condition/ Length of specimen in dry condition]

4.6.2 Sorptivity Test

Sorptivity test measures the capillary rise of water, from time to time till its saturation, measured in terms of change in weight with reference to initial weight, over a period of time ,in a 100mm diameter concrete disk of 50 mm thickness which has been extracted from a concrete specimen and prepared according to the sizes as mentioned above. This test was performed following the provisions of ASTM C 1585. Initially the so prepared concrete disks are subjected to drying at 50 °C and 95% RH for three days, thereafter the same were sealed and placed for 15 days in a bowl. Prior to the placement of the concrete disks in testing trays, the disk's side surface sealed with water resistance coating like epoxy and top surface closed with the help of a transparent plastic sheet with rubber bands and weight of the same to be noted as initial weight and time of placement in the testing tray, which is partly filled with water and having some kind of supporting arrangements like non-absorbent rods on which the prepared specimens to be kept for observing the Sorptivity. Typical arrangement of the Sorptivity test presented in Fig.4.12. Sorptivity is measured in units 10^{-4} g/mm^2/minute$^{1/2}$.

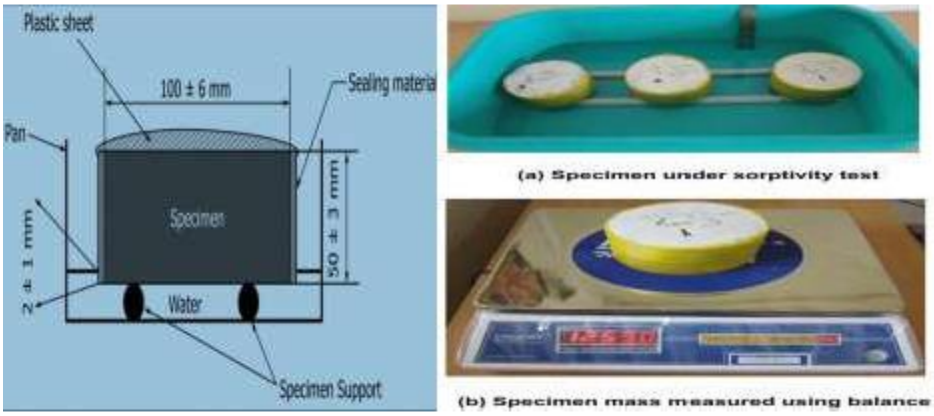


Fig. 4.12 Accessories for measurement of Sorptivity[68]

4.6.3 Water Permeability Test

Permeability test of concrete specimen tested as per the procedure spelt in IS 516(Part2/Sec.1):2018. Permeability measured in units of 'mm' representing the water percolation depth from surface of concrete when subjected to a hydrostatic pressure of 5 N/mm^2 for 3 days . The specimens under the permeability test, after 3 days of pressure test, will be split in a CTM by placing the specimens over a steel rod of suitable diameter and similar rod will be placed over the top end of the specimen so that splitting force can be exerted and length in a platen .After the splitting of the specimen carefully the specimens will be taken out and average depth of water percolated into the body of the specimen from the top side will be measured using any precision scale like Vernier calliper. The less depth of water penetration in the above tested specimens will indicate the denseness of the same. Typical arrangement of Water Permeability Test is presented in Fig.4.13. Water Permeability is measured in units ‘mm’.

Fig 4.13 Accessories for Permeability Test Arrangements of Concrete Specimen[86]

4.6.4 Resistance to Sulphate ion ingression

Resistance to Sulphate ion ingression in prismatic samples was measured as per the procedures spelt in ASTM C1012/C1012M on a prismatic specimen of size 25mmx25mmx285mm . The specimens will be prepared using the mortar portion screened out from the sampled concrete over a IS 4.75mm sieve .Specimens so moulded as above will be left in the moulds till 24 hours in a 95% RH environment chamber. Prior to subjecting the demoulded specimens to aggressive sulphate solution ponding, all the specimens to be carefully marked with IDs and initial lengths of the same will be noted using a precision length comparator and then the same will be immersed in a prepared Na_2SO_4 solvent, where in each 1 litre of solution consists of 50 grams of Na2SO4, to simulate the aggressive conditions of sulphate attack. For each intermittent period of intended measurement of sulphate resistance , all the specimens will be measured for change in length with reference to the initial length. Excessive change in length and damages that occurred to the specimens will indicate the deficiency of the mix against sulphate attack. Typical arrangement of Sulphate ion ingression test is presented in Fig.4.14. Sulphate ion ingression is indirectly measured as the expansion of specimen after subjecting the specimens to specified immersion in Na_2SO_4 solution and measured in units '%' length change over the length of control sample.

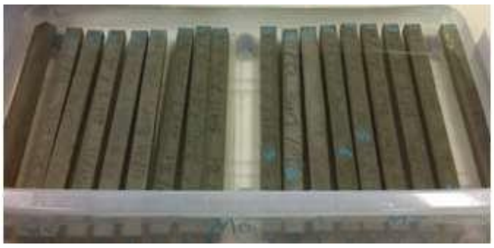


Fig 4.14 Accessories for Resistance to Sulphate ion ingression[72]

4.6.5 Resistance against penetration of Cl^- Ions

ASTM series specification C1543 spells the procedure of test resistance against penetration of Cl^- ions into the body of concrete. The slab formed concrete specimens of size 600mm X300mmX100mm will be prepared, and after hardening of the same, for subjecting the top surface to ponding with Cl^- rich 3% NaCl solvent and to avoid evaporation loss of solvent the ponded surface will be covered with suitable transparent polythene sheet. Whenever the resistance to Cl^- ion resistance test needs to be performed , from the specimens the above NaCl solution carefully drained off so that a 25mm diameter and 40mm length concrete core can be extracted and crushing the same concrete powder can be prepared for determining the Cl^- ion content using the provisions of IS 4032 .Excessive Cl^- in concrete will indicate the deficiency of the mix against chloride attack and there by indirectly indicating the recipe creating an environment conducive for reinforcement corrosion. Cl^- ion ingression is directly measured as the % Cl^- present in the specimen after subjecting the specimens to specified ponding of NaCl solution and measured in units '%' Cl^- present in the sample.

Fig 4.15 Accessories for Resistance to Chloride Ion Ingression [52]

4.7 Microscopic Analysis (Scanning Electron Microscope)

Scanning Electron Microscope (SEM), a category of electron microscope that scans the surfaces through electron beam affecting at squat energy levels for exploring the surfaces to the required level of magnification. SEM proving to be a useful research tool for microscopic study of material for characterisation and also to study of change in the micro structure of the same, with time, upon combined with other intended materials or subjected reactive forces. A typical SEM equipment is presented in Fig.4.16.

Fig. 4.16 Accessories of Scanning Electron Microscope[75]

4.8 XRD Analysis

XRD, a category of diffraction analysis used to study the characterisation of materials, constituents , phase changes, arrangements of crystals, amorphous nature of materials etc., using X rays impinged over the surface of the specimen. XRD proving to be a useful research tool for study of material for characterisation, mineral composition, and also to study of changes in the phases of the same, with time, upon combined with other intended materials or subjected reactive forces. A typical XRD equipment is presented in Fig.4.17.

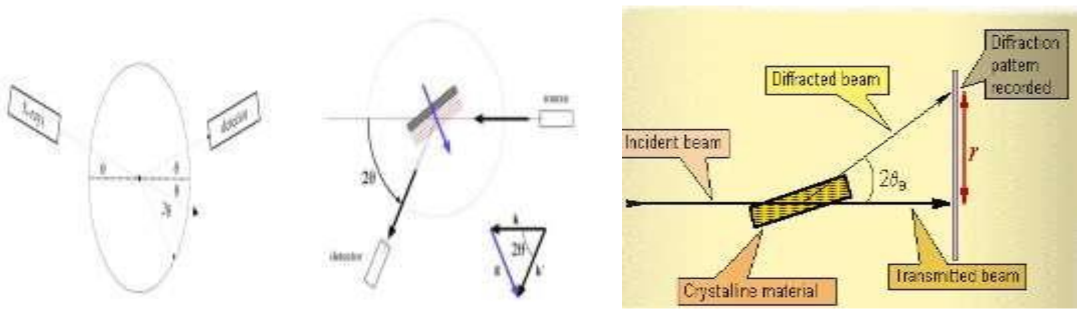


Fig. 4.17 Accessories of XRD[98]

4.9 Fourier Transform Infra Red (FT-IR) Analysis

FTIR ,an infrared spectroscopy method used for analysis of materials where in one can determine the material composition, consistency and other similar material characteristics. . A typical FTIR equipment is presented in Fig.4.18.

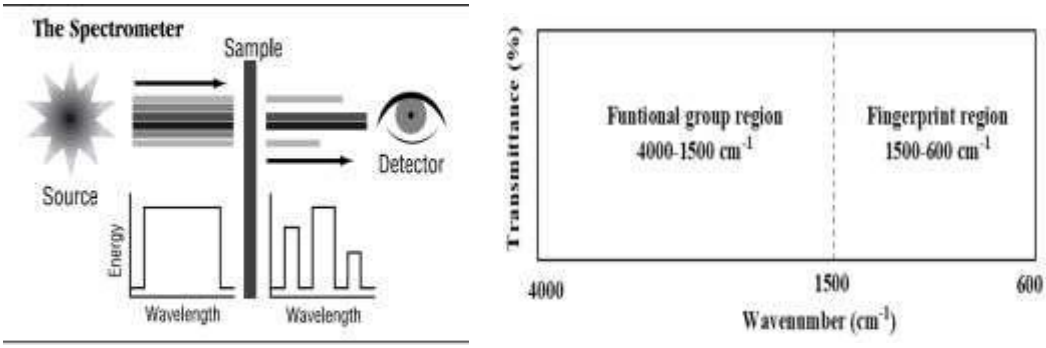


Fig. 4.18 Accessories of FTIR[102]

4.10 Durability Tests (conducted in field conditions)

4.10.1 Abrasion Resistance Test of Concrete

4.10.1.1 Equipment for measuring abrasion resistance of concrete surface

Abrasion resistance is the resistance to surface wear against abrading wheel rotating at a specified speed and causing surface abrasion of the concrete specimen placed in the abrasion machine. An abrasive charge is spread uniformly over the concrete specimen to simulate the field conditions. Abrasion resistance measured as the loss of thickness of surface of concrete subjected to abrasion force. Abrasion resistance of concrete in this study is tested as per the procedure as detailed under Annex E of IS 15658 :2021. A typical abrasion resistance test equipment is shown in Fig.4.19. Formulae for determining the abrasion resistance of concrete presented hereunder.

Average loss of volume of specimen ΔV representing abrasion loss , in units of 1000 mm^3per 5000 mm^2

$$\Delta V = (\text{initial weight } m_1 - \text{final weight } m_2) / \text{ density } `\rho'$$

Fig. 4.19 Accessories of Abrasion Resistance Test of Concrete Specimens[107]

4.10.2 Bond Test of old concrete to new concrete

Bond between old to new concrete was measured using the provisions of ASTM series C 882. A typical bond test arrangement is shown in Fig.4.20. Formulae for determining the bond strength of concrete presented hereunder.

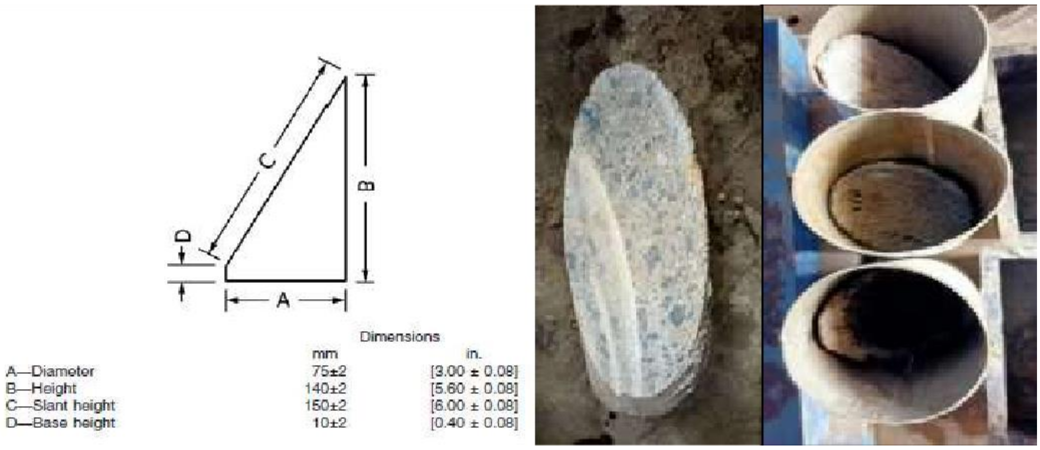


Fig. 4.20 Dummy section for creating a joint for Bond strength[111]

In this test, for measuring the bond strength amongst substrate and repair material, substrate concrete specimen needs to be cut to the required shape as per the dimensions of the 'dummy sections' shown in the above Fig. These cut sections are cleaned properly and moistened lightly and placed in the cylindrical mould for casting the new concrete and creating a joint between the substrate and repair material. Upon hardening of concrete, the casted specimens are kept in the water curing tank maintained at 27$\pm$ 2^{0}C till 28 days /the period of testing. For testing the bond strength

, compression testing machine to be used and the rate of loading will be 14 N/mm^2/minute. Strength of bond between old concrete and new concrete will be expressed as Bond Strength, N/mm^2 = Load at failure (N)/Area of slanted dummy section in mm^2. As per EN 1503-4 for class 3 repair works the bond strength for structural repair works shall be >1.5 N/mm^2.

4.10.3 Movement Restraining Test.

This test measures the characteristics of material against the restraining movement. In this test the material whose nature against restrained movement needs to be studied, will be poured in to the interior part of a prepared steel section like angle. The ends of the steel sections will be closed temporarily till the setting time of concrete material and after setting of the same wet curing is carried out for a typical period of time say 3days. The steel section in this study will simulate the restraining movement to the material under test. Surface of concrete will be examined, over a period of time, for the defects like cracks, wrapping etc., A typical movement restraining test arrangement is shown in Fig.4.21.

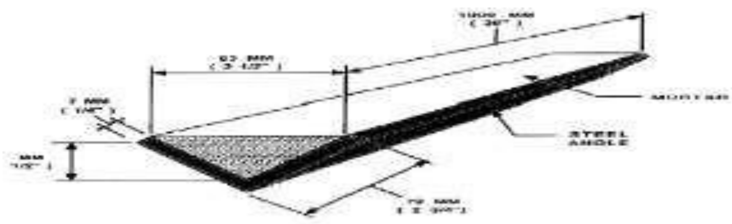


Fig.4.21 Typical movement restraining test arrangement[14]

4.10.4 Restrained Shrinkage Test

This test measures the characteristics of material against the restrained shrinkage. In this test the material whose nature against restrained shrinkage needs to be studied, will be laid on a prepared steel channel. The sides and ends of the steel channel will be closed temporarily till the setting time of concrete material and after setting of the same, wet curing is carried out for a typical period of time say 3days. The steel channel in this study will simulate the restraining movement to the material, under test, against shrinkage. Surface of concrete will be examined, over a period of time

,for the defects like separation, wrapping etc., A typical restrained shrinkage test arrangement is shown in Fig.4.22 where in the marked dimensions are in inches.

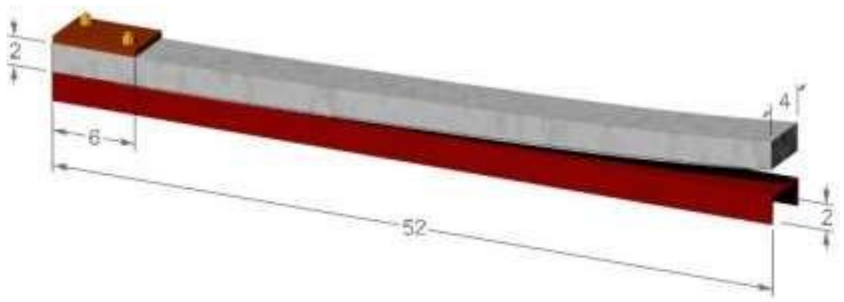


Fig.4.22 Typical restrained shrinkage test arrangement[9]

4.11 Mix Proportioning of SCC

This section provides a brief discussion on the principles of SCC mix proportioning.

4.11.1 SCC Mix Proportioning Principles

SCC mix proportioning principles can be listed as below

a) Less coarser materials

b) Higher paste material

c) Less water 'w'/powder 'p' on volume basis (where powder represents such material, including all the constituents of concrete, which is below the size of 125microns)

d) Use of HRWR super plasticizer

4.11.2 SCC Mix Proportioning Approach

Rigorous laboratory trials need to be carried for SCC recipe in arriving to a suitable combinations of proportions.

Approach for SCC recipe:

a) Determine the target mean compressive strength of the mix.

b) Select the air content based on the specified nominal maximum size of aggregate.

c) Select water-cement/cementitious materials ratio.

d) Choose arbitrary combinations for trial SCC

   i. Fix quantity of water per cubic meter of concrete , from the range 150kg/m^3 - 210kg/m^3.

   ii. Fix quantity of cement or cementitious materials per cubic meter of concrete, from the range 400 kg/m^3 - 600 kg/m^3.

   iii. Fix HRWRA quantity per cubic meter of concrete based on water reducing capacity

   iv. Fix quantity of powder per cubic meter of concrete

   v. Fix quantity of fine sized aggregates per cubic meter of concrete

   vi. Fix quantity of coarse sized aggregates per cubic meter of concrete

   vii. Determine volume of powder(V_{Powder})and volume of water(V_{Water})

   viii. Determine V_{water} / V_{Powder} , if the ration is not falling in the range 0.85 - 1.10 ,then make suitable adjustments, as relevant.

e) Determine the quantities of all concrete making materials required for 1st trial of SCC in laboratory mixer .

f) Observe carefully the mix for any excessive bleeding, settlement of coarser parts etc., if all are Ok then conduct basic tests like spread of mix by slump flow test , flow time test in V shaped funnel, obstruction to flow in L shaped box and resistance to separation in segregation resistance test, in fresh condition, on the SCC mix for observing the characteristics.

g) If the mix doesn't satisfy the basic SCC characteristics, then trouble shoot for adjusting the proportions according to the deficiency nature of mix and then prepare the trial mix and carry the basic SCC tests in fresh state.

h) On satisfactory fresh conditions of mix, cast the specimens for testing the properties hard state.

4.11.3 Targeted values of properties of SCC recipe in fresh state

Targeted values of the SCC properties in fresh state to be achieved for this research study is presented hereunder in Table.4.2

Table 4.2
Targeted values of properties of SCC recipe in fresh state

Test	Property of the SCC mix	Class/category of the SCC mix	Acceptable Range	Relevant Specification followed for the test
Spread of mix (Slump Flow)	Free flowing nature	SF_1	550mm-650mm	IS 1199
V- funnel	Viscosity	VF_2	9seconds -25 seconds	IS 1199
L- box	Passing ability	-	0.85-1.0	IS 1199
Resistance to separation of mix (Segregation Resistance)	Resistance to Segregation	SR2	<15%	IS 1199

4.12 SCC Mix Proportioning

4.12.1 Details of typical SCC recipe

Details of the SCC mix proportioning is presented hereunder

a) Grade designation of the SCC mix(F_{ck}) : M 40

b) W/cm : 0.35

c) Type of cement : OPC53 grade conforming to IS 269:2015

d) Maximum size of aggregates : 10 mm

e) Exposed environmental circumstances : Moderate

f) Characteristics of SCC Mix targeted

1) Spread of mix : SF1 (550 mm – 650 mm)
2) Obstruction flow ratio : at least 0.8
3) Flow time through V shaped funnel : ClassV2 (9seconds -25seconds)
4) Resistance to Separation : SR2(≤15%)

f) Site quality control : 'Good'

g) Coarse Aggregate nature : Crushed Granite

h) Fine Aggregate nature : River Sand

i) Maximum Quantity of Cement per cubic meter of concrete : 450 kgs

j) Additives-Chemical :Super plasticizer HRWRA-PCE

k) Mineral admixture : Flyash conforming to IS 3812 (Part1)

4.12.2 Details of material characteristics

a) Type of Cement- OPC 53 Grade : Nuvista
b) Specific Gravity$_{\textbf{Cement}}$: 3.14
c) HRWRA : Perma Plast
d) Specific Gravity of materials:
   a. Specific Gravity$_{\text{Coarse aggregate}}$: 2.76
   b. Specific Gravity$_{\text{Fine aggregate}}$: 2.64
   c. Specific Gravity$_{\text{HRWRA}}$: 1.13
e) Water Absorption(WA):
   a. Coarser aggregate :0.4 %
   b. Finer aggregate :1.3%

f) Free (surface) moisture %
   1) Coarser sized aggregates :0%
   2) Finer sized aggregates :0%

g) Sieve analysis:

Gradation of Coarser sized aggregates and finer sized aggregates conducted following the provisions of IS 2386 Part1 and the same is presented hereunder in Table 4.3.

Table 4.3
Gradation of coarser sized aggregates CA(10mm)

I.S. Sieves	Collected weight on each sieve (Grams)	Total collective weight on cumulative basis (Grams)	Collected weight-retained	Collected weight-passing	Limits of Passing as per Table No.7(Cl6.1 & 6.2) of IS 383:2016
			Cumulative %		
12.5mm	0	0	0	100	100
10mm	136	136	2.7	97.3	85-100
4.75mm	4179	4315	86.3	13.7	0-20
2.36mm	465	4780	95.6	4.4	0-5
Pan	220	5000	100		
Total	5000				

Gradation of fine sized aggregates-River Sand, is presented in Table 4.4

Table 4.4
Gradation of fine sized aggregates-River Sand

I.S. Sieves As per IS 460	Collected weight on each sieve (Grams)	% Collected weight	% Cumulative basis		Controls according to Table 9(Cl.6.3) of IS 383:2016		
			Collected weight-retained	Collected weight-passing	Zone- I	Zone -II	Zone- III
10.0 mm	0	0	0	100	100	100	100
4.75 mm	25	2.5	2.5	97.5	90-100	90-100	90-100
2.38 mm	59	5.9	8.4	91.6	60-95	75-100	85-100
1.18 mm	93	9.3	17.7	82.3	30-70	55-90	75-100
600 micron	91	9.1	26.8	**73.8**	15-34	35-59	60-79
300 micron	468	46.8	73.6	26.4	5-20	8-30	12-40
150 micron	182	18.2	91.8	8.2	0-10	0-10	0-10
Pan	82	8.2	100				
Total	1000						

The above fine aggregate i.e. river sand satisfies the Zone III passing requirement of IS 383:2016.

Powder content (material <125 micron) from the above fine aggregate i.e. River sand is approximately 6%.

4.12.3 Target strength(F_{ck})for mix at 28 days

$F'_{ck} = F_{ck}$ +1.65x Standard Deviation ‘s’
or
$F'_{ck} = F_{ck} + 6.50$
whichever is higher

where F'_{ck} = Average targeted compressive strength- at 28 days,

F_{ck} = Average compressive strength- at 28 days,

s = Standard Deviation.

From Table-2 of IS 10262:2019, the standard deviation for M40 grade is, '*s*' = 5.0 N/mm^2.

Therefore, Average targeted compressive strength- at 28 days

i) $F'_{ck} = F_{ck} + 1.65 *$ Standard Deviation 's'

$= 40.0 + 1.65*5.0 = 48.250$ N/mm^2

From Table 1 of IS 10262:2019, the value of 'X' for M40 grade is, 6.50 N/mm^2.

ii) $F'_{ck} = F_{ck} + 6.50$

$= 40.0+6.50 = 46.50$N/mm^2

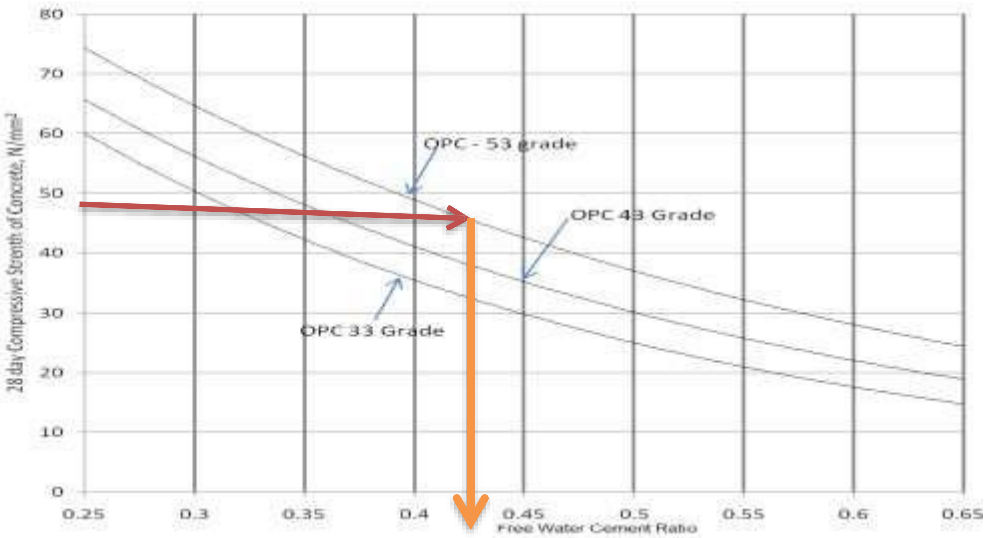
In the above the higher value is 48.250 N/mm^2 . Thus average targeted compressive strength- at 28 days for the trail mx of M40 Grade SCC is the higher value amongst the values of (i) and (ii) ,

4.12.4 % of Entrapped air in the mix(V_{Air})

Entrapped air in the mix for CA 10mm size is 1.5 % , according to Table No. 3 of IS 10262:2019.

4.12.5 Fixing of free Water/Cementitious materials

Selection of free Water/Cementitious materials was done using the Fig.1 of IS 10262:2019 which is reproduced as Graph 4.1 hereunder.



Graph 4.1 Relationship between free W/C and target concrete strength
[Reproduced Fig.1 of IS 10262:2019]

From the above Graph , for OPC 53 grade of cement , the water/cementitious materials as obligatory for achieving the average target compressive strength of 48.250 N/mm^2 works out to be 0.42. However aimed at achieving durability of SCC mix the water/cementitious materials reduced further and adopted as 0.350 and the same is < 0.45, the maximum limit set for 'moderate' conditions of environmental conditions, according to Table No.5 of IS 456:2000.

Hence adopted W/cm is 0.35 < 0.45, hence O.K.

4.12.6 SCC Mix constituents for Trial No.1

For carrying the SCC Trail No.1 i.e. first trial of SCC , the proportions of materials fixed as mentioned under

4.12.7 Proportioning for initial SCC mix

4.12.7.1 Fixing of quantity of water , quantity of cement and fly ash

Generally, water requirement for SCC varies between 150 to 210 kg/m^3. Since the class of slump flow targeted for class SF1 having a slump flow between 550 to 650 mm. This type of flow will be possible with moderately higher water content. To start with, a water content of 185.0 kgs/m^3 was selected for the initial proportioning of trial mix.

This water content of 185.0 kgs/m^3 will relate to a quantity of cementitious materials of 528 kgs/m^3 say 530 kgs/m^3 for a free water /cementitious ratio of 0.35 as adopted through 4.12.5**.**

Further as the cementitious material quantity of 530 kgs/m^3 needs to be distributed into quantity of OPC and quantity of fly ash. In this case, the flyash quantity was considered as 25.0 % by weight of total cementitious materials. Therefore, the OPC content works out to be i.e. 75% of 530 kgs is for 397.5 kgs/m^3 and flyash quantity works out to be 132.5 kgs/m^3.

4.12.7.2 Selection of Chemical Admixture(HRWRA) Content

Keeping in view the required slump flow of 550mm-650mm, an PCE based HRWRA of 0.9 % by weight of total cementitious materials ,considered initially. Hence the quantity of chemical admixture = (0.9/100) x 530 = 4.77 kg/m^3.

4.12.7.3 Fixing of Powder material quantity and quantity of finer sized aggregates

As per the Cl.8.3 of IS 10262:2019, for SCC mix the powder material quantity needs to be in the range 400 kgs/m^3 - 600 kgs/m^3. In this particular research study, since the SR2 and V2 was targeted for SCC mix; the mix needs to have enough fines and shall be adequately cohesive. Thus, a powder material quantity of 590 kg/m^3 was fixed initially. As discussed above, this powder material quantity will embrace of the whole OPC quantity, whole flyash quantity, and around 6.0% of Zone- III fine sized aggregates.

Thus the quantity of fines as essential to be backed by the finer sized aggregates (River Sand) = Quantity of Powder Material – (Quantity of flyash content+ Quantity of OPC)

= 590-(397.5+132.5) = 60.0 kgs/m^3

Here as the finer sized aggregates has 6.0 % < 125 microns, the quantity of finer sized aggregates required in order to contribute 6.0% of powder materials = 60/0.06 = 1000 kg/m^3.

4.12.7.4 Fixing of quantity of coarser sized aggregates

Considering V_{CA} as the total volume of coarser sized aggregates.

Supposing for1.0 m^3 of SCC mix,

V_{CA} = (1-V_{Air}) - (volume proportion of water +volume proportion of cement + volume proportion of flyash + volume proportion of HRWRA + volume of finer sized aggregates)

$$V_{ca} = (1-V_{air}) - (V_{Water} + V_{Cement} + V_{Flyash} + V_{HRWRA} + V_{FA})$$

$$V_{ca} = (1-0.01) - \left(\frac{185}{1*1000} + \frac{397.5}{3.14*1000} + \frac{132.5}{2.20*1000} + \frac{4.77}{1.13*1000} + \frac{1000}{2.64*1000}\right)$$

$$= 0.99 - (0.185 + 0.126 + 0.06 + 0.004 + 0.379)$$

$$= 0.99-0.754$$

$$= 0.236$$

Quantity of Coarser sized aggregates = (V_{CA}* Specific Gravity$_{CA}$ * 1000)

= 0.236 * 2.76 * 1000

= 651 kgs/m^3 ≈ 650 kgs/m^3

4.12.7.5 Powder material quantity on volume basis

Let volume of Powder material quantity be V_{PC}

$V_{PC} = (V_{Cement} + V_{Flyash} + V_{125\ micron\ portion\ of\ Fine\ Aggregate})$

$V_{PC} = (397.5/(3.14 \times 1000)) + ((132.5 / (2.2 \times 1000)) + ((60 /(2.64 \times 1000))$

$V_{PC} = 0.208\ m^3$

From the above $V_{Water} = 0.185\ m^3$

Thus ,ratio of volume of water to powder by volume = $V_{PC} / V_{Water} = 0.185/ 0.208 = 0.89$

As for SCC mix ,The V_{PC} / V_{Water} needs to be in the range 0.85 to 1.10. In this case, it is Ok.

If V_{PC} / V_{Water} not in the range 0.85 to 1.10 ,trouble-shooting to be done for arriving to SCC recipe in the following manner

- If $V_{PC} / V_{Water} < 0.85$, then the quantity of finer sized aggregates to be lessened so that V_{PC} / V_{Water} increases accordingly.
- If $V_{PC} / V_{Water} > 1.1$, then the then the quantity of finer sized aggregates to be increased so that V_{PC} / V_{Water} decreases accordingly.
- In the above two situations, the recipe needs to be re-calculated according to the adjustments done
- Various combinations of coarser sized aggregates (CA10mm) and different proportions of finer sized aggregates (river sand) was tried so as to ascertain the suitable combinations of CA10mm and sand for qualifying the SCC characteristics. After several such trials, the combination finalised was coarse aggregate CA10mm as 45% and river sand as 55% in total aggregate content by weight.

4.13 SCC recipe for Trial mix No.1

a) Quantity of OPC 53 Grade =397.5 kgs/m^3
b) Quantity of flyash =132.5 kg/m3
c) Quantity of water (free water) = 185kgs/m^3
d) Quantity of finer sized aggregates (SSD basis) =1000 kgs/m^3
e) Quantity of Coarser sized aggregates (SSD basis) =651 kgs/m^3
f) Quantity of HRWRA- PCE =4.77 kgs/m^3,
g) w/cementitious materials =0.35

h) Quantity of powder material quantity =590 kgs/m3
i) V_{PC} / V_{Water} =0.89

4.14 Tests on fresh state of SCC Mix

(a) (b) (c) (d)

Fig.4.23 Slump Flow of Mix with proportions of Trail Mix No.1 and subsequent adjustments

In this initial trials of research study, as the slump flow was observed to be not meeting the minimum 550mm spread as shown in Fig 4.23 (a) , the necessity was sensed to slightly modify the trial mix no. 1 ,as arrived through 4.12 and 4.13 above,. Thus the proportions as arrived vide 4.13 were slightly modified in each successive case like Fig.4.23(b) , Fig.4.23(c) till the slump flow was satisfactory as shown in the above Fig.4.23(d) .

4.14.1 Fine tuned mix recipe for attaining satisfactory Slump Flow[After Adjustment]

a) Quantity of OPC 53 Grade =397.5 kgs/m^3
b) Quantity of flyash =132.5 kgs/m^3
c) Quantity of water (free water) = 185.5kgs/m^3
d) Quantity of finer sized aggregates (SSD basis) = 913 kg/m^3
e) Quantity of Coarser sized aggregates (SSD basis) = 747 kg/m^3
f) Chemical admixture = 6.36 kg/m^3
g) w/cementitious materials = 0.35
h) Quantity of powder material quantity = 586 kg/m^3
i) V_{PC} / V_{Water} = 1.02

4.14.2 Further Trials

Additionally, trials no.3 and 4 were carried by modifying the w/cementitious materials in 3rd mix as 0.385 i.e. + 10 % of 0.35 and in 4th trial mix the w/cementitious materials was kept as 0.315 i.e. - 10 % of 0.35 . A graph, between w/cementitious materials ratio 0.315,0.350 and 0.385 and corresponding 28th days compressive strengths, was plotted to establish the required w/cementitious materials ratio for the targeted average 28th days compressive strengths

4.15 Mix proportions arrived for various grades and types of SCC after the adjustments

SCC Mix recipe arrived for carrying the intended research, after effecting the necessitated adjustments, are presented in Table 4.5. Targeted characteristics of SCC ,sample testing plan etc., are presented in Table 4.6 to Table 4.11.

Table 4.5

Cementitious Material's (CM) Composition Range (%) and No.of SCC Mix Trials Planned to be carried in This Study

Targeted Grade of SCC Mix	Mix Code	Cementitious Materials(CM) Composition Range (%)						Total CM Kg/m^3	W/ CM Ratio	Fibre (% by Volume)				HRWR PCE Admixture (% by weight of CM)	No. of SCC Mix Trials planned to be carried in this study
		Binder	Moderate SCM As part replacement of OPC		Reactive SCM As part replacement of OPC		Highly Reactive SCM As part replacement of OPC			ARF		PPF			
		OPC 53 Gr	FA	GGBFS	MK	UGGB FS	Nano Alumina (NA)			6 mm	12/15 mm	6 mm	12 mm		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
M40	SUMK	50-75	25	-	0-12.5	0-12.5	-	530	0.35	0.5	0.5	-	-	1.2	6
M50	SCC_{FMK} SCC_{GMK}	50-75	25	25	-	-	-	540	0.35	-	-	-	-	1.0	18
M50	SCC_{GM}	50	-	40	10	-	-	540	0.30	-	-	-	-	0.7 to1.1	6
M50	$Hy_{FSCCType1}$	50	-	40	10	-	-	550	0.33	-	0-0.5	-	0-0.5	1.2	4
M50	$Hy_{FSCCType2}$	50	-	40	10	-	-	550	0.33	-	0-0.5		0-0.5	1.2	4
M60	SCC_{MK}	65-72.5	25	-	2.5-10	-	-	560	0.33	-	-	-	-	1.2	5
M60	F_{SCCMK}	64-71.5	25	-	2.5-10	-	-	560	0.33	-	1	-	-	1.2	4
M60	$SCC_{HyFR-NA}$	50	-	37-40	10	-	0-3	560	0.33	-	0.5	-	0.5	1.4	5

Table 4.6

Targeted characteristics of SCC Recipes

SCC mix grade Targeted	**Mix Denoted**	**Targeted characteristics of SCC Mix**									
		Fresh State				**Hardened State**			**F_{CK} at 28 days**	**'s' for Mix Proportioning as per IS 10262:2019 Table 2 Cl.4.1.2.3**	**F'_{CK} at 28 days = F_{CK} +1.65*s**
		Spread (Slump Flow)	**V Funnel Flow time**	**Flow ratio in 'L' Box**	**SR**	**Final Setting Time**	**1 Day Compressive Strength**	**1 Day Tensile Strength**			
		mm	Seconds	Ratio	(%)	Minutes	MPa (N/mm^2)	MPa (N/mm^2)	MPa (N/mm^2)	MPa (N/mm^2)	MPa (N/mm^2)
M40	SUMK	550-650	9-25	0.85	<15	600	20	1	40	5	48.25
M50	SCC_{GMK}	550-650	9-25	0.85	<15	600	20	1	50	5	58.25
M50	SCC_{FMK}	550-650	9-25	0.85	<15	600	25	2	50	5	58.25
M50	SCC_{GM}	550-650	9-25	0.85	<15	600	25	2	50	5	58.25
M50	$Hy_{FSCC_{Type1}}$	550-650	9-25	0.85	<15	600	25	2	50	5	58.25
M50	$Hy_{FSCC_{Type2}}$	550-650	9-25	0.85	<15	600	25	2	50	5	58.25
M60	SCC_{MK}	550-650	9-25	0.85	<15	600	25	2.5	60	5	68.25
M60	$F_{SCC_{MK}}$	550-650	9-25	0.85	<15	600	25	2.5	60	5	68.25
M60	$SCC_{HyFR-NA}$	550-650	9-25	0.85	<15	600	25	2.5	60	5	68.25

Table 4.7
Sample Testing Plan for Characteristics of SCC Recipes

Target Grade of SCC Mix	Mix Code	Sample Testing Plan for Characteristics of SCC Mix								
		Fresh State				Hardened State				
		Spread (Slump Flow)	V Funnel Flow time	Flow ratio in 'L' Box	Segregation Resistance	Setting Time	Shrinkage	Compressive Strength	Tensile Strength	Durability Characteristics
M40	SUMK	*	*	*	*	*	*	*	*	*
M50	SCC_{GMK}	*	*	*	*	*	*	*	*	*
M50	SCC_{FMK}	*	*	*	*	*	*	*	*	*
M50	SCC_{GM}	*	*	*	*	*	*	*	*	*
M50	$Hy_{FSCCType1}$	*	*	*	*	*	*	*	*	*
M50	$Hy_{FSCCType2}$	*	*	*	*	*	*	*	*	*
M60	SCC_{MK}	*	*	*	*	*	*	*	*	*
M60	F_{SCCMK}	*	*	*	*	*	*	*	*	*
M60	$SCC_{HyFR-NA}$	*	*	*	*	*	*	*	*	*

* Denotes -Yes

Table 4.8

Details of laboratory equipment used for estimating fresh-state of SCC Recipes

Name of the Test	Equipment Name	Relevant Specification IS/IRC/MoRTH/ASTM/AASHTO etc.,			SCC Mix Characteristics measured	Units of measurement
		Specification	Clause No.	Environment conditions for test, if any		
Spread (Slump Flow)	Flow Table	IS 1199-P6-2018	Section.1	Ambient Temperature	Flowability	mm
V Funnel Flow time	V Funnel		Section.2		Viscosity	Seconds
Flow ratio in 'L' Box	L Box		Section.3		Passability	ratio
Segregation Resistance	Sieves 4.75mm & Pan		Section.4		Resistance to Segregation	%

Table 4.9

Laboratory equipment used for evaluating hardened state characteristics of SCC Recipes

Name of the Test	Equipment Name	Specimen		Relevant Specification IS/IRC/MoRTH/ASTM/AASHTO etc					SCC Mix Characteristics measured	Units of measure ment
		Shape	Size 'mm'	Specific ation	Testing Specifica tion	Clause No.	Rate of loading	Environment conditions		
Compressive Strength	CTM	Cube	150X150X 150	IS 14858: 2000	IS 516 (Part 1/Sec 1) : 2021	3	14 N/mm^2 /min	Ambient Temperature	Compression Strength	MPa (N/mm^2)
Split Tensile	CTM	Cylinder	100X200			5	1.2 N/mm^2		Splitting Tensile	MPa

Name of the Test	Equipment Name	Specimen		Relevant Specification IS/IRC/MoRTH/ASTM/AASHTO etc					SCC Mix Characteristics measured	Units of measure ment
		Shape	Size 'mm'	Specific ation	Testing Specifica tion	Clause No.	Rate of loading	Environment conditions		
Strength							/min		Strength	(N/mm^2)
Flexure Strength	CTM	Beam	500x100x 100			4	1.8 KN/min		Flexural Strength	MPa (N/mm^2)
MoE	CTM	Cylinder	100X200		IS 516 (Part 8/Sec 1) : 2020	4	14 MPa/min		Elasticity Modulus	MPa (N/mm^2)

Table 4.10
Laboratory equipment used for evaluating durability characteristics of SCC Recipes

Name of the Test	Equipment Name	Specimen		Relevant Specification IS/IRC/MoRTH/ASTM/AASHTO etc			SCC Mix Characteristics measured	Units of measurement
		Shape	Size	Specification	Clause No.	Environment conditions maintained during test		
Shrinkage	Length Comparator	Prismatic	75 × 75 × 300 mm	IS 516 (Part 6) : 2020	4	27 ± 2°C	Change in length of specimen with age	%
Resistance to Cl^- Ion penetration	Core Drilling and Core trimmer	Slab	300mmX 600mmX 100mm	ASTM C-1543		27 ± 2°C	Penetration of Cl^- ion	%
Resistance to SO_3^- ion penetration	Length Comparator	Prismatic	25x25x 285mm	ASTM C1012/ C1012M		27 ± 2°C	Penetration of SO_3^- ion	%

Name of the Test	Equipment Name	Specimen		Relevant Specification IS/IRC/MoRTH/ASTM/AASHTO etc			SCC Mix Characteristics measured	Units of measurement
		Shape	**Size**	**Specification**	**Clause No.**	**Environment conditions maintained during test**		
Water Permeability	Concrete permeability equipment	Cube/ Cylinder	150mm/ 100mmX 200mm	IS 516 (Part 2)/Section 1 : 2018	5.4	27 ± 2°C	Water penetration under pressure	mm
Water Absorption	Water tank having constant water level	Cube/ Cylinder	150mm/ 100mmX 200mm	IS 516 (Part 2)/Section 1 : 2018	4	27 ± 2°C	Water absorption	%
Volume of permeable voids	Water bath	Cube/ Cylinder	150mm/ 100mmX 200mm	ASTM C 642	5	27 ± 2°C	Voids in concrete	%
Initial Surface Absorption	Initial Surface Absorption	Cube	150mm	IS 516 (Part 2/Sec 2) : 2020	5	27 ± 2°C	Water absorption	ml/(m^2s)
Sorptivity	Water tub	Cylindrical Cut sections	100mm dia. X 50mm depth	ASTM C 1585	5	27 ± 2°C	Capillary water rise	10^{-4} mm/$s^{1/2}$
Abrasion Resistance	Abrasion testing machine	Cube Cut sections	100mm	IS 15658 :2021	7.3 Annex E	27 ± 2°C	Surface Wear	1000 mm^3 per 5000 mm^2
Slant Shear Strength	Compression test	Cylindrical sections	100mmX 200mm	ASTM C 882	6	27 ± 2°C	Bond with substrate	N/mm^2

Table 4.11
Specimen Sizes of samples for evaluating hardened state characteristics of SCC Recipes

Name of the Test	**Specimen shape**	**Size of the specimen**	**Total No. of SCC Mix Trials planned to be carried in this study**	**Age of specimen planned for strength testing**	**SCC Mix Characteristics measured for strength**	**Age of specimen planned for durability testing**	**Specimen shape**	**Size of the specimen (mm)**
			Ref (Table 4.4, Column No.15)	**Hrs/ Days(D)**		**Days(D) Ref(Table, Column No)**		
Compressive Strength	Cube	150X150 X150	28	16Hrs,1D, 3D,7D,28D, 56D,90D, etc	Compressive Strength	7D,28D, 56D	Cube	150X150X 150
Split Tensile Strength	Cylinder	100X200	28	16Hrs,1D, 3D,7D,28D, 56D,90D, etc	Split Tensile Strength	7D,28D, 56D	Cylinder	100X200
Flexure Strength	Beam	500X100 X 100	28	16Hrs,1D, 3D,7D,28D, 56D,90D,etc	Flexure Strength	7D,28D, 56D	Beam	500x100x 100

4.16 Methodology of SCC, FSCC and HyFSCC Mix-Trials, Specimens casting, curing , testing and analysis

Methodology of mixing of various ingredients of mix and casting of samples is presented in the Fig.4.24 and Fig.4.25 hereunder

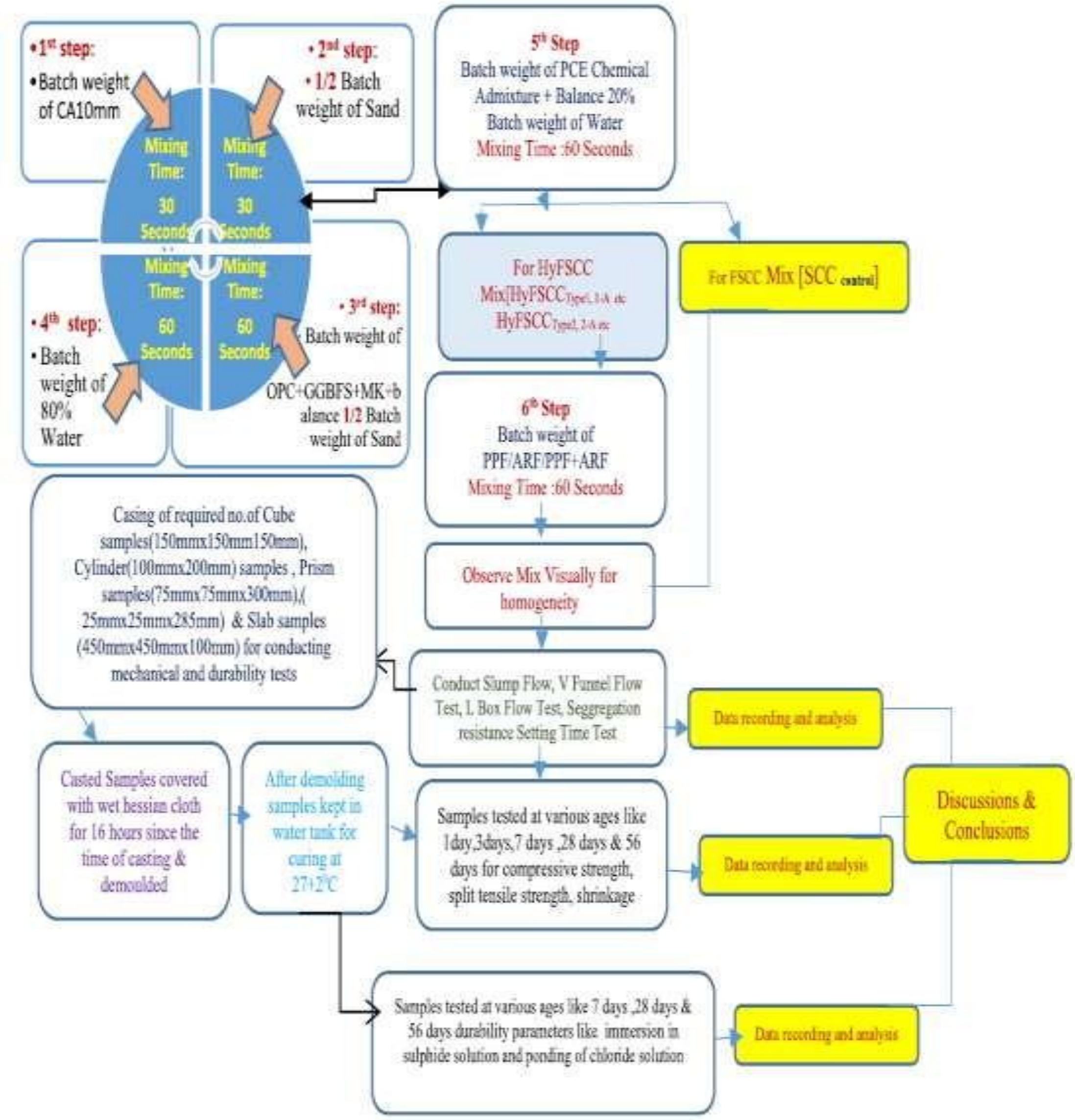


Fig.4.24 Flow Chart Methodology of SCC, FSCC and HyFSCC Mix-Trials, Specimens casting, curing , testing and analysis

Fig.4.25 Flow Chart -Mixing of Hy_{FSCC} Mix in pan mixer

4.17 Experiments and Test Carried for SCC,F_{SCC} and Hy_{FSCC} recipes

Various experiments carried and tests done on SCC, F_{SCC} and Hy_{FSCC}, Hy_{FSCCNA} recipes ,analysis carried out for the same and comparative analysis made is presented in Chapter 5 ,Chapter 6 and Chapter 7 .

CHAPTER 5

HYBRID FIBRE REINFORCED SELF COMPACTING CONCRETE

5.0 Procedure for Arriving Mix Propositions of SCC with reactive SCM-MK

In Chapter 4 of this thesis, after adjustments to the initial trials, a typical SCC recipe was arrived using the concrete making materials like OPC, Flyash, CA10mm , Sand, Water and Chemical admixture. Now, in this chapter the above arrived proportions was further cultured in order to proportion SCC recipe with favourable materials as identified through extensive literature survey carried and discussed in Chapter 2 of this thesis and evaluated several such proportioned SCC mix for fresh state, hardened state and durability properties to achieve the set objectives as discussed in Chapter 1 of this thesis. The procedure embraced to determine the appropriate proportions of SCC was designed in two different steps for establishing influence of various replacement levels of MK in combination with, fixed quantity of flyash and GGBFS, as moderately reactive SCMs, on the properties of SCC. In the 1^{st}- stage, behaviour of paste-phase and mortar-phase was observed for the proportioned pastes and mortars of OPC, GGBFS and MK blends (denoted as GMK_{Paste}/ GMK_{Mortar} respectively) and OPC, flyash and MK blends (denoted as (denoted as FMK_{Paste}/ GMK_{Mortar} respectively). The GMK_{Paste}/ GMK_{Mortar} behaviour was examined by the miniature formed slump flow measurement and miniature formed 'V' funnel-flow time test, as per the EFNARC 2005 guidelines, to fix the materials proportions essential for meeting the criteria of SCC i.e. spread of 200mm-250mm and 'V' funnel flow time of <8 seconds. The procedure adopted for arriving to a suitable combinations of cementitious materials for the desired properties is presented in Fig.5.1.The second stage of this study was consisted in studying the behaviour of SCC recipes prepared with OPC, GGBFS and MK and OPC, flyash and MK as against the behaviour of control SCC recipes wherein MK was omitted from the above mix recipes and 25% of partial replacement of OPC done with GGBFS and flyash respectively. The so proportioned SCC control recipes as done above were termed as $SCC_{GMKSeries0}$ and $SCC_{FMKSeries0}$. In the subsequent SCC recipe of $SCC_{GMKSeries}$, the OPC yet again was substituted with MK, a reactive SCM, at a variation level of 2.50% in successive trials like 2.50%,5.00%, 7.50%,10.00%,12.50%,15.00%,17.50% and 20.00%. The resulted SCC recipes were labelled, accordingly to the proportion of MK in the SCC recipe, as $SCC_{GMK2.50}$, $SCC_{GMK5.00}$, $SCC_{GMK7.50}$, $SCC_{GMK10.00}$, $SCC_{GMK12.50}$, $SCC_{GMK15.00}$, $SCC_{GMK17.50}$ and $SCC_{GMK20.00}$.

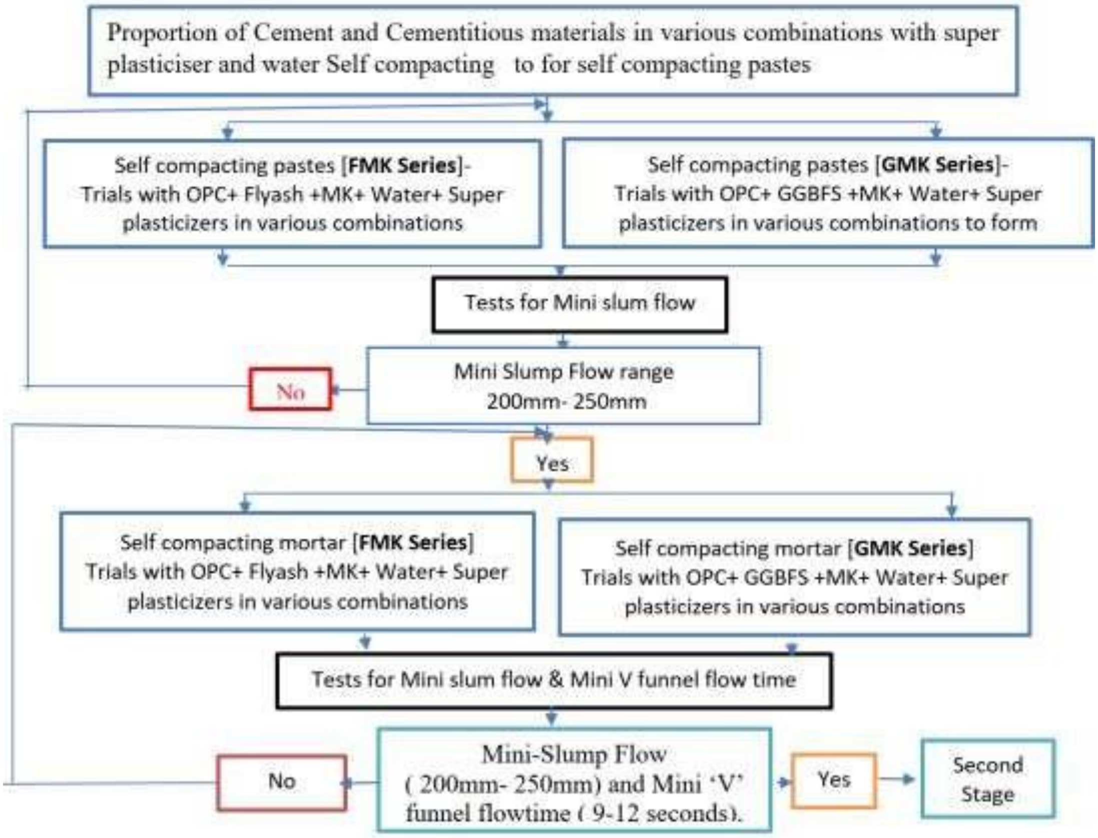


Fig.5.1 Flow Chart -1st Stage Study on Proportion of Self Compacting Pastes and Mortar

Similarly, the other SCC recipes based on flyash wherein OPC was further partially replaced with MK from 2.50 % to 20.00% were termed as $SCC_{FMK2.50}$, $SCC_{FMK5.00}$, SCCFMK7.50, $SCC_{FMK10.00}$, $SCC_{FMK12.50}$, $SCC_{FMK15.00}$, $SCC_{FMK17.50}$ and $SCC_{FMK20.00}$. For proportioning each type of $SCC_{GMKseries}$ and $SCC_{FMKseries}$, a total cementitious material by weight was maintained as 540 Kgs/m^3 and free 'w/cm' was maintained as 0.35. Thus, in this way 9 no.s of SCC_{GMK} series recipes and 9 no.s of SCC_{FMK} series recipes prepared proportionately, as presented in Table5.1 and Table5.2 and scrutinized in phase 1. The properties evaluated for the proportioned SCC mix is discussed in the subsequent paras.

5.1 SCC$_{GMKseries}$ and SCC$_{FMKseries}$ recipe properties

5.1.1 SCC$_{GMKseries}$ and SCC$_{FMKseries}$ recipe properties in fresh condition

SCC$_{GMKseries}$ and SCC$_{FMKseries}$ were evaluated for SCC aspects like spread flow, ‘V’ funnel flow time, resistance to separation, time for initial set and time require for final set following the provisions of IS 1199 Part 7. Test arrangements and equipment used for SCC mix proportioning and testing of fresh state properties is presented in Fig.5.2. Table 5.3 depicts SCC$_{FMKseries}$ and Table 5.4 depicts SCC$_{GMKseries}$ properties respectively. Fig.5.3 and Fig.5.4 represents of spread of SCC$_{FMKseries}$ recipes and SCC$_{GMKseries}$ recipes respectively. Graph 5.1 represents variation of spread of SCC$_{GMKseries}$ and SCC$_{FMKseries}$ with respect to variation in % MK. Graph 5.2 represents variation of final setting time of SCC$_{GMKseries}$ and SCC$_{FMKseries}$ with respect to variation in % MK. Fig.5.5and Fig.5.6 represents setting time test of SCC$_{GMKseries}$ and SCC$_{FMKseries}$ respectively.

(a) Flow Table **(b) Pan Mixer** **(c) SCC Fresh State Test Equipment**

Fig.5.2 Test arrangements and Equipment for Fresh State properties of SCC

Table 5.1

Mix Proportion of $SCC_{FMKseries}$

Sl.No	Mix ID	Binder materials Composition(BM)			Constituents (Kgs/m^3)				
		OPC-53 Gr (%)	Flyash (%)	MK (%)	Total BM	CA10	Sand	HRWRA PCE based Admixture	Quantity of Water
1	$SCC_{FMK0.00}$	75.00	25.00	0.00	540	750	915	5.40	190
2	$SCC_{FMK2.50}$	72.50	25.00	2.50	540	750	915	5.40	190
3	$SCC_{FMK5.00}$	70.00	25.00	5.00	540	750	915	5.40	190
4	$SCC_{FMK7.50}$	67.50	25.00	7.50	540	750	915	5.40	190
5	$SCC_{FMK10.00}$	65.50	25.00	10.00	540	750	915	5.40	190
6	$SCC_{FMK12.50}$	62.50	25.00	12.50	540	750	915	5.40	190
7	$SCC_{FMK15.00}$	60.00	25.00	15.00	540	750	915	5.40	190
8	$SCC_{FMK17.50}$	57.50	25.00	17.50	540	750	915	5.40	190
9	$SCC_{FMK20.00}$	55.00	25.00	20.00	540	750	915	5.40	190

Table 5.2
Mix Proportion of $SCC_{GMKseries}$

Sl. No	Mix code	Binder materials Composition(BM)			Constituents (Kgs/m^3)				
		OPC - 53 Gr (%)	GGBFS (%)	MK (%)	Total Binder Materials	CA 10mm	Sand	HRWRA PCE based Admixture	Quantity of Water
1	$SCC_{GMK0.00}$	75.00	25.00	0.00	540	750	915	5.40	190
2	$SCC_{GMK2.50}$	72.50	25.00	2.50	540	750	915	5.40	190
3	$SCC_{GMK5.00}$	70.00	25.00	5.00	540	750	915	5.40	190
4	$SCC_{GMK7.50}$	67.50	25.00	7.50	540	750	915	5.40	190
5	$SCC_{GMK10.00}$	65.50	25.00	10.00	540	750	915	5.40	190
6	$SCC_{GMK12.50}$	62.50	25.00	12.50	540	750	915	5.40	190
7	$SCC_{GMK15.00}$	60.00	25.00	15.00	540	750	915	5.40	190
8	$SCC_{GMK17.50}$	57.50	25.00	17.50	540	750	915	5.40	190
9	$SCC_{GMK20.00}$	55.00	25.00	20.00	540	750	915	5.40	190

Table 5.3

Characteristics of $SCC_{FMKseries}$ in fresh condition

Sl.No	Mix code	Tested as per IS 1199					
		Spread (Slump - flow)	Flow time through 'V'funnel	Flow ratio in 'L' box	Resistance against separation (SR)	Time required for initial set 'IST'	Time required for final set 'FST'
		'mm'	'seconds'	'H_2/H_1'	'%'	minutes	minutes
1	$SCC_{FMK0.00}$	630	16	0.94	12.20	490	560
2	$SCC_{FMK2.50}$	610	20	0.92	12.30	460	520
3	$SCC_{FMK5.00}$	608	21	0.91	12.60	400	505
4	$SCC_{FMK7.50}$	595	23	0.90	13.20	380	490
5	$SCC_{FMK10.00}$	580	24	0.88	13.50	340	460
6	$SCC_{FMK12.50}$	550	38	0.74	20.20	300	410
7	$SCC_{FMK15.00*}$	530	40	0.71	20.60	Not carried	Not carried
8	$SCC_{FMK17.50*}$	500	49	0.68	21.30	Not carried	Not carried
9	$SCC_{FMK20.00*}$	460	54	0.65	22.70	Not carried	Not carried

Note :*Further than 12.5% of replacement level of MK in the $SCC_{FMKseries}$ the mix ceased to demonstrate SCC characteristics. Hence other intended parameters of the mix evaluated for SCC_{FMK0} to $SCC_{FMK12.5}$.

Table 5.4

Characteristics of $SCC_{GMKseries}$ in fresh condition

Sl. No	Mix ID	Tested as per IS 1199					
		Spread (Slump flow)	Flow time through 'V'funnel	Flow ratio in 'L' box	Resistance against separation (SR)	Time required for initial set 'IST'	Time required for final set 'FST'
		'mm'	'seconds'	'H_2/H_1'	'%'	minutes	minutes
1	$SCC_{GMK0.00}$	640	15	0.96	13.20	460	540
2	$SCC_{GMK2.50}$	630	17	0.91	13.60	440	530
3	$SCC_{GMK5.00}$	610	19	0.88	14.20	390	490
4	$SCC_{GMK7.50}$	590	22	0.85	14.40	370	460
5	$SCC_{GMK10.00}$	560	24	0.81	14.60	350	440
6	$SCC_{GMK12.50}$	550	25	0.72	16.80	310	390
7	$SCC_{GMK15.00*}$	500	40	0.68	21.40	Not carried	Not carried
8	$SCC_{GMK17.50*}$	490	46	0.68	22.70	Not carried	Not carried
9	$SCC_{GMK20.00*}$	440	52	0.68	23.10	Not carried	Not carried

Note :*Further than 12.5% of replacement level of MK in the $SCC_{GMKseries}$ the mix ceased to demonstrate SCC characteristics. Hence other intended parameters of the mix evaluated for SCC_{FMK0} to $SCC_{FMK12.5}$.

Fig.5.3 Slump Flow Test of $SCC_{FMKseries}$ recipes

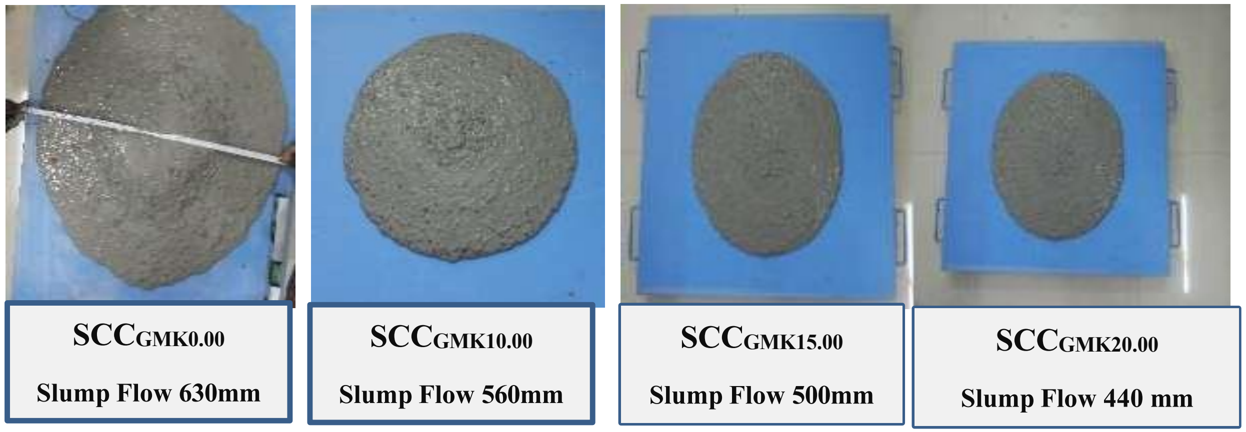
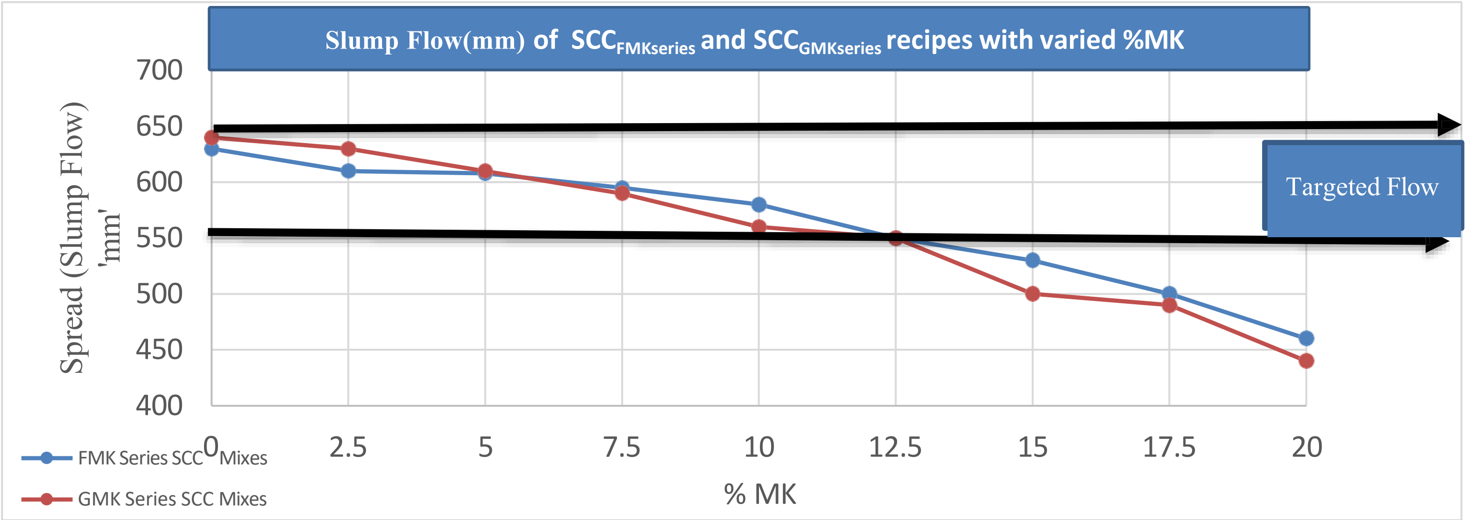
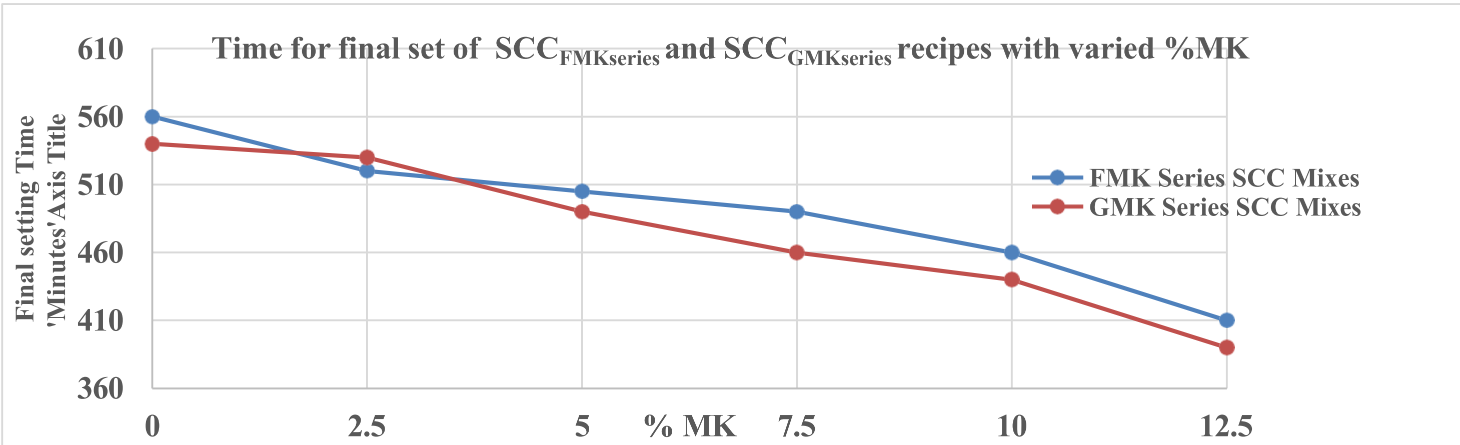


Fig.5.4 Slump Flow Test of $SCC_{GMKseries}$ recipes



Graph 5.1 Variation of Slump Flow(mm) of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes with varied %MK



Graph 5.2 Variation of Time for final set of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes with varied %MK

Time for initial set of $SCC_{FMK0.00}$

Time for initial set of $SCC_{FMK10.00}$

Time for final set of $SCC_{FMK0.00}$

Fig.5.5 Setting Time Test of $SCC_{FMKseries}$ recipes

Time for initial set of $SCC_{GMK0.00}$

Time for initial set of $SCC_{GMK10.00}$

Time for final set of $SCC_{GMK0.00}$

Fig.5.6 Setting Time Test of $SCC_{GMKseries}$ recipes

5.1.2 Mechanical Properties of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes

Compressive strength and Split tensile strength of proportioned $SCC_{GMKseries}$ and $SCC_{FMKseries}$ recipes, after its hardening, was assessed for various ages, from 1day to 90- days following the provisions of latest revision of IS 516 as spelt in Part 4 for properties like. Equipment used for testing of mechanical parameters of SCC are presented in Fig.5.7 and Table 5.4 and Table 5.5 depicts Mechanical Properties of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes.

5.1.3 Durability properties of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes

Durability characteristics such as shrinkage carried out as per the provisions of IS 516, sorptivity, resistance to ingression of Cl^- ion and resistance to SO_3^- carried on as per the provisions of ASTM C1585, ASTM C1543 as per the provisions of ASTM C1012 respectively. Equipment used for testing of durability properties of SCC are presented in Fig.5.8. Besides these tests, adiabatic rise in temperature of FMK and GMK series SCC mix were also carried using temperature sensors placed in the respective specimen in order to evaluate the maximum rise in core temperature with reference to near surface temperature of casted specimen under such study, time required to reach maximum core temperature and temperature gradient.

Fig. 5.7 Arrangements for mechanical testing of concrete

Fig. 5.8 Arrangements for Durability test of concrete

Table 5.5
Mechanical strength properties of $SCC_{FMKseries}$ recipes

Sl. No	Mix code	Compression Strength (N/mm²)						Splitting Tensile Strength (N/mm²)						MoE(Ec) 10^3 N/mm^2
		1-Day	3-Days	7-Days	28-Days	56-Days	90-Days	1-Day	3-Days	7-Days	28-Days	56-Days	1-Day	28-Days
1	$SCC_{FMK0.00}$	12.14	22.71	30.76	42.14	43.87	43.91	0.86	0.97	2.16	3.24	3.30	3.32	31.20
2	$SCC_{FMK2.50}$	13.75	26.37	38.34	48.04	48.76	48.79	0.94	1.08	2.62	3.28	3.34	3.36	31.90
3	$SCC_{FMK5.00}$	13.88	27.62	39.4	48.61	48.94	49.02	0.98	1.41	2.71	3.41	3.46	3.47	32.60
4	$SCC_{FMK7.50}$	13.96	28.43	39.86	49.66	49.80	49.85	0.99	1.46	2.88	3.56	3.61	3.63	33.40
5	$SCC_{FMK10.00}$	14.09	28.68	40.26	49.78	49.90	49.92	1.01	1.52	2.94	3.59	3.64	3.68	34.10
6	$SCC_{FMK12.50}$	14.22	28.76	40.44	49.81	49.97	50.05	1.08	1.59	2.98	3.61	3.68	3.76	34.30

Table 5.6
Mechanical strength properties of $SCC_{GMKseries}$ recipes

Sl.No.	Mix Code	Compression Strength (N/mm^2)						Splitting Tensile Strength (N/mm2)						MoE(Ec) 10^3 N/mm^2
		1-Day	3-Days	28-Days	28-Days	56-Days	90-Days	1-Day	3-Days	7-Days	28-Days	56-Days	90-Days	28-Days
1	$SCC_{GMK0.00}$	13.18	13.68	23.98	33.06	43.94	53.96	0.91	0.99	2.19	3.29	3.36	3.42	32.40
2	$SCC_{GMK2.50}$	14.62	16.82	28.69	38.67	48.81	58.87	0.97	1.16	2.76	3.37	3.39	3.48	33.20
3	$SCC_{GMK5.00}$	14.91	17.94	29.76	38.84	49.06	59.09	1.01	1.47	2.86	3.64	3.51	3.56	34.60
4	$SCC_{GMK7.50}$	14.97	18.19	29.92	39.81	49.94	50.02	1.06	1.53	2.91	3.69	3.69	3.72	35.10
5	$SCC_{GMK10.00}$	15.09	18.90	30.98	40.02	50.25	50.29	1.13	1.58	3.06	3.73	3.74	3.78	35.90
6	$SCC_{GMK12.50}$	15.16	19.21	31.06	40.84	50.46	50.87	1.19	1.67	3.19	3.81	3.83	3.88	36.10

Table 5.7
Time dependent Shrinkage of $SCC_{FMKseries}$ recipes

Sl.No	Mix code	MK %	%Change in length of specimen over time (-)					
			1-Day	3-Days	7- Days	28-Days	56-Days	90-Days
1	$SCC_{FMK0.00}$	0.00	0.009	0.011	0.012	0.015	0.016	0.016
2	$SCC_{FMK2.50}$	2.50	0.010	0.012	0.013	0.016	0.017	0.017
3	$SCC_{FMK5.00}$	5.00	0.018	0.021	0.023	0.024	0.024	0.025
4	$SCC_{FMK7.50}$	7.50	0.026	0.031	0.037	0.040	0.040	0.041
5	$SCC_{FMK10.00}$	10.00	0.036	0.044	0.044	0.047	0.047	0.048
6	$SCC_{FMK12.50}$	12.50	0.047	0.051	0.057	0.068	0.068	0.069

Table 5.8
Time dependent Shrinkage of $SCC_{GMKseries}$ recipes

Sl.No	Mix code	MK %	%Change in length of specimen over time (-)					
			1-Day	3-Days	7- Days	28-Days	56-Days	90-Days
1	$SCC_{GMK0.00}$	0.00	0.007	0.007	0.008	0.009	0.010	0.010
2	$SCC_{GMK2.50}$	2.50	0.008	0.009	0.009	0.010	0.011	0.011
3	$SCC_{GMK5.00}$	5.00	0.009	0.009	0.010	0.013	0.013	0.013
4	$SCC_{GMK7.50}$	7.50	0.010	0.011	0.018	0.019	0.020	0.020
5	$SCC_{GMK10.00}$	10.00	0.012	0.013	0.015	0.016	0.017	0.018
6	$SCC_{GMK12.50}$	12.50	0.014	0.016	0.018	0.019	0.020	0.021

Table 5.9

Durability Properties of $SCC_{FMKseries}$ recipes

Sl.No	Mix code	%MK	Core Temperature Maximum ^0C	Time to reach Maximum core Temperature Hrs	Near surface Temperature of SCC mix ^0C	Temp Gradient ^0C Carried as per IS 7861-1	Sorptivity (10^{-4} g/mm2/$min^{1/2}$) At 28 days S_i (Secondary rate of absorption) Carried as per ASTM C1585	Surface resistance To Abrasive forces At 28 Days mm^3per 5000 mm^2 [Annex E-IS 15658]	Sulphate Resistance Length @ 1d/28d Carried as per ASTM C1012	%Chloride In cover region (40mm from surface) At 90days Carried as per ASTM C1543
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)=(4)-(6)**	**(8)**	**(9)**	**(10)**	**(11)**
1	$SCC_{FMK0.00}$	0.00	46.2	29.4	29.3	16.9	1.17	5640	1.21	0.0096
2	$SCC_{FMK2.50}$	2.50	46.6	29.1	29.5	17.1	1.11	5610	1.16	0.0087
3	$SCC_{FMK5.00}$	5.00	47.8	28.7	30.4	17.4	0.98	5580	1.12	0.0081
4	$SCC_{FMK7.50}$	7.50	49.7	28.4	32.1	17.6	0.91	5560	1.10	0.0072
5	$SCC_{FMK10.00}$	10.00	49.9	27.9	32	17.9	0.72	5510	1.06	0.0061
6	$SCC_{FMK12.50}$	12.50	50.2	26.2	32	18.2	0.46	5490	1.02	0.0034

Table 5.10
Durability Properties of $SCC_{GMKseries}$ recipes

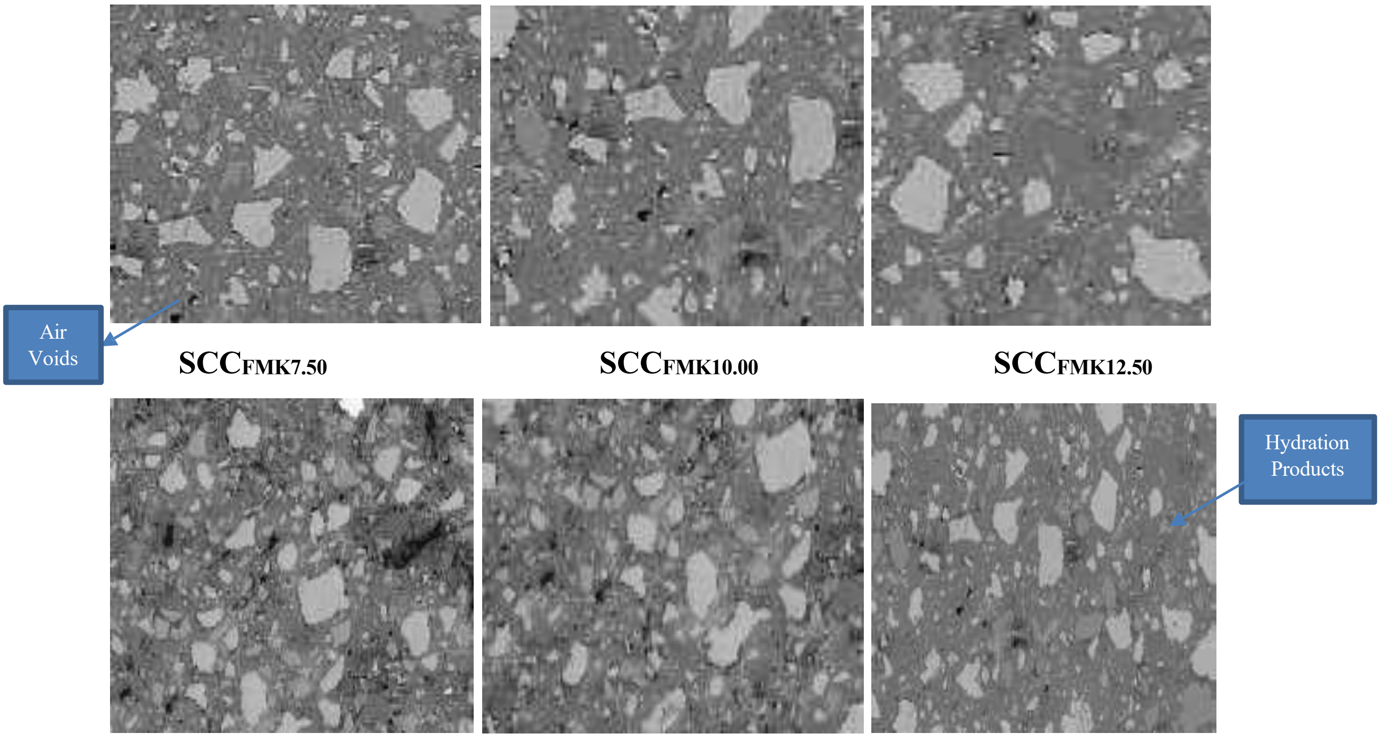
Sl.No	Mix code	%MK	Core Temperature Maximum ^0C	Time to reach Maximum core Temperature Hrs	Near surface Temperature of SCC mix ^0C	Temp Gradient ^0C Carried as per IS 7861-1	Sorptivity (10^{-4} g/mm2/min$^{1/2}$) At 28 days S_i (Secondary rate of absorption) Carried as per ASTM C1585	Surface resistance To Abrasive forces At 28 Days mm^3per 5000 mm^2 [Annex E- IS 15658]	Sulphate Resistance Length @ 1d/28d Carried as per ASTM C1012	%Chloride In cover region (40mm from surface) At 90days Carried as per ASTM C1543
(1)	(2)	(3)	(4)	(5)	(6)	(7)=(4)-(6)	(8)	(9)	(10)	(11)
1	$SCC_{GMK0.00}$	0.00	47.6	29.1	30.2	17.4	1.21	5590	1.16	0.0082
2	$SCC_{GMK2.50}$	2.50	48.8	28.9	30.6	18.2	1.04	5540	1.09	0.0068
3	$SCC_{GMK5.00}$	5.00	49.7	26.2	31.4	18.3	0.89	5510	1.06	0.0051
4	$SCC_{GMK7.50}$	7.50	50.3	25.8	31.6	18.7	0.76	5490	1.04	0.0044
5	$SCC_{GMK10.00}$	10.00	50.6	24.1	31.5	19.1	0.61	5470	1.01	0.0037
6	$SCC_{GMK12.50}$	12.50	51.8	22.1	32.4	19.4	0.36	5440	0.96	0.0028

5.2 Analysis of Results – Properties of $SCC_{FMKseries}$, $SCC_{GMKseries}$ recipes

5.2.1 Analysis of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes in fresh condition

5.2.1.1 Spread(Slump Flow)

Partial replacement of cement with supplementary cementing materials, depending upon chemical nature and specific surface area, lessens the quantity of water[66] for workability, as related to control SCC recipe $SCC_{FMK0.00}$ and $SCC_{GMK0.00}$.It can be seen from Table 5.2 that once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, slump flow, as compared to control mix SCC_{FMK0} was decreased from 3.16% to 12.60%.However,the lessening in slump flow was from 1.50% to 14.00% as was perceived for alike variants of %MK in $SCC_{GMKseries}$. Thus, greater decline in slump flow of $SCC_{GMKseries}$ could be endorsed to rapidity in response of MK in existence of GGBFS than the response of MK in presence of flyash[68]. This lessening of slump flow was further continued after %MK improved beyond 12.50% in both the $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes and the recipes stopped to display SCC characteristics at more than 12.50% of MK in $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes. This effect properly matches with the consequence of study [72] with only variation that the SCM used was Silica fume. Photomicrograph images at 1000X magnification level of the $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes at 7.50%,10.00% and 12.50 % MK content at 7days age in the respective paste matrix is presented in Fig.5.9. Through these photomicrographs, it can be observed that $SCC_{GMKseries}$ recipe presents compact microstructure as compared to microstructure of $SCC_{FMKseries}$ series at same replacement levels and ages. This quicker reactions of MK in the company of GBBFS than in the company of flyash can be indirectly perceived from the data of rise in temperature of various $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes as presented in Table 5.9 and Table 5.10 under column no. 4,5,6,7 validates the quickness of response of MK in concern of GGBFS than in the concern of flyash as stated above. Added, it was perceived that for both the $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes, the extreme % MK that could be partially replaced in OPC was established to be 12.50% for spread flow class of SF1 ranging from 550mm-650mm.



$SCC_{FMK7.50}$ $SCC_{FMK10.00}$ $SCC_{FMK12.50}$

$SCC_{GMK7.50}$ $SCC_{GMK10.00}$ $SCC_{GMK12.50}$

Fig. 5.9 Photomicrograph images at 1000X magnification level of the FMK series and GMK series SCC mix at 7.5%,10.0% and 12.5 % MK content at 7days

5.2.1.2 V Funnel Flow

It can be seen from Table 5.3 that, while %MK changed from 2.50% to 10.00% i.e. in $SCC_{FMKseries}$ recipes $SCC_{FMK2.50}$ to $SCC_{FMK10.00}$, the 'V' funnel flow time, as compared to control mix SCC_{FMK0}, improved from 25.00% to 50.00%.However, mentioning to the data of Table 5.4, for alike deviations of %MK in $SCC_{GMKseries}$, 'V' funnel flow time perceived to improve from 13.30% to 60.00% .Therefore advancement in 'V' funnel flow time in $SCC_{GMKseries}$ could be credited to speediness in response of MK in concern of GGBFS than the response of MK in concern of flyash. Furthermore, afar of 12.50% of MK in $SCC_{FMKseries}$, this effect was similarly perceived in $SCC_{GMKseries}$ recipes. This was in tallying through the explanations prepared in [74,82] with the solitary omission that the responsive SCM was RHA. Added to this, it was detected that in this present research, the escalation of 'V' funnel flow time was further advanced after %MK improved afar to 10.00% in both the recipes of $SCC_{FMKseries}$ as well as $SCC_{GMKseries}$. At 10.00% of MK ,as replacement of OPC, the targeted V funnel flow time ranging 9seconds to 25seconds could be achieved i.e. V2 class in both the recipes of $SCC_{FMKseries}$ as well as $SCC_{GMKseries}$.

5.2.1.3 L Box Flow

It can be seen from Table 5.3 that, while %MK changed from 2.50% to 10.00% i.e. in $SCC_{FMKseries}$ recipes, $SCC_{FMK2.50}$ to $SCC_{FMK10.00}$, the ratio of flow depth as measured in 'L box flow test , observed to be shrunk from 2.10% to 6.40% as equated to reference mix SCC_{FMK0}.Though from Table 5.4, it can be perceived that the reduction ratio of flow depth was from 5.20% to 15.60% for comparable deviations of %MK in $SCC_{GMKseries}$, recipes. It was detected in this study that afar to 12.50% of MK ,in both the $SCC_{FMKseries}$, $SCC_{GMKseries}$ recipes, the mix stopped to satisfy the SCC characteristics. More reduction in the depth ratio, in L box test, could be related to swift response of MK, due to higher specific surface area-as can be seen from Table 3.4**.** in relation with GGBFS than the response of MK in presence of flyash as was also detected in the study [92,99] excluding that silica fume ,ultrafine slag was used as reactive SCM in those respective studies. For the present study, it was perceived that, in $SCC_{FMKseries}$ as well as $SCC_{GMKseries}$ recipes, this decline in the depth ratio, in L box test ,was further advanced afar to 10.00% of MK. The extreme replacement level of MK was detected to be 10.00% for realizing the succeeding flow depth ratio (i.e. H_2/H_1=0.8) for both $SCC_{FMKseries}$ as well as $SCC_{GMKseries}$ recipes.

5.2.1.4 Resistance to separation(SR)

It can be seen from Table 5.3 that, while %MK changed from 2.50% to 10.00% i.e. in $SCC_{FMKseries}$ recipes, $SCC_{FMK2.50}$ to $SCC_{FMK10.00}$, segregation ratio improved from 2.50% to 4.20% as equated to the control mix SCC_{FMK0}. But, for comparable deviations of %MK in $SCC_{GMKseries}$ recipes, as could be perceived from Table 5.4, the witnessed surge in the segregation ratio was from 1.40% to 7.90%. Further to this, it was detected in this study that afar to 12.5% of MK, in both the $SCC_{FMKseries}$, $SCC_{GMKseries}$ recipes, the mix stopped to satisfy SCC characteristics. Consequently, this greater rise in the segregation ratio in $SCC_{GMKseries}$ recipes could be related to the higher degree of response of MK, due to its higher specific surface area, as can be seen from Table 4, thus instigating faster responses, in existence of GGBFS than the response of MK in existence of flyash. This type of opinion was also furnished in the study [75] with the lone allowance was that lime stone powder(LSP) was used as

SCM in the referred study. For this existing research, it was detected that the rise in the segregation ratio was more when %MK increased beyond 10% in the FMK series, whereas the increase in segregation ratio was perceived to be more beyond 7.50% MK in $SCC_{GMKseries}$. The cause for more segregation ratio in the SCC mix of $SCC_{GMK7.50}$ etc., can be allotted to the elemental configuration of GGBFS instituting greater CaO quantity than flyash, as can be seen from Table 3.10 and material characterisations of GGBFS, Flyash and MK as per the XRD as accessible in Fig.3.11 in chapter 3 of this thesis. This higher CaO quantity in toting to the greater Al_2O_3 quantity as present in MK, could be attributed to the faster responses triggering the concerned $SCC_{GMKseries}$ recipes to behave as fast setting mix. The extreme replacement level of MK, as partial replacement of OPC, was perceived to be 10.00% and 7.50% for $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes respectively.

5.2.1.5 Time required for initial set

It can be seen from Table 5.3 that, while %MK changed from 2.50% to 10.00% i.e. in $SCC_{FMKseries}$ recipes, $SCC_{FMK2.50}$ to $SCC_{FMK10.00}$, the time required for initial set of concrete lessened from 6.10% to 30.60% as compared to control mix SCC_{FMK0}.While from the data of Table 5.4, it can be perceived that lessening in the setting time of concrete was from 4.30% to 23.90% for analogous deviations of %MK in $SCC_{GMKseries}$ recipes. This greater reduction in the time for initial set of concrete of $SCC_{FMKseries}$ recipes could be associated to the resulted compact filling of matrix owing to the sphere-shaped particles of flyash as matched to non-spherical particle shapes of GGBFS. This observation was remained incongruous to the outcomes of study [76] where flyash and MK existed as partial replacements of OPC, where it was stated that SCMs integration in the concrete, as part replacement of OPC, will display mostly late setting than the reference mix arranged with OPC simply. In this existing study, it was perceived that this reduction in the initial set time of concrete was higher when %MK improved afar to 10% in the $SCC_{FMKseries}$ recipes, but the decrease in the initial set time of concrete was perceived to be higher afar to 7.5% MK in $SCC_{FMKseries}$ recipes. Further to this, it was detected in this study that for attaining higher decrease in the initial set time, the extreme substitution level of MK was detected to be 10.00% and 7.50% in SCC mix of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes respectively.

5.2.1.6 Time required for final set of concrete

It can be beheld from Table 5.3 that while %MK changed from 2.50% to 10.00% i.e. in $SCC_{FMKseries}$ recipes, $SCC_{FMK2.50}$ to $SCC_{FMK10.00}$, the final set time reduced from 7.10% to 17.80% as equalled to control mix $SCC_{FMK0.00}$. Whereas for alike deviations of %MK in $SCC_{GMKseries}$ recipes, the perceived reduction in the final set time was from 1.80% to 18.50%. Accordingly, this higher reduction in the final set time of SCC consisting of SCM groupings of GGBFS and MK could be accredited to higher degree of response of MK in existence of GGBFS than the response of MK in attendance of flyash. The cause for this higher reduction of final set time for $SCC_{GMK7.5}$ etc., recipes could be consigned to the substance arrangements of GGBFS instituting higher CaO quantity than flyash, as also can be seen from Table 3.10 and material characterisations of GGBFS, Flyash and MK as per the XRD as obtainable through Fig.3.11 in chapter 3 of this thesis. This greater CaO quantity, in adding to the higher Al_2O_3 quantity as existent in MK, could be ascribed to the faster responses instigating the relevant $SCC_{GMKseries}$ recipes to behave as fast setting mix. It was also observed in this present study that the reduction in the final set time was higher when %MK augmented afar to 10% in both the $SCC_{FMKseries}$, $SCC_{GMKseries}$ recipes. Further to this, it was observed that for attaining sophisticated reduction in the final set time of concrete, the extreme substitution level of MK was observed to be 10.00% in both the mix SCC mix of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes.

5.3 Analysis of Hardened state properties of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes

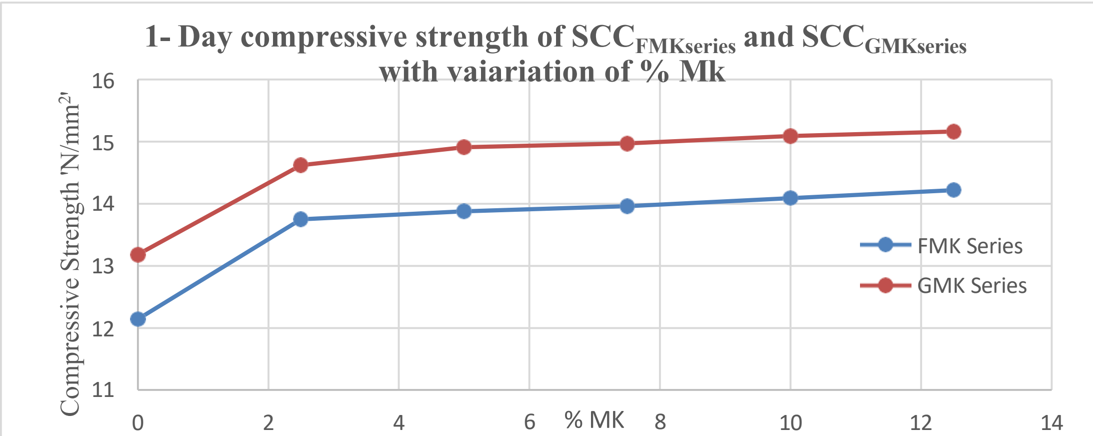
5.3.1 Compressive Strength

This test was carried out on specimens of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes at various ages, from 1-day to 90-days, in CTM as shown in Fig.5.10 and the results of the same presented in Table 5.5 and Table 5.6 and Graph 5.3. It can be understood from Graph 5.3 that at 1-day age, the compressive strength as noted for SCC_{FMK0} was 12.10 N/mm^2, whereas for $SCC_{FMK0.00}$ the 1day compressive strength as noted was 13.20 N/mm^2. For the recipe of $SCC_{FMKseries}$, wherever MK's proportion was improved from 2.50% to 12.50%, the mix has presented a rise in compressive strength for all from 1-day to 90-days. For mix $SCC_{FMK12.5}$, the compressive strength witnessed, at 1-day, was 14.20 N/mm^2 ,whereas the equivalent compressive strength for $SCC_{GMK12.5}$ was 15.20 N/mm^2. It can be realized from the data of Table 5.5 and Table 5.6 that, as the %MK rises from 2.50% to 12.50%, the escalation in 1-day compressive strength was detected to be minimal afar to 10% of MK in both the recipes of $SCC_{FMKseries}$ and $SCC_{GMKseries}$. The rise in 1- day compressive strength for $SCC_{GMKseries}$, at 12.5% MK, was more by 1.00 N/mm^2 related to 1-day compressive strength of $SCC_{FMKseries}$ at the comparable % MK. The presentation of MK in existence of GGBFS perceived to be more, than in existence of flyash for reaching greater strength at early-age. In addition, this observation matched with the specified statement as spelt in one of the former related study [83] wherein it was revealed that while using any greater specific surface area SCMs like MK, RHA, ultrafine GGBFS etc., as part replacement of OPC, careful scrutiny to be made for the conceivable influences of same in both fresh-state as well as hardened-state condition of the mix. In terms of MoE, at 28-days, the same trend of steady increase , as was perceived in compressive-strength results, for the SCC recipes of SCC_{FMK} and SCC_{GMK} were observed.

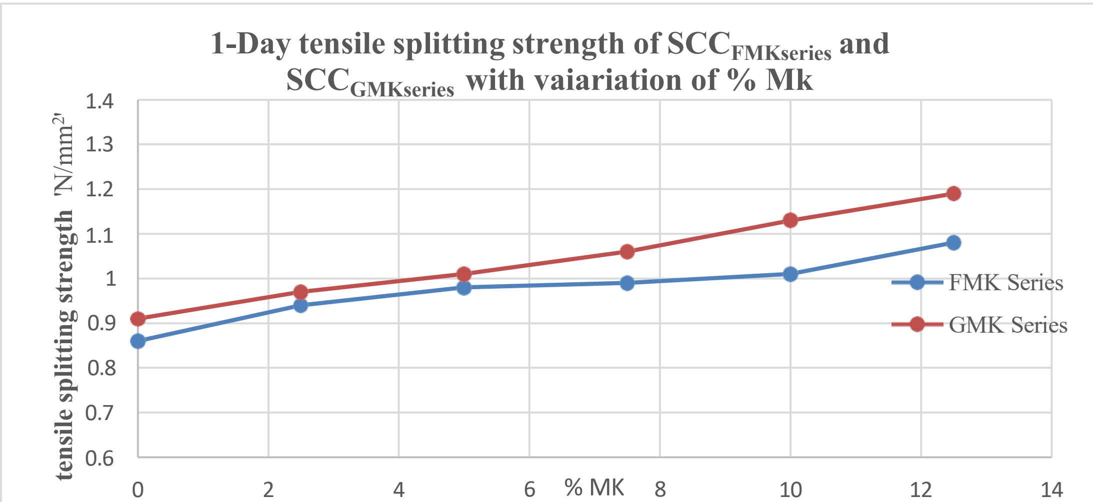
5.3.2 Tensile Splitting Strength

This test was carried out on specimens of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes at various ages, from 1-day to 90-days, in CTM, with a relevant jig, as shown in Fig.5.10 and the results of the same presented in Table 5.5 and Table 5.6 and Graph 5.4. It can be understood from Graph 5.4 that the tensile splitting strength of $SCC_{FMK0.00}$ and $SCC_{GMK0.00}$ recipes was nearly alike. When in successive $SCC_{FMKseries}$ recipes, where MK's content varied from 2.50% to 12.50%, the consequential $SCC_{FMKseries}$ recipes were stemmed in tensile splitting strength from 1-day to 90-days. For mix $SCC_{FMK12.5}$, wherein OPC was partly substituted with 12.50%MK, the tensile splitting strength, at 1-day, recorded was 2.10 N/mm^2, while for $SCC_{FMK12.500\ at}$ 1-day, tensile splitting strength was 2.20 N/mm^2. It can also be understood from the data of Table 6 and Table 7 that, as the %MK rises from 2.50% to 12.50%, the rise in 1-day tensile splitting strength was perceived to be negligible afar to 10.00% of MK for both the recipes of $SCC_{FMKseries}$ and $SCC_{GMKseries}$. Further, the increase in 1-day tensile splitting strength for $SCC_{GMKseries}$, at 12.50% MK, was extra by 0.10 N/mm^2 as related to 1-day tensile splitting strength of $SCC_{FMKseries}$ recipes, at analogous % MK. The enactment of MK, in existence of GGBFs detected to be higher, than in the existence of flyash, for attaining higher early-age tensile splitting strength. This observation appears to be supportive with the consequence of the study [91].

Fig.5.10 Compression testing and Tensile Splitting Strength testing and MoE test of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ specimens



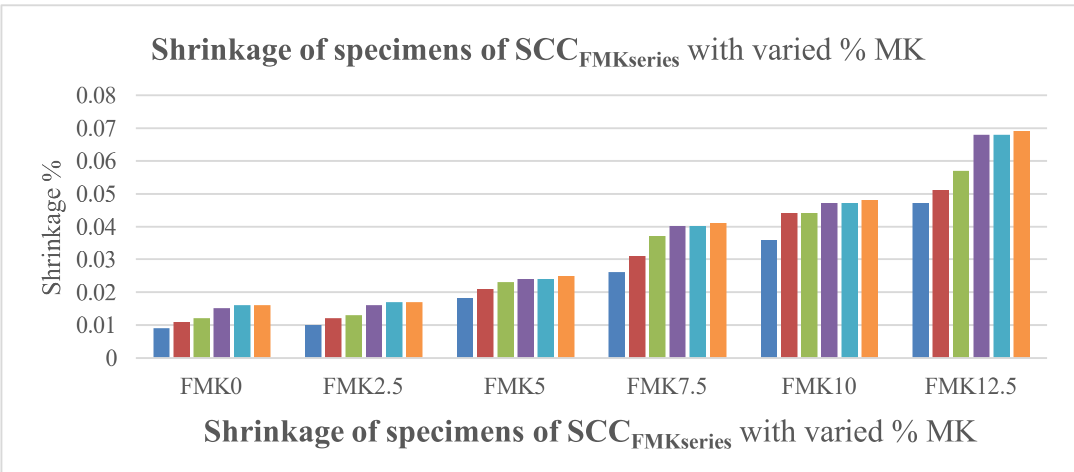
Graph 5.3 1- Day compressive strength of $SCC_{FMKseries}$ and $SCC_{GMKseries}$



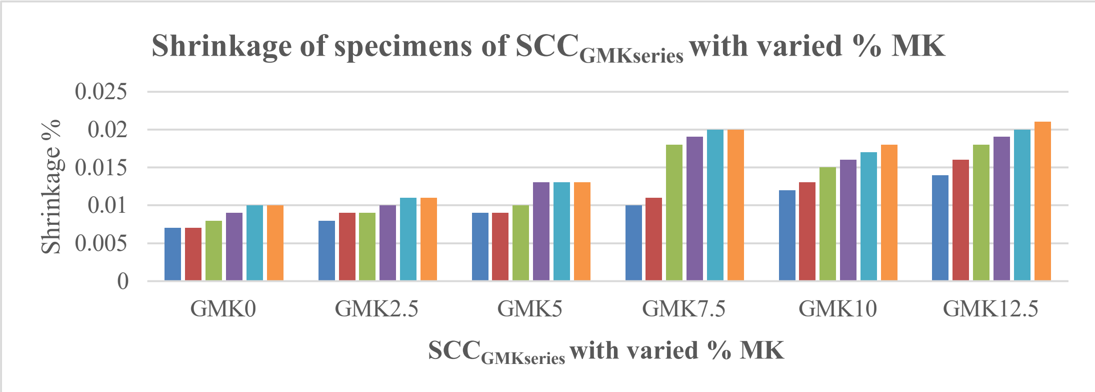
Graph 5.4 1-Day tensile splitting strength of $SCC_{FMKseries}$ and $SCC_{GMKseries}$

5.3.3 Drying Shrinkage(DS)

This test was carried out on specimens of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ recipes at various ages, from 1-day to 90-days, in a length comparator, with a relevant standard reference bar, as shown is shown in Fig.5.11. Table 5.7, Table 5.8, Graph 5.5 and Graph 5.6 respectively represents the DS test results of specimens of $SCC_{FMKseries}$ and $SCC_{GMKseries}$. It can be perceived from the data of Table 5.7 and Table 5.8 that, the DS of SCC_{GMK0} at 1- day of was reduced by 22.20% than the DS of $SCC_{FMK0.00}$. Once in successive $SCC_{FMKseries}$ recipes, whenever MK's content changed from 2.50% to 12.50%, the resulted mix presented minimal rise in DS from 1-day to 90-days. The DS at 1-day of $SCC_{FMK12.5}$ was $47*10^{-3}$ and the same for $SCC_{GMK12.5}$ was $14*10^{-3}$. In relation to reduction in DS over control mix- SCC_{GMK0} and SCC_{FMK0}, at corresponding substitution of MK from 2.50% to 12.50%, $SCC_{GMK2.5}$ to $SCC_{GMK12.5}$ recipes did well as related to $SCC_{FMK2.5}$ to $SCC_{FMK12.5}$ recipes. This was fairly in agreement with the consequence of the study [109] where the merely omission was that the reactive SCM used was micro silica. It can further be identified that in decrease of DS, MK's show in existence of GGBFS perceived to be more, than MK's show in existence of flyash. This can be credited to the fast reaction of MK in $SCC_{GMKseries}$ than the reactiveness of MK in $SCC_{FMKseries}$ and the same can be noticed in Fig. 5.12 which represents photomicrograph pictures of 1- day specimens of $SCC_{FMKseries}$, $SCC_{GMKseries}$ at MK's proportions of 7.50%,10.00% and 12.50%. Thus MK, due to its chemistry and higher affinity seems to be more well-suited with GGBFS than with flyash [105].



Graph 5.5 Shrinkage of specimens of $SCC_{FMKseries}$ with varied % MK



Graph 5.6 Shrinkage of specimens of $SCC_{GMKseries}$ with varied % MK

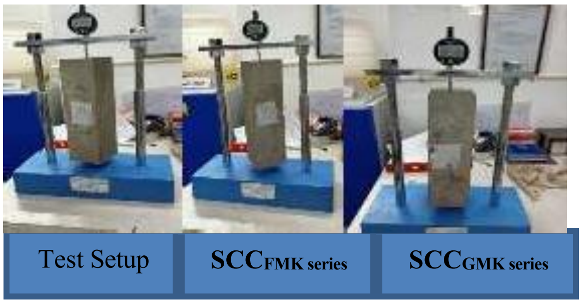


Fig.5.11 Shrinkage Test on specimens of $SCC_{FMKseries}$, SCC_{GMK} series

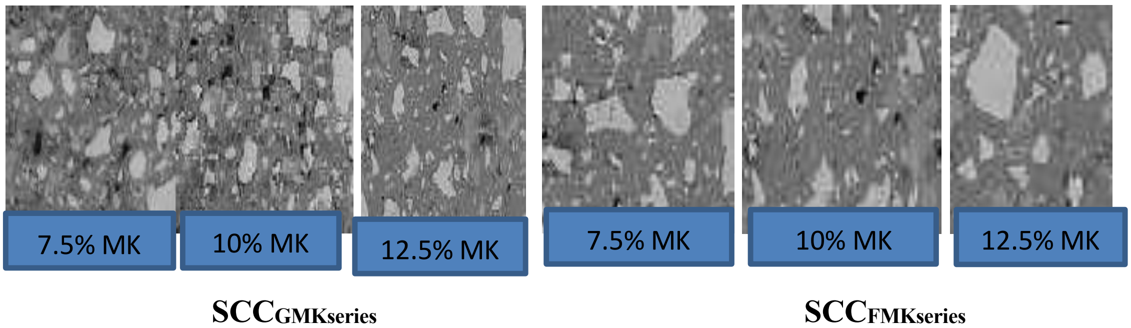
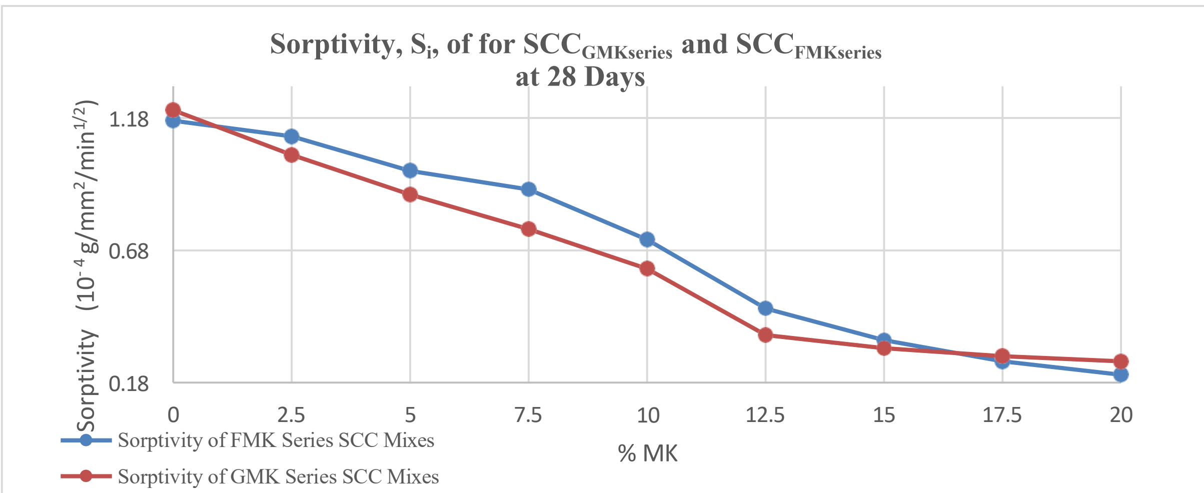


Fig. 5.12 photomicrographs of 1- day old $SCC_{GMKseries}$ and $SCC_{FMKseries}$ mix at 7.5%,10% and 12.5% MK

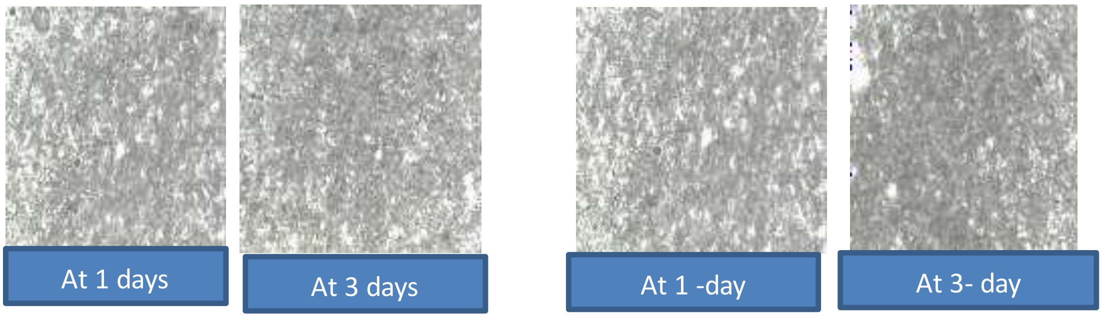
5.3.4 Sorptivity-Secondary rate of absorption(S_i)

Secondary rate of absorption (S_i) carried as per the provisions of ASTM C 1585, on the sliced core specimens of 100mm diameter adjusted to the required length of 50mm. Concrete cores were extracted from casted slab specimen at 28 days. The sorptivity test arrangements presented in Fig.5.13 and the test results presented in Fig.5.15, Table 5.10. It can be understood that in $SCC_{FMKseries}$, through the % rise of MK in the mix, reduction of S_i occurred. The S_i values of $SCC_{FMKseries}$ reduced from 5.12% to 60.67% related to S_i values of SCC_{FMK0} ,once %MK diverted from 2.50% to 12.50%. While S_i values were noted to be decreased higher and were in the range from 14.04% to 70.24% for alike deviations of %MK in $SCC_{GMKseries}$. Thus the higher reduction in S_i of $SCC_{GMKseries}$ can be ascribed to fast- reactions of MK in concern of GGBFS than the similar reactions of MK in concern of flyash and the equivalent can be perceived in Fig.5.14 which represents Photomicrographs of micro structure development, at 1000X magnification, of mortar portions of $SCC_{GMKseries}$ and $SCC_{FMKseries}$ at 10% MK quantity, at 1-day and 3-days. Added to this, it was detected that, the reduction in S_i was minimal when %MK was improved afar to 10.00% in both $SCC_{GMKseries}$ and $SCC_{FMKseries}$, indicating the attainment of saturation level of MK at 10%. In furtherance to this , it was also perceived in this study that 12.50% of MK was extreme limit for achieving lesser S_i values in both $SCC_{GMKseries}$ and $SCC_{FMKseries}$.

Fig.5.13 Sorptivity test arrangement for $SCC_{GMKseries}$ and $SCC_{FMKseries}$



Graph 5.7 Sorptivity, S_i, of for $SCC_{GMKseries}$ and $SCC_{FMKseries}$ at 28 Days



$SCC_{FMKseries}$ **$SCC_{GMKseries}$**

Fig. 5.14 Photomicrograph images of $SCC_{GMKseries}$ and $SCC_{FMKseries}$ mortar portion at 1 day and 3 days

5.3.5 Abrasion resistance

Testing arrangements for measuring abrasion of specimens of concrete is as per Fig.4.19. Test results measures the surface wear i.e. loss in volume per 5000 mm^2. The lesser the value of the surface wear the greater will be the abrasion resistance. Table 5.10 presents the test results of abrasion resistance of specimens of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ at 28-days. It can be seen from Table 5.10 that the abrasion resistance of control mix $SCC_{FMK0.00}$ was 5640 mm^3per 5000 mm^2 and the same for $SCC_{GMK0.00}$ was 5590 mm^3per 5000 mm^2 . It was observed that when part of OPC was replaced by 5% of MK, the abrasion resistance of $SCC_{FMK5.00}$ and $SCC_{GMK5.00}$ was observed to be increased and hence the surface wear was reduced to 5580 mm^3per 5000 $mm^{2.}$, 5510 mm^3per 5000 mm^2 respectively. This increase in abrasion resistance of $SCC_{FMK5.00}$ and $SCC_{GMK5.00}$, as compared to control mix $SCC_{FMK0.00}$ and $SCC_{GMK0.00}$, was due to the inclusion of reactive MK in to the cementitious system having higher fineness than the OPC ,flyash and GGBFS, which though initially causes densification of microstructure of the concrete due to pore refinement [62] but requires sufficient $Ca(OH)_2$ for the secondary reactions of GGBFS for forming strength ensuing CSH gel [63]. It was also observed that when high reactive MK was included into the cementitious system and was added as part replacement of OPC by 7.50% to 10.00%, i.e. for the mix $SCC_{FMK7.50}$ and $SCC_{FMK10.00}$; $SCC_{GMK7.50}$ and $SCC_{GMK10.00}$, the abrasion resistance of the respective mix was increased slightly 5560 mm^3 to 5510 mm^3per 5000 mm^2; 5490 $mm^3$to 5470 mm^3per 5000 mm^2 respectively as compared to control mix $SCC_{FMK0.00}$ and $SCC_{GMK0.00}$. This increase in abrasion resistance of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ can be acknowledged to the existence of high reactive MK, in the cementitious system, causing acceleration of hydration reactions and there by resulting to the development of dense microstructure [65.].Further, it was observed that, in the same cementitious system, when %MK was further increased from 10.00% to 12.50% i.e. for the mix $SCC_{FMK12.50}$ and $SCC_{GMK12.50}$, there was again a marginal increase in the abrasion resistance of mix $SCC_{FMK12.50}$ and $SCC_{GMK12.50}$ to 5490 mm^3per 5000 mm^2, 5440 mm^3per 5000 mm^2 respectively. This increase in abrasion resistance is coinciding with the outcome of increase in compressive strength and increase in tensile splitting strength of the respective $SCC_{FMK12.50}$ and $SCC_{GMK12.50}$ mix as discussed above in 5.3.1 and 5.3.2. This slight increase of abrasion resistance indicates the attainment of saturation level of %MK in the experimented cementitious system. This was in agreement with the findings of study[74] wherein, except that the reactive SCM used in that study was RHA and the moderately reactive SCM used was flyash as part replacement of OPC.

5.3.6 Adiabatic Rise in Temperature and Temperature Gradient (Difference in Temperature from Core to near surface) of SCC Mix

Adiabatic rise in temperature study was carried as per the provisions of IS 7861 and the test arrangements made are shown in Fig.5.15 used for measuring the 'Temperature Gradient' which is difference in Temperature from Core to near surface. This test gives an important indication about the time period required for the attainment of maximum rise in core temperature, which can be used an indirect representation of quickness of hydration reactions, maturity of mix etc., and the rise in temperature depends on the mix proportions, reactive proportions of materials/SCMs, fineness of material, w/cm etc. In this study, for the above test PT-100 type Thermocouples capable of detecting a temperature change of 0.10^0C and data logger CT-716U was used to capture the temperature history similar to the study [86] as required to monitor the rise in temperature, maximum time required for attaining the temperature gain etc., which were the prime requirements to arrive at suitable proportions as carried out in this study in proportioning $SCC_{FMKseries}$ and $SCC_{GMKseries}$ with varied % MK as part replacement of OPC. Mould, non-absorbent and non-conducting type, size used for the study was 300.00mmx300.00mmx300.00mm. Thermocouples, two numbers, of PT-100 firmly secured, one at centre and the other at near- surface area, were located in respective moulds, covered in all interior sides with suitable insulating layers to avoid slurry leakage as well as temperature flow to surroundings, before placement of $SCC_{FMKseries}$ and $SCC_{GMKseries}$.Variation in temperature of mix, with the passage of time, was continuously recorded after the time of addition of water to $SCC_{FMKseries}$ and $SCC_{GMKseries}$ from 30.00 minutes to 30.00 hours. The gradient of temperature for the $SCC_{FMKseries}$ and $SCC_{GMKseries}$ presented in Table 5.9 and Table 5.10. It can be perceived from the data of Table 5.9 and Table 5.10 that, at 1- day, temperature increase in inner core of $SCC_{FMK0.00}$ was 46.2^0C whereas the same for $SCC_{GMK0.00}$ was 47.6^0C. Once in successive $SCC_{FMKseries}$ with MK varying from 2.05% to 12.50%, the mix has caused rise in temperature of interior core-portion ranging from 46.6^0C to 50.2^0C from 20.00 hours to 30.00 hours. The gradient of temperature perceived at 26.20 hrs for mix $SCC_{FMK12.50}$ was 18.20^0C. While the 19.40^0C was the recorded gradient of temperature as detected at 22.10 hours for $SCC_{GMK12.50}$. It can also be perceived that there was minimal rise in gradient of temperature beyond 10.00% of MK in both $SCC_{FMKseries}$ and $SCC_{GMKseries}$. This observation was fairly coinciding through the consequence of the study[92] barring that micro silica was proportioned as reactive SCM in that recipe . Further, in this study, $SCC_{GMKseries}$ observed to have higher gradient of temperature and higher 1-day strength than $SCC_{FMKseries}$. The reason for higher rise in gradient of temperature in the $SCC_{GMK7.50}$, $SCC_{GMK10.00}$ and $SCC_{GMK12.50}$ can be allocated to the substance configuration of GGBFS instituting higher CaO% than flyash, as can be seen from the characterisation of MK as presented under Table 3.10 and material characterisations of GGBFS, Flyash and MK as per the XRD as presented in Fig. 3.11 in chapter 3 of this thesis. This greater CaO% in totalling to the greater Al_2O_3 % as existing in MK, can be accredited to the faster responses triggering the concerned $SCC_{GMKseries}$ to behave as fast-setting recipes. Also these consequences remained equally matching with the result of the study[57] excluding that, in that study, the high reactive SCM used was RHA and filler was quartz powder.

Test Setup-Insulated hot box

Sensors for measuring temperature

Specimens in hot box

Sealed hot box with fixed near surface temperature sensors

Monitoring Temperature in core – $SCC_{FMKseries}$

Monitoring Temperature in core - $SCC_{GMKseries}$

Fig.5.15 Temperature Gradient Test of $SCC_{GMKseries}$ and $SCC_{FMKseries}$

5.3.7 Sulphate Resistance- confrontation to SO_3^- ions ingression

Sulphate Resistance i.e. measure of ingression of SO_3^- ions in to the body of concrete, was performed as per the provisions of ASTM series C-1012.In this test, for moulding the specimens as required for conducting the test, partitioned portion of $SCC_{GMKseries}$ and $SCC_{FMKseries}$ recipes through IS 4.75mm sieve- size- was used. The so casted specimens were subjected to immersion in the solution of Na_2SO_4.This test was carried as per the procedure presented and discussed under 4.8.4 in chapter 4. The test arrangements presented in Fig.5.16 and test outcome presented in Table 5.9, Table 5.10 and Graph 5.8. This test gives an important indication of the likely possibility of the resistance of proportioned concrete against the ingress of SO_3^- ions and due to this ingress of SO_3^- ions there occurs expansion in the specimens and the same can be measured as the change in length of the specimen, subjected to inundation in the solution of Na_2SO_4, over a period of time. As can be grasped from the data of Table 5.9 and Table 5.10, that escalation in resistance to SO_3^- ions ingression detected with the % rise of MK in the mix of $SCC_{FMKseries}$. For $SCC_{FMKseries}$ recipes when %MK ranged from 2.50% to 12.50%, confrontation to SO_3^- ions ingression was amplified from 4.12% to 15.71% as compared to SCC_{FMK0}. While for alike deviations of %MK in $SCC_{GMKseries}$, the detected rise in confrontation to SO_3^- ions ingression was from 6.02 % to 17.23%. Therefore, the greater rise in confrontation to SO_3^- ions ingression in $SCC_{GMKseries}$ can be ascribed to fast-reactions of MK in concern of GGBFS than the similar reactions of MK in concern of flyash. This increase in in confrontation to SO_3^- ions ingression was negligible once %MK augmented afar to 12.50% in both the recipes of $SCC_{FMKseries}$ and $SCC_{GMKseries}$. This observation was fairly conducive with the consequence of the study [71] in which lone allowance was that ceramic-waste powder was incorporated as moderate reaction causing SCM and microsilica was incorporated as sensitive SCM. It can be stated that for increase in confrontation to SO_3^- ions ingression, MK's performance in existence of GGBFS perceived to be more, than MK's performance in existence of flyash. This can be qualified to fast-reactions of MK in $SCC_{GMKseries}$ than in $SCC_{FMKseries}$ and the same can be apparent, in Fig. 5.19 , in the mortar mix images of Photomicrograph of 1-day and 3- days of $SCC_{FMKseries}$ and $SCC_{GMKseries}$. The 12.50% substitution of MK was observed to be pragmatic for realizing the increase in confrontation to SO_3^- ions ingression in both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$.

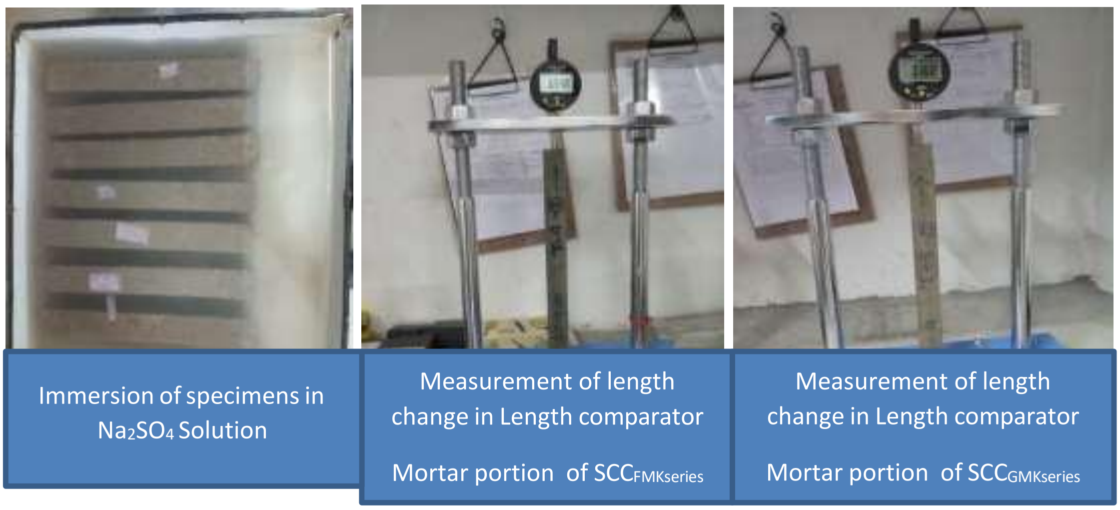
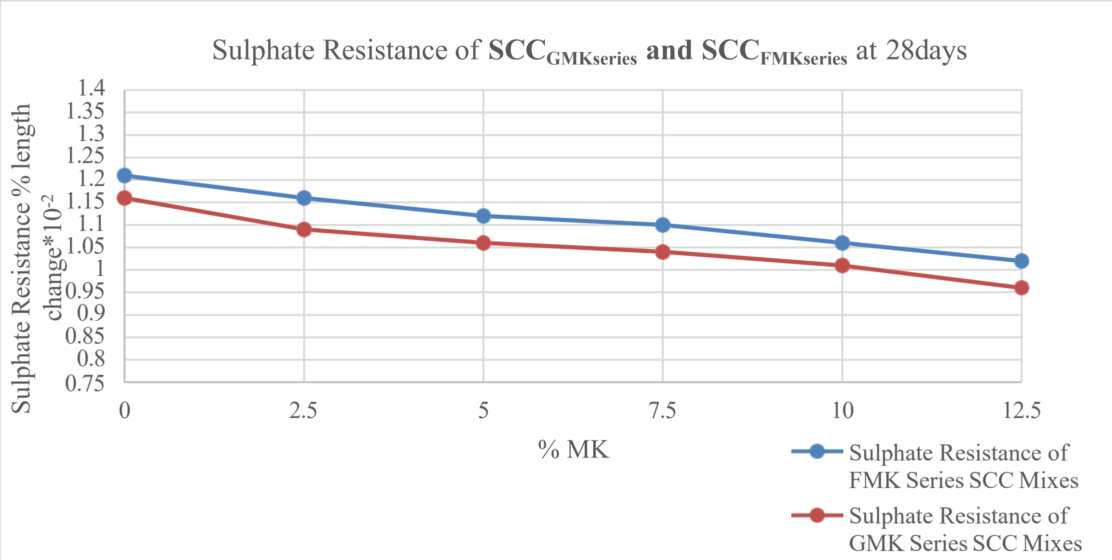


Fig.5.16 Test arrangements for measuring sulphate resistance of specimens of $SCC_{GMKseries}$ and $SCC_{FMKseries}$



Graph 5.8 Sulphate Resistance of specimens with varied % MK $SCC_{GMKseries}$ and $SCC_{FMKseries}$ at 28days

5.3.8 Chloride Resistance- confrontation to ingression of Cl^- ions

Chloride Resistance test i.e. measure of ingression of Cl^- ions in to the body of concrete ,was carried out as per the ASTM 1543 . Slab specimens of 600mm length X 300mm width and 100mm thickness were casted for each type of mix and the surface of slab was ponded after 1day age with the solution of 3% NaCl . This test was carried as per the procedure presented and discussed under 4.8.5 in chapter 4 of this thesis. The test arrangements are presented in Fig.5.17 and tested values presented in Table 5.9, Table 5.10 and Graph 5.9. Test results of this experiment contributes an important hint of the expected possibility of the confrontation of proportioned concrete against ingress of Cl^- ions and due to this ingress the change in Cl^- will be resulted for the specimen and the same can be measured as the change in $\%Cl^-$ of the specimen, subjected to inundation in the chloride rich solution, over a period of time. As can be comprehended from the data of Table 5.9 and Table 5.10 that rise in confrontation to ingression of Cl^- ions was detected with the % increase of MK in the $SCC_{FMKseries}$. The confrontation to ingression of Cl^- ions was augmented from 9.36 % to 64.59 % related to $SCC_{FMK0.00}$ when %MK varied from 2.50% to 12.50% i.e. for the mix $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$. But, for alike deviations of %MK in $SCC_{GMKseries}$, perceived rise in confrontation to ingression of Cl^- ions was from 17.06 % to 68.30%. Consequently, the greater rise in resistance to confrontation to ingression of Cl^- ions in $SCC_{GMKseries}$

can be qualified to fast-reactions of MK at early-ages in concern of GGBFS than the similar reactions of MK in concern of flyash. This effect was earlier agreed in the study [89] where single exclusion was that lime-stone powder was used as SCM and RHA was used as reactive SCM. It can be identified that for rise in confrontation to ingression of Cl^- ions ,MK's performance in existence of GGBFS perceived to be higher than MK's performance in existence of flyash. This can be accredited to fast-reactions of MK in $SCC_{GMKseries}$ than in $SCC_{FMKseries}$ and the same can be supposed in the Photomicrograph images, presented in Fig. 5.19, of mortar portions of $SCC_{FMKseries}$ and $SCC_{GMKseries}$ at 1-day and 3-days. This rise in confrontation to ingression of Cl^- ions was minimal when %MK augmented afar to 12.50% in both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$. The extreme substitution %MK was sensed to be 12.50% for accomplishing intensification in confrontation to ingression of Cl^- ions for both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$.

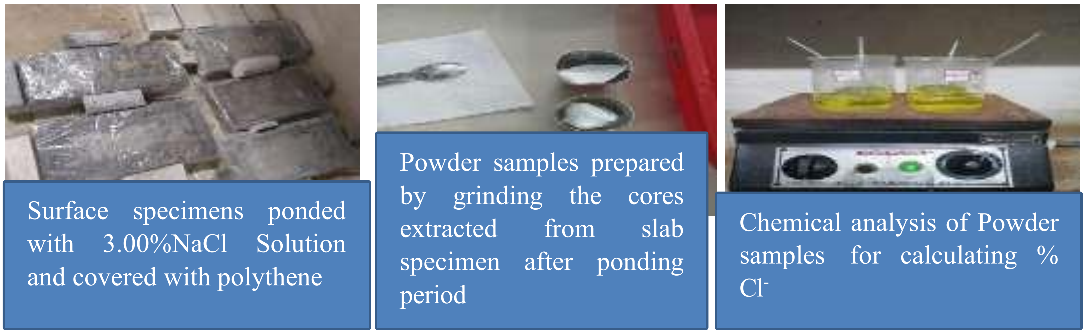
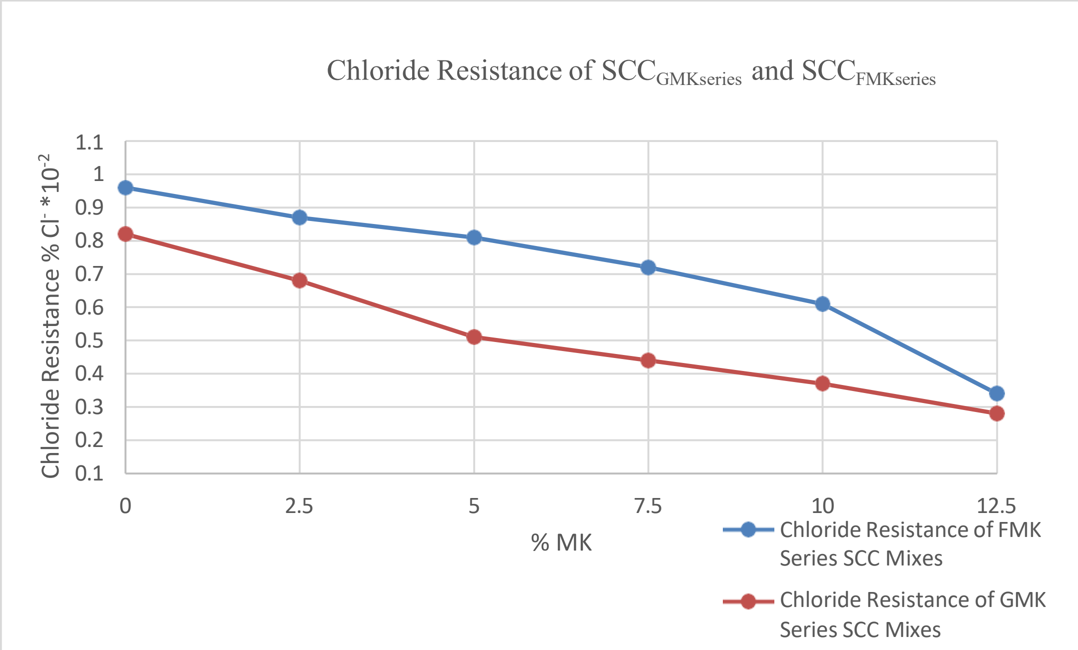


Fig.5.17 Test arrangements for Chloride content in specimen subjected to 3.00% NaCl ponding



Graph 5.9 Chloride content in FMK series and GMK series specimen after subjected to 3.00% NaCl ponding for 28 days

5.3.9 Summary of study on effects of variable % of MK in company of fixed % of GGBFS and flyash in $SCC_{GMKseries}$ and $SCC_{FMKseries}$

The subsequent deductions can be strained from the above directed investigational work:

1) Fast- reactions of MK in concern of GGBFS was detected than the comparable reactions of MK in concern of Flyash.
2) Slump-flow drop was extra once %MK augmented outside 12.50% in both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$.
3) 'V' funnel- flow time rise was higher when %MK augmented outside 10.00% in both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$.
4) Decline in the flow-depth ration in the 'L' shaped box was greater after 10.00%MK in both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$.
5) Decline in the time for final set of concrete was higher while %MK augmented outside 10.00% in both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$.
6) For managing higher early-age strength of $SCC_{GMKseries}$ and $SCC_{FMKseries}$ recipes, MK's enactment in existence of GGBFS was pragmatic than MK's enactment in existence of flyash.

7) Rise in 1-day age strength was minimal afar to 12.50% of MK in both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$.
8) Water-sorptivity shrunk through the rise in % MK in both the $SCC_{GMKseries}$ and $SCC_{FMKseries}$.
9) Intensification in confrontation to ingression of Cl^- ions was more in $SCC_{GMKseries}$ as related to $SCC_{FMKseries}$.
10) Auxiliary examinations need to be conceded in $SCC_{GMKseries}$ at varied % of combinations of MK+GGBFS for betterment of properties at early-age of recipes of $SCC_{GMKseries}$.

5.4 Study on Effect of part replacement of OPC with GGBFS+MK on properties of SCC

From the study conducted as stated under 5.0 and the associated observations of the same as listed under 5.3.8, further study was planned to explore the effects of varied blends of MK+GGBFS, as part substitution in OPC, in order to find out optimum proportion of GGBFS that could style the SCC towards more sustainability as well as succeeding in producing SCC having characteristic of fast setting and early strength gaining nature. Hence,for carrying further investigations 2 no.s of SCC mix, as control mix, where first mix was proportioned with 100% OPC as cementitious material and second with GGBFS as moderately reacting SCM and maintaining binder material proportion OPC- 50.00% and GGBFS-50.00%, the recipes were respectively coded as $SCC_{0.00}$ and $SCCG_{M0.00}$,for relating with the enactment of the consequence of MK in the subsequent SCC recipes that were casted varying % MK from 5.00% to 20.00% as part substitution of GGBF in each subsequent trial. Accordingly, the proportioned recipes were coded as $SCC_{GM5.00}$, $SCC_{GM10.00}$, $SCC_{GM15.00}$ and $SCC_{GM20.00}$. For instance, $SCC_{GM10.00}$ represents a SCC recipe with 40.00% GGBFS, as moderately reacting SCM and 10.00% MK, reactive SCM. So, in this auxiliary exploration on the stimulus of different mixtures of %GGBFS+%MK on properties of SCC, a total of six numbers of SCC recipes i.e. $SCC_{0.00}$, $SCC_{GM0.00}$, $SCC_{GM5.00}$, $SCC_{GM10.00}$, $SCC_{GM15.00}$ and $SCC_{GM20.00}$ were prepared and the same are presented in Table 5.11. The so prepared recipes were tested in both fresh-state as well as in hardened-state for flow properties, strength related properties and also for durability. The results of same is discussed in subsequent sections.

Table 5.11

SCC recipes with varied combinations of %GGBFS+%MK

Sl. No	SCC Mix designation	Total Cementitious Material	Cementitious Material(CM) (% by Weight)			CA10mm+ River Sand		Quantity of Water [w/cm=0.35]	Admixture (%CM)
			OPC	GGBFS	MK	CA 10mm	River Sand		PCE
		Kgs/m^3	'%'	'%'	'%'	Kgs/m^3	Kgs/m^3	Kgs/m^3	'%'
1	SCC$_{0.00}$	540	100	0	0	750	915	190	1.00
2	SCC$_{GM0.00}$	540	50	50	0	750	915	190	1.00
3	SCC$_{GM5.00}$	540	50	45	5	750	915	190	1.00
4	SCC$_{GM10.00}$	540	50	40	10	750	915	190	1.00
5	SCC$_{GM15.00}$	540	50	35	15	750	915	190	1.00
6	SCC$_{GM20.00}$	540	50	30	20	750	915	190	1.00

Table 5.12

Rheology and Time for initial and final set of SCC recipes

Sl.No	SCC Mix Code	GGBFS %	MK %	Slump-Flow 'SF'	'V' funnel-flow time	Time for initial set(IST)	Time for final set (FST)
				mm	seconds	minutes	minutes
1	SCC$_{0.00}$	0.00	0.00	600	18.40	400	570
2	SCC$_{GM0.00}$	50.00	0.00	650	16.18	490	690
3	SCC$_{GM5.00}$	45.00	5.00	630	20.86	440	620
4	SCC$_{GM10.00}$	40.00	10.00	590	23.37	370	510
5	SCC$_{GM15.00}$	35.00	15.00	570	24.16	320	470
6	SCC$_{GM20.00}$	30.00	20.00	540	27.83	310	440

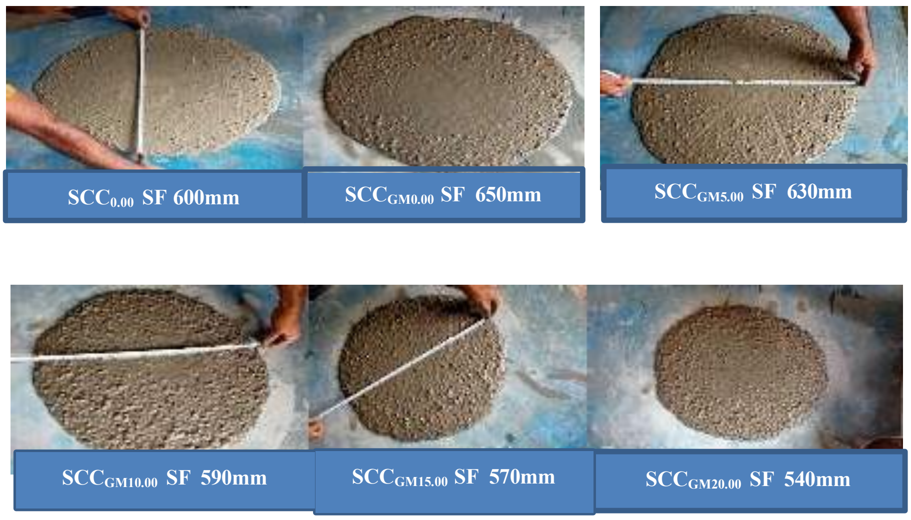


Fig.5.18 Change of Slump flow with variation in combinations of GGBFS+MK

5.4.1 Analysis of Results -Influence of part replacement of OPC with GGBFS+MK on characteristics of SCC

5.4.1.1 Analysis of Results: Properties in fresh-state of SCC

5.4.1.2 Slump-Flow

Table 5.12 denotes the slump-flow of various SCC recipes that were studied and the deviations in slump-flow with mention to various groupings of %GGBFS+%MK. After glancing to the data of Table 5.12 ,it can be perceived that once %MK augmented from 5.00% to 10.00% and keeping the total SCM(GGBFS+MK) proportion to 50.00% i.e. for the mix $SCC_{GM5.00}$ and $SCC_{GM10.00}$, the slump-flow observed for $SCC_{GM5.00}$ improved by 5.00% and the same for $SCC_{GM10.00}$ was reduced by 1.66% as related to control mix $SCC_{0.00}$ .Whereas for $SCC_{GM0.00}$, the slump-flow increased by 8.30%**.** This sophisticated rise in slump- flow of $SCC_{GM0.00}$ recipes can be ascribed to the lessening in demand for water due to the adding of GGBFS, as part replacement of OPC, and the same is in agreement with [116]. Likewise, the qualified decrease in slump-flow of $SCC_{\mathbf{GM5.00}}$ recipes can be ascribed to the beginning of faster hydration-reactions owing to adding of sensitive MK, though in lesser quantity. Nevertheless, as detected from the laboratory trials, for the $SCC_{GM15.00}$, 5.00% shrunk in slump-flow noticed and for the $SCC_{GM20.00}$, there was 10.00% drop in slump-flow linked to reference mix $SCC_{0.00}$ and also the mix ended to display SCC characteristics. This drop in slump-flow at advanced %MK can be ascribed to the early-reactions of MK[93] .This statement is in covenant with the conclusion of the study[99] with the one exception that fine slag -powder was admixed to prepare concrete. So, it can be mentioned that for achieving comparable flow in the existence of MK in the binder system of OPC+GGBFS, water demand was noticed to be higher due to higher surface area, finer particle ranges, as earlier presented in Table3.10 in chapter 3, and the elemental composition of MK. Additionally, it was also perceived that for the above blends, the extreme substitution level of MK was proven to be 10.00% for achieving the beset slump-flow ranging from 550mm to 650mm. Fig.5.18 represents the change of Slump flow with variation in combinations of GGBFS+MK.

5.4.1.3 'V' Funnel -Flow Time

It can be realized from the data of Table 5.12 ,that while %MK changed from 5.00% to 10.00% i.e. for the mix $SCC_{GM5.00}$ and $SCC_{GM10.00}$, the resultant 'V' funnel-flow time was augmented from 13.36% to 26.73% as equalled to 'V' funnel-flow time of control mix $SCC_{0.00}$ and whereas for $SCC_{GM0.00}$ the decline in 'V' funnel-flow time was 12.06%**.** When %MK was ranged further to 15.00% i.e. for the mix $SCC_{GM15.00}$, the increase in 'V' funnel-flow time was 31.33%**.** It was also detected that with the advancement in %MK to 20.00% there occurred 51.24% rise in 'V' funnel-flow time as linked to control mix $SCC_{0.00}$ and the mix ended to display the SCC characteristics. Added to this,it was also noticed from the data that afar to 10% of %MK ,there was sophisticated influence on 'V' funnel-flow time. This developed consequence on 'V' funnel-flow time beyond 10.00 % MK in the above binder system can be recognized to faster-reactions of MK owed to its sophisticated surface area as perceived from the Table 3.4 in chapter 3 of this thesis. The same occurrences was also witnessed in the study[105].

5.4.1.4 Time for Initial Set

From the data of time for initial set as presented in Table 5.12, it can be grasped that , as related to time for initial set of control mix of $SCC_{0.00}$, once %MK changed from 5.00% to 10.00% i.e. for the recipes $SCC_{GM5.00}$ and $SCC_{GM10.00}$, the initial set time improved by 10.00% for $SCC_{GM5.00}$ and the same was reduced to 7.50%. But for $SCC_{GM0.00}$, the time for initial set was augmented by 22.50%**.** Moreover, it was illustrious that when %MK was 15.00% i.e. for the mix $SCC_{GM15.00}$, there was still decrease in the time for initial set by 20.00% and with the additional rise in %MK to 20.00% there arisen 22.50% reduction in the time for initial set, as compared to control mix $SCC_{0.00}$. This reduction in time for initial set of the above investigated recipes can be ascribed to the early-reactions of MK in the binder system comprising of OPC+GGBFS. Also, outside the replacement level of 10.00% of MK, there was sophisticated consequence on time for initial set. This greater influence on time for initial set can be coherent to the particle size refinement of MK and with comparative rise in content by 5.00% for each subsequent recipes, MK might have underway its supremacy over the soberly reactive GGBFS and henceforth the combination commenced to drop its flow- characteristics as detected through slump-flow test ,as debated under 5.3.1.2, and 'V' Funnel -Flow Time test ,as conversed under 5.3.1.3.This was also properly agreeing with the remarks made in the study[61] with solitary difference that OPC was partly replaced by flyash and slag **.**

5.4.1.5 Time for Final Set

From the data of time for final set as presented in Table 5.12, it can be grasped that, as related to time for final set of control mix of $SCC_{0.00}$, once %MK increased to 5.00%, for the mix $SCC_{GM5.00}$, the time for final set was augmented to 8.78%. As the %MK further increased to 10.00%, for the mix $SCC_{GM10.00}$, the time for final set was decreased to 10.52%. Whereas , for $SCC_{GM0.00}$ the time for final set was augmented by 23.20% .This increase in the time for final set was understandable owed to the sophisticated proportion of GGBFS in the $SCC_{GM0.00}$. It was also illustrious that, when %MK increased to 15.00% i.e. for the mix $SCC_{GM15.00}$, there occurred 17.53% decrease in the time for final set .Through additional rise in %MK to 20.00% there happened 22.81% drop in the time for final set as linked to control mix $SCC_{0.00}$. It was also illustrious that for the above investigated recipes, outside the 10.00% replacement level of %MK, there was developed influence on the time for final set. This sophisticated influence on the time for final set can be rational to the finer sized particles of MK and with comparative rise of %MK by 5.00% in each subsequent trial, MK might have underway its supremacy over the moderately reactive GGBFS and henceforth the mix began to fail to spread freely as noticed through slump- flow test, discussed under 5.3.1.2 and 'V' Funnel -Flow Time test, as discussed under 5.3.1.3. This observation was also equally concurring with the clarifications prepared in the work [55,57] with mere difference that reactive SCM used was RHA and lime stone powder used as moderately reactive SCM.

5.5 Analysis of Results-SCC characteristics in hardened- state of $SCC_{0.00}$, $SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

5.5.1 Compressive Strength of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

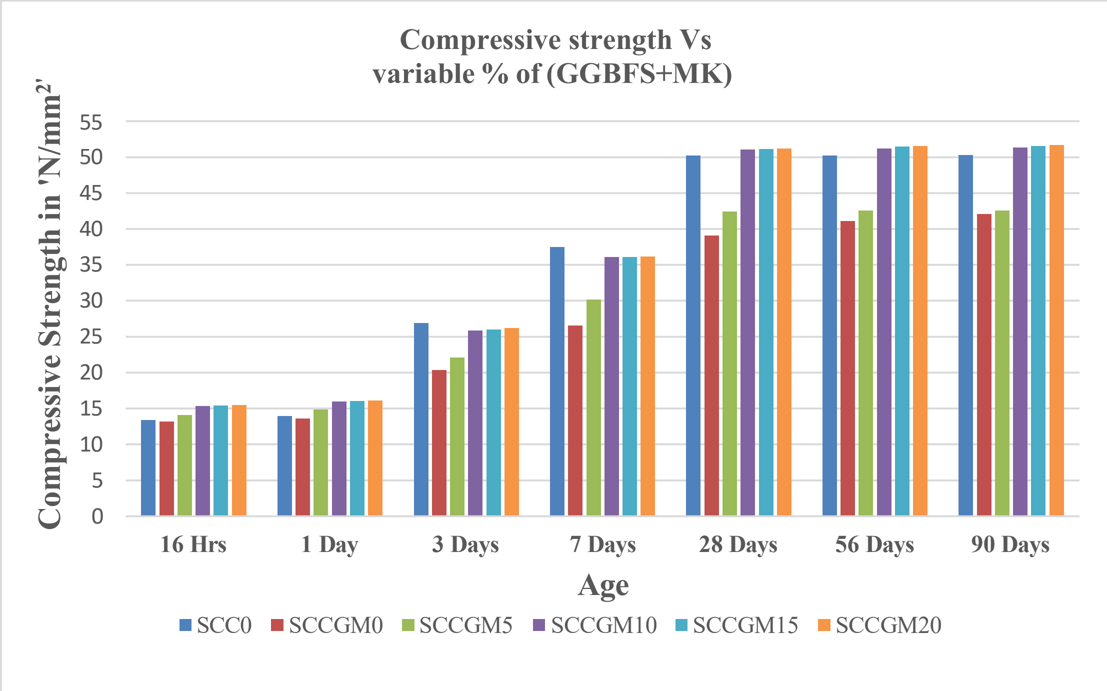
From the data in Table 5.13 and Graph 5.10,it can be understood that, the compressive strength at 16-Hours of $SCC_{0.00}$ was 13.41N/mm^2.It was also perceived that once part of OPC was substituted by 50.00% GGBFS i.e. for $SCC_{GM0.00}$, the compressive strength was reduced to 13.17 N/mm$^{2.}$ This reduction in compressive strength was owed to the presence of moderately reactive GGBFS in to the binder-system, till the availability of enough $Ca(OH)_2$ required for secondary actions of

SCMs[64]. Added to this, it can be detected that while reactive MK was involved into the binder-system and the same was incorporated as part substitution of GGBFS ranging from 5.00% to 10.00%, i.e. for the mixCC$_{GM5.00}$ and SCC$_{GM10.00,}$ the compressive strength at 16-Hours was improved to 14.11 N/mm^2, 15.35 N/mm^2 correspondingly. This rise in compressive strength of individual recipe can be ascribed to the incidence of reactive MK, in the binder system, triggering quickening of hydration-reactions [75]. In the identical binder-system, when %MK was further augmented from 15.00% to 20.00% i.e. for the mix SCC$_{GM15.00}$ and SCC$_{GM20.00,}$ there was nominal rise in the compressive strength at 16-Hours, specifying the saturation level of %MK in the above binder-system. This was in dissimilarity to the outcomes of study [87,97] where it was revealed that %MK, up to 15.00%, yields constructive influence on the concrete strength improvement, the likely deviation of reflection in this study and the quoted study might be the use of hybrid-fibre combinations by 0.25% to 0.50% by volume fractions in concrete in the cited study, thus encouraging for advanced examinations .In this contemporary study ,it was also seen that for the SCC mix, beyond 16-Hours also, all the experimented recipes established an rise in compressive strength from 1-day to 90-days. In terms of MoE, at 28-days, the same trend of steady increase, as was perceived in compressive-strength results, for the SCC recipes of SCC$_{GMseries}$ observed.

Table 5.13

SCC$_{0.00}$, SCC$_{GM0.00}$ and SCC$_{GMseries}$ Compressive strength with variation in % MK 16-Hours to 90- Days

SCC Recipe Code	GGBFS	MK	Compressive strength-N/mm^2							MoE(Ec) 10^3 N/mm^2
	%	%	16hr	1Day	3Days	7Days	28Days	56Days	90Days	28Days
SCC$_{0.00}$	0.00	0.00	13.40	13.92	26.89	37.44	50.2	50.26	50.29	36.90
SCC$_{GM0.00}$	50.00	0.00	13.01	13.64	20.37	26.56	39.06	41.12	42.05	29.60
SCC$_{GM5.00}$	45.00	5.00	14.12	14.87	22.08	30.18	42.46	42.52	42.58	30.70
SCC$_{GM10.00}$	40.00	10.00	15.36	15.94	25.89	36.06	51.08	51.24	51.31	33.20
SCC$_{GM15.00}$	35.00	15.00	15.40	16.02	26.02	36.09	51.14	51.47	51.54	34.40
SCC$_{GM20.00}$	30.00	20.00	15.50	16.09	26.2	36.17	51.17	51.6	51.67	35.10



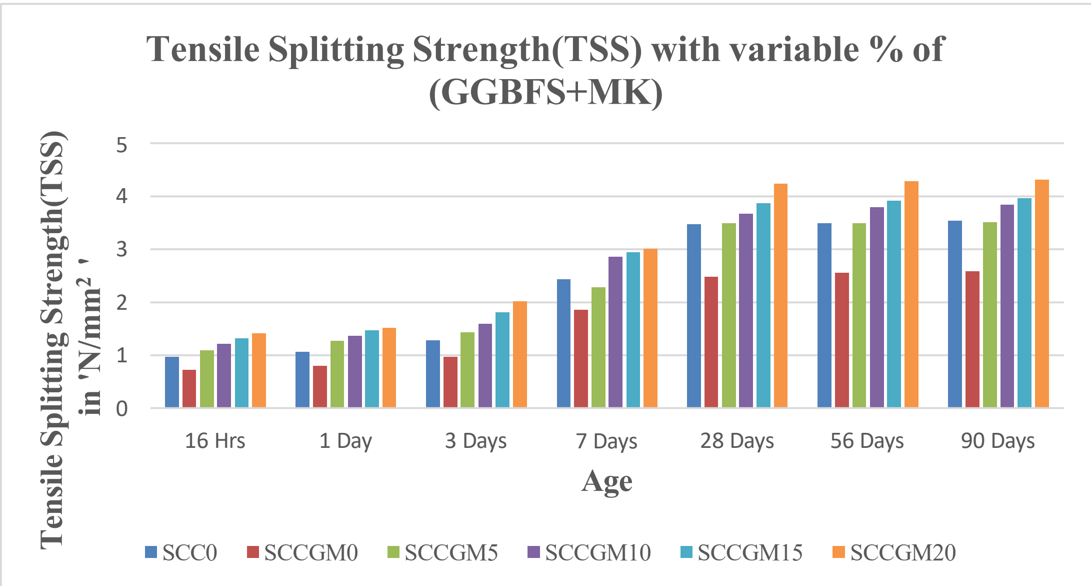
Graph 5.10 Compressive Strength of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK from 16 hrs. to 90 days age

5.5.2 Tensile Splitting Strength(TSS) of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

From the data of Table 5.14 and Graph 5.11, it can be understood that TSS at 16-Hours of $SCC_{0.00}$ i.e. control mix, was 0.96 N/mm^2. It was observed that when part of OPC was substituted by 50.00% GGBFS i.e. for $SCC_{GM0.00}$ mix, the TSS was reduced to 0.71 N/mm$^{2.}$ This reduction in TSS was owing to the presence of soberly responsive GGBFS in the binder-system which initially origins slow reactions till the handiness of adequate $Ca(OH)_2$ as compulsory for secondary-reactions of SCMs[64]. It was also perceived that once the reactive MK was involved into the binder-system and was included as partial substitution of GGBFS ranging from 5.00% to 10.00%, i.e. for the mix$CC_{GM5.00}$ and $SCC_{GM10.00,}$ the TSS at 16-Hours was augmented to 1.08 N/mm^2, 1.21 N/mm^2 correspondingly. This rise in TSS of respective SCC recipes can be ascribed to the incidence of sensitive MK, in the binder-system, triggering quickening of hydration-reactions[59]. In the identical binder-system, once %MK was further augmented from 15.00% to 20.00% i.e. for the mix $SCC_{GM15.00}$and $SCC_{GM20.00,}$ there occurred minimal rise in the 16-Hours TSS signifying the capacity level of %MK in the above investigated binder-system. This was in dissimilarity to the outcome of study[75,81] where it was exposed that %MK , up to 20.00%, yields optimistic influence on gain of concrete strength. But, the early-age strength improvement of admixed sophisticated finer sized materials ,in the concrete, was affirmed in the study[63].In this up-to-date study, it was also seen that for the SCC mix beyond 16-Hours also, all the trials established a rise in compressive strength from 1-day to 90-days. Fig.5.19 represents the Tensile Splitting Strength(TSS) test arrangements made for the above study.

Table 5.14
Tensile Splitting Strength(TSS) of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

SCC Mix ID	GGBFS %	MK %	Tensile Splitting Strength(TSS) of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ at various ages N/mm^2						
			16-hours	1-Day	3-Days	7-Days	28-Days	56-Days	90-Days
$SCC_{0.00}$	0.00	0.00	0.97	1.06	1.28	2.44	3.47	3.49	3.54
$SCC_{GM0.00}$	50.00	0.00	0.72	0.80	0.97	1.86	2.48	2.56	2.59
$SCC_{GM5.00}$	45.00	5.00	1.09	1.27	1.43	2.29	3.49	3.50	3.51
$SCC_{GM10.00}$	40.00	10.00	1.22	1.36	1.59	2.86	3.67	3.80	3.84
$SCC_{GM15.00}$	35.00	15.00	1.32	1.47	1.81	2.94	3.87	3.92	3.96
$SCC_{GM20.00}$	30.00	20.00	1.42	1.52	2.02	3.01	4.24	4.28	4.32



Graph 5.11 Tensile Splitting Strength(TSS) of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK from 16 hrs to 90 days age

Fig.5.19 Tensile Splitting Strength(TSS) test arrangements

5.5.3 Durability properties of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

5.5.3.1 Drying Shrinkage(DS) % of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

Fig.5.20 representing the DS test of the prismatic specimens of various SCC mix. Test data is presented in Table 5.15 and Graph 5.12. It can be perceived from the data that the DS at 16-Hours of $SCC_{0.00}$ i.e. control mix, was 0.008. It was observed that when OPC was substituted by 50.00% of GGBFS i.e. for $SCC_{GM0.00}$, the DS was augmented to 0.009· This rise in DS was owed to the presence of moderately reactive GGBFS in to the binder-system having sophisticated finer sized particles than the OPC, which primarily origins drop in dimensions of specimens due to leisurely responses of GGBFS till the disposal of adequate $Ca(OH)_2$, as compulsory for secondary-reactions of SCMs [65]. It was also detected that once the reactive MK was incorporated into the binder- system and was included as partial substitution of GGBFS by 5.00% to 10.00%, i.e. for the mix $SCC_{GM5.00}$ and $SCC_{GM10.00}$, the DS at 16-Hours was somewhat augmented to 0.010 to 0.011 correspondingly as compared to $SCC_{0.00}$. This minor rise in DS of corresponding SCC recipes can be ascribed to the incidence of sensitive MK, in the binder-system, triggering quickening of hydration-reactions[75] and the identical interpretations was maintained from the conclusions of microstructure development for various ages and as shown in Fig.5.21 representing the Photomicrographs at 1000X magnification, of SCC recipes. In the identical binder-system, when %MK was furthermore augmented from 15.00% to 20.00% i.e. for the mix $SCC_{GM15.00}$ and $SCC_{GM20.00}$, there was rise in the 16-Hours DS signifying accumulation of more magnitude of finer sized materials in to the binder-system. This was in fine arrangement with the conclusions of study [88] wherein excluding that the moderately reactive SCM used in that study was flyash and sensitive SCMs included were MK and Clay. In this contemporary study, it was also seen that for the SCC mix beyond 28-days, all the above trials confirmed a marginal increase in DS from 1-day to 90-days. But, in all the cases the DS was well within the permissible limits of 0.15% at 28 days.

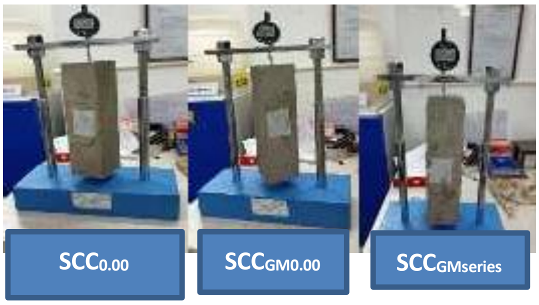


Fig.5.20 DS Test of SCC Mix

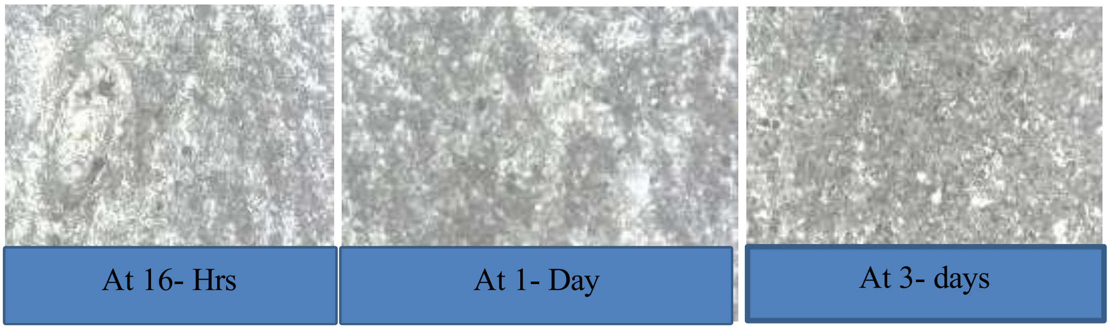
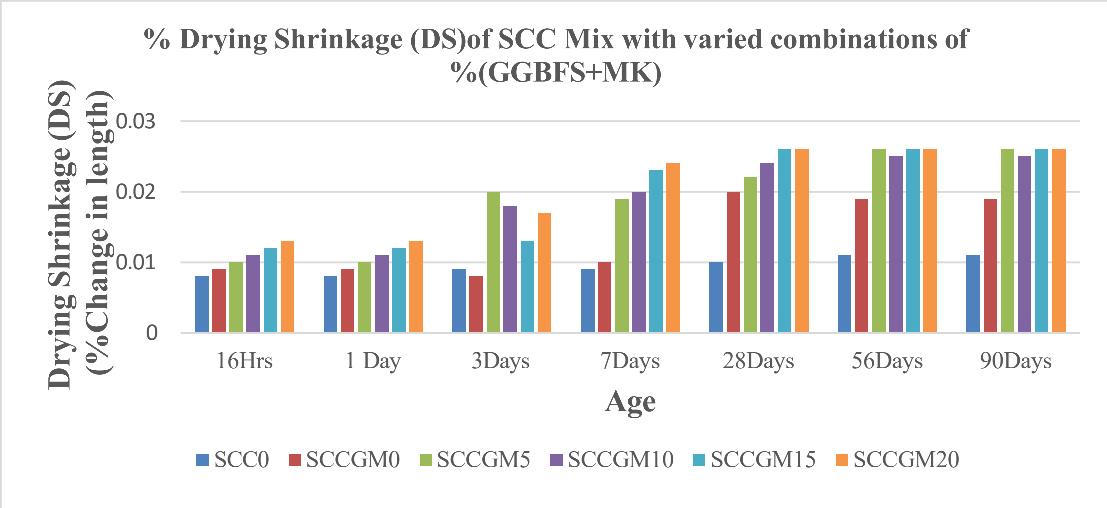


Fig.5.21 Photomicrographs(X1000) of SCC$_{GM10.00}$ mix showing microstructure development

Table 5.15
Drying Shrinkage (DS)of SCC Mix with varied combinations of %(GGBFS+MK)

Sl.No	Mix ID	GGBFS %	MK %	%Drying Shrinkage(DS) of SCC Mix (-)						
				16-Hrs	1-Day	3-Days	7-Days	28-Days	56-Days	90-Days
1	SCC$_{0.00}$	0.00	0.00	0.008	0.008	0.009	0.009	0.010	0.011	0.011
2	SCC$_{GM0.00}$	50.00	0.00	0.009	0.009	0.008	0.010	0.020	0.019	0.019
3	SCC$_{GM5.00}$	45.00	5.00	0.010	0.01	0.020	0.019	0.022	0.026	0.026
4	SCC$_{GM10.00}$	40.00	10.00	0.011	0.011	0.018	0.02	0.024	0.025	0.025
5	SCC$_{GM15.00}$	35.00	15.00	0.012	0.012	0.013	0.023	0.026	0.026	0.026
6	SCC$_{GM20.00}$	30.00	20.00	0.013	0.013	0.017	0.024	0.026	0.026	0.026



Graph.5.12 Drying Shrinkage (DS)of SCC Mix with varied combinations of %(GGBFS+MK)

5.5.3.2 Initial Surface Absorption Test(*ISAT*) of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

Initial surface absorption test(ISAT)arrangements, as per IS 516 (Part 2/Sec 2) : 2020 are shown in Fig.5.22. Test results of ISAT at 28 days on the test conducted on specimens of experimented SCC mix is presented in Table 5.16 and Graph 5.13. From the data of Table 5.16, it can be perceived that at 30-minutes, ISAT for control mix $SCC_{0.00}$ was 1.18 ml/m^{2}s and when 50.00% OPC was replaced by GGBFS in the cementitious system, the ISAT value was decreased to 1.13 ml/m^{2}s. Besides, it was also noticed that, at the same 30-minutes time, upon the institution of reactive MK, in to the binder-system, as partial substitution of GGBFS, in the fraction of 5.00% in the SCC mix, ISAT value was reduced to 1.04 ml/m^{2}s and with the more rise in %MK from 10.00% to 20.00% ,the ISAT value, at same 30-minutes time, was furthermore reduced to 0.88 ml/m^{2}s to 0.78 ml/m^{2}s correspondingly and thus signifying the drop in surface-absorption due to the densified micro-structure owed to the incorporation of finer SCMs in to the binder- system[52] .The total ISAT values, at 60-minutes, also displayed alike tendencies of decline with the escalation in %MK in the above experimented SCC recipes. It was also detected that outside 10.00% MK quantity in the above experimented SCC recipes, there was a minimal reduction in the ISAT values at both 30-minutes and 60- minutes. This minor drop in the ISAT of relevant SCC mix can be accredited to the incidence of sensitive MK, in the binder-system, triggering quickening of hydration-reactions [64]. This was in covenant to the conclusions of study [67-68] wherein excluding that the sensitive SCM used in that study was ultra-fine slag and RHA and the recipe considered was geopolymer-concrete. In this contemporary study, it was also seen that for the SCC mix outside 7-days, all the trials confirmed a minimal drop in ISAT from 28-days to 90-days owing to accomplishment of maturity of reactions and impenetrable microstructure. These equivalent interpretations were pronounced in the study[65] from the conclusions of microstructure advancement for various ages of concrete .

Table 5.16
Durability Properties of SCC_0,SCC_{GM0} and SCC_{GMK} series

Sl. No	Mix Code	% GGBFS	% MK	ISAT ml/m^2s At 28 Days		Permeability At 28 Days	Abrasion Resistance At 28 Days
				At 30 - Minutes	At 60-Minutes	10^{-12} m^2/s	mm^3per 5000 mm^2
1	$SCC_{0.00}$	0.00	0.00	1.17	2.32	0.79	5960
2	$SCC_{GM0.00}$	50.00	0.00	1.12	2.09	0.61	5840
3	$SCC_{GM5.00}$	45.00	5.00	1.03	1.98	0.19	5870
4	$SCC_{GM10.00}$	40.00	10.00	0.87	1.85	0.16	5990
5	$SCC_{GM15.00}$	35.00	15.00	0.82	1.79	0.15	6020
6	$SCC_{GM20.00}$	30.00	20.00	0.79	1.76	0.13	6040

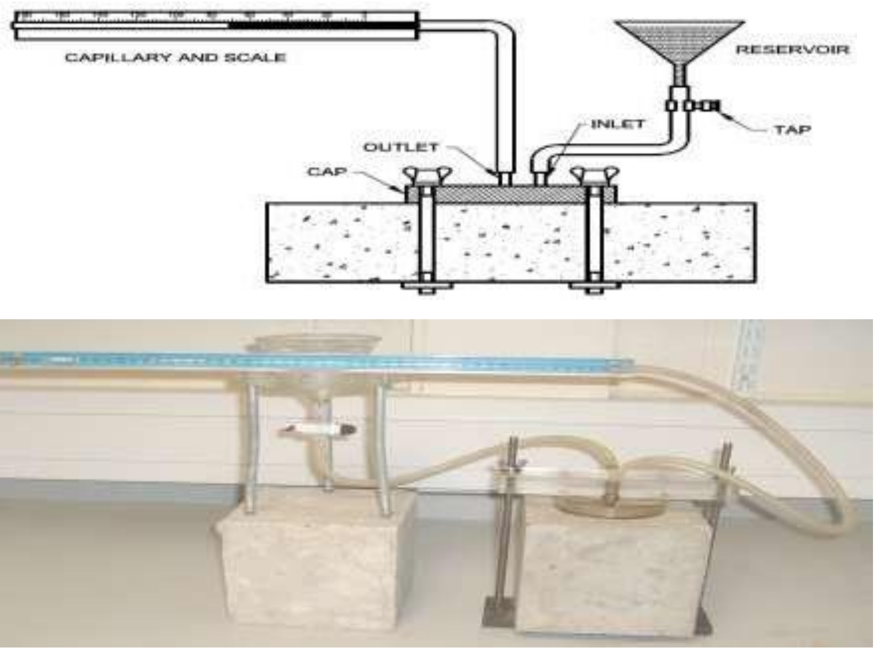
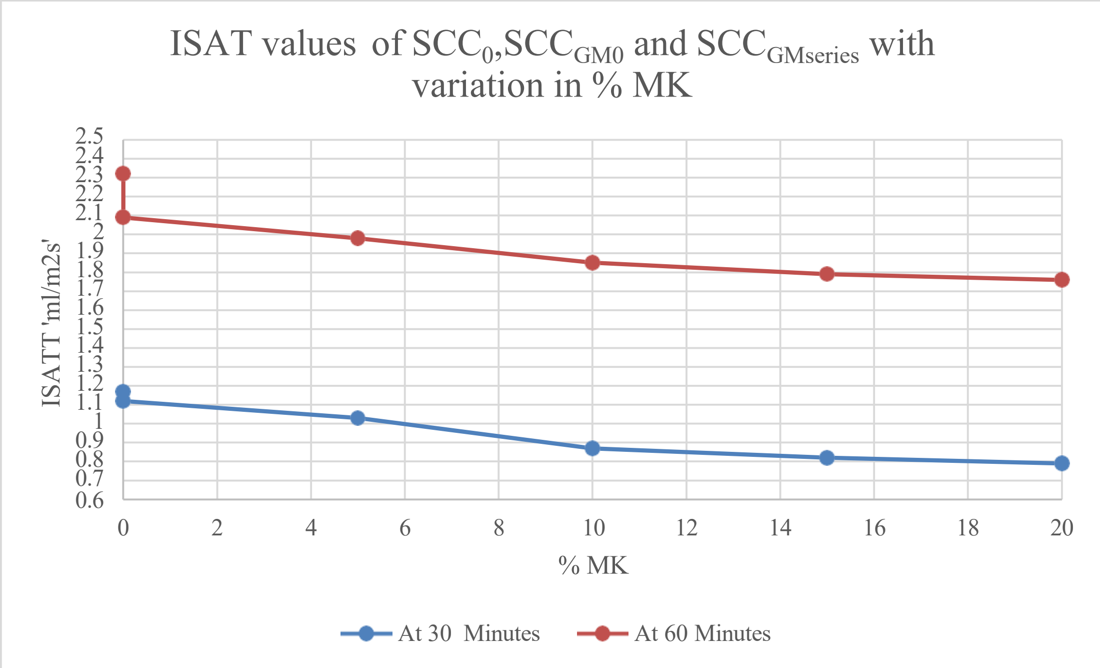


Fig.5.22 Test Arrangements for Initial Surface Absorption Test(ISAT)



Graph 5.13 ISAT values of SCC_0,SCC_{GM0} and SCC_{GMK} series with variation in % MK

5.5.3.3 Permeability of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK Permeability test arrangements as per IS 516(Part 2/Sec1):2018 are shown in Fig.5.23. Test results of permeability, on the experimented mix SCC mix, carried on the specimens of 100mm diameter at 28-days presented in Table 5.16 and Graph 5.14. It can be perceived from the data of Table 5.16 ,that the permeability value for control mix $SCC_{0.00}$ was $0.78x10^{-12}$ m^2/s. It was observed that when part of OPC was replaced by 50.00% GGBFS i.e. for $SCC_{GM0.00}$ mix, the permeability was reduced to $0.62x10^{-12}$ m^2/s. This drop of permeability was owing to the presence of moderately reactive GGBFS in to the cementitious system having higher fineness than the OPC, which initially causes densification of microstructure of the concrete due to pore refinement [72]. It was also observed that when high reactive MK was introduced into the cementitious system and was added as part replacement of GGBFS by 5.00% to 10.00%, i.e. for the mix $SCC_{GM5.00}$ and $SCC_{GM10.00}$, the permeability was further decreased slightly to $0.18x10^{-12}$ m^2/s , $0.17x10^{-12}$ m^2/s respectively as compared to control mix $SCC_{0.00}$. This minor drop in permeability of respective SCC mix can be recognized to the incidence of reactive MK, in the cementitious system, triggering quickening of hydration-reactions and there by consequence of dense microstructure

[75] and the equivalent observations was maintained from the conclusions of microstructure development for several ages and as shown in Fig.5.21 expressing the Photomicrographs at 1000X magnification at 16-Hours, 1-day and 3- days' time of $SCC_{GM10.00}$ mix illustrating the microstructure development at early-ages. In the equivalent binder system, when %MK was further augmented from 15.00% to 20.00% i.e. for the mix $SCC_{GM15.00}$ and $SCC_{GM20.00,}$ there was again a minimal reduction in the permeability to $0.16x10^{-12}$ m^2/s , $0.14x10^{-12}$ m^2/s respectively. This drop in permeability directs the accomplishment of saturation level of %MK in the experimented binder- system. This was in covenant to the conclusions of study [76] wherein excluding that the sensitive SCM used in that study was ultra-fine slag and RHA and the concrete studied was geopolymer- concrete.

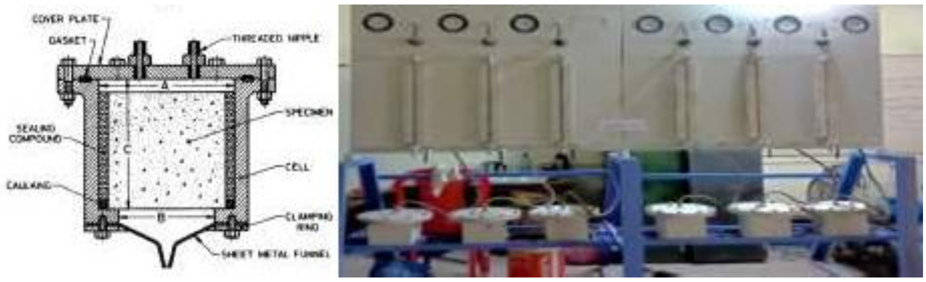
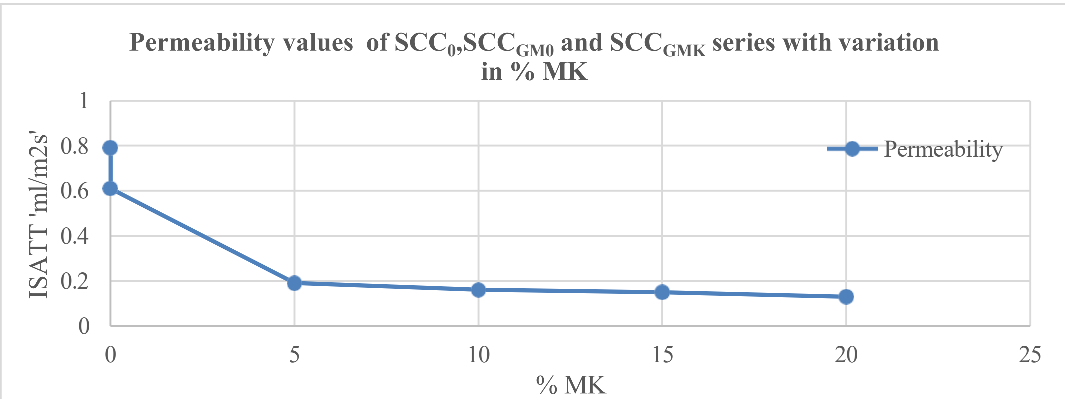


Fig.5.23 Permeability test arrangements as per IS 516(Part 2/Sec1):2018



Graph.5.14 Permeability values of SCC_0,SCC_{GM0} and SCC_{GMK} series with variation in % MK

5.5.3.4 Abrasion resistance of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

Testing arrangements of abrasion resistance of concrete ,as per Annex E-IS 15658 :2021, are shown in Fig.5.24. Test results of abrasion resistance of SCC mix carried on the specimens at 28-days presented in Table 5.16. It can be grasped from Table

5.16 that the abrasion resistance of control mix $SCC_{0.00}$ was 5960 mm^3per 5000 mm^2. It was observed that when part of OPC was replaced by 50.00% GGBFS i.e. for $SCC_{GM0.00}$, the permeability was decreased to 5840 mm^3per 5000 $mm^{2.}$ This decrease of abrasion resistance, of SCC_{GM0} mix as compared to SCC_0 mix, was due to the inclusion of moderately reactive GGBFS in to the cementitious system having higher fineness than the OPC, which though initially causes densification of microstructure of the concrete due to pore refinement [79] but requires sufficient $Ca(OH)_2$ for the secondary reactions of GGBFS for forming strength ensuing CSH gel [82]. It was also observed that when high reactive MK was included into the cementitious system and was added as part replacement of GGBFS by 5.00% to 10.00%, i.e. for the mix $SCC_{GM5.00}$ and $SCC_{GM10.00,}$ the abrasion resistance of $SCC_{GM5.00}$ and $SCC_{GM10.00}$ mix was increased slightly to 5870 mm^3per 5000 mm^2 and· 5990 mm^3per 5000 mm^2 respectively as compared to control mix $SCC_{GM0.00}$. This increase in abrasion resistance of SCC_{GM5} can be recognized due to the presence of high sensitive MK, in the cementitious system, causing quickening of hydration-reactions and there by resulting to the development of dense microstructure[87]and the same views is maintained from the findings of microstructure development as can perceived through the Photomicrographs at 1000X magnification at 16 hrs, 1day and 3 days time of SCC_{GM10} mix depicting the microstructure development at early ages as shown in Fig.5.21. Further it was observed that, in the same cementitious system, once %MK was further augmented from 15.00% to 20.00% i.e. for the mix $SCC_{GM15.00}$ and $SCC_{GM20.00,}$ there was again a minimal rise in the abrasion resistance of $SCC_{GM15.00}$ and $SCC_{GM20.00}$ to 6020 mm^3per 5000 mm^2, 6040 mm^3per 5000 mm^2 respectively. This increase in abrasion resistance coincides with the outcome of rise in strength of the respective $SCC_{GM15.00}$ and $SCC_{GM20.00}$ recipes as discussed above in 5.4.1 and 5.4.2. This minor rise of abrasion resistance designates the accomplishment of saturation level of %MK in the experimented binder-system. This was in covenant to the conclusions of study [92] excluding that the sensitive SCM used in that study was micro silica and the moderately reactive SCM used was lime-stone powder as partial substitution of OPC.

Fig.5.24 Abrasion Resistance Test Arrangements and Measurements

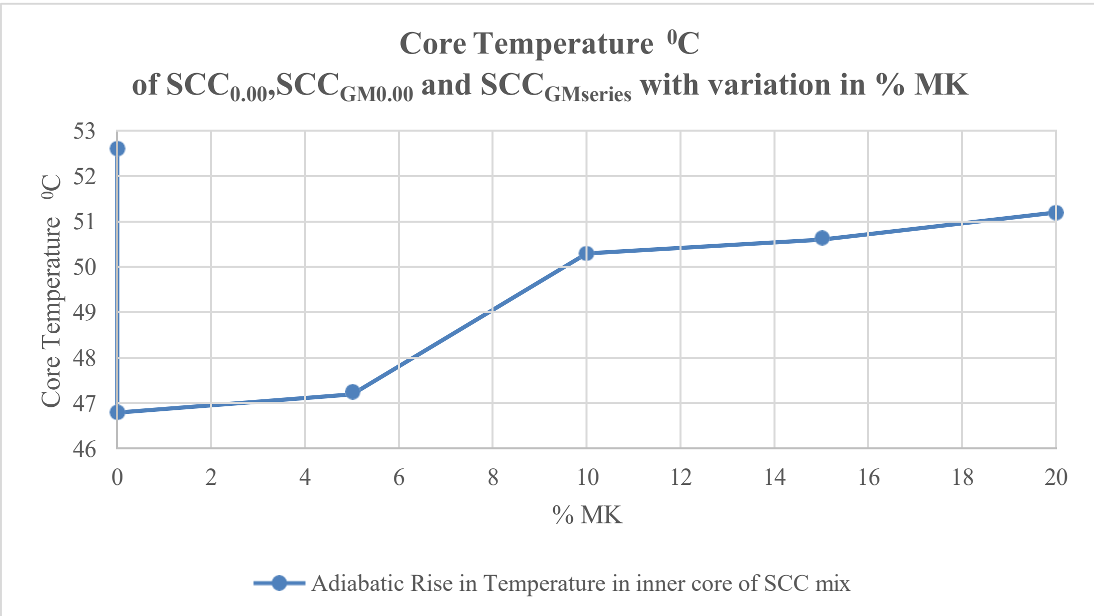
5.5.3.5 Adiabatic Rise in Temperature and Temperature Gradient (Difference in Temperature from Core to near surface) of SCC_0,SCC_{GM0} and SCC_{GMK} series

Adiabatic rise in temperature study was carried as per the provisions of IS 7816 and the test arrangements made was similar as discussed above under 5.3.4. The test arrangements were made as such that required to monitor the rise in temperature, maximum time required for attaining the temperature gain etc., which were the prime requirements to series of SCC mix with varied % GGBFS + % MK as part replacement of OPC. Variation of temperature was continuously recorded, after the addition of water to binder-system , from 30.00 minutes to 30.00 hrs. duration. The temperature-gradient, i.e. temperature difference between inner-core and near-surface of concrete, for the above experimented series SCC mix presented in Table 5.17 and Graph 5.15. It can be perceived from the Table 5.17 that, early age (1 day) temperature increase in inner core of $SCC_{0.00}$ was 52.60^0C whereas the same for $SCC_{GMK0.00}$ was 46.80^0C. When in subsequent mix as the % MK varied from 5.00% to 10.00%, the mix has resulted an increase in rise in temperature of inner core in the range 47.20^0C to 50.30^0C for all the periods i.e. from 20.00 hours to 30.00 hours. The temperature gradient observed at 25.80 hrs. for mix $SCC_{GMK10.00}$ was 19.10^0C whereas the least temperature gradient observed at 26.20 hrs. for SCC_{GMK5} was 15.40^0C. It can also be observed that there was marginal increase in temperature gradient beyond 10.00% of MK in $SCC_{GMK15.00}$ and $SCC_{GMK20.00}$ series of SCC mix. This is equally in covenant with the conclusion of the study [75] with the exception that micro silica was used as reactive SCM.MK's performance can be consigned to its chemical composition as it contains higher Al_2O_3 as can be seen from the chemical characterisation of MK as presented in Table 3.10 and material characterisations of MK as per the particle size distribution and XRD as presented in Fig. 3.11 and discussed in chapter 3 of this thesis. The higher CaO% in GGBFS in accumulation to the higher Al_2O_3% as present in MK, can be attributed to the quicker reactions causing the concerned SCC_{GMK10} mix to behave sustainable concrete as well as a fast setting mix. These results were also fairly matching with the consequence of the study[82] except that the high reactive SCM used was rice husk ash in that study.

Table 5.17

Adiabatic rise in Temperature of SCC_0,SCC_{GM0} and SCC_{GMK} series

SL No	Mix ID	GGBFS %	MK %	Maximum Rise in Temperature at core in SCC mix ⁰C	Time require to reach maximum core temperature 'Hrs'	Average Near Surface Temperature of SCC Mix ⁰C	Temperature Gradient ⁰C
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8) =(5)- (6)
1	$SCC_{0.00}$	0.00	0.00	52.6	29.1	31.1	21.5
2	$SCC_{GM0.00}$	50.00	0.00	46.8	28.9	31.6	15.2
3	$SCC_{GM5.00}$	45.00	5.00	47.2	26.2	31.8	15.4
4	$SCC_{GM10.00}$	40.00	10.00	50.3	25.8	31.2	19.1
5	$SCC_{GM15.00}$	35.00	15.00	50.6	24.1	31.4	19.2
6	$SCC_{GM20.00}$	30.00	20.00	51.2	22.1	31.6	19.6



Graph 5.15 Core Temperature⁰C of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

5.5.3.6 Resistance to penetration of SO_3^- Ion ingression

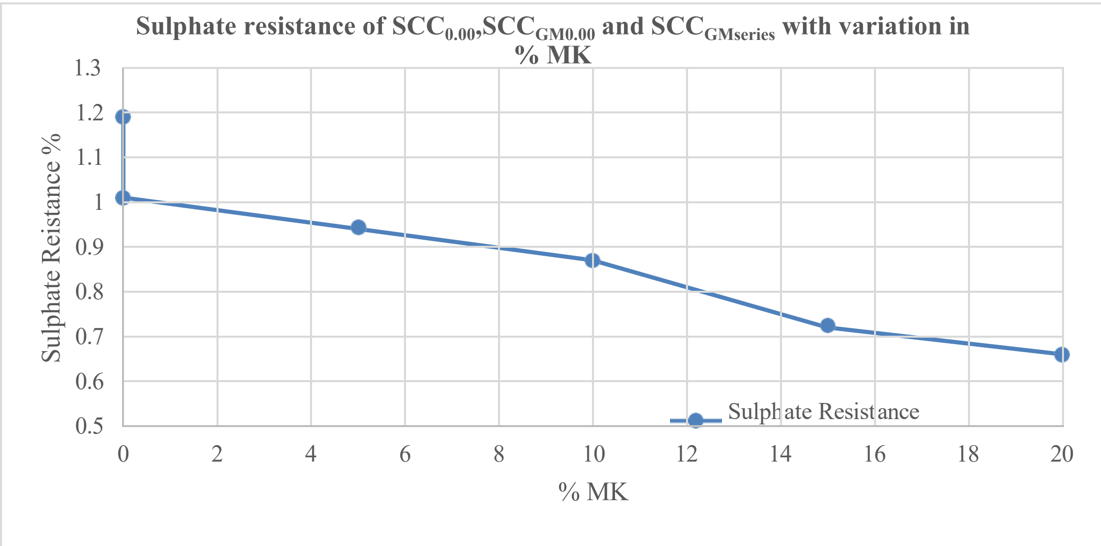
Sulphate Resistance test i.e. measure of ingression of SO_3^- ions in to the body of SCC was carried as per the ASTM C 1012 and was in similar to the procedure as explained in 5.5.3 . Resistance to penetration of SO_3^- Ion ingression results presented in Table 5.18 and Graph 5.16.

Table 5.18

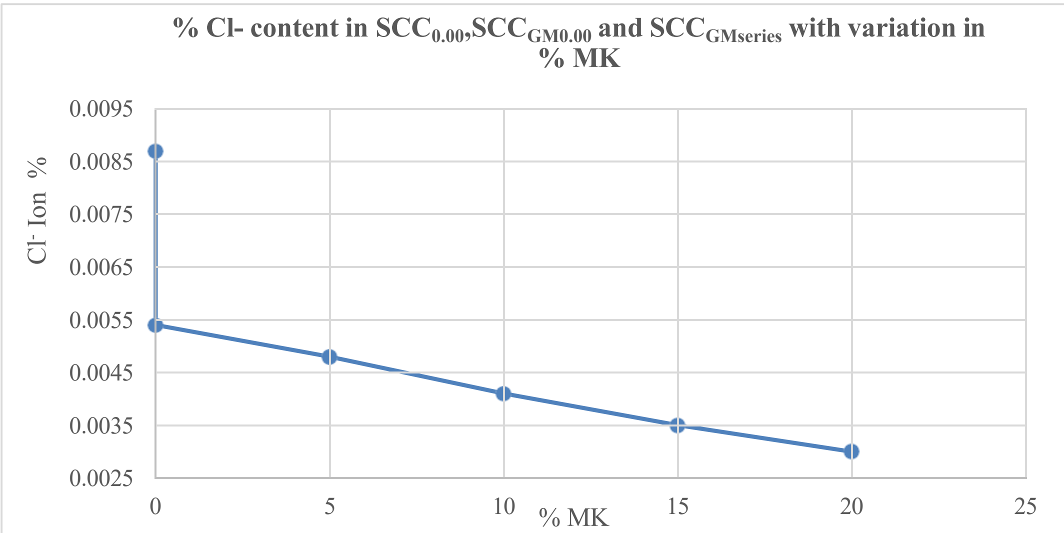
Resistance to SO_3^- Ion ingression and Cl^- Ion ingression in SCC mix

Sl.No	Mix ID	GGBFS %	MK %	Sulphate Resistance % Length @ 1d/28d Tested as per ASTM C 1012	%Chloride In cover region (40mm from surface) At 90days Carried as per ASTM C1543
(1)	(2)	(3)	(4)	(5)	(6)
1	$SCC_{0.00}$	0.00	0.00	1.19	0.0087
2	$SCC_{GM0.00}$	50.00	0.00	1.01	0.0054
3	$SCC_{GM5.00}$	45.00	5.00	0.94	0.0048
4	$SCC_{GM10.00}$	40.00	10.00	0.87	0.0041
5	$SCC_{GM15.00}$	35.00	15.00	0.72	0.0035
6	$SCC_{GM20.00}$	30.00	20.00	0.66	0.0030

As can be seen from the Table 5.17, that rise in the resistance to SO_3^- ion ingression perceived with the augmented % MK in the mix $SCC_{GMseries}$. At 1- day, the change in length of specimens, with reference the change in length of specimens at 28 days, immersed since from 1-day to 28-days in Na_2SO_4 ,was measured as the indirect indication of Sulphate resistance of respective specimen. For SCC_0 the sulphate ion ingression resistance was observed to be 1.19 % whereas when 50% of OPC was replaced with GGBFS, the resulting mix SCC_{GM0} has resulted an increase in sulphate resistance and it was 1.01%. When reactive MK was introduced, as a part replacement of GGBFS, into the cementitious system the sulphate resistance of resulting mix was further observed to be increased. In this present study the sulphate resistance was observed to be increased from 21.01 % to 45.54% as compared to sulphate ion ingression resistance of SCC_0. This is in line with the outcome of the study[55,57] where in only exception was that lime stone powder was used as SCM and rice husk ash was used as reactive SCM. The extreme replacement level of MK was perceived to be 10.00% for achieving increase in resistance to SO_3^- ion ingression. The similar vision was sustained from the conclusions of microstructure development as can perceived through the Photomicrographs at 1000X magnification at 16-Hours, 1-day and 3- days time of $SCC_{GM10.00}$ mix depicting the microstructure development at early ages as shown in Fig.5.21 supports this observation as it can be observed that with the % MK increase up to 10.00% , the densification of microstructure was effective for experimented SCC and beyond 10.00% of MK ,the excess quantity of MK will act as dormant material. .



Graph 5.16 Sulphate resistance of $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK



Graph 5.17 % Cl- content in $SCC_{0.00}$,$SCC_{GM0.00}$ and $SCC_{GMseries}$ with variation in % MK

5.5.3.7 Resistance to penetration of Cl^- Ion ingression in SCC mix

Chloride ion ingression resistance test i.e. measure of ingression of Cl^- ions into the body of concrete , was carried out as per the ASTM 1543 .This test was carried as per the procedure presented in 4.8.5 in chapter 4 of this thesis. Chloride ion ingression resistance test results are presented in Table 5.18and in Graph 5.17. It can be seen that for SCC_0 the %Cl^- ion present was 0.0087% in the concrete core specimens extracted from slab specimens, after subjecting to 3% NaCl solution ponding for 28 days. Whereas when 50% of OPC was replaced with GGBFS , the resulting mix SCC_{GM0} has resulted a decrease in %Cl^- ion present and it was 0.0054%. When reactive MK was introduced, as a part replacement of GGBFS, into the cementitious system ,the resulting mix ,after subjecting to the same ponding of NaCl solution as mentioned above, was further observed to exhibit less % of Cl^- ions content . In this present study the %Cl^- ion present was observed to be decreased from 44.83 % to 65.82% as compared to sulphate ion ingression resistance of SCC_0. This was in line with the outcome of the study[66] wherein only exception was that lime stone powder was used as SCM and rice husk ash was used as reactive SCM. In this current study, the maximum replacement level of MK was observed to be 10.00% for achieving increase in Chloride resistance. The identical views was retained from the conclusions of microstructure development as can perceived through the Photomicrographs at 1000X magnification at 16-Hours, 1-day and 3-days time of $SCC_{GM10.00}$ mix depicting the microstructure development at early ages as shown in Fig.5.21 , as it can be observed that with the % MK increase up to 10.00% , the densification of microstructure was effective for experimented SCC and beyond 10.00% of MK ,the excess quantity of MK will act as dormant material.

5.6 Observations drawn from the study on Influence of part replacement of OPC with GGBFS+MK on SCC characteristics

The succeeding deductions pinched from the investigated studies:

1. MK's incorporation in SCC as a high reactive SCM increases the water demand but the cohesiveness of the mix increases and $SCC_{GM10.00}$ i.e. mix resulting with OPC replacement level by MK as10.00% in combination with

GGBFS by 40.00%, observed to result satisfactory slump flow and V funnel flow time.

2. In terms of final setting time of SCC mix, there was continues decrease in final setting time with increase in %MK. Beyond 10.00% MK i.e. for the SCC mix $SCC_{GM10.00}$ onwards like $SCC_{GM15.00}$ and $SCC_{GM20.00}$ there was marginal decrease in final setting time in all the experimented SCC mix.

3. There was improvement of compressive strength of SCC mix with the increase of % MK. At 16-Hours the compressive strength of SCC mix containing 50.00% OPC,40.00%GGBFS and 10.00%MK attained 15.00N/mm^2. There was also a gradual increase in compressive strengths with the increase in %MK in SCC mix for various ages from 1-day to 90-days.

4. There was enhancement in split tensile strength of all the SCC mix with increased %MK.

5. In terms of durability of concrete the indirect indicators like ISAT, Permeability and Abrasion resistance of experimented SCC mix, it was observed that with the increase in % MK, the durability of concrete improved

6. High reactiveness of MK can be advantageously used for overcoming the slow setting and less early age strength related to high level replacement of low reactive SCMs like GGBFS in the concrete mix.

7. OPC Replacement level of MK by 10.00%, in association with 40.00% GGBFS can be conveniently used for developing early strength sustainable SCC concrete mix for fast track repairs/constructions and in precast building block manufacturing industries.

8. Further investigations are required to evaluate the OPC+GGBFS+MK cementitious system by integrating the compatible fibres in order to achieve superior tensile properties for advocating the same to use in fast track construction and repair works.

5.7 Effect of part replacement of OPC with GGBFS+MK in groupings with PP Fibre and AR Fibre on properties of SCC Mix

Based on the various results of tests carried on several SCC mix as experimented to evaluate the impact of partial substitution of OPC by groupings of varied %GGBFS+%MK , on the characteristics of SCC in fresh-state as discussed above under 5.3, in hardened state as discussed above under 5.4 , the durability studies of the same as analysed under 5.5 and the summary of the results as listed and briefed under 5.6 ,it was observed that for the experimented mix the combinations of OPC by 50%, GGBFS by 40% and MK by 10% (forming a total binding material groupings as 540 kgs/m^3) at w/cm ratio of 0.35 was resulted in 15.94 N/mm^2 compressive strength and 0.73 N/mm^2tensile splitting strength at 16-Hours. Hence, for further improving the early-age compressive strength and tensile properties of above SCC mix auxiliary experiments were carried out on the above combinations of binding materials i.e. OPC by 50.00%, GGBFS by 40.00% and MK by 10.00% by increasing the total cementitious material content by 10.00 Kgs/m^3 and thus keeping the total binder material content as 550.00 Kgs/m^3 and the ration of 'w/cm' was brought down to 0.33,aggregate contents accordingly adjusted as CA10mm as 740.00 Kgs/m^3 ,FA as 900.00 Kgs/m^3 and groupings with the PP Fibre and AR Fibre by a total % of 1.00% by volume of the SCC. Experimented mix proportion of SCC mix is presented in Table 5.18. Through the literature survey as discussed in Chapter 2, PP Fibres and AR Fibres were observed to be the potential synthetic fibres for developing sufficient tensile strength of SCC. It was also observed through the literature survey that the fibres effectiveness can be exploited when the fibres were mixed in hybrid combinations either fibres of different lengths of same material or fibres of different materials [125]. So, auxiliary experiments on the above arrived cementitious materials were carried using the combinations of PP Fibre and AR Fibre so that their combined proportion by volume of SCC will be 1.00%. It was also learnt through literature survey that inclusion of fibres in to the SCC system will reduce the slump flow , V funnel flow etc., rheology characteristics .Thus in order to compensate this loss in rheological properties of SCC mix ,upon inclusion of fibres, some trials for arriving at a suitable proportion of PCE based chemical admixture was essential and the same was carried in the subsequent trials and is discussed under 5.7.1 onwards.

5.7.1 Experiment design of Hybrid-Fibre Reinforced Self Compacting Concrete(Hy_{FSCC})

Hy_{FSCC} recipes were prepared keeping the total binder material content as 550.00 Kgs/m^3 and the ration of 'w/cm' as 0.33, adjusted aggregate contents as CA10mm as 740.00 Kgs/m^3, FA as 900.00 Kgs/m^3 and fibre groups with varied % PP-Fibre and

AR-Fibre to form a total hybrid combination of 1.00% by volume of the SCC. The details of mix and evaluation of the same presented hereunder.

5.7.2. Concrete mixing, samples casting and samples curing

$SCC_{control}$, $Hy_{FSCC\text{-}Type\text{-}1}$ and $Hy_{FSCC\text{-}Type\text{-}2}$ concrete recipe presented in Table 5.19. $SCC_{control}$ and Hy_{FSCC} preparation was as per the Fig.4.9 and Fig.4.10 as presented in Chapter 4.

Table 5.19

$SCC_{control}$, $Hy_{FSCC\text{-}Type\text{-}1}$ and $Hy_{FSCC\text{-}Type\text{-}2}$ concrete mix proportion

Mix Code	Proportion of Binder Material (BM) (% By weight)			Groupings of fibre by volumetric proportion of concrete (%)		Concrete making materials (Kg/m^3)				
	OPC 53 Gr (%)	GGBFS (%)	MK (%)	PP-F (%)	AR-F (%)	Total BM	CA 10mm	Sand	PCE Admixture	Free Water
$SCC_{Control}$	50.00	40.00	10.00	0.00	0.00	550.00	740.00	900.00	6.60	181.50
$Hy_{FSCCType1\text{-}A}$	50.00	40.00	10.00	1.00	0.00	550.00	740.00	900.00	6.60	181.50
$Hy_{FSCCType1\text{-}B}$	50.00	40.00	10.00	0.70	0.30	550.00	740.00	900.00	6.60	181.50
$Hy_{FSCCType1\text{-}C}$	50.00	40.00	10.00	0.60	0.40	550.00	740.00	900.00	6.60	181.50
$Hy_{FSCCType1\text{-}D}$	50.00	40.00	10.00	0.50	0.50	550.00	740.00	900.00	6.60	181.50
$Hy_{FSCCType2\text{-}A}$	50.00	40.00	10.00	0.00	1.00	550.00	740.00	900.00	6.60	181.50
$Hy_{FSCCType2\text{-}B}$	50.00	40.00	10.00	0.30	0.70	550.00	740.00	900.00	6.60	181.50
$HyF_{SCCType2\text{-}C}$	50.00	40.00	10.00	0.40	0.60	550.00	740.00	900.00	6.60	181.50

5.8 Test results of part replacement of OPC with GGBFS+MK in grouping with PP Fibre and AR Fibre on properties of $SCC_{control}$, $Hy_{FSCC\text{-}Type\text{-}1}$ and $Hy_{FSCC\text{-}Type\text{-}2}$ concrete

5.8.1 Analysis of results on Fresh-state properties

In the laboratory trials, the situation stayed confirmed that a 50.00% OPC + 40.00% GGBFS + 10.00% MK mixture was suitable for PCE chemical admixtures with 1.00% cementitious material, resulting in a slump flow of 590mm and a V funnel flow of 23.4 seconds. When admixed with PP-F + AR-F fibres in hybrid combinations (1.00%) by volume fraction, the slump flow was observed to be reduced, falling in the range of 430mm - 460mm. This decrease in slump flow was consistent with the findings of the study[126] due to the presence of discrete fibres impeding the flow properties of the mix[129]. In order to reach a Slump Flow Target of SF1 Category, ranging from 550mm to 650mm, PCE Chemical Admixture Dosage Trials were conducted with a PCE content increase of 1.00%-1.40%, increasing by 0.05% in each successive experiment. The results of these trials indicated that the $Hy_{FSCC\ Type\ 1}$ and Type 2 mix, at a PCE Content of 1.20%-1.400%, met both the Slump Flow Target and the V funnel Flow Time (9-25 seconds) of 640mm for $SCC_{Control\ Mix}$. This is consistent with other research studies which have shown that more PCE is used in a mix with less W/BM [132]. This was in line with the results of other research studies [130, 134]. The higher the slumping of the flow, the more concrete will be able to be reache and fill at each formwork location. The addition of PCE increases the cementitious system's cohesion and flow, resulting in a decrease in rheology constrictions. PCE adsorbs on the surface roots of the cementitious particle, resulting in de-flocculation and parting-off characteristics until the period of equilibrium of the PCE-based chemical admixture, which is dependent on the proportion, fineness, and w/cm of the cementitious materials and the chemical nature, polymer chain lengths, and characteristics of the PCE admixture. This results in a greater comparative amount of water being available due to the lubrication of the cementitious system, resulting in increased fluidity in the matrix. The fresh state properties of $SCC_{Control}$, as well as the various $Hy_{FSCC\text{-}Type\ 1}$ and $Hy_{FSCC\text{-}Type2}$ mixes, will be discussed in the following paragraphs.

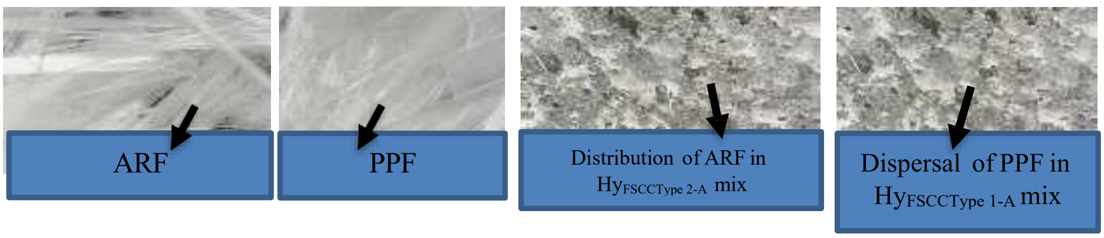
5.8.2 Slump-Flow of $SCC_{Control}$,$Hy_{FSCCType1}$ and $Hy_{FSCCType2}$ recipe

The slump-flow of the $SCC_{Control}$ and the different Hy_{FSCC} recipe tested in this study, the difference in slump-flow with reference to %PP-F, %AR-F and some combinations of %PP-F + % AR-F, shown in Table 5.20, Graph 5.18. As per the data of Table 5.20, the slump flow rate of the $SCC_{Control}$ recipe was higher (i.e. 640 mm) than the slump-flow of the $Hy_{FSCC\text{-}Type\ 1}$ (with PP-F percentage varying from 0 .00% to 1.00%) and $Hy_{FSCC\text{-}Type2}$ mixed (with AR-F varying from 0.00% to 1.00%). The slump-flow of $Hy_{FSCC\text{-}Type\ 1}$ recipe reduced from 6.25% to 12.50% when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, the same was decreased from 9.38% to 12.50% as AR-F% changed from 0.00% to 1.00%. These results are objectively consistent with the consequences of the study on the hybrid combination of synthetic fibres and steel fibres on the slump-flow properties of concrete for a study [136]. In the present test, it was observed that the minimum slump-flow was 560 mm for $Hy_{FSCCType\ 2\text{-}C}$ recipe (i.e. at 0.50% PP-F + 0.50% AR-F) and maximum reduction of same was 600 mm for $Hy_{FSCCType\ 1\text{-}A}$ recipe (i.e. at 1.00% PP-F +0.00%AR-F). These identical outcome was noted in the consequences of the study[135] in which a maximum slump-flow decrease of 13.00% ,compared to the control recipe, was observed when polyolefin fibres were incorporated into the SCC. The modification amid the present outcome of study and the consequences of [125] was practical due to the use of adapted fibre size, w/bm and PCE in this study. The slump-flow of the $Hy_{FSCCType\ 2\text{-}A}$ mixture (i.e. 0.00% PP-F + 1.00% AR-F) was 580 mm.

Table 5.20

Fresh state properties of Slump-Flow of $SCC_{Control}$, Hy_{FSCC}-Type1 and $Hy_{FSCC\ \text{-}Type2}$

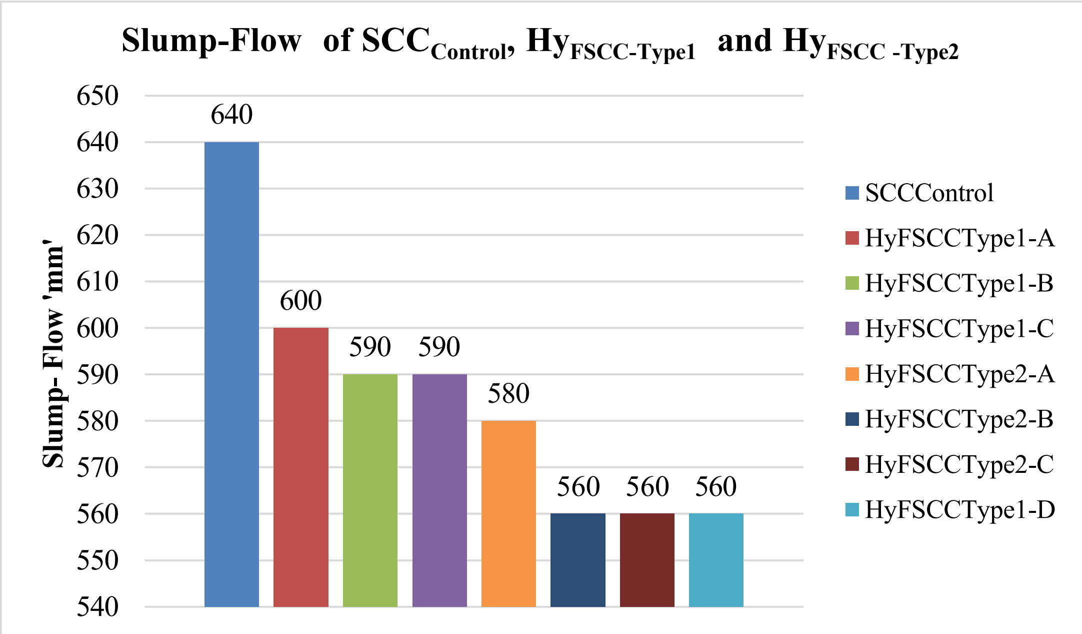
Mix Code	PP-F	AR-F	Slump-flow	'V'funnel flow time	'L' box flow ratio	Segregation Resistance	Time for Initial Set 'IST'	Time for Final Set 'FST'
	(%)	(%)	'mm'	'seconds'	h_2/h_1	(%)	Minutes	Minutes
$SCC_{Control}$	0.00	0.00	640	12	0.94	15.00	480	580
$Hy_{FSCCType1\text{-}A}$	1.00	0.00	600	19	0.86	18.00	440	510
$Hy_{FSCCType1\text{-}B}$	0.70	0.30	590	17	0.85	16.00	430	490
$Hy_{FSCCType1\text{-}C}$	0.60	0.40	590	17	0.87	16.00	430	490
$Hy_{FSCCType1\text{-}D}$	0.50	0.50	560	21	0.83	19.00	400	470
$Hy_{FSCCType2\text{-}A}$	0.00	1.00	580	20	0.82	18.00	460	540
$Hy_{FSCCType2\text{-}B}$	0.30	0.70	560	21	0.84	16.00	450	520
$Hy_{FSCCType2\text{-}C}$	0.40	0.60	560	21	0.82	16.00	440	520
$Hy_{FSCCType2\text{-}D}$	0.50	0.50	550	24	0.80	17.00	410	490



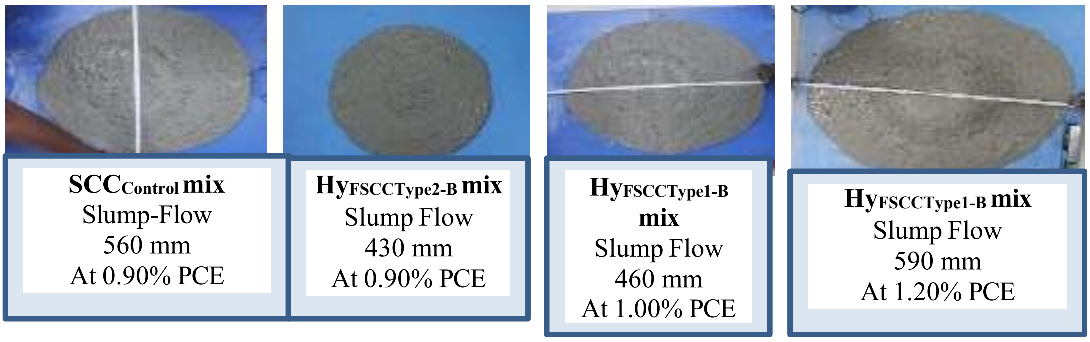
(a) (b) (c) (d)

Fig.5.25 Photo micro-graphs – magnification level 1000X

The apparent cause for additional slump-flow in case of simply PP-F united SCC recipe may be owing to improved incorporation into the SCC recipe by PP-F than AR-F, as observed concluded the photo micro graph (at 1000X magnification) presented in Fig.5.25 of both the mix at above % integration.Fig.5.26 represents the slump-flow of various SCC recipes investigated.



Graph 5.18 Slump-Flow of SCC$_{Control}$, HyFSCC-Type-1 and Hy$_{FSCC\ -Type2}$

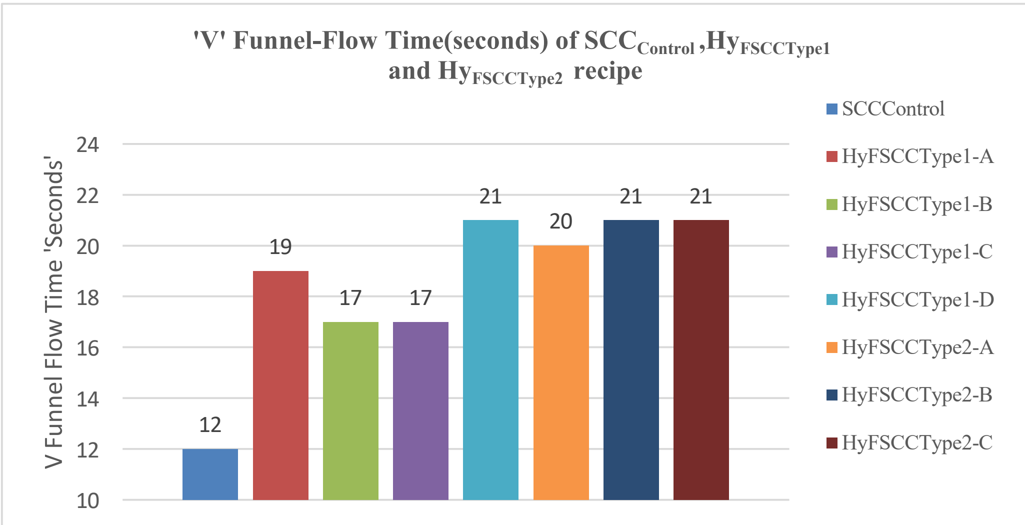


(a) (b) (c) (d)

Fig.5.26 Slump flow of SCC$_{Control}$,HyFSCC$_{Type1}$ and HyFSCC$_{Type2}$ mix

5.8.3 'V' funnel- flow time of SCC$_{Control}$,Hy$_{FSCCType1}$ and Hy$_{FSCCType2}$ recipe

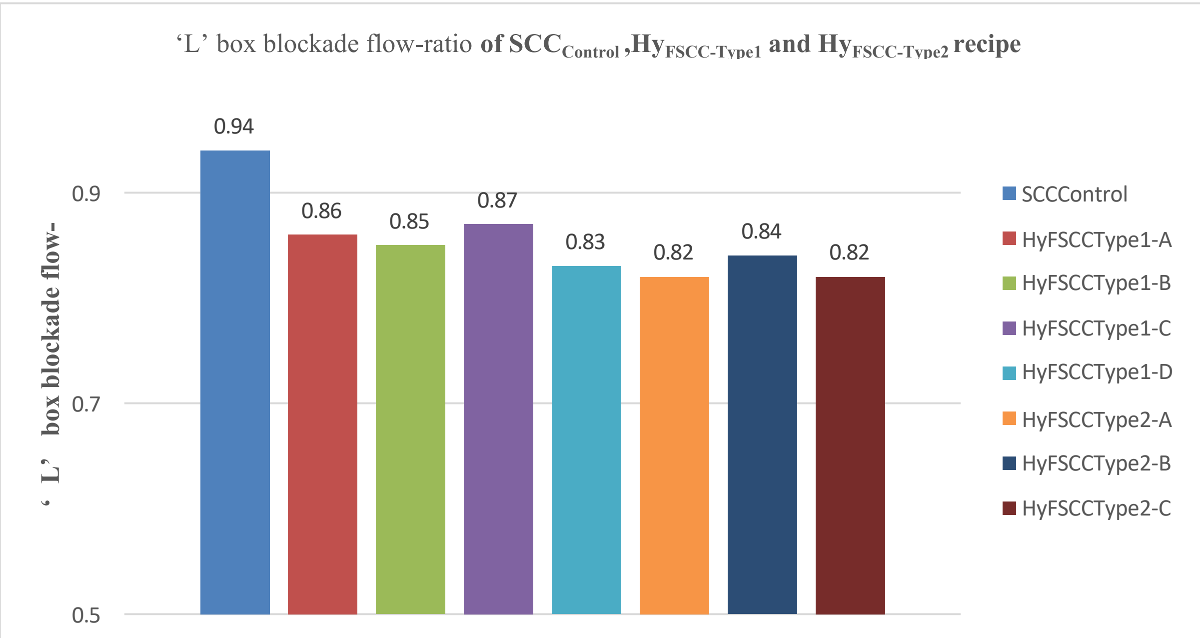
'V' funnel-flow time of SCC$_{Control}$ and various Hy$_{FSCC}$ recipes investigated in this study, differences in 'V' funnel-flow time with mention to % of PP-F, %AR-F and some combinations of %PP-F +%AR-F, is shown in Table 5.20, Graph 5.19. Accordingly, 'V' funnel-flow time of SCC$_{Control}$ mix was noticed to be 12 seconds. This consequence brings into line with the effect of the study [126] wherein it was showcased that by means of the optimum quantity of 10.00% MK in concrete, enough viscidness was attained for the SCC mix and thus boosting the mix to flow quickly through the narrowing spaces of 'V' funnel. In this contemporary study, it was pragmatic that, when connected to 'V' funnel-flow time of SCC$_{Control}$ recipe, the flow time of $Hy_{FSCC-Type\ 1}$ mix (with %PP-F varied from 0.00% to 1.00%) and $Hy_{FSCC-Type\ 2}$ mix (with AR-F varied from 0.00% to 1.00%) improved. This rise in flow time was due to the existence of PP-F and AR-F fibres in various groupings in the investigated SCC mix. The effects attained for 'V' funnel-flow time test, in this study, was characteristically allied with effect established by the study[129] but the merely variation was that, in that study fibres of 6mm length were used and outside of 0.50% volume fraction of polyolefin fibres in SCC .There was significant rise in the obstruction and hence caused into higher 'V' funnel-flow time of recipe to pass through the 'V' funnel. In this existing study, the $Hy_{FSCCType\ 1}$ recipe instigated in higher 'V' funnel-flow time from 58.32% to 75.00% and the 'V' funnel-flow time for recipe of $Hy_{FSCC-Type\ 2}$ was raised from 66.66% to 75.10% .The minimum 'V' funnel-flow time perceived was 17 seconds for $Hy_{FSCC-Type\ 1-B}$ and $Hy_{FSCC-Type\ 1-C}$. Maximum 'V' funnel-flow time observed was 21 seconds for $Hy_{FSCC-Type\ 2-B}$ and $Hy_{FSCC-Type\ 2-C}$.



Graph 5.19 'V' Funnel flow time of $SCC_{Control}$,$Hy_{FSCCType1}$ and $Hy_{FSCCType2}$ mix

5.8.4 'L' box blockade flow-ratio of $SCC_{Control}$,$HyF_{SCC-Type1}$ and $HyF_{SCC-Type2}$ recipe

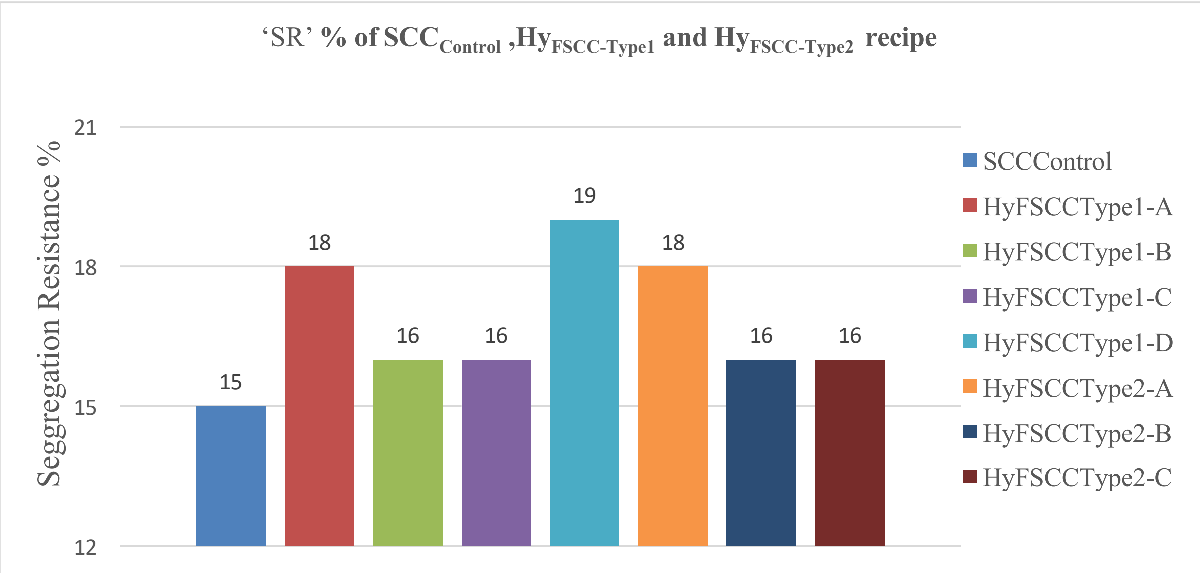
'L' box blockade flow-ratio of $SCC_{Control}$ recipe and various Hy_{FSCC} recipe investigated in this study, deviations in 'L' box blockade flow-ratio with mention to % of PP-F,%AR-F and several groupings of %PP-F +%AR-F, is presented in Graph 5.20. 'L' box blockade flow-ratio of $SCC_{Control}$ mix was 0.94. When linked to 'L' box blockade flow-ratio of $SCC_{Control}$ mix , the 'L' box blockade flow-ratio of $Hy_{FSCC-Type\ 1}$ recipe (with %PP-F varied from 0.00% to 1.00%) and $HyF_{SCC-Type2}$ mix (with AR-F varied from 0.00% to 1.00%) was condensed. This decrease in the 'L' box blockade flow-ratio was due to the existence of PP-F and AR-F fibres in different groupings in the investigated mix. These results continued to be equitably reassuring with the outcome of study[52] wherein the small 'L' box blockade flow-ratio was observed for the fibre united SCC mix, was due the termination forms of the incorporated fibre, leading to small curbs to the fresh concrete recipe against movement[56,78,65-68,88].In this present study, it was observed that ,compared to 'L' box blockade flow-ratio of $SCC_{Control}$ mix, 'L' box blockade flow-ratio of HyFSCC-Type-1 reduced from 8.50% to 11.69% and the 'L' box blockade flow-ratio for mix of HyFSCC-Type-2was reduced from 10.63% to 12.76% .The minimum 'L' box blockade flow-ratio was 0.82 for $Hy_{FSCC-Type2-A}$ and $Hy_{FSCC-Type2-C}$. Maximum 'L' box blockade flow-ratio was 0.87 for $Hy_{FSCCType\ 1-C}$.



Graph 5.20 'L' box blockade flow-ratio of $SCC_{Control}$,$Hy_{FSCC-Type-1}$ and $Hy_{FSCC-Type-2}$ recipe

5.8.5 Segregation Resistance(SR) % of $SCC_{Control}$,$HyF_{SCC-Type1}$ and $HyF_{SCC-Type2}$ recipe

'SR' (%) of $SCC_{Control}$ recipe and different Hy_{FSCC} recipe tried in this study and deviations in 'SR' with mention to % PP-F, %AR-F and some combinations of %PP-F +%AR-F is presented in Graph 5.21. 'SR' of $SCC_{Control}$ recipe was 15.00%. When linked to 'SR' of $SCC_{Control}$ recipe, the 'SR' of $Hy_{FSCC-Type\ 1}$ recipe (with %PP-F variations from 0.00% to 1.00%) and $Hy_{FSCC-Type\ 2}$ mix (with AR-F varied from 0.00% to 1.00%) raised. This rise in 'SR' was due to the existence of PP-F and AR-F fibres in several groupings in the tested recipes. These results were in contrast to the results of the outcome [129] wherein it was cited that for attaining the same SR, as of control mix, the adding of steel fibres of one type not at all affected the requirement of water for the recipe to maintain SCC characteristics. However, adding of other smaller diameters and dimensions of steel fibres in to the mix, the assertion of water requirement was reduced for fluidity the recipe. The contrast of present study result with the results of study [131] may be due to the causes of sensible nature of AR-F and PP-F fibres which necessitated extra water than the steel fibres for sustaining the same flow behaviour in the recipe. In this present study, it was observed that when compared to 'SR' of $SCC_{Control}$ mix, 'SR' of $Hy_{FSCC-Type\ 1}$ raised from 20.00% to 26.65% and the 'SR' for mix of $Hy_{FSCC-Type\ 2}$ was raised from 6.67% to 20.04%. The minimum 'SR' was 16.00% for $Hy_{FSCC-Type2-B}$ and $Hy_{FSCC-Type2-C}$. Maximum 'SR' was 19.00% for $_{HyFSCCType\ 1-D}$.

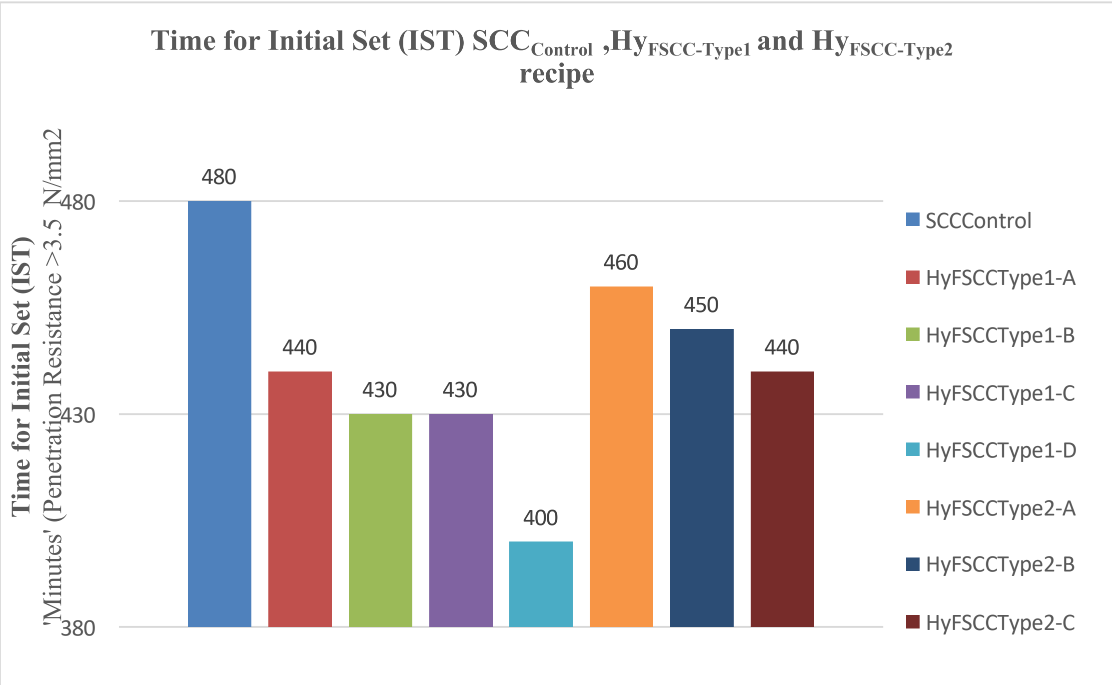


Graph 5.21 'SR' % of $SCC_{Control}$,$HyF_{SCC-Type1}$ and $HyF_{SCC-Type2}$ recipe

5.8.6 Time for initial set (IST) of $SCC_{Control}$,$Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipe

'IST' of $SCC_{Control}$ recipe and several Hy_{FSCC} recipes investigated in this study and deviations in 'IST' with mention to % PP-F, %AR-F and some groupings of %PP-F +%AR-F is presented in Graph 5.22. The 'IST' of $SCC_{Control}$ mix was 480 minutes.

When matched to the 'IST' of $SCC_{Control}$ recipe, the IST of $Hy_{FSCC-Type\ 1}$ recipe (with %PP-F varied from 0.00% to 1.00%) and $Hy_{FSCC-Type\ 2}$ recipe (with AR-F varied from 0.00% to 1.00%) shortened. This shortening in the 'IST' was due to the to the existence of PP-F and AR-F fibres in many groupings in the formed recipes moreover the causes of fast-reactions of MK owing to its fineness and higher quantity of Al_2O_3. These results were in rational agreement with the result of the study[128]. In this present study, it was perceived that when equalled to $SCC_{Control}$ recipe, the 'IST' of the ensued recipes of $Hy_{FSCC-Type\ 1}$ decreased from 8.72% to 16.66% and the 'IST' for recipe for $Hy_{FSCC\ -Type\ 2}$ was shrunk from 4.16% to 8.32% .The minimum 'IST' noticed was 400 minutes for $Hy_{FSCC-Type1-D}$. Maximum 'IST' as noticed was 460 minutes for $Hy_{FSCC-Type\ 2-A}$.

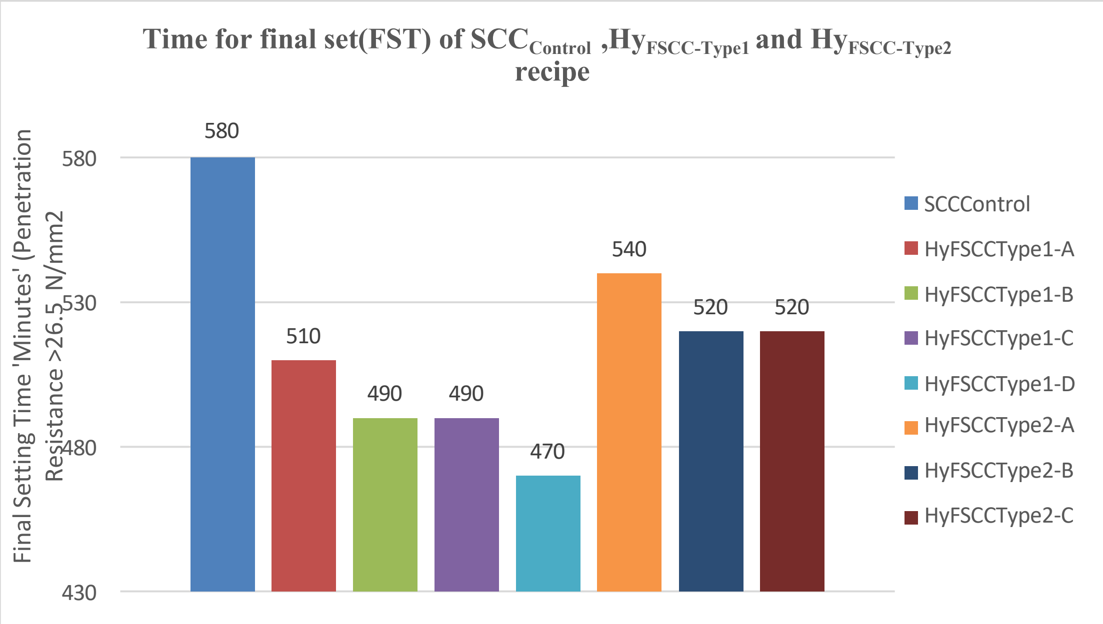


Graph 5.22 Time for Initial Set (IST) of $SCC_{Control}$,$Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipe

5.8.7 Time for final set(FST) of $SCC_{Control}$,$Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipe

The 'FST' of $SCC_{Control}$ recipe and many Hy_{FSCC} mix as experimented in this study and the deviations in the observed 'FST' with mention to % of PP-F, %AR-F and some groupings of PP-F +AR-F is presented in Graph 5.23. It can be perceived the 'FST' of $SCC_{Control}$ mix was 580 minutes. When related to the 'FST' of $SCC_{Control}$ mix, the 'FST' of $Hy_{FSCC-Type\ 1}$ recipe (with %PP-F varied from 0.00% to 1.00%) and

$Hy_{FSCC-Type\ 2}$ recipe (with AR-F varied from 0.00% to 1.00%) shortened. This shortening in the 'FST' was owed to the prevalence of PP-F and AR-F fibres in different groupings in the recipes further to the causes of fast-reactions of MK due to its higher specific surface area and higher quantity of Al_2O_3[66,69]. In this present study , it was witnessed that when compared to the 'FST' of $SCC_{Control}$ mix ,the 'FST' of $Hy_{FSCC-Type\ 1}$ reduced from 12.06 to 18.96% and the 'FST' for recipe of $Hy_{FSCC-Type\ 2}$ was decreased from 6.30% to 10.32% .The minimum 'FST' noticed was 470 minutes for $Hy_{FSCCType1-D}$ and the maximum FST observed was 540 minutes for HyFSCC-Type2-A.



Graph 5.23 Time for final set(FST) of $SCC_{Control}$,$Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipe

5.9 Hardened-state properties of $SCC_{Control}$,$Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipes

5.9.1 Compressive strength test of $SCC_{Control}$,$Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipes $SCC_{Control}$ recipe and some Hy_{FSCC} recipes investigated in this study were tested for strength at various ages like 16-hours,1-day,3-days,7-days,28-days, 56-days and 90-days.The deviations in strength of the $SCC_{Control}$ recipe and different Hy_{FSCC} recipes, with age and with mention to % PP-F, %AR-F and some combinations of %PP-F +%AR-F is presented in Table 5.21. Also, the compressive force on the specimens was stopped on observing the presence of the preliminary reasonable hairline crack on the surface of the specimen. It can be perceived from the data of

Table 5.21 that ,at 1- day the compressive strength of SCC$_{Control}$ mix was 24.10 N/mm^2. When linked to compressive strength, for all the ages of test, of SCC$_{Control}$ recipe , the compressive strengths of Hy$_{FSCC-Type\ 1}$ recipe (with %PP-F varied from 0.00% to 1.00%) and Hy$_{FSCC-Type\ 2}$ recipe (with AR-F varied from 0.00% to 1.00%) increased. The 1-day compressive strength of the caused recipe of HyF$_{SCC-Type\ 1}$ raised from 6.21% to 10.78% and the1-day compressive strength of Hy$_{FSCC-\ Type\ 2}$ recipe was raised from 10.79% to 12.02%. The 1-day minimum compressive strength was 25.60 N/mm^2 for Hy$_{FSCCType1-A}$ and the maximum was 27.00 N/mm^2 for Hy$_{FSCCType2-C}$. All the investigated recipes of HyFSCC-Type-1 and Hy$_{FSCC-\ Type2}$ have resulted the 1-day compressive strength more than 25.00 N/mm^2 as well as the target average strength > 58.25 N/mm^2 at 28 days. Compressive strength of all the recipe were progressively perceived to be improved from 16-hrs to 90-days. The compressive strength increase, of all the recipes with age, was faster during the ages of 16-hrs to 3-days and later on the advance in compressive strength was gentler for the ages of 7-days to 90-days. This was since the existence of MK in the recipe which reacted swiftly through the hydration-reactions and also due to its chemical nature having higher quantity of Al_2O_3, greater specific surface area and fine sized particles present [59,65]. Hy$_{FSCCType1-D}$ i.e. recipe comprising 0.50%PP-F +0.50%AR-F displayed rational recipe showcased steady increase of compressive strength from 16-hrs to 90-days. The failure forms of the specimens were perceived to be reasonable and the same is presented in Fig.5.27.In terms of MoE at 28-days the same trend of steady increase , as was perceived in compressive-strength results, for the SCC recipes of Hy$_{FSCC-Type-1}$ and Hy$_{FSCC-Type-2}$ observed.

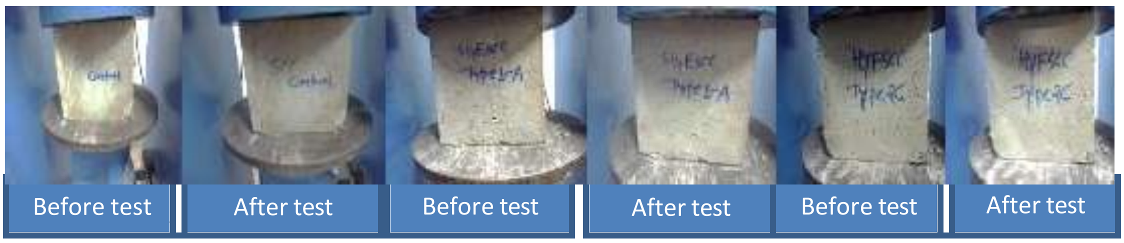


Fig.5.27 Compressive strength test of SCC$_{Control}$,Hy$_{FSCC-Type1}$ and Hy$_{FSCC-Type2}$ recipes

Table 5.21
Compressive Strength of $SCC_{Control}$,$Hy_{FSCC-Type-1}$ and $Hy_{FSCC-Type-2}$mix

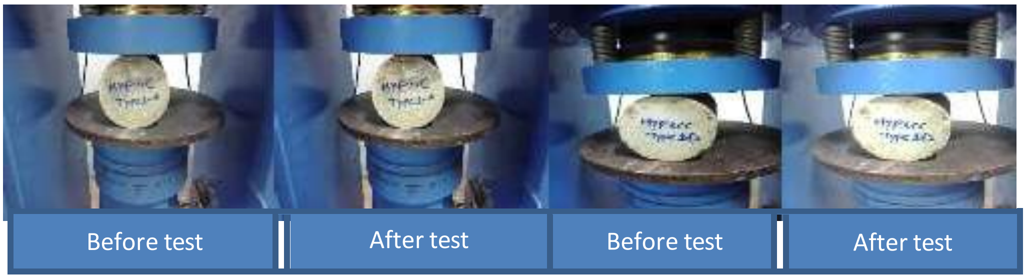
Mix code	Compressive Strength(N/mm^2)							MoE(Ec) 10^3 N/mm^2
	16-Hrs	1-Day	3-Days	7-Days	28-Days	56-Days	90-Days	28- Days
$SCC_{Control}$	19.20	24.10	33.20	54.80	58.70	59.60	59.69	37.50
$Hy_{FSCCType1-A}$	22.40	25.60	36.10	56.20	66.20	70.20	70.26	34.10
$Hy_{FSCCType1-B}$	23.60	26.20	38.20	56.80	66.90	70.60	70.64	34.60
$Hy_{FSCCType1-C}$	24.10	26.40	38.40	60.20	67.50	70.90	70.92	35.20
$Hy_{FSCCType1-D}$	24.40	26.70	39.40	60.90	67.90	71.40	71.47	35.30
$Hy_{FSCCType2-A}$	24.80	26.70	39.60	58.60	68.20	71.80	71.86	33.80
$Hy_{FSCCType2-B}$	25.80	27.10	40.40	59.20	68.90	72.60	72.64	34.50
$Hy_{FSCCType2-C}$	26.10	27.00	41.10	61.10	69.40	72.80	72.86	34.90

5.9.2 Tensile Splitting Strength(TSS) of $SCC_{Control}$,$Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipes

$SCC_{Control}$ recipe and different Hy_{FSCC} recipe investigated in this study were confirmed for TSS at various ages like 16-hrs, 1-day,3-days ,7-days ,28-days, 56-days and 90-days. Deviations in TSS of the $SCC_{Control}$ recipe and different Hy_{FSCC} recipes with age, with mention to % of PP-F, %AR-F and some groupings of %PP-F +%AR-F is presented in Table 5.22. Fig.5.28 represents the TSS test of HyFSCC-Type1 and HyFSCC-Type2 recipes.

Table 5.22
Tensile Splitting Strength(TSS) of $SCC_{Control}$,$Hy_{FSCC-Type-1}$ and $Hy_{FSCC-Type-2}$recipe

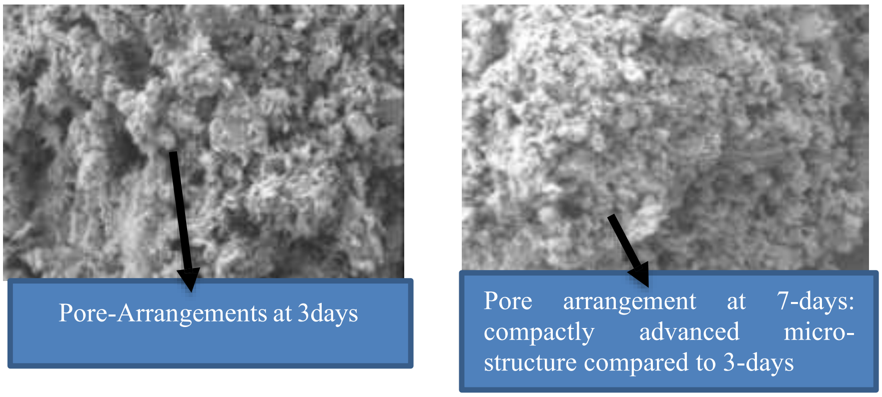
Mix ID	Split Tensile Strength(SPS) (N/mm^2)						
	16-Hrs	1-Day	3-Days	7 -Days	28 -Days	56-Days	90-Days
$SCC_{Control}$	1.60	1.80	1.91	2.17	5.22	5.37	5.39
$Hy_{FSCCType1-A}$	1.95	2.10	2.18	2.42	5.38	5.41	5.44
$Hy_{FSCCType1-B}$	2.09	2.30	2.42	2.44	5.41	5.44	5.47
$Hy_{FSCCType1-C}$	2.12	2.30	2.44	2.47	5.43	5.44	5.49
$Hy_{FSCCType1-D}$	2.21	2.40	2.47	2.51	5.46	5.48	5.52
$Hy_{FSCCType2-A}$	2.11	2.30	2.42	2.54	5.46	5.72	5.78
$Hy_{FSCCType2-B}$	2.07	2.20	2.43	2.56	5.44	5.68	5.72
$Hy_{FSCCType2-C}$	2.04	2.20	2.46	2.56	5.42	5.69	5.75



(a) (b) (c) (d)

Fig.5.28 TSS test of $Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipes

It can be perceived from the data of Table 5.22 that ,at 1 day, the TSS of $SCC_{Control}$ recipe was 1.80 N/mm^2. When related to TSS of $SCC_{Control}$ recipe, the TSS of $Hy_{FSCC\ Type\ 1}$ mix (with %PP-F varied from 0.00% to 1.00%) and $Hy_{FSCC-Type\ 2}$ mix (with AR-F varied from 0.00% to 1.00%) developed for all the ages of test. The TSS of $Hy_{FSCC\ Type\ 1}$ improved from 16.66% to 33.32% and the TSS for $Hy_{FSCC-Type\ 2}$ recipe was improved from 22.21% to 27.76%. This was since the existence of AR-F and PP-F fibres in different hybrid groupings. The 1-day minimum TSS was 2.10 N/mm^2 for $Hy_{FSCCType1-A}$. For $Hy_{FSCCType2-D}$, the TSS was 2.40N/mm^2 and it was perceived to be the maximum amongst all the experimented recipes. All the recipes of $Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$were beyond the targeted 1-day TSS of 2.00 N/mm^2. The failure formations of the specimens verified for TSS was seeming to be adequate and the same is offered in Fig.5.33. The TSS of all the recipes were increasingly perceived to be improved from 16-hrs to 90-days. The gain in TSS of all the tried recipes was faster during the ages of 16-hrs to 3-days and later on for the ages of 7-days to 90-days, the gain in TSS was moderate. This was since of the existence of MK in the recipe which reacted quickly during the hydration-reactions and also due to its chemical nature having greater quantity of Al_2O_3, higher specific surface area and finer sized materials. This contemporary study reveals the gain in the TSS and was in disagreement with the outcome of study [82,98] of MK's influence in a conventional concrete recipe. This may be owed to the synergetic consequence of MK and GGBFS in the binder system producing compact micro-structure and thus refining the pore arrangements of the mix. This can be agreed evidently from the Fig.5.29 wherein SEM images of hardened-mortar matrix salvaged from the specimens after the TSS at 3-days and 7-days of $Hy_{FSCCType1-D}$ i.e. mix consisting 0.50%PP-F +0.50%AR-F. In all the experimented recipe the $Hy_{FSCCType1-D}$ recipe marginally exhibited satisfactory TSS from 16-hrs to 90-days. These outcomes were in equivalent disposition to the consequence [102] of reflection of improved TSS in the SCC recipe arranged with 10.00% to 15.00% MK. But merely difference of the present study was that during 7-days to 28-days, the TSS was markedly altered in relation to that of the TSS of 28-days to 90-days. This was owing to the faster to hydration-reaction of fine sized particles as present in MK during the initial ages up to 7-days and later on owed to the ancillary hydration-reactions of GGBFS till 28-days. Beyond 28-days the minimal rise in TSS may be accredited to the proximate termination of hydration-reactions in the investigated recipes.



(a) **(b)**

Fig. 5.29(a-b)SEM images at 1-micron level of mortar (retrieved after TSS test)of Hy$_{FSCCType\ 1\text{-}D}$ recipe at 3-days and 7-days

5.9.3 Linear Shrinkage(LS) of SCC$_{Control}$,Hy$_{FSCC\text{-}Type1}$ and Hy$_{FSCC\text{-}Type2}$ recipes

SCC$_{Control}$ recipe and various Hy$_{FSCC}$ recipes investigated in this study were verified for the LS , at various ages like 1-day,3-days ,7-days ,28-days and 56-days. Deviations in LS of the SCC$_{Control}$ recipe and some Hy$_{FSCC}$ recipes with age, with mention to % PP-F, %AR-F and some groupings of %PP-F +%AR-F is presented in Table 5.23. As can be perceived from the data of Table 5.23 , the LS of SCC$_{Control}$ recipe ,at 1- day, was (-) 0.0110. When equated to LS of SCC$_{Control}$ recipe, the LS of Hy$_{FSCCType\ 1}$ recipe (with %PP-F varied from 0.00% to 1.00%) and Hy$_{FSCCType\ 2}$ mix (with AR-F varied from 0.00% to 1.00%) lessened for all the tested periods. The LS of Hy$_{FSCC\text{-}Type\ 1}$ recipe, for the tested periods, lessened from 18.17% to 54.49% and the LS for mix of Hy$_{FSCC\text{-}Type\ 2}$ was lessened from 27.29% to 63.58%. The 1-day minimum LS was (-)0.004 for Hy$_{FSCC\text{-}Type1\text{-}D}$ and the maximum LS was (-)0.008 was for Hy$_{FSCCType1\text{-}B}$ and Hy$_{FSCCType2\text{-}A}$. The LS of all the investigated recipes of Hy$_{FSCC\text{-}}$

$_{Type1}$ and $Hy_{FSCC-Type2}$were increasingly perceived to be lessened from 1-day to 56-days. The LS of all the recipes was more during 1-day to 3-days and later on for the ages of 7-days to 56-days, the LS was marginal. This was since of the existence of MK in the recipe which might has reacted rapidly through the hydration-reactions and also due to its chemical nature having higher quantity of Al_2O_3, higher specific surface area and finer sized particles. Later on PP-F and AR-F fibres prevented the LS because of nature of dispersal of these fibres in the matrix. These outcomes were in arrangement of the opinions revealed in the study where the consequence of beneficiation of reduced LS of concrete was stated owed to the existence of fibres in the ITZ regions of concrete and the similar can be perceived through the photo micro-graph as presented in the Fig.5.25 (c) and (d).In the above recipes ,the $Hy_{FSCC-Type1-D}$ i.e. recipe involving 0.50%PP-F +0.50%AR-F slightly displayed less LS from 1-day to 56-days.

Table 5.23
Linear Shrinkage(LS) of $SCC_{Control}$,$Hy_{FSCC-Type-1}$ and $Hy_{FSCC-Type-2}$recipes

Mix ID	1-Day	3-Days	7-Days	28-Days	56-Days
	%Linear Shrinkage(LS) (-)				
$SCC_{Control}$	0.0110	0.0090	0.0600	0.0500	0.0030
$Hy_{FSCC-Type1-A}$	0.0090	0.0080	0.0080	0.0050	0.0020
$Hy_{FSCC-Type1-B}$	0.0080	0.0080	0.0080	0.0060	0.0060
$Hy_{FSCCT-ype1-C}$	0.0060	0.0060	0.0060	0.0060	0.0060
$Hy_{FSCCT-ype1-D}$	0.0050	0.0040	0.0040	0.0040	0.0040
$Hy_{FSCC-Type2-A}$	0.0080	0.0070	0.0070	0.0070	0.0070
$Hy_{FSCC-Type2-B}$	0.0060	0.0060	0.00600	0.0060	0.0060
$Hy_{FSCC-Type2-C}$	0.0040	0.0030	0.003	0.0030	0.0030

5.10 Durability tests of $SCC_{Control}$,$Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipes

5.10.1 Enlargement of specimens on soaking in Sulphate-solution

$SCC_{Control}$ recipe and various Hy_{FSCC} recipe investigated in this study were verified, at various ages like 7-days ,28-days and 56-days, for enlargement of specimens on soaking in solution of Na_2SO_4 (sulphate as SO_3^-). The greater the enlargement of specimens, the smaller will be the confrontation against ingression of sulphate-ions(SO_3^-).Deviations in enlargement of specimens of the $SCC_{Control}$ recipe and

Table 5.26
Durability Properties of $SCC_{Control}$,HyFSCC-Type-1 and HyFSCC-Type-2recipes

Sl. No	Mix ID	Maximum core Temperature ^0C	Time for reaching Maximum core Temperature Hrs	Average Near surface temperature ^0C	Temp Gradient ^0C	'Permeability' -At 28 Days 10^{-14} m^2/s	Abrasion resistance mm^3per 5000 mm^2
(1)	(2)	(3)	(4)	(5)	(6)=(3)-(5)	(7)	(8)
1	$SCC_{Control}$	52.2	25.2	30.4	21.8	74	5960
2	$Hy_{FSCC-Type1-A}$	50.4	24.9	30.1	20.3	71	5820
3	$Hy_{FSCC-Type1-B}$	50.1	25.1	30.6	19.5	64	5640
4	$Hy_{FSCCT-ype1-C}$	50.8	25.4	30.3	20.5	59	5170
5	$Hy_{FSCCT-ype1-D}$	51.2	24.3	30.8	20.4	45	4950
6	$Hy_{FSCC-Type2-A}$	50.3	24.6	30.9	19.4	76	5790
7	$Hy_{FSCC-Type2-B}$	49.8	24.2	30.2	19.6	55	5580
8	$Hy_{FSCC-Type2-C}$	49.6	24.1	30.3	19.3	53	5410

different Hy_{FSCC} recipes, with age , with mention to % PP-F ,%AR-F and some combinations of %PP-F +%AR-F presented in Table 5.24.From the data of Table 5.24,as observed in this study, it was perceived that for specimens of $SCC_{Control}$ recipe, the enlargement was 0.008mm with mention to length of the same specimen at 1-day. Related to the enlargement of specimens of $SCC_{Control}$ recipe, the enlargement of specimens of $Hy_{FSCC-Type-1}$ and $Hy_{FSCC-Type-2}$ recipes observed to be less through the all ages. For the recipe $Hy_{FSCC-Type\ 1}$ the enlargement of the specimens, at 7-days, decreased from 37.50% to 50.00% and the expansion of the specimen for mix of $Hy_{FSCC-Type\ 2}$,was lessened from 62.50% to 75.00%.The 7-days minimum % enlargement was 0.030 for the recipe $Hy_{FSCC-Type2-A}$,$Hy_{FSCC-Type2-B}$ and $Hy_{FSCC-Type2-C}$. The maximum % enlargement of the specimens was 0.040 for the recipe $Hy_{FCCType1-A}$, $Hy_{FSCC-Type1-B}$ and $Hy_{FSCC-Type1-C}$. Enlargement of all the specimens of investigated recipes of $Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ observed to be lessened gradually from 7- day to 56-days. At 7-days, enlargement of the specimens of all the recipes was more and later on, for the ages of 28-days to 56-days, the enlargement of the specimens was perceived to be gentler. This was since of the existence of MK in the mix that perhaps reacted rapidly through the hydration-reactions and also due to its chemical nature of having higher quantity of Al_2O_3, higher specific surface area and fine sized particles. In this the finer particles of the MK might have helped in refinement of pore arrangements and which in turn supposed to be offered confrontation against permeation of foreign constituents into the specimens. These results were fairly approving with the visions as specified in the study[125]. During the periods beyond 7-days, PP-F and AR-F fibres were perceived to detain the enlargement of the specimens since dispersal of fibres in the matrix as verified through the photo micro-graph presented in the Fig.5.25 (c) and (d).Specimens of $Hy_{FSCCType2-C}$ i.e. mix comprising 0.50%PP-F +0.50%AR-F marginally exhibited less enlargement from 7-day to 56-days .

5.10.2 Confrontation to chloride (Cl^-) ion penetration

$SCC_{Control}$ recipe and different Hy_{FSCC} recipes investigated in this study were verified, at various ages like 7-days ,28-days and 56-days, for Cl^- ion present in the concrete core specimens as were taken out at 7-days ,28-days and 56-days from the slab samples casted of $SCC_{Control}$ recipes and various HyF_{SCC} recipes. These slab samples surface was maintained ponded with 3.00% NaCl solution for the above periods of intended ages of testing for Cl^-. The higher the Cl^- ion content in the concrete core specimen, the slighter will be the confrontation against ingression of Cl^- ion in the concrete. Deviations in % Cl^- in concrete core specimens of the $SCC_{Control}$ recipe and various Hy_{FSCC} recipes, with age, with mention to % PP-F, %AR-F and some combinations of %PP-F +%AR-F is presented in in Table 5.25. It can be seen from the data of Table 5.25 that, for $SCC_{Control}$ recipe, the % Cl^-, at 7-days of, was $9*10^{-3}$. Equated to the % Cl^- of $SCC_{Control}$ recipe, the % Cl^- of $Hy_{FSCC-Type1}$ and $Hy_{FSCC-Type2}$ recipe, perceived to be reduced during the all ages. % Cl^- of $Hy_{FSCC-Type\ 1}$ reduced from 33.30% to 44.42% and the % Cl^- for recipe of $Hy_{FSCC\ Type\ 2}$ lessened from 11.13% to 22.17%. The minimum % Cl^- at 7-days' was $5*10^{-3}$ for $HyF_{SCCType1-B}$ recipe. Maximum % Cl^- at 7 days' was $8*10^{-3}$ for recipes $Hy_{FSCCType2-B}$ and $Hy_{FSCCType2-C}$.

Table 5.27

Confrontation to Sulphate ion ingression of $SCC_{Control}$,$Hy_{FSCC-Type-1}$ and $Hy_{FSCC-Type-2}$

Mix code	Enlargement of specimens ($*10^{-2}$) (%)		
	At 7-Days	At 28-Days	At 56-Days
$SCC_{Control}$	0.090	0.050	0.050
$Hy_{FSCC-Type1-A}$	0.080	0.060	0.060
$Hy_{FSCC-Type1-B}$	0.050	0.040	0.030
$Hy_{FSCCT-ype1-C}$	0.050	0.040	0.030
$Hy_{FSCCT-ype1-D}$	0.050	0.040	0.030
$Hy_{FSCC-Type2-A}$	0.040	0.040	0.030
$Hy_{FSCC-Type2-B}$	0.030	0.030	0.010
$Hy_{FSCC-Type2-C}$	0.030	0.030	0.010

From the data of above Table 5.25 , it can be perceived, that the % Cl^- in the investigated recipes of $Hy_{FSCC-Type-1}$ and $Hy_{FSCC-Type-2}$ was progressively perceived to be reduced for the tested periods. At 7-days, the % Cl^- in specimens, for investigated recipes, was higher and during the later on periods it was lessened steadily. The obvious reasons for this may be due to the chemical compounds present in MK as well as its fine sized particles which might have prompted the faster reactions of MK with the hydration products thus filling the pore space to reduce pore sizes which there by resulted in to denser matrix presenting less room for infiltration of foreign materials in to the matrix . These results were observed to be indorsing with the outcome of the study[18]. Also the existence of PP-F and AR-F fibres in the mix might have amended the denseness of specimens since the nature of dispersal of these fibres in the mix. Specimens of $Hy_{FSCCType1-D}$ i.e. mix consisting 0.50%PP-F+0.50%AR-F slightly demonstrated even confrontation to Cl^- on dispersion for the test period.

Table 5.28
Confrontation to ingression of Cl^- in $SCC_{Control}$,$Hy_{FSCC-Type-1}$ and $Hy_{FSCC-Type-2}$

Mix code	% Cl^- in 40mm thick concrete core slice		
	At 7-days	At 28-days	At 56-days
$SCC_{Control}$	$9*10^{-3}$	$6*10^{-3}$	$5*10^{-3}$
$Hy_{FSCC-Type1-A}$	$6*10^{-3}$	$4*10^{-3}$	$3*10^{-3}$
$Hy_{FSCC-Type1-B}$	$6*10^{-3}$	$4*10^{-3}$	$3*10^{-3}$
$Hy_{FSCCType1-C}$	$5*10^{-3}$	$4*10^{-3}$	$3*10^{-3}$
$Hy_{FSCCT-ype1-D}$	$5*10^{-3}$	$4*10^{-3}$	$3*10^{-3}$
$Hy_{FSCC-Type2-A}$	$7*10^{-3}$	$3*10^{-3}$	$2*10^{-3}$
$Hy_{FSCC-Type2-B}$	$8*10^{-3}$	$3*10^{-3}$	$2*10^{-3}$
$Hy_{FSCC-Type2-C}$	$8*10^{-3}$	$3*10^{-3}$	$2*10^{-3}$

5.10.3 Permeability

Permeability of $SCC_{control}$ and Hy_{FSCC} mix with variation of individual varieties of PP Fibre and AR Fibre but keeping the fibre grouping to 1.00 % by volume fraction of proportioned SCC mix. Similar arrangements for testing of Permeability, as per IS 516(Part 2/Sec1):2018, shown in Fig.5.24 was adopted. Test results of permeability, on the experimented mix $SCC_{control}$ and Hy_{FSCC} mix, were carried on the specimens of 100mm diameter at 28-days is presented in Table 5.26. It can be perceived from Table 5.26 that, the permeability value for control mix $SCC_{control}$ was $74*10^{-14}$ m^2/s and for the mix $Hy_{FSCCType1-A}$, where solely 1.00% PP-F was added in to the cementitious system, permeability was dipped to $71x10^{-14}$ m^2/s. This slight dip in permeability was due to the inclusion of fibre groupings of into the mix [126]. Similarly, as the individual PP Fibre content, in fibre groupings of PP Fibre and AR Fibre, was varied from 0.70 % to 0.50%, the resulted $Hy_{FSCCType1\text{-}B}$, $Hy_{FSCCType1\text{-}C}$ and $Hy_{FSCCType1\text{-}D}$ mix demonstrated further dip in permeability varying from 64 $*10^{-14}$ m^2/s to 45 $*10^{-14}$ m^2/s corresponding to the ordered of decrease in PP fibre content. Whereas, when solely 1.0% AR Fibre content was added, the resulted mix $Hy_{FSCCType2\text{-}A}$ has resulted slight higher permeability than $SCC_{control}$ mix, the registered permeability in this $Hy_{FSCCType2\text{-}A}$ mix was 76 $x10^{-14}$ m^2/s. Similarly, as the individual AR-F content, in fibre groupings of PP-F fibre and AR-F fibre, was varied from 0.70% to 0.60%, the resulted $Hy_{FSCCType2\text{-}B}$, $HyF_{SCCType2\text{-}C}$ mix demonstrated dip in permeability from $55*10^{-14}$ m^2/s and $53*10^{-14}$ m^2/s corresponding to the ordered of decrease in AR fibre content. The probable reasons for dip in the permeability can be assigned to the combined effect of groupings of PP-F and AR-F. This was in reasonable covenant with the findings of the scholarship [130] but thru the lone deviation was hybrid combinations of synthetic bar chip fibres +natural fibre were used in that study. As can be observed from the Table 5.26, the minimum permeability recorded was 45 $*10^{-14}$ m^2/s for $HyF_{SCCType1\text{-}D}$ mix.

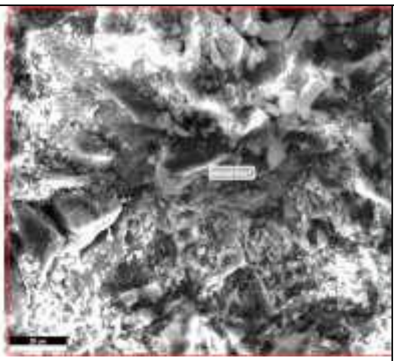
5.10.4 Abrasion resistance

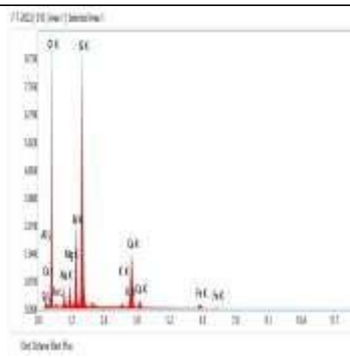
Testing arrangements of abrasion resistance of concrete ,as per Annex E-IS 15658 :2021, are shown in Fig.5.26 were followed in the abrasion resistance test of $SCC_{control}$ and HyF_{SCC} mix. Test results of abrasion resistance of $SCC_{control}$ and HyF_{SCC} mix with variation individual varieties of PP-F fibre and AR-F fibre but keeping the fibre grouping to 1.0 % by volume fraction of proportioned SCC mix. Test results of abrasion resistance , on the experimented mix $SCC_{control}$ and HyF_{SCC} mix, were carried on the cube shaped specimens of 71$\pm$0.5mm at 28-days and is presented in Table 5.26. It can be perceived from Table 5.26 that the abrasion resistance value for control mix $SCC_{control}$ was 5960mm^3 per 5000mm^2 and for the mix $HyF_{SCCType1\text{-}A}$, where solely 1% PP-F was added in to the cementitious system, abrasion resistance was increased to 5820mm^3 per 5000$mm^{2.}$ This increase in permeability was due to the inclusion of fibre groupings of into the mix [131]. Similarly, as the individual PP Fibre content, in fibre groupings of PP-F fibre and AR-F fibre, was varied from 0.7 % to 0.5%, the resulted $HyF_{SCCType1\text{-}B}$, $Hy_{FSCCType1\text{-}C}$ and $HyF_{SCCType1\text{-}D}$ mix demonstrated further increased abrasion resistance and was ranging from 5640mm^3 per 5000mm^2 to 4950 mm^3 per 5000mm^2 corresponding to the ordered of decrease in PP-F fibre content. Whereas, when solely 1.0% AR Fibre content was added, the resulted mix $HyF_{SCCType2-A}$ has resulted slight higher abrasion resistance than $SCC_{control}$ mix, the registered abrasion resistance in this $HyF_{SCCType2-A}$ mix was 5790mm^3 per 5000mm^2. Similarly, as the individual AR-F fibre content, in fibre groupings of PP-F Fibre and ARG-F Fibre, was varied from 0.7 % to 0.6%, the resulted $HyF_{SCCType2-B}$, $HyF_{SCCType2-C}$ mix demonstrated increased abrasion resistance 5580mm^3 per 5000mm^2 and 5410mm^3 per 5000mm^2 corresponding to the ordered of decrease in AR fibre content. It was noticed that, abrasion resistance of mix where PP fibre content is more than AR fibre content i.e. $HyF_{SCCType1-A}$, $HyF_{SCCType1-B}$ and $HyF_{SCCType1-C}$, in an overall fibre content of 1.00%, the abrasion resistance was observed to be more the mix where AR-F fibre content is more than PP-F fibre content i.e. $HyF_{SCCType2-A}$, $HyF_{SCCType2-A}$ and $HyF_{SCCType2-C}$ .The probable reasons for increase in abrasion resistance can be assigned to the predominant effect of PP-F fibre over AR-F fibre in the experimented cementitious system. This was in line with the findings of the study [128] but with the only variation was hybrid combinations of bamboo jute+ glass fibre were used in that study. As can be observed from the Table 5.26, the maximum recorded abrasion resistance was 4950mm^3 per 5000mm^2 for $HyF_{SCCType1-D}$ recipe.

5.10.5 Microstructure Development of $Hy_{FSCCType1-D}$ recipe at 3- Days and 7-days

Microstructure Development of $Hy_{FSCCType1-D}$ recipe at 3- Days and 7-days was studied with the service of 'EDX'(Energy dispersive X-ray Spectroscopy) which affords major formations of a reacted matrix. On a SEM image of a reacted matrix under the investigation, a minute part of interest picked and engrossed meticulously to get the elements existing in that minute area and the elements are conveniently indicated in a graphical pattern where abscissa designates the vitality of ionisation whereas ordinate directs the reckonings. A sophisticated reckoning of an individual constituent represents its higher occurrence in that reacted matrix. The Microstructure Development $Hy_{FSCCType1-D}$ recipe at 3- Days and 7-days is presented under Fig.5.30(a-b). It was observed that with growing age towards maturity i.e., from 3-days to 7-days in the $Hy_{FSCCType1-D}$ recipe , 'Si' reckoning became improved and 'Ca' reckoning became varied due to ingestion in pozzolonic response and formation of

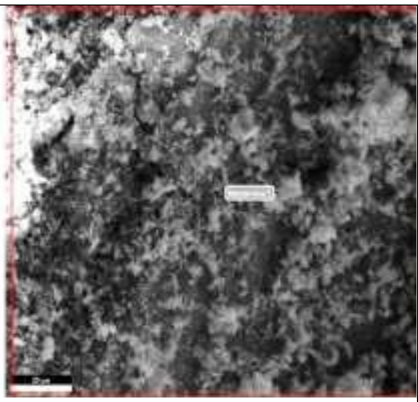
'C-S-H' and 'C-A-S-H' gel. This outcome tallies with the study [49] wherein the only variation was that microsilica was used as high reactive SCM.

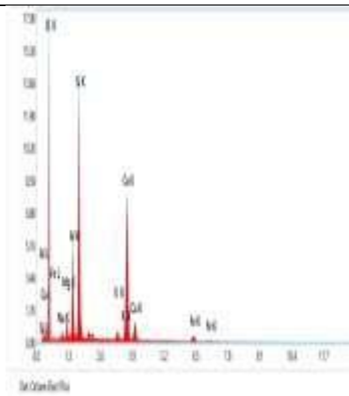




Element	Weight %	Atomic %
O K	57.4	71.3
Na K	3.5	3.0
Mg K	2.1	1.7
Al K	6.5	4.8
Si K	19.6	13.9
K K	0.4	0.2
Ca K	9.2	4.5
Fe K	1.4	0.5

(a) $HyF_{SCCType1-D}$ recipe at 3- Days





Element	Weight %	Atomic %
O K	59.0	74.4
Na K	1.3	1.1
Mg K	1.4	1.2
Al K	5.3	4.0
Si K	13.4	9.6
K K	0.9	0.5
Ca K	17.2	8.7
Fe K	1.5	0.5

(b) $HyF_{SCCType1-D}$ recipe at 7-days

Fig.5.30(a-b) Microstructure Development of $HyF_{SCCType1-D}$ recipe at 3- Days and 7-days

5.10.6 Adiabatic Rise in Temperature and Temperature Gradient (Difference in Temperature from Core to near surface)

Adiabatic rise in temperature study was carried as per the provisions of IS 7816 and the test arrangements made was similar as discussed above under 5.3.4. The test arrangements were similar to 5.3.4 and was made as such that required to monitor the rise in temperature, maximum time required for attaining the temperature gain etc., which were the prime requirements to series of $SCC_{control}$ and HyF_{SCC} mix. On a continuous basis variations in temperature were recorded, from ½ hour to 1-1/6 day, after adding of water to binder system. The $Temperature_{Gradient}$ (i.e. $Temperature_{(Inner-Core)}$ - $Temperature_{(Near-Surface)}$) of the experimented series mix with variations in individual varieties of PP-F fibre ,AR-F fibre but keeping the fibre grouping to 1.00 %

by volume fraction of proportioned SCC mix. Test results of temperature monitoring offered in Table 5.26. It can be perceived from the Table 5.24 that, Early age (1 day) temperature increase in inner core of $SCC_{control}$ was 52.2^0C whereas the same for and for the mix $HyF_{SCCType1-A}$, where solely 1% PP-F fibre was added in to the cementitious system temperature of core was decreased to 50.4^0C. This decrease in temperature of core was due to the inclusion of fibre groupings of into the mix which may slightly hinder the hydration reactions as similarly observed in the study [127] except the variation that oil palm fibres were used in that study. Correspondingly, as the individual PP Fibre content, in fibre groupings of PP-F fibre and AR-F fibre, was varied from 0.70 % to 0.50%, the resulted $Hy_{FSCCType1-B}$, $Hy_{FSCCType1-C}$ mix demonstrated firstly decrease in rise in temperature of core corresponding 0.70% PP Fibre and registered temperature of corresponding $Hy_{FSCCType1-B}$ mix as 50.1^0C. But for 0.6% PP-F fibre content i.e. as the AR-F fibre content was correspondingly increased from 0.30% to 0.40% for $Hy_{FSCCType1-C}$,it was observed that temperature of resulting mix $Hy_{FSCCType1-C}$ increased to 50.8^0C. Whereas, when solely 1.00% AR Fibre content was added, the resulted mix $HyF_{SCCType2-A}$ has registered 50.3^0C, slightly lower temperature of core than $SCC_{control}$ mix. Similarly, as the individual AR Fibre content, in fibre groupings of PP-F fibre and AR-F fibre, was varied from 0.70 % to 0.60%, the resulted $HyF_{SCCType2-B}$, $HyF_{SCCType2-C}$ mix demonstrated further decrease in rise in core temperature corresponding to the order of 49.8^0C and 49.6^0C respectively responding to the relative AR-F fibre content of 0.70% and 0.60%. It was noticed that, decrease in rise in core temperature was more in mix where AR-F fibre content is more than PP-F fibre content i.e. $HyF_{SCCType2-A}$, $HyF_{SCCType2-B}$ and $HyF_{SCCType2-C}$,in a overall fibre content of 1.00%.The probable reasons for decrease in temperature of core of such recipe can be apportioned to the predominant effect of PP-F fibre over AR-F fibre in the experimented cementitious system causing less hindrance in hydration-reactions . This was in mark with the conclusions of the study [129] but with the only variation was that study was pertained to geopolymer concrete. As can be observed from the Table 5.26, the maximum recorded rise in temperature of core for the HyF_{SCC} mix was 51.2^0C for $HyF_{SCCType1-D}$ mix i.e. for the mix containing groupings of 0.50%PP-F +0.50% AR-F.

5.11. Summary of tests of part replacement of OPC with GGBFS+MK in grouping with PP-F and AR-F on properties of HyF$_{SCC}$ recipes (involving of whole 1.00% hybrid fibres)

Established on the tests conducted on freshly mixed recipe, tests conducted for strength hardened specimens, during 16-hrs to 90-days, durability properties of specimens during7-days to 56-days' age the subsequent inferences acknowledged:

1) As the %PP-F was lessened relative to %AR-F, the flowability lessened and resistance to segregation increased compared to similar properties of SCC$_{Control}$ recipe.
2) Time for initial set as well as time for final set improved in the Hy$_{FSCC}$ mix as the %PP-F content was lessened in association to %AR-F.
3) Compressive-strength and TSS improved as the %PP-F was reduced in association to %AR-F.
4) Hy$_{FSCC-Type2-C}$ recipe containing of 0.40%PP-F+0.60%AR-F, confirmed slightly higher compressive-strength and slightly lower TSS as compared to Hy$_{FSCC-Type1-D}$ recipe i.e. mix comprising of 0.50% PP-F+0.50%AR-F.
5) All the recipes resulted in 1-day compressive-strength > 25.00 N/mm2 and TSS > 2.00 N/mm^2.
6) In the recipe containing combination of fibre groupings of 0.40%PP-F+0.60%AR-F, slightly achieved resistance to shrinkage and durability against the enlargement on soaking in sulphated liquid medium.
7) In the recipe containing combination of fibre groupings of 0.50% PP-F+0.50%AR-F , slightly achieved durability against permeation of Cl^- ions.
8) Auxiliary examinations were felt obligatory on the optimised recipe of Hy$_{FSCC-Type1-D}$ directive to amend further the microstructure by addition of minimal magnitude of prospective nano-sized material like nano-alumina so that early-age strength properties could be improved while preserving the SCC characteristics.

5.12 Effect of part replacement of OPC with GGBFS in grouping with MK+NA in combination with 0.5% PP-F and 0.5% AR-F on properties of SCC

Based on the various results of tests carried under 5.7, the analysis of the same as carried under 5.8 and summary of the results as listed under 5.11,it was observed that for the experimented mix the combinations of OPC by 50.00%, GGBFS by 40.00% and MK by 10.00% (forming a binder-material of 550.00 kgs/m^3 and at w/cm ratio of 0.33) in grouping with 0.50%PP-F + 0.50%AR-F at 1-day was resulted compressive strength of 26.70 N/mm^2 and tensile splitting strength of 2.40 N/mm^2 .Hence further experiments were carried out with an aim to proportion a Hy_{FSCC} mix with highly reactive nano alumina as a part replacement of high reactive MK to further densify the microstructure of the Hy_{FSCC} mix as was experimented above. The above combinations of cement and moderately reactive GGBFS blend i.e. in a total cementitious material OPC was by weight 50.00%, GGBFS was by weight 40.00% and the balance 10.00% by weight of MK (as tried under 5.7) was split into of reactive and highly reactive materials in assemblage with the MK+NA, wherein the individual proportions of MK and NA are varied by 0.50% in each trial so that the total MK+NA was 10.00%. Also the favourable groupings PP-F fibre and AR-F fibre for forming hybrid fibre combinations, which was observed through trials as discussed under 5.7, i.e. 0.50% of PP-F fibre and 0.50% PP-F fibre, by volumetric proportion of concrete was incorporated. Thus with these combinations further experiments were carried on the Hy_{FSCC} mix and the same is discussed under 5.13 onwards.

5.13 Experiment design

In order to achieve the directed setting time, strength as well as sustainability, this investigational study was deliberated to scrutinize the hybrid fibre reinforced HyF_{SCC} consisting of total binder content with fixed proportion of 50.0% of OPC, 40.00%GGBFS and combined proportion of 10.00% of high reactive SCMs combinations as MK+NA. In each such trial of above Hy_{FSCC} mix, MK was varied from 7.00% to 9.50% and NA proportion was varied from 0.50% to 3.00% in the reverse order so that the combined proportion of MK+NA will be 10.00%. In addition to this, a constant hybrid combination of fibre reinforcement was implemented, as 1.00% of volumetric fraction of concrete. In the above composed Hy_{FSCC} mix, the hybrid combination of fibres comprising of PP-F fibre by 0.50% and AR-F fibre by 0.50% was used in each trial. In this way six numbers of $Hy_{FSCC\text{-}MK\text{-}NA}$ recipe (mix was termed as $SCC_{HyFR\text{-}NA}$) were produced and the same were codified as $SCC_{HyFR\text{-}NA0.50}$, $SCC_{HyFR\text{-}NA1.00}$, $SCC_{HyFR\text{-}NA1.50}$, $SCC_{HyFR\text{-}NA2.0}$,$SCC_{HyFR\text{-}NA2.50}$ and $SCC_{HyFR\text{-}}$

$_{NA3.00}$ respectively according to the varied %NA as mentioned in the subscript. In order to assess the characteristics of above $SCC_{HyFR-NA}$ mix, a reference mix, codified as SCC $_{HyFR-NA0.0,}$ was proportioned without addition of NA. The mix proportion is presented in Table 5.27. Properties of these SCC $_{HyFR-NA0.00}$, $SCC_{HyFR-NA}$ mix, in fresh state, were scrutinised as per applicable standards of Indian Standard IS 1199 Part 6 :2018 with factors of 'SF', 'VF_T', '$L_{Box\ flow-ratio}$', time for initial set ,time for final set was carried out as per IS 1199 Part 7 :2018. Also $SCC_{HyFR-NA0.00}$, $SCC_{HyFR-NA}$ mix characteristics, in hardened-state, the parameters were evaluated,at16_{Hours},1_{day},3_{days},7_{days},28_{days},56_{days},90_{days}, CS, TSS, LS, Modulus of Elasticity (MoE), as per applicable Indian Standard IS 516:2018. Furthermore SCC $_{HyFR-NA0}$, $SCC_{HyFR-NA}$ mix characteristics for robustness i.e. durability were also judged at the time intervals of 7_{days},28_{days},56_{days},90_{days} for abrasion resistance, penetration confrontation compared to sulphate ions and chloride ions by the provisions of relevant Indian Standards and ASTM standards. SCC $_{HyFR-NA0.00}$, $SCC_{HyFR-NA}$ mix properties in fresh and hardened state are presented in Table 5.28, Table 5.29 and Table 5.30 and the same is discussed in the later paras.

Table 5.27

SCC $_{HyFR-NA0}$ and SCC_{HyFRNA} mix proportions

Mix Code	Binding Materials(BM) proportions(%)				Fibre composition (volumetric%)		Constituents (Kgs/m^3)				
	OPC-53 Gr	GGBFS	MK	NA	PP-F (%)	AR-F (%)	Total BM	CA 10mm	Sand (FA)	PCE based HRWRA Admixture	Free-Water
$SCC_{HyFR-NA0.00}$	50.00	40.00	10.00	0.00	0.50	0.50	560	720	910	7.84	185
$SCC_{HyFR-NA0.50}$	50.00	40.00	9.50	0.50	0.50	0.50	560	720	910	7.84	185
$SCC_{HyFR-NA1.00}$	50.00	40.00	9.00	1.00	0.50	0.50	560	720	910	7.84	185
$SCC_{HyFR-NA1.50}$	50.00	40.00	8.50	1.50	0.50	0.50	560	720	910	7.84	185
$SCC_{HyFR-NA2.00}$	50.00	40.00	8.00	2.00	0.50	0.50	560	720	910	7.84	185
$SCC_{HyFR-NA2.50}$	50.00	40.00	7.50	2.50	0.50	0.50	560	720	910	7.84	185
$SCC_{HyFR-NA3.00}$	50.00	40.00	7.00	3.00	0.50	0.50	560	720	910	7.84	185

5.14 Results of part replacement of OPC with GGBFS+MK +NA in grouping with PP Fibre and AR Fibre on properties of SCC

5.14.1 Analysis of results on Fresh-state characteristics

5.14.1.1 Water demand and Chemical admixture demand for producing SCC mix of targeted slump flow

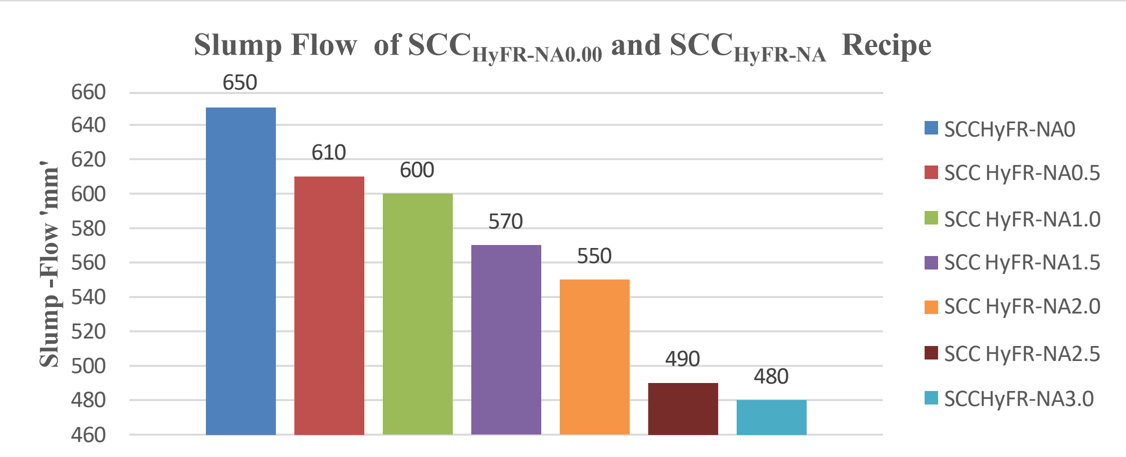
Water demand of $SCC_{HyFR-NA}$ mix, i.e. nano alumina admixed mix, increases for producing satisfactory slump flow concrete mix as related to the requirement of water for control mix SCC_{HyFR} i.e. mix without any nano alumina admixed mix. The increase in water demand for combinations of GGBFS+MK+NA was since of higher fine sized particles and increased specific surface area and chemical nature of NA [118,120]. As can be seen from studies conducted and discussed under section 5.7 above, merger of fibres in the recipe will also rises the requirement of water of concrete in making the similar slump-flow related to recipe without fibres [121]. Hence, in order to achieve a targeted slump-flow of SF1 category i.e. slump flow of 550mm to 650mm, the chemical admixture of HRWA type(PCE -capable of dropping quantity of water by 30.00-40.00%) quantity trials were performed by increasing the PCE ranging from 1.20% - 1.40% .Concluded from the recipes, it was detected at 1.40% of PCE, the resulted $SCC_{HyFR-NA}$ recipe, with several blends of NA, was sustaining both the targeted SF as well as VF_T of 9seconds-25 seconds. At 1.4% of PCE chemical admixture content the slump flow of the reference recipe $SCC_{HyFR-NA0.00}$ was 650mm for 0.00% NA content. Fresh-state characteristics of the $SCC_{HyFR-NA000}$ and $SCC_{HyFR-NA}$ mix debated succeeding sub-sections.

5.14.2 'Slump-Flow(SF)'

SF of control recipe $SCC_{HyFR-NA0.00}$ and various $SCC_{HyFR-NA}$ recipe as investigated in this study, differences in SF with mention to several combinations of % MK + % NA, is presented in Table 5.28, Graph 5.24. As can be perceived from the Table 5.28 that, the SF of recipe $SCC_{HyFR-NA0.00}$, was higher(650mm) when related to the SF of $SCC_{HyFR-NA}$ mix (with various combinations of % MK -varied from 7.00% to 10.00% + NA -varied from 0.00% to 3.00%). The SF of $SCC_{HyFR-NA}$ recipe was lessened from 4.67% to 25.00% by varying NA from 0.00% to 3.00%. These results were appropriately in prearrangement with the outcome of the study[122] on the behaviour of incorporation of nano sized materials in concrete on SF .As can further be observed from the data of the above Table 5.28 that ,the minimum SF attained was 480mm for the recipe $SCC_{HyFR-NA3.00}$ (i.e. at 3.00% NA), and maximum SF was 610mm for $SCC_{HyFR-NA0.50}$ recipe(i.e.at 0.50% NA). These results were confirmed to the consequence of the learning[123] where a dropping in SF, as compared to control mix, was observed when nano-sized materials were admixed in the SCC. The variance amongst the present outcome of this study with the findings of[124], was reasonable due to the presence of nano-sized materials i.e. high specific surface area . The SF of mix of $SCC_{HyFR-NA2.00}$ (i.e. at 2.00% of NA) was 550mm and beyond 2.00% of NA adding, the concrete mix stopped to demonstrate SCC characteristics. The likely cause for less SF in case of higher contents of %NA>2.00% can be accredited to build-up effect owed to concern of high surface-area materials and the identical can pragmatic through the photo micro-graph (at 1000 times magnification level), as offered in Fig.5.31 of both the mix at above % integration.Fig.5.32 represents the SF of control mix $SCC_{HyFR-NA0.00}$ and many investigated $SCC_{HyFR-NA}$ recipes.

Table 5.28
Fresh State Properties of $SCC_{HyFR-NA0}$ and $SCC_{HyFR-NA}$ Mix

Sl. No	Mix code	Properties					
		SF	VF_T	$L_{Box\ flow\ ratio}$	Segregation resistance	Time for initial set	Time for final set
		'mm'	'seconds'	'h2/h1'	%	'minutes'	'minutes'
1	$SCC_{HyFR-NA0.00}$	650	10	0.92	13.8	460	520
2	$SCC_{HyFR-NA0.50}$	610	16	0.91	14.4	380	500
3	$SCC_{HyFR-NA1.00}$	600	20	0.90	14.7	350	460
4	$SCC_{HyFR-NA1.50}$	570	22	0.86	14.9	330	430
5	$SCC_{HyFR-NA2.00}$	550	25	0.85	15.0	320	410
6	$SCC_{HyFR-NA2.50}$	490	31	0.67	22.4	Recipe not satisfied SCC properties	
7	$SCC_{HyFR-NA3.00}$	480	40	0.62	24.6		



Graph 5.24 Slump-Flow of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ Recipe

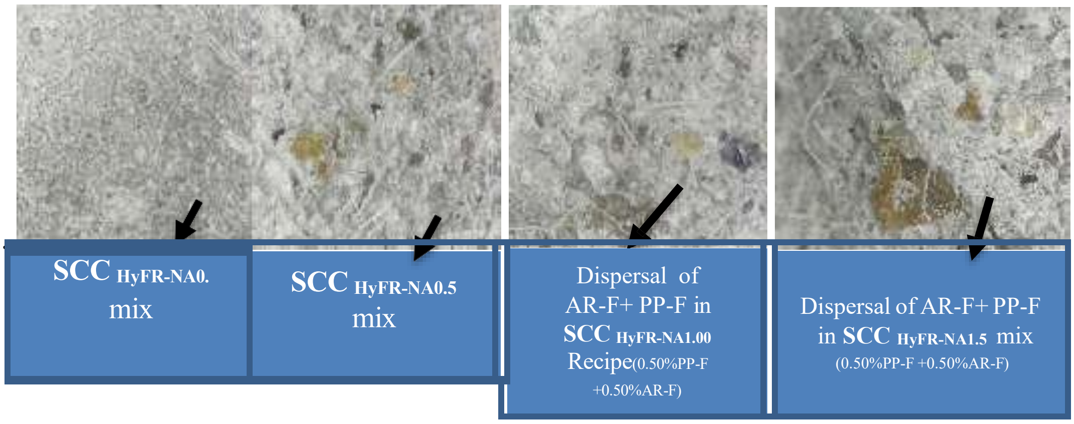


Fig.5.31 Photo micrographs at 1000 times amplification level

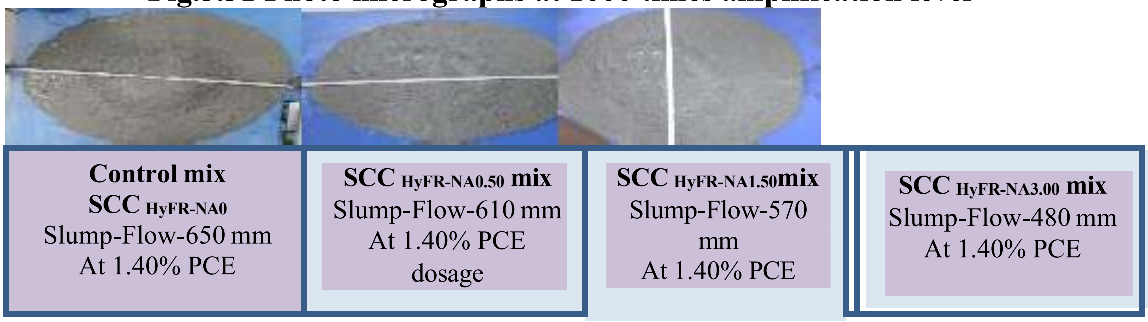
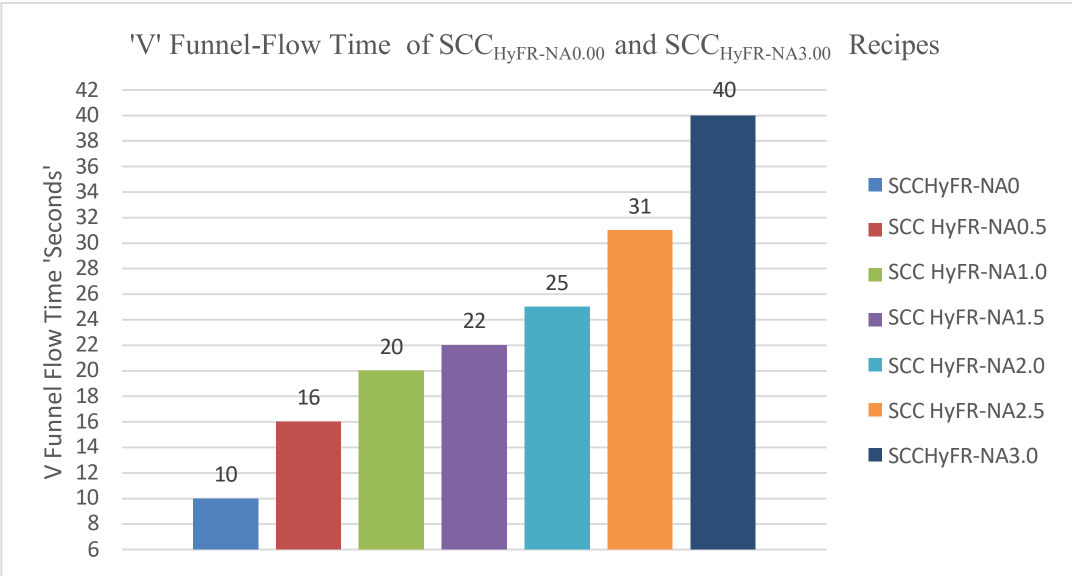


Fig.5.32 Slump-Flow of reference recipe, $SCC_{HyFR-NA0}$ and $SCC_{HyFR-NA}$ recipes.

5.14.3 'V funnel-flow time(VF_T)'

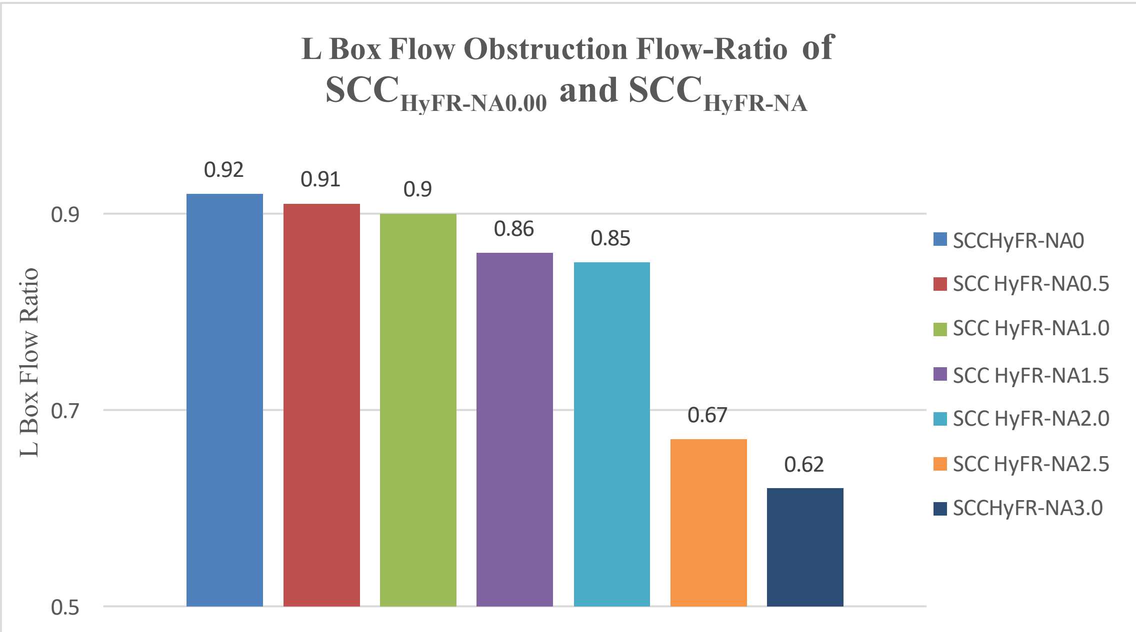
'V' funnel-flow time of control recipe $SCC_{HyFR-NA0.00}$ and several investigated $SCC_{HyFR-NA}$ recipes investigated in this study, differences in V' funnel-flow time with mention to % of NA, is presented in Table 5.28, Graph 5.25. As can be observed from the above data, rounded off time of 'V' funnel-flow of $SCC_{HyFR-NA0.00}$ recipe was 10 seconds. This result was in line up with the consequence of the study [118.] wherein it was demonstrated that by means of the ideal quantity of 10.00% MK in concrete, adequate viscosity was attained for the SCC mix and thus encouraging the mix to rapidly flow through the contracted space of 'V' funnel. In this present study, it was observed that, when related to 'V' funnel -flow time of $SCC_{HyFR-NA0.00}$ mix, the flow time augmented for $SCC_{HyFR-NA}$ mix (with %NA varied from 0.00% to 3.00%). This increase in flow time was owing to the existence of higher fineness materials in the concrete mix which obviously requires more quantity of water for wetting the surface. Besides this there was sizable rise in the obstruction and hence resulted in increased 'V' funnel-flow time of recipe to pass through the 'V' funnel .The results extended in 'V' funnel-flow time test, in this study, was normally allied with outcome established by[127] with the lone variance was that in the study nano material was nano silica in the SCC . In this contemporary study, the $SCC_{HyFR-NA}$ mix resulted in increased 'V' funnel-flow time from 33.30% to 233.30% as compared to the 'V' funnel-flow time for mix of control mix $SCC_{HyFR-NA0.00}$. The minimum 'V' funnel-flow time was 16 seconds for $SCC_{HyFR-NA0.5}$ and the maximum V funnel flow time was 40 seconds for $SCC_{HyFR-NA3.0}$. 'V' funnel-flow time for $SCC_{HyFR-NA2.00}$mix (i.e. at 2.00% of NA) was 25 seconds and beyond 2.00% of NA addition, the concrete mix terminated to confirm SCC characteristics.



Graph 5.25 V Funnel Flow Time of $SCC_{HyFR-NA0}$ and $SCC_{HyFR-NA}$ Mix

5.14.4 'L' box obstruction flow-ratio

'L' box obstruction flow-ratio of control recipe $SCC_{HyFR-NA0.00}$ and several investigated $SCC_{HyFR-NA}$ recipe experimented in this study, variations in 'L' box obstruction flow-ratio with mention to % NA is presented in Table 5.28, Graph 5.26. According to the above data , the 'L' box obstruction flow-ratio of $SCC_{HyFR-NA0.00}$ mix was 0.90. When related to 'L' box obstruction flow-ratio of control $SCC_{HyFR-NA0}$ mix, there was observed a reduction in 'L' box obstruction flow-ratio of $SCC_{HyFR-NA}$ mix (with %NA varied from 0.00% to 3.00%). This lessening in the 'L' box obstruction flow-ratio was owing to the existence of higher surface area materials which obviously display clogging effect [116]. These results were impartially supportive with the outcome of study[118] wherein the low 'L' box obstruction flow-ratio, as was detected for the SCC mix integrated with nano sized materials, was due to the clogging effects[115,119].In this present study, it was observed that when equated to the SCC mix of $SCC_{HyFR-NA0.00}$ recipe, the 'L' box obstruction flow-ratio of $SCC_{HyFR-NA}$ mix reduced from 4.35% to 34.02% .The minimum 'L' box obstruction flow-ratio was 0.62 for $SCC_{HyFR-NA3.0}$ and maximum 'L' box obstruction flow-ratio was 0.90 for $SCC_{HyFR-NA0.5}$ and beyond 2.00% of NA addition i.e. $SCC_{HyFR-NA0.50}$, the concrete mix ceased to endorse the least SCC characteristics.

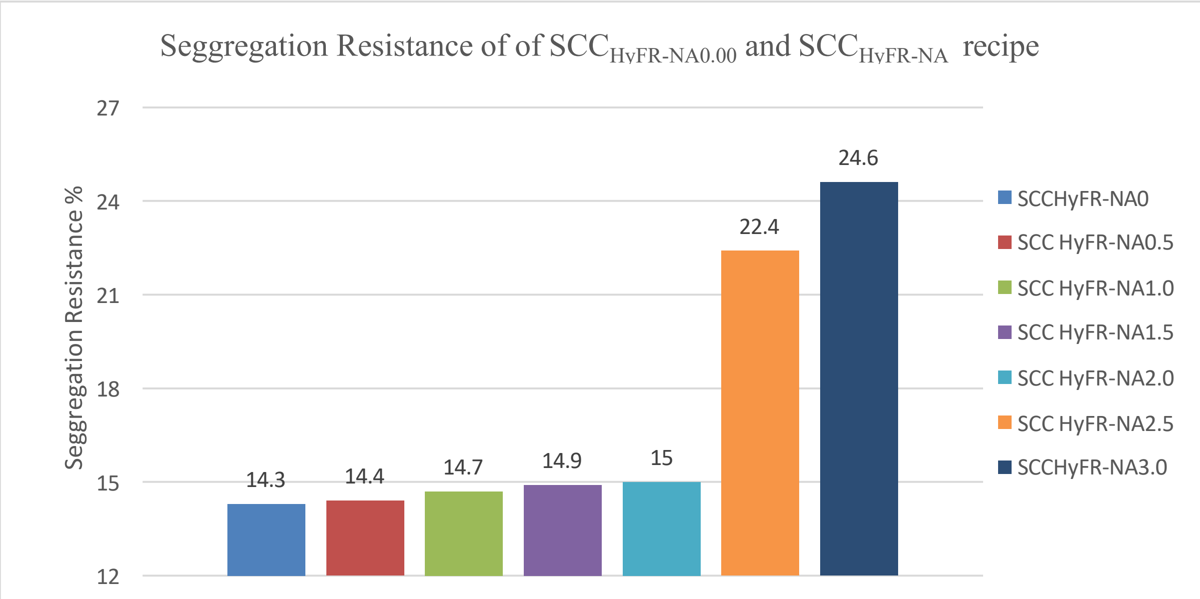


Graph 5.26 L Box Flow Obstruction Flow-Ratio of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$

5.14.5 Segregation-Resistance(SR) %

%'SR' of control recipe of $SCC_{HyFR-NA0.00}$ and various investigated $SCC_{HyFR-NA}$ tested in this study and differences in %'SR' with mention to % NA is presented in Table 5.28 and Graph 5.27. SR of $SCC_{HyFR-NA0.00}$ recipe was 14.30%. When related to %'SR' of $SCC_{HyFR-NA0.00}$, the %'SR' raised for $SCC_{HyFR-NA}$ mix (with %NA varied from 0.00% to 3.00%).This rise in %'SR' was due to the existence of higher surface area materials, which naturally necessitates extra water for covering their entire surface area and at less water content , the concrete recipe would results in sluggish mix. These results were acceptable with the consequences of the conclusion of a similar study[117]. In this present study, it was detected that when related to the

%'SR' of $SCC_{HyFR-NA0.00}$ recipe, the %'SR' of $SCC_{HyFR-NA}$ recipes improved from 2.86% to 75.70%. The minimum %'SR' was 14.40% for $SCC_{HyFR-NA0.50}$ and the mmaximum %'SR' was 24.60% for $SCC_{HyFR-NA3.00}$ and also it was noticed that beyond 2.00% of NA addition i.e. $SCC_{HyFR-NA2.00}$, the concrete recipe terminated to attest the SCC characteristics.



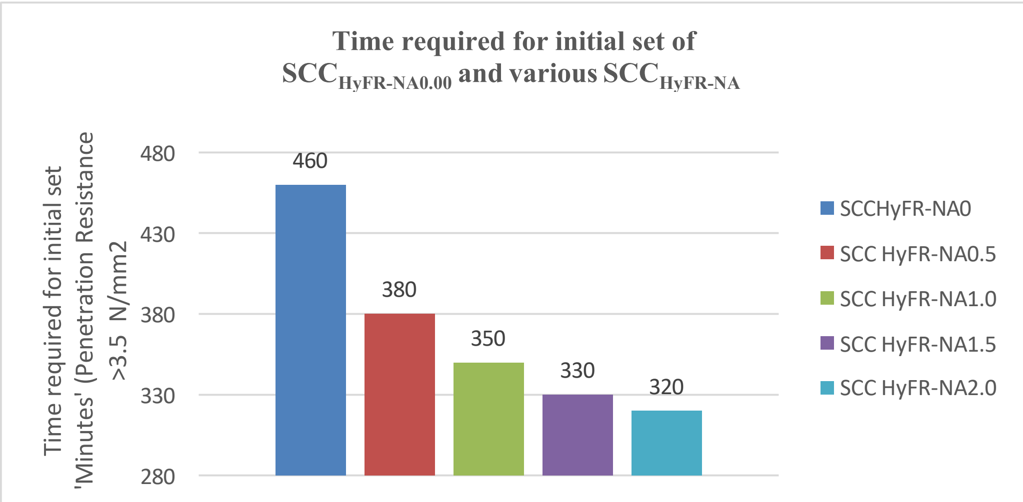
Graph 5.27 %'SR' of $SCC_{HyFR-NA0}$ and $SCC_{HyFR-NA}$ recipes

5.14.6 Time required for initial and final set of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes

Through fresh-state study on $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ as discussed under 5.8, it was detected that for the investigated mix groupings of 50.00% OPC+40.00% GGBFS, and varied groupings of MK+NA, beyond 8.00% MK +2.0% NA addition i.e. $SCC_{HyFR-NA2.00}$, the concrete recipe concluded to validate the SCC characteristics. Hence, the time required for initial set and final set of the $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes were consequently restricted to % NA additions of 0.50% to 2.00% in variations of 0.50% respectively in sequential trials and hence maintaining the % MK from 9.50% to 8.00% so as to hold the collective proportions of MK+NA as 10.00% by weight of total binder materials. The time required for initial set and final set of the $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes are debated in the subsequent subdivisions.

5.14.6.1 Time required for initial set of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes

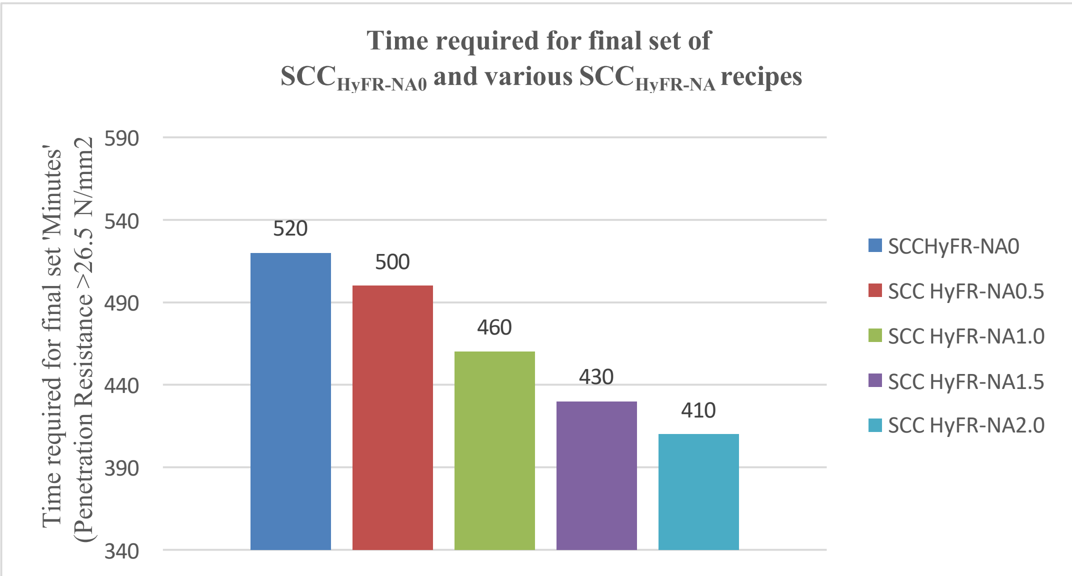
The time required for initial set of control recipe $SCC_{HyFR-NA0.00}$ and various investigated $SCC_{HyFR-NA}$ recipes tested and differences in the time required for initial set with mention to % NA is presented in Table.5.28 and Graph 5.28. It can be perceived from the data of the above that,the time required for initial set of $SCC_{HyFR-NA0.00}$ mix was 460 minutes. When related to the time required for initial set of $SCC_{HyFR-NA0.00}$ recipe, the time required for initial set lessened for $SCC_{HyFR-NA}$ mix (with %NA varied from 0.00% to 2.00%). This lessening in the time required for initial set was owing to the existence of higher finer sized particles as well as the facts of fast-reactions of MK+NA owing to its greater fineness as equated to OPC and GGBFS and higher % of Al_2O_3[120]. These consequences were in coherent and covenant with the conclusion of the study [127]. In this study ,it was detected that when related to $SCC_{HyFR-NA0.00}$ recipe, the time required for initial set of the resulted recipes of $SCC_{HyFR-NA}$ lessened from 20.81% to 34.47%. The minimum the time required for initial set was 320 minutes for $SCC_{HyFR-NA2.000}$ and the maximum the time required for initial set was 380 minutes for $SCC_{HyFR-NA0.50}$.



Graph5.28 Time required for initial set of $SCC_{HyFR-NA0}$ and various $SCC_{HyFR-NA}$ recipes

5.14.6.2 Time required for final set of recipes

Time required for final set of control recipe $SCC_{HyFR-NA0.00}$ and several investigated $SCC_{HyFR-NA}$ recipes and differences in the time required for final set with mention to % NA is presented in Table.5.28 and Graph 5.29 and from the data of the same it can be perceived that, time required for final set of $SCC_{HyFR-NA0.00}$ recipe was 520 minutes. When correlated to time required for final set of $SCC_{HyFR-NA0.00}$ mix, time required for final set lessened for $SCC_{HyFR-NA}$ mix (with %NA varied from 0.00% to 2.00%). This drop in time required for final set was owing to the to the existence of higher finer sized particles in addition to the explanations of fast-reactions of MK+NA owed to its larger specific surface areas as equated to OPC and GGBFS and higher % Al_2O_3. These consequences were in non-discriminatory line with the outcome of the study [119,76]. In this present study, it was observed that when compared to $SCC_{HyFR-NA0.00}$ mix, time required for final set of the resulted recipes of $SCC_{HyFR-NA}$ decreased from 20.81% to 3.31%. The minimum time required for final set was 410 minutes for $SCC_{HyFR-NA2.00}$ and the maximum time required for final set was 500 minutes for $SCC_{HyFR-NA0.50}$.



Graph 5.29 Time required for final set of $SCC_{HyFR-NA0}$ and various $SCC_{HyFR-NA}$ recipes

5.15 Hardened-state characteristics of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes

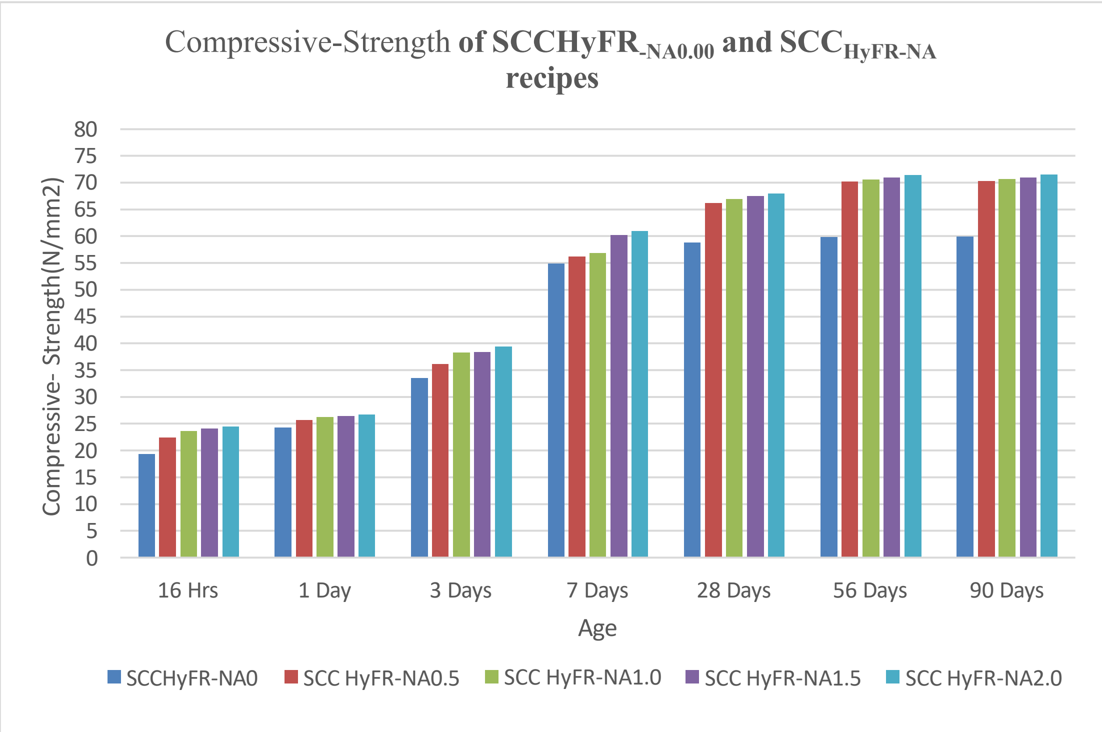
5.15.1 Compressive strength

As discussed above under 5.8.6, through fresh state study on $SCC_{HyFR-NA0}$ and $SCC_{HyFR-NA}$ as discussed under 5.8, it was observed that for the experimented mix combinations of 50.00% OPC+40.00% GGBFS, and varied groups of MK+NA , beyond 8.00% MK +2.00% NA adding i.e. $SCC_{HyFR-NA2.00}$, the concrete recipe concluded to verify the SCC characteristics. Hence the characteristics of the $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes were consequently limited to % NA additions of 0.50% to 2.00% in differences of 0.50% in respectively succeeding trials and hence maintaining the % MK from 9.50% to 8.00% so as to hold the combined proportions of MK+NA as 10.00% by weight of binder content. $SCC_{HyFR-NA}$ Control recipe $SCC_{HyFR-NA0.00}$ and various investigated $SCC_{HyFR-NA}$ recipes in this study were confirmed for compressive-strength at many ages like 16-Hrs,1-day,3-days ,7-days ,28-days , 56-days , and 90days. Differences in compressive strength of the control mix $SCC_{HyFR-NA0.00}$ and several investigated $SCC_{HyFR-NA}$ recipes in this study, with age, with mention to % NA is presented in Table 5.29 and graphical representations of the same is presented in Graph 5.30. Also the compressive energy on the subjected specimen was terminated on observing the preliminary fine hairline crack on the surface. From the data of the above it can be perceived that, at 16-hrs the compressive-strength of $SCC_{HyFR-NA0.00}$ recipe was 19.30 N/mm^2. After related to the compressive-strengths of $SCC_{HyFR-NA0.00}$ recipes, the compressive-strengths of $SCC_{HyFR-NA}$ recipes(with %NA varied from 0.50% to 2.00%) raised for all the ages of test. The 16-Hrs compressive-strength of the prepared recipes of $SCC_{HyFR-NA}$ raised and were falling in the range from 22.40 N/mm^2 to 24.40 N/mm^2 and at 1-day the compressive-strength was 24.30 N/mm^2 for the same $SCC_{HyFR-NA0}$ recipe it was raised and was falling in the range from 25.60 N/mm^2 to 26.70 N/mm^2 for $SCC_{HyFR-NA}$ recipe for diverse combination of % NA from 0.50% to 2.00%. For all the investigated recipes of several $SCC_{HyFR-NA}$ recipes observed to exhibited the target 1-day compressive-strength > 25.00 N/mm^2 as well as the targeted mean strength >58.25 N/mm^2 at 28-days. Compressive-strength of all the recipes were progressively detected to be augmented from 1-day to 28-days and later on for the ages 28- days forwards to 90-days, the surge in compressive-strength was minimal as related to initial rise from 16-Hrs to 28-days. Further, it was detected that improvement in compressive- strength of all the recipes, with age, was fast during the early-ages of 16-hrs to 3-days and later on the improvement in compressive-strength was lesser for the ages of 7-days to 28-days. This was since of the occurrence of sensitive SCMs and highly sensitive SCM i.e. MK and NA correspondingly in the recipes, which responded rapidly during the hydration -reactions and also owing to chemical composition of having higher % Al_2O_3, higher fineness and fine sized particles [69,85]. $SCC_{HyFR-NA1.00}$ i.e. recipe consisting 1.00% NA+9.00% MK slightly exhibited acceptable mix for both early-age compressive-strength from 16-Hrs to 3-days as well as for improvement of the same at later on ages. The failure forms of the specimens were detected to be acceptable and the same is presented in Fig.5.33. In terms of MoE at 28-days the same trend of steady increase , as was perceived in compressive-strength results, for the SCC recipes of $SCC_{HyFR-NA}$ recipes observed.

Table 5.29

Compressive Strength Test Results of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipe

Sl. No	Compressive Strength (N/mm^2)							MoE(Ec) 10^3 N /mm^2
	Mix Code	1_{Day}	3_{Days}	7_{Days}	28_{Days}	56_{Days}	90_{Days}	28_{Days}
1	$SCC_{HyFR-NA0.00}$	24.30	33.50	54.90	58.80	59.84	59.88	35.20
2	$SC_{HyFR-NA0.50}$	25.60	36.10	56.20	66.20	70.20	70.26	35.90
3	$SC_{HyFR-NA1.00}$	26.20	38.20	56.80	66.90	70.60	70.64	36.30
4	$SCC_{HyFR-NA1.50}$	26.40	38.40	60.20	67.50	70.90	70.92	36.80
5	$SCC_{HyFR-NA2.00}$	26.70	39.40	60.90	67.90	71.40	71.47	37.10



Graph 5.30 Compressive-Strength of $SCCHyFR_{-NA0.00}$ and $SCC_{HyFR-NA}$ at various ages

Fig.5.33 Failure pattern under compression of SCCHyFR-NA0.00 and $SCC_{HyFR-NA}$ mix at 28-days

5.15.2 Tensile Splitting Strength(TSS)

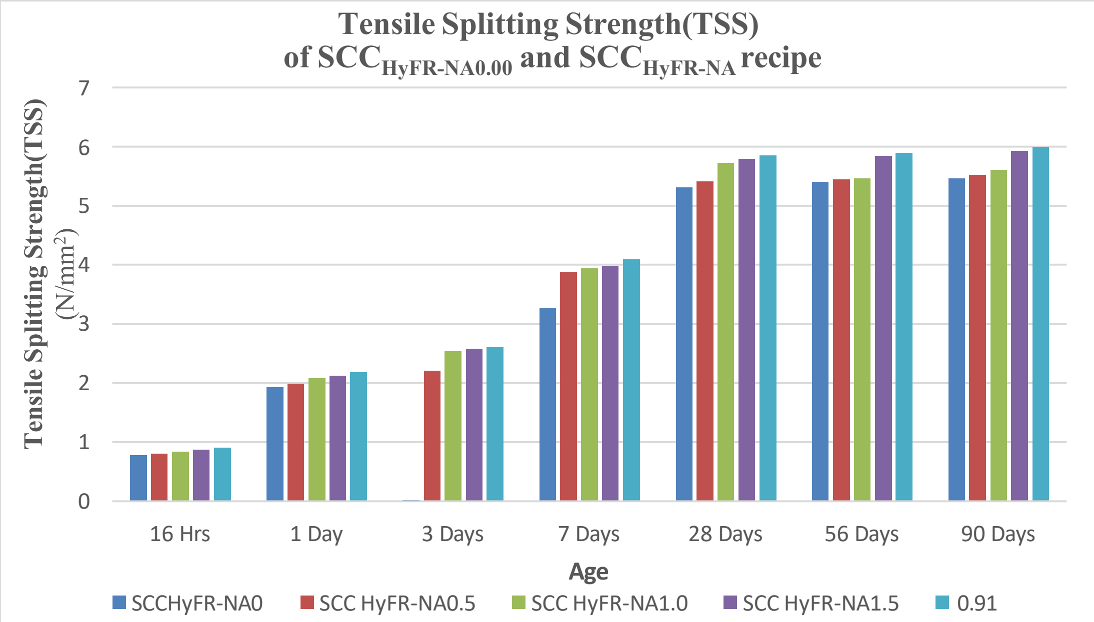
Control recipe $SCC_{HyFR-NA0.00}$ and various investigated $SCC_{HyFR-NA}$ recipes, in this study, were verified for TSS at various ages like 16-Hrs,1-day,3-days ,7-days ,28-days , 56-days and 90-days. Differences in TSS of the control recipe $SCC_{HyFR-NA0.00}$ and various investigated $SCC_{HyFR-NA}$ recipes, in this study, with age, with mention to % NA is presented in Table 5.30 and graphical representations of the same is presented in Graph 5.31. Also the tensile energy applied on the specimen was stopped on noticing the initial crack fine hairline on the surface. It can be perceived from the data of the above that, At 16-hrs the TSS of $SCC_{HyFR-NA0.00}$ recipe was 0.78 N/mm^2. When related to the TSS of $SCC_{HyFR-NA0.00}$ mix, the TSS of $SCC_{HyFR-NA}$ mix (with %NA varied from 0.50% to 2.00%) augmented for all the ages of test. The 16- Hrs. TSS of the resulted recipe of $SCC_{HyFR-NA}$ raised and was in the range from 0.81 N/mm^2 to 0.91 N/mm^2 and at 1-day the TSS was 1.93 N/mm^2 for the same $SCC_{HyFR-NA0.00}$ recipe. For $SCC_{HyFR-NA}$ having diverse combinations of % NA from 0.50% to 2.00%,the TSS was increased and was observed in the range from 1.99 N/mm^2 to 2.18 N/mm^2. All the investigated recipes of various $SCC_{HyFR-NA}$ have displayed the 1-day TSS >2.00 N/mm^2. The TSS of all the recipe were progressively detected improvement from 1-day to 28-days as well as for later on for the ages 28-days forwards to 90-days, the increase in strength was fringe as related to initial increase from 16-Hrs to 28-days. Further to this , it was also detected that, the improvement in the TSS of all the recipes, with age, was fast during the ages of 16-hrs to 3-days and later on the improvement in the TSS was sluggish for the ages of 7-days to 28-days. This was since of the existence of PP-F fibres and AR-F fibres above and beyond the existence of sensitive SCM and highly sensitive SCM i.e. MK and NA respectively in the recipe which responded quickly during the hydration-reactions[120] and also due to chemical composition having higher % Al_2O_3, higher fineness and fine sized particles [84,93].SCC$_{HyFR-NA1.00}$ i.e. mix consisting 1.00% NA +9.00% MK slightly displayed reasonable recipe for early age TSS from 16-Hrs to 3-days as well as for the TSS at later on ages. The failure forms of the specimens were noticed to be reasonable and the same is presented in Fig.5.34. SEM images of the control mix SCC$_{HyFR-NA0.00}$ and SCC$_{HyFR-NA1.00}$ mix at 16- Hrs,1-day age is presented in Fig.5.35. These results were in consistently inclined towards the consequence of observed enhanced test outcomes of the TSS in the SCC mix prepared with MK falling the range of 10.00%–15.00% [76]. But the lone dissimilarity of the present study was that during 7-days to 28-days ,the TSS was substantially different against the TSS of 28-days to 56-days. This was since the faster hydration-reaction of fine sized particles of MK during the early-ages up to 7-days and later on due to the secondary hydration-reactions of GGBFS till 28-days. Beyond 28-days the fringe rise in the TSS may be attributed to the near terminating of hydration-reactions in the investigated recipes.

Table 5.30

Split Tensile Strength Test Results of SCC$_{HyFR-NA0}$ and SCC$_{HyFR-NA}$ Mix

Sl. No	Tensile Splitting Strength (N/mm^2)							
	Mix code	16 $_{Hrs}$	1$_{Day}$	3$_{Days}$	7$_{Days}$	28$_{Days}$	56 $_{Days}$	90 $_{Days}$
1	SCC$_{HyFR-NA0.00}$	0.78	1.93	0.02	3.26	5.31	5.40	5.46
2	SCC $_{HyFR-NA0.50}$	0.81	1.99	2.21	3.88	5.41	5.44	5.52
3	SCC $_{HyFR-NA1.00}$	0.84	2.08	2.54	3.94	5.72	5.46	5.61
4	SCC $_{HyFR-NA1.50}$	0.87	2.12	2.58	3.98	5.79	5.84	5.92
5	SCC $_{HyFR-NA2.00}$	0.91	2.18	2.61	4.09	5.85	5.89	5.99

Fig.5.34 Tensile Splitting Strength(TSS) of SCC$_{HyFR-NA0.00}$ and SCC$_{HyFR-NA}$ recipe



Graph 5.31 Tensile Splitting Strength(TSS) of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipe

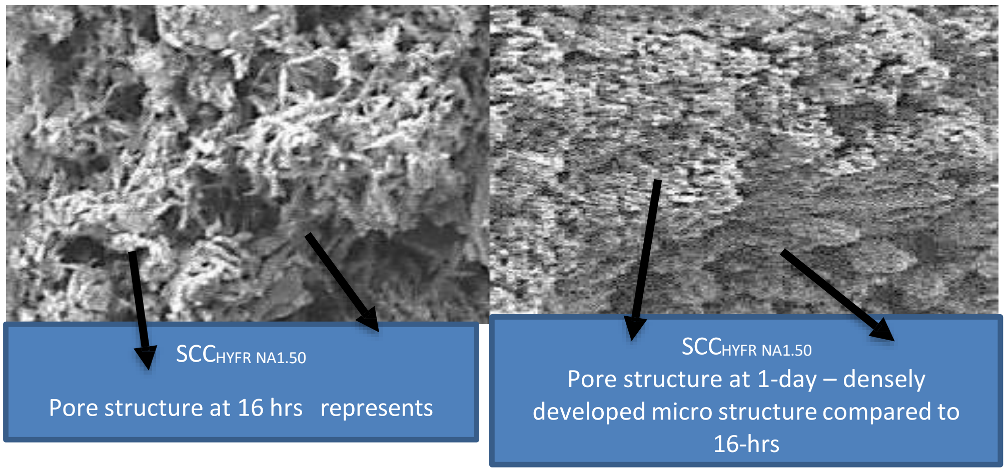


Fig.5.35

SEM pictures at 1-micron level of mortar(retrieved after TSS test)of $SCC_{HyFR-NA1.00}$ Mix at 16-hrs and at 1-day

5.16 Characteristics evaluated for durability of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes

5.16.1 Linear-Shrinkage (LS)

$SCC_{HyFR-NA0.00}$ and various investigated $SCC_{HyFR-NA}$ recipes, in this study, were verified for the linear-shrinkage (LS) , at various ages like 16-hrs,1-day,3-days ,7-

days ,28-days , 56-days and 90-days. Differences in LS of the $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes with age, with mention to % NA is presented in Table 5.31

Table 5.31
Linear-Shrinkage (LS)of $SCC_{HyFR-NA0.00}$ and various experimented $SCC_{HyFR-NA}$ recipes

Mix code	16-Hrs	1-day	3-Days	7-Days	28 -Days	56- Days	90 -Days
	%Linear-Shrinkage (LS)with respect to standard length gauge(-)						
$SCC_{HyFR-NA0.00}$	0.014	0.011	0.009	0.060	0.050	0.003	0.003
$SCC_{HyFR-NA0.50}$	0.009	0.008	0.007	0.007	0.007	0.005	0.005
$SCC_{HyFR-NA1.00}$	0.009	0.008	0.008	0.006	0.006	0.006	0.006
$SCC_{HyFR-NA1.50}$	0.009	0.008	0.006	0.006	0.006	0.006	0.006
$SCC_{HyFR-NA2.00}$	0.008	0.007	0.004	0.004	0.004	0.004	0.004

As perceived from the data of Table 5.31, the LS of control recipe $SCC_{HyFR-NA0.00}$, at 16-hrs and at 1-day, was (-) 0.014 and (-)0.011. When related to the LS of control recipe $SCC_{HyFR-NA0.00}$ the LS of recipe $SCC_{HyFR-NA}$ mix (with %NA varied from 0.50% to 2.00%) lessened for all the ages of tests. The LS of $SCC_{HyFR-NA}$ mix , for the tested ages, reduced from (-) 0.004 to (-)0.009. The 1-day minimum LS was (-)0.007 for $SCC_{HyFR-NA2.00}$. The maximum LS at 1-day was (-) 0.008 was for $SCC_{HyFR-NA0.50}$, $SCC_{HyFR-NA1.00}$ and $SCC_{HyFR-NA1.50}$. The LS of all the investigated $SCC_{HyFR-NA}$ recipes were gradually detected to be lessened from 1-day to 90- days. The LS of all the recipes was more during 1-day to 3-days and later on for the ages of 7- days to 56-days, the LS was slower. This was since of the existence of NA in adding to MK in the recipe which might has reacted quickly during the hydration-reactions and also due to chemical composition having higher % Al_2O_3, higher fineness and fine sized particle[97]. Later on fibres of PP-F and AR-F detained the LS since of nature of dispersal of these fibres in the combination[103]. These consequences were in arrangement with the explanations revealed in the study[96] wherein the beneficiation effect of reduction of LS of concrete was stated due to the existence of fibres in the ITZ area of concrete and the same can be seen through SEM images of the $SCC_{HyFR-NA1.50}$ mix at 16 Hrs. and at 1-Day as presented in Fig.5.35 correspondingly. $SCC_{HyFR-NA1.00}$ mix consisting 1.00% NA+9.00% MK marginally displayed less LS from 16-hrs. to 90-days.

5.16.2 Permeability

Permeability of $SCC_{HYFR\text{-}NA0.00}$ and $SCC_{HYFR\text{-}NA}$ recipes with variations individual % NA but keeping the grouping of (MK+NA) to 10.00 % by weight of total binder materials of proportioned recipes of $SCC_{HYFR\text{-}NA}$. Similar arrangements for testing of Permeability, as per IS 516(Part 2/Sec1):2018, shown in Fig.5.24 was adopted. Test results of permeability, on the experimented mix $SCC_{HYFR\text{-}NA0}$ and $SCC_{HYFR\text{-}NA}$, were carried on the specimens of 100mm diameter at 28-days is presented in Table 5.32. It can be seen from Table 5.32 that the permeability value for control mix $SCC_{HYFR\text{-}NA0}$ was $0.44*10^{-12}$ m^2/s and for the mix $SCC_{HYFR\text{-}NA0.5}$, where 9.50% MK +0.50% NA was furthered into the cementitious system, permeability was dipped to $0.41x10^{-12}$ m^2/s. This slight dip in the permeability was due to the inclusion of highly reactive NA [106.]. Similarly, as the individual NA content, in fibre groupings of MK and NA, was varied from 1.00 % to 2.00%, the resulted $SCC_{HYFR\text{-}NA1.00}$, $SCC_{HYFR\text{-}NA1.50}$ and $SCC_{HYFR\text{-}NA2.00}$ mix demonstrated further dip in the permeability extending from $0.37*10^{-12}$ m^2/s to $0.31*10^{-12}$ m^2/s consistent to the ordered of increase in %NA. The probable reasons for dip in the permeability of these mix can be consigned to the combined effect of groupings of MK+NA and predominance of NA's presence as nano sized reactive material causing densification of microstructure as compared to $SCC_{HYFR\text{-}NA0}$ with the increase of NA in the mix. This was in reasonable arrangement with the conclusions of the study[119] but with the only disparity was alumina nano fibres were used in that study on UHPFRC . In this study it was observed that the lessening in permeability was marginal beyond 1.50% of NA. Also as can be detected from the Table 5.30, the minimum permeability recorded was $0.31*10^{-12}$ m^2/s for $SCC_{HYFR\text{-}NA2.00}$ recipe.

5.16.3 Abrasion resistance

Testing arrangements of abrasion resistance of concrete, as per Annex E-IS 15658 :2021, are shown in Fig.5.30 were followed in the abrasion resistance test of $SCC_{HYFR\text{-}NA0.00}$ and $SCC_{HYFR\text{-}NA}$ recipes. Test outcomes of abrasion resistance of $SCC_{HYFR\text{-}NA0.00}$ and $SCC_{HYFR\text{-}NA}$ mix with variation with variations individual % NA but keeping the grouping of (MK+NA) to 10.00 % by weight of total binder materials of balanced $SCC_{HYFR\text{-}NA}$ recipes. It can be seen from Table 5.32 that, the abrasion resistance for control mix $SCC_{HYFR\text{-}NA0.00}$ was $4890mm^3$ per $5000mm^2$ and for the mix

$SCC_{HYFR-NA0.5}$, where 9.50% MK +0.50% NA was furthered into the binder system, abrasion resistance was increased to 4840mm^3 per 5000mm^2. This slight increase in abrasion resistance was due to the inclusion of highly reactive NA and was fairly in concurrence with the explored consequence of the study [76,109,126.] with lone disparity that graphene oxide was used as nano inclusion in that study. Similarly, as the individual NA content, in fibre groupings of MK and NA, was varied from 1.00 % to 2.00%, the resulted $SCC_{HYFR-NA1.00}$, $SCC_{HYFR-NA1.50}$ and $SCC_{HYFR-NA2.00}$ mix demonstrated further increase in abrasion resistance of resulting mix and the values were observed to be ranging from 4420mm^3 per 5000mm^2 to 4370mm^3 per 5000mm^2 corresponding to the ordered increase in NA content. The probable reasons for increase in abrasion resistance of these mix can be relegated to the combined effect of groupings of MK+NA and predominance of NA's presence as nano sized reactive material causing densification of microstructure as compared to $SCC_{HYFR-NA0}$ with the increase of NA in the mix. This was in reasonable arrangement with the conclusions of the study[122] but with the solitary difference was nano-alumina fibres were used in that study on UHPFRC. In this study it was observed that, the reduction in abrasion resistance was fringed beyond 1.50% of NA. As can be detected from the Table 5.30, the maximum recorded abrasion resistance was 4370mm^3 per 5000mm^2 for the recipe $SCC_{HYFR-NA2.00}$.

Table 5.32

Durability Properties of $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipes

Sl. No	Mix code	MK %	NA %	Maximum core Temperature ^0C	Time for reaching Maximum core Temperature Hrs	Average Near surface temperature ^0C	Temp Gradient ^0C	28-Days Water-Permeability 10^{-12} m^2/s	Abrasion resistance mm^3 per 5000 mm^2
1	$SCC_{HyFR-NA0.00}$	10.00	0.00	51.6	28.9	31.1	20.5	0.44	4890
2	$SCC_{HyFR-NA0.50}$	9.50	0.50	52.1	28.1	31.2	20.9	0.41	4840
3	$SCC_{HyFR-NA1.00}$	9.00	1.00	52.6	25.7	31.6	21.0	0.37	4420
4	$SCC_{HyFR-NA1.50}$	8.50	1.50	52.9	25.2	31.4	21.5	0.33	4390
5	$SCC_{HyFR-NA2.00}$	8.00	2.00	53.7	23.8	32.2	21.5	0.31	4370

5.16.4 Adiabatic Rise in Temperature and Temperature Gradient (Difference in Temperature from Core to near surface)

Adiabatic rise in temperature study was carried as per the provisions of IS 7816 and the test arrangements made was similar as discussed above under 5.3.4. The test arrangements were similar to 5.3.4 and was made as such that required to monitor the rise in temperature, maximum time required for attaining the temperature gain etc., which were the prime requirements to series of $SCC_{HYFR-NA0}$ and $SCC_{HYFR-NA}$ mix . Temperature-history was incessantly recorded after the adding of water to binder from 30.00 minutes to 30.00 hrs period. The temperature-gradient, i.e. temperature difference between inner-core and near-surface of concrete, for the experimented series of recipes. Table 5.32 represents the test results of adiabatic rise in temperature of $SCC_{HYFR-NA0.00}$ and $SCC_{HYFR-NA}$ recipes with variation individual % NA however keeping the grouping of MK+NA to 10.00% by weight of total binder materials of formulated recipes of $SCC_{HYFR-NA}$. It can be understood from the data of Table 5.32 that the temperature of core for control recipe for $SCC_{HYFR-NA0.00}$ was 51.6^{0}C and for the mix $SCC_{HYFR-NA0.5}$, where 9.50% MK +0.50% NA was furthered into the cementitious system, abrasion resistance was increased to 52.1^{0}C. This slight rise in core temperature was due to the addition of highly reactive NA and was equally in consensus with the study outcome of [118] with solitary difference that 5.00% Nano alumina of ϒ-phase was used in that study. Similarly, as the individual %NA, in fibre groupings of MK and NA, was varied from 1.00 % to 2.00%, the resulted $SCC_{HYFR-NA1.00}$, $SCC_{HYFR-NA1.50}$ and $SCC_{HYFR-NA2.00}$ mix established additional increase in core-temperature of resulting recipes and the values were observed to be ranging from 52.6^{0}C to 53.7^{0}C corresponding to the ordered increase in NA content. The probable reasons for increase in abrasion resistance of these mix can be relegated to the combined effect of groupings of MK+NA and predominance of NA's presence as nano sized reactive material causing acceleration in hydration reactions and thus densification of microstructure as compared to $SCC_{HYFR-NA0.00}$ with the increase of NA in the mix. This was in reasonable arrangement with the conclusions of the study[120] but with the only difference was nano fibres were used in that study along with alumina. In this present study , as can be observed from the Table 5.30, the maximum recorded core-temperature was 53.7^{0}C for the mix $SCC_{HYFR-NA2.00}$.

5.16.5 Confrontation to enlargement of specimens on dipping in Sulphate-solution

$SCC_{HyFR\text{-}NA0.00}$ and various investigated $SCC_{HyFR\text{-}NA}$ recipes in this study were verified, at various ages like 7-days ,28-days and 56-days, for expansion of specimens[hardened-mortar] on dipping in to solution of Na_2SO_4 (sulphate as SO_3^-). The higher the enlargement of specimen the smaller will be the confrontation against ingression of sulphate-ions. Differences in enlargement of specimens of the control recipe $SCC_{HyFR\text{-}NA0.00}$ and $SCC_{HyFR\text{-}NA}$ mix with age , with mention to % NA are presented in Table 5.33.

Table 5.33

Confrontation to enlargement of specimens on dipping in Sulphate-solution of $SCC_{HyFR\text{-}NA0.00}$ and various experimented $SCC_{HyFR\text{-}NA}$ recipes

Mix code	% Enlargement in length(*10^2)		
	7-Days	28-Days	56-Days
$SCC_{HyFR\text{-}NA0.00}$	0.090	0.050	0.050
$SCC_{HyFR\text{-}NA0.50}$	0.060	0.060	0.050
$SCC_{HyFR\text{-}NA1.00}$	0.050	0.040	0.030
$SCC_{HyFR\text{-}NA1.50}$	0.040	0.040	0.030
$SCC_{HyFR\text{-}NA2.00}$	0.040	0.040	0.030
$SCC_{HyFR\text{-}NA2.50}$	0.040	0.040	0.030
$SCC_{HyFR\text{-}NA3.00}$	0.030	0.030	0.010

From the data of the above Table 5.33 , was detected that, for $SCC_{HyFR\text{-}NA0.00}$ recipe specimen, the enlargement (i.e. change in length) was 0.008mm with respect to the measured length at 1- day. Related to the enlargement of specimens of $SCC_{HyFR\text{-}NA0\cdot00}$ the enlargement of specimens of $SCC_{HyFR\text{-}NA}$ recipe reduced during the all ages. At 7-days, the enlargement of the specimens of all the recipes was more and later on, for the ages of 28- days to 56 -days, the enlargement of the specimens were detected to be gentler. This was since the existence of NA in adding to MK in the recipe responding quickly through the hydration-reactions and also due to chemical nature of having higher %Al_2O_3, higher fineness and finer sized particles. Higher specific surface area of the NA and MK might have also aided in pore structure refinement and which in turn might has offered confrontation against infiltration of foreign-materials in to the body of the specimens. These results were seemingly supportive with the interpretations as stated in the study[132]. Further to this, during the periods beyond 7-days, PP-F and AR-F fibres were pragmatic in arresting the variation in length of the specimen since of nature of dispersal of these fibres in the mix as confirmed through the photo micro graphs and SEM images as presented in the Fig.5.35.

5.16.6 Confrontation to penetration of Chloride (Cl^-) ion

$SCC_{HyFR-NA0.00}$ and various tested $SCC_{HyFR-NA}$ recipe, in this study were verified, at ages like 7-days ,28-days and 56-days, for %Cl^- ion content in the concrete core-specimens extracted at 7-days ,28-days and 56-days from the slab samples casted of recipe of $SCC_{HyFR-NA0.00}$ and various experimented $SCC_{HyFR-NA}$ recipes. Differences in %Cl^- in concrete core-specimens of the $SCC_{HyFR-NA0.00}$ and $SCC_{HyFR-NA}$ recipe with age, with mention to % of NA is presented in in Table 5.34. For the control recipe $SCC_{HyFR-NA0.00}$, the %Cl^- of the extracted concrete core- specimen, at 7-days of ponding, was $9*10^{-3}$. Compared to the %Cl^- of extracted concrete core- specimens of the control recipe $SCC_{HyFR-NA0.00}$, the %Cl^- of extracted concrete core- specimens of $SCC_{HyFR-NA}$ mix , detected to be lessened during the all-ages of ponding with the solution. The %Cl^- of $SCC_{HyFR-NA}$ recipe decreased from 0.050% to 0.010% at 56-days of ponding. The minimum %Cl^- at 56-days age of ponding was 0.0010 for $SCC_{HyFR-NA3.0}$. Maximum Cl^- ion content at 56 days age was 0.005 for $SCC_{HyFR-NA0.5}$. The of all the specimens of experimented mix of $SCC_{HyFR-NA0}$ and various experimented $SCC_{HyFR-NA}$ mix were gradually observed to be decreased from 7 days to 56 days. the %Cl^- of the specimen of all the recipe was more during 7-days and for later on for the ages of 28-days to 56-days, it was reduced regularly. This drop in the %Cl^- was because of the existence of NA and MK in the mix which responds rapidly during the hydration-reactions and also due to chemical composition having higher % Al_2O_3, higher fineness and finer sized particles. Higher specific surface area of the NA and MK might has added aid in pore-refinement and which in turn propositioned confrontation against dispersion of foreign-materials in to the body of concrete. These consequences were confirmative with the outcome of the study. Existence of PP-F and AR-F in the recipe might further improved the resistance to the infiltration of Cl^- in to the specimens since of nature of dispersal of these fibres in the recipe.

Specimens of SCC $_{HyFR-NA1.00}$ i.e. mix consisting 1.00% NA + 9.00% MK slightly displayed a bit uniform confrontation to Cl^- ion infiltration from 7-day to 56-days.

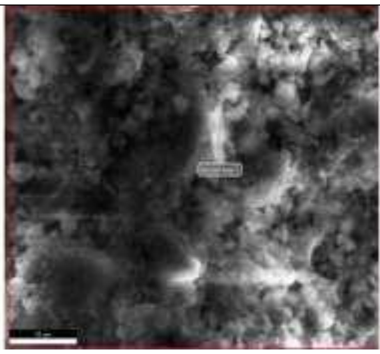
Table 5.34

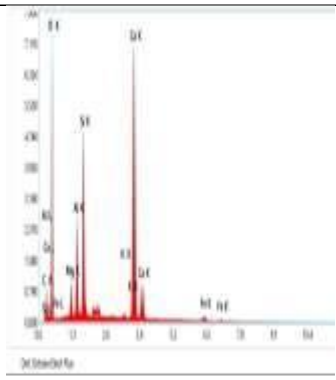
Resistance to Chloride ion ingression of SCC$_{HyFR-NA0}$ and various experimented SCC$_{HyFR-NA}$ mix

Mix Code	% Cl^- in 40mm thick concrete-core		
	7-Days	28-Days	56-Days
SCC$_{HyFR-NA0.00}$	0.009	0.006	0.005
SCC $_{HyFR-NA0.50}$	0.005	0.005	0.005
SCC $_{HyFR-NA1.00}$	0.005	0.005	0.005
SCC $_{HyFR-NA1.50}$	0.005	0.005	0.003
SCC $_{HyFR-NA2.00}$	0.004	0.004	0.003

5.16.7 Microstructure Development of SCC$_{HyFR-NA}$ Recipes at early age(1-Day)

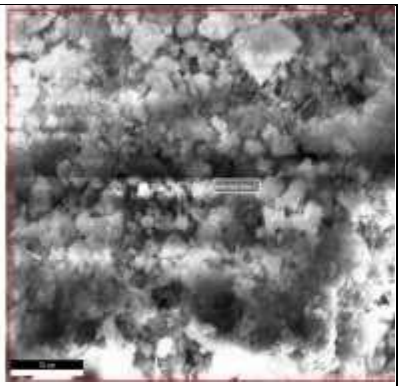
Microstructure Development of SCC$_{HyFR-NA}$ recipes at early age(1-Day) was studied with the help of 'EDX'(Energy dispersive X-ray Spectroscopy) which affords primary configurations of a reacted matrix. On a SEM image of a matrix under the exploration, a tiny area of interest chosen and focused closely to get the elements present in that tiny area and the elements are conveniently indicated in a graphical pattern where abscissa designates the vitality of ionisation whereas ordinate directs the reckonings. A sophisticated reckoning of an individual constituent represents its higher occurrence in that reacted matrix. The Microstructure Development of SCC$_{HyFR-NA}$ recipes at early age(1-Day) is presented under Fig.5.36. It was observed that that with increasing percentage of NA from 0.50% to 1.50% in the SCC$_{HyFR-NA}$ recipes, 'Si' reckoning became improved and 'Ca' reckoning became varied due to ingestion in pozzolonic response and formation of 'C-S-H' and 'C-A-S-H' gel. This outcome tallies with the study [68] wherein the only variation was that microsilica was used as high reactive SCM.

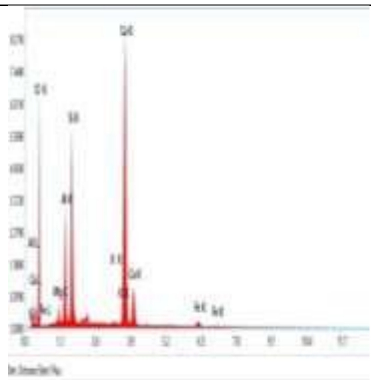




Element	Weight %	Atomic %
C K	5.3	8.7
O K	54.5	68.1
Mg K	1.8	1.5
Al K	4.3	3.2
Si K	7.8	5.5
K K	0.3	0.1
Ca K	25.2	12.6

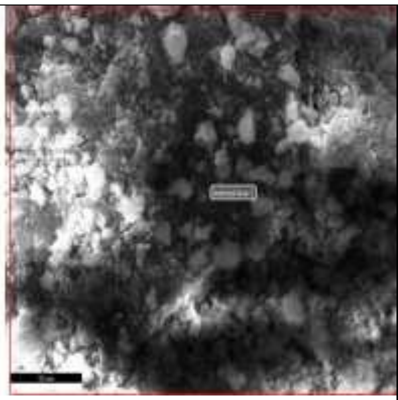
(a)Hy$_{FSCCNA0.5}$

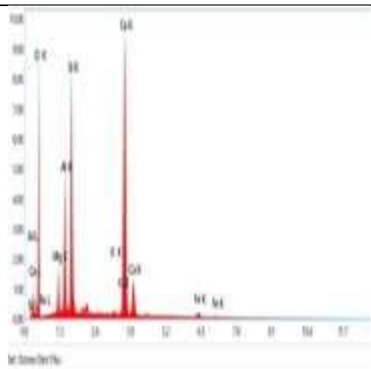




Element	Weight %	Atomic %
O K	52.8	71.0
Mg K	1.0	0.9
Al K	5.6	4.5
Si K	8.9	6.8
K K	0.3	0.1
Ca K	30.2	16.2
Fe K	1.3	0.5

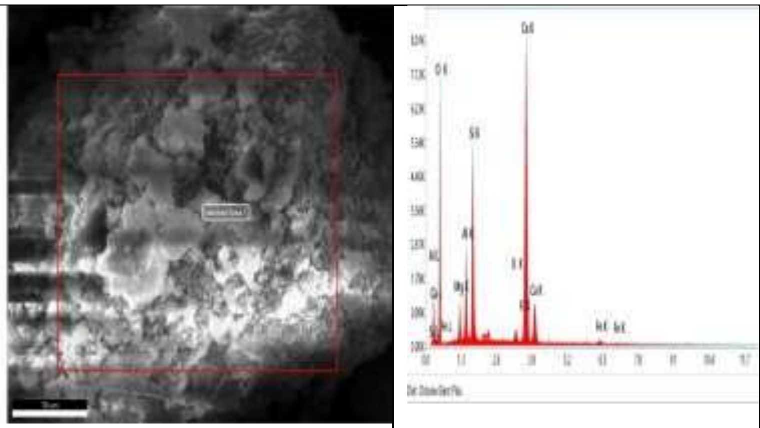
(b)Hy$_{FSCCNA1.0}$





Element	Weight %	Atomic %
O K	51.8	69.5
Mg K	2.4	2.1
Al K	6.4	5.1
Si K	10.6	8.1
K K	0.3	0.2
Ca K	27.5	14.7
Fe K	1.0	0.4

(c)Hy$_{FSCCNA1.5}$



Element	Weight %	Atomic %
O K	54.9	72.7
Mg K	2.0	1.7
Al K	4.1	3.3
Si K	8.2	6.2
K K	0.9	0.5
Ca K	29.1	15.4
Fe K	0.8	0.3

(d)$Hy_{FSCCNA2.0}$

Fig.5.36 Microstructure Development of $SCC_{HyFR-NA}$ Recipes at early age(1-Day)

5.17. Summary of tests of part replacement of OPC with GGBFS+MK+NA in grouping with PPF- Fibre and ARF- Fibre on properties of SCC

Constructed on the fresh-state tests, mechanical-tests at various ages from 1-day to 56- days and durability-tests directed from 7-days to 56-days age ,the subsequent inferences were made:

1) For the $SCC_{HyFR-NA}$ mix (consisting of total 1.00% hybrid fibre content of 0.50%PP-F +0.50%AR-F), as the %NA was increased, Slump-flow reduced, 'V' funnel-flow time increased, 'L' Box blockade ratio reduced and segregation-resistance augmented as related to $SCC_{HyFR-NA0.00}$ mix.
2) The mix terminated to validate SCC characteristics beyond 2.00% of NA adding in association with MK consisting a reactive MK and highly reactive NA wherein total %MK+%NA was maintained at 10.00%.
3) Compared to control recipe $SCC_{HyFR-NA0.00}$, as the %NA was increased, the time required for initial set as well as time for final set lessened in the $SCC_{HyFR-NA}$ mix,
4) As the % NA increased ,the compressive-strength and tensile splitting strength increased, for all the ages, in the $SCC_{HyFR-NA}$ mix.
5) Durability characteristics of the $SCC_{HyFR-NA}$ mix like linear shrinkage, resistance to SO_3^- and Cl^- ion ingression were observed to be decreased with the increase in the %NA, in association with MK forming a total high reactive SCM content of 10.00%.

CHAPTER 6

FIELD STUDIES ON SCC_{HyFRNA} RECIPE

6.0 General

Experiments and tests carried in field on SCC_{HyFRNA} mix of this research study is presented and discussed in this chapter.

6.1 Field Studies on SCC_{HyFRNA} Recipe

Based on the performance, after various laboratory scale tests, results of SCC_{HyFRNA} recipe conducted and discussed in Chapter No.5, the following SCC_{HyFRNA} recipes were selected for field testing for various parameters. The plan of various field studies conducted, details of mix proportioning, fresh state properties and hardened state properties of SCC_{HyFRNA} mix is presented in Table 6.1, Table 6.2 and Table 6.3.

Table 6.1

Proportions of SCC_{HyFRNA} recipe selected for the field studies

Mix Code	Cementitious Material(cm)/Binding Materials(BM) proportion				Fibre composition (volumetric%)		Material Proportions(Kg/m^3)				
	OPC-53 Gr (%)	GGBFS (%)	MK (%)	NA (%)	PP Fibre 6mm (%)	AR Fibre 12mm (%)	Total BM	CA 10mm	Sand (FA)	PCE Admixture	Free Water
$SCC_{HyFR-NA0}$	50	40	10	0	0.5	0.5	560	750	915	6.60	190
$SCC_{HyFR-NA0.5}$	50	40	9.5	0.5	0.5	0.5	560	750	915	7.56	190
$SCC_{HyFR-NA1.0}$	50	40	9.0	1.0	0.5	0.5	560	750	915	7.56	190
$SCC_{HyFR-A1.5}$	50	40	8.5	1.5	0.5	0.5	560	750	915	7.56	190
$SCC_{HyFR-A2.0}$	50	40	8.0	2.0	0.5	0.5	560	750	915	7.56	190

6.2 Shrinkage(Linear) at various ages of the selected SCC_{HyFRNA} mix

Shrinkage(linear), an important performance requirement for concrete subjected to natural factors like wind, temperature etc.

6.2.1 Procedure adopted for Shrinkage Test at site conditions

The selected mix proportions, as listed under Table 6.1 ,were chosen for evaluation of linear shrinkage with time where in the specimens were subjected to open environment and covered till the final setting time for the mix category as arrived in final setting time test as presented in Table 6.4. 1 No. of prismatic specimen, for each category of mix, of length 300mm X width 75mmX 75 mm thickness was casted in moulds with reference pins at each end and left open to environment, after final setting time, to simulate field conditions. For each such casted prismatic specimen, change in length was measured for the periods 16 Hrs,1days,3days,7days,28 days and 56 days using length comparator and the readings were recorded accordingly. Fig.6.1 and Fig.6.2 represents the specimens and shrinkage(Linear) carried at various ages of the selected SCC_{HyFRNA} mix.

Table6.2
Fresh state properties of the selected SCC_{HyFRNA} mix

Sl. No	Identity of Recipe	Rheology					
		Slump flow	V_{Funnel} Flow-Time	Flow Ratio through L shaped Box	SR	Time required for Initial Set	Time required for Final Set
		mm	Sec'	h2/h1	%	Minutes	Minutes
1	$SCC_{HyFR-NA0}$	645	12	0.94	14.0	480	540
2	$SCC_{HyFR-NA0.5}$	635	18	0.90	14.4	380	500
3	$SCC_{HyFR-NA1.0}$	600	20	0.88	14.7	350	460
4	$SCC_{HyFR-NA1.5}$	570	22	0.86	14.9	330	430
5	$SCC_{HyFR-NA2.0}$	550	25	0.75	15.0	320	410

Table 6.3
Early age strength of the selected SCC_{HyFRNA} mix

Sl. No	SCC ID	Compressive Strength				Split Tensile Strength			
		16 hr	1 Day	'3' Days	'7' Days	16 hr	24 hrs	'3' Days	'7' Days
		N/mm²				N/mm²			
1	SCC $_{HyFR-NA0}$	16.42	16.52	27.91	44.02	1.17	1.21	1.36	1.55
3	SCC $_{HyFR-NA0.5}$	17.04	17.16	29.38	49.84	1.34	1.40	1.42	1.51
3	SCC $_{HyFR-NA1.0}$	16.96	17.05	29.41	49.67	1.30	1.49	1.54	1.68
4	SCC $_{HyFR-NA1.5}$	16.91	16.96	29.43	48.29	1.31	1.46	1.51	1.61
5	SCC $_{HyFR-NA2.0}$	16.82	16.91	29.46	48.36	1.37	1.48	1.56	1.72

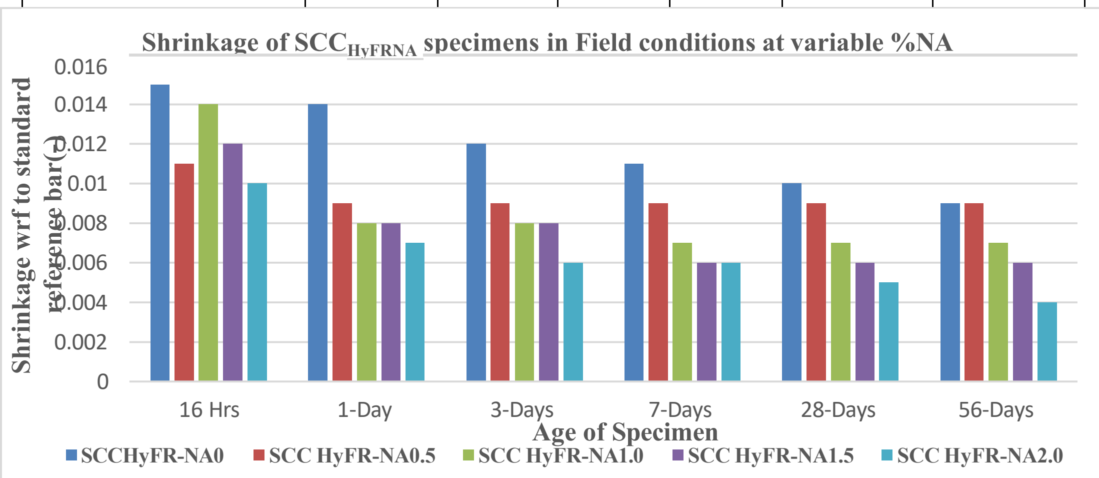
Fig.6.1 Prismatic Specimens of SCC_{HyFRNA} recipe for Shrinkage Test

Fig.6.2 Shrinkage test Specimens of SCC_{HyFRNA} using length comparator

Table 6.4

Shrinkage at various ages of the selected SCC_{HyFRNA} recipes

Mix ID	16 Hrs	1Day	3Days	7Days	28 Days	56 Days
	%Shrinkage with reference to standard reference bar of 300mm (-)					
$SCC_{HyFR-NA0}$	0.017	0.015	0.087	0.061	0.052	0.036
$SCC_{HyFR-NA0.5}$	0.011	0.009	0.009	0.009	0.009	0.009
$SCC_{HyFR-NA1.0}$	0.014	0.008	0.008	0.007	0.007	0.007
$SCC_{HyFR-NA1.5}$	0.012	0.008	0.008	0.006	0.006	0.006
$SCC_{HyFR-NA2.0}$	0.010	0.007	0.006	0.006	0.005	0.004



Graph 6.1 Shrinkage of SCC_{HyFRNA} specimens in Field conditions at variable %NA

It can be seen from the Table 6.4 and Graph 6.1 that the shrinkage of all SCC_{HyFRNA} mix containing reactive and highly reactive SCM combinations of MK + NA, in various proportions resulted in less shrinkage, as compared to control sample and other category of mix, for all the periods of tests from 16hrs to 56days.It was also observed that the SCC $_{HyFR-NA1.5}$ mix containing 8.5% MK + 1.5% NA has resulted reasonably less has resulted less shrinkage compared to other SCC_{HyFRNA} mix.

6.3 German Angle Test at various ages of the selected SCC_{HyFRNA} recipe

This test involves of pouring of concrete mix, under test, in a MS angle having the dimensions as shown in Fig.6.3 .This test mainly intended to measure the bond between new concrete with a rigid substrate. To simulate rigid substrate MS angle was used in a study and the same method is adopted in this study to evaluate the bond of various SCC_{HyFRNA} recipe with the rigid substrate like the MS angle. Firstly, the MS angle was thoroughly cleaned to remove loose scale, oil, grease etc., unwanted materials by a suitable method like abrading the inside surface of MS angle with sand paper and dusting off the same. In the original method of German angle test, bond agent was rubbed to the interior surfaces before casting. But, in this study no such coating was applied and only slightly moistening the inner surface was done before pouring the SCC_{HyFRNA} recipe. 1 No. specimen was cast in MS angle for each category of mix. The specimens were covered with polythene sheet till the final setting time, as arrived and presented in Table 6.2, after this the polythene sheet was removed and the specimens were left open to environment and observed for 56 days for failures, if any, like de bonding, appearance of cracks etc. Fig.6.3 represents SCC $_{HyFR-NA1.5}$ mix as casted in this test and Table 6.5 shows the test results of German angle test.

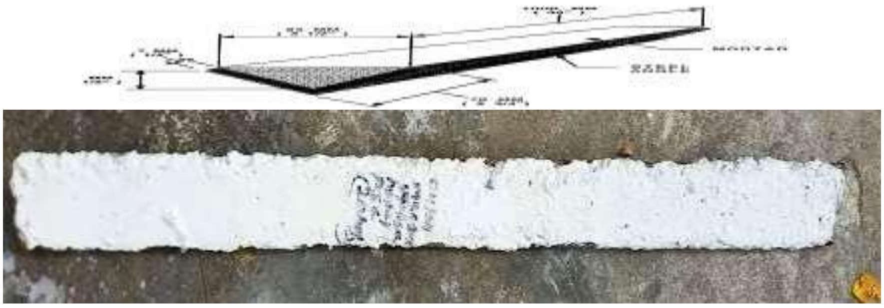


Fig.6.3 German Angle Test on SCC $_{HyFR-NA1.5}$

Table 6.5
German Angle test at various ages of the selected SCC$_{HyFRNA}$ recipe

Mix ID	16 Hrs	1Day	3Days	7Days	28 Days	56 Days
	Visual observation for signs of debonding, cracks etc					
SCC$_{HyFR-NA0}$	No	No	No	No	No	No
SCC $_{HyFR-NA0.5}$	No	No	No	No	No	No
SCC $_{HyFR-NA1.0}$	No	No	No	No	No	No
SCC $_{HyFR-NA1.5}$	No	No	No	No	No	No
SCC $_{HyFR-NA2.0}$	No	No	No	No	No	No

It can be observed from the above table that all the mix categories passed this test satisfactorily. No cracking or de-bonding was observed both in the initial ages and at 56 days.

6.4 SPS Plate Test(SPT) at various ages of the selected SCC$_{HyFRNA}$ recipe

The SPS Plate Test (SPT)was used to estimate the net warp of concrete under test against restrained shrinkage. SPT consist of a MS Channel of length 1320 mm having 2 no.s of holes of suitable size spaced diagonally at 150mm as shown in Fig.6.4. The dimensions of MS channel were 50mmX 100mm X1.5mm thickness. These holes in the channel was intended for tightening of bolts using a 50mmX100mmX1.5mm thick MS plate having coinciding holes as of above MS channel for passing the bolts through it. The casted specimen thickness was 50mm and was forming a shape of beam. The casted beam specimens were fixed with tightening of bolts at one end, using the above MS plate, to resemble a free cantilever of length 1170mm.In the original test an epoxy bonding compound was applied to the exterior surface of channel before casting the specimen. But in this study no such coating was applied and only slightly moistening exterior surface of channel was done before pouring the SCC $_{HyFR-NA}$ mix. 1 No. of specimen on MS channel was cast for each category of mix. The specimens were covered with polythene sheet till the final setting time, as arrived and presented in Table 6.2, after this the polythene sheet was removed and the casted specimens were left open to environment and observed for 56 days for failures, if any, like de bonding, appearance of cracks, tip deflection against restraint etc. Fig. 6.4 represents SCC $_{HyFR\text{-}NA1.5}$ mix as casted in this test and Table 6.6 shows the test results of SPT .

Fig.6.4 SPS Plate test on SCC$_{HyFRNA}$ specimen

Table 6.6
SPT at various ages of the selected SCC$_{HyFRNA}$ mix

Mix ID	16 Hrs	1Day	3Days	7Days	28 Days	56 Days
	Observation for signs of debonding, cracks, tip deflection etc.,					
SCC$_{HyFR\text{-}NA0}$	0.00	0.00	0.00	0.07	0.07	0.08
SCC $_{HyFR\text{-}NA0.5}$	0.00	0.00	0.00	0.04	0.04	0.04
SCC $_{HyFR\text{-}NA1.0}$	0.00	0.00	0.00	0.04	0.04	0.04
SCC $_{HyFR\text{-}NA1.5}$	0.00	0.00	0.00	0.00	0.00	0.00
SCC $_{HyFR\text{-}NA2.0}$	0.00	0.00	0.00	0.00	0.00	0.00

It can be observed from the above table that all the mix categories passed this test satisfactorily as the tip deflection was negligible. No cracking or de-bonding was observed both in the initial ages and at 56 days.

6.5 Abrasion Resistance Test at various ages of selected SCC$_{HyFRNA}$ recipe

Abrasion resistance, an important performance requirement for concrete subjected to rolling loads and other abrasive loads repetitive in nature. For instance concrete pavements, bridge decks are exposed to quite aggressive actions from moving traffic.

6.5.1 Procedure of Abrasion Resistance Test

The selected mix proportions as listed under Table 6.1 were selected for evaluation of abrasion resistance test. 1 No. of slab specimen, for each category of mix for each period of test, of size 500mm X300X 200 mm thickness was cast and was subjected to abrasion using a floor polishing machine. In each case revolutions 2850 $\pm$ 10 to simulate the accelerated abrasion of filed situations.

a. Before start of test each slab specimens was marked at centre and initial reading was taken with a digital depth gauge and the reading then set to zero.

b. For each period of abrasion resistance test ,the slab specimens was subjected to 2850 $\pm$ 10 wheel revolution.

c. After abrasive rotation of the wheel of the machine, the average depth of 8 nos. randomly chosen locations, on the tested slab specimen, were recorded with digital depth gauge as the depth of abrasion of the slab specimen for the age of test.

Table 6.7 represents the abrasion resistance observations and can be that the abrasion resistance of SCC_{HyFRNA} recipe having mix ID SCC $_{HyFR\text{-}NA1.5}$ i.e. mix containing highly reactive SCM combinations of MK at 8.5% +NA at 1.5% resulted satisfactory abrasion resistance for all the periods of tests from 16hrs to 56days.It was also observed that the SCC $_{HyFR\text{-}NA1.5}$ mix has resulted less has resulted less abrasion and demonstrated high abrasion resistance to abrasive loads. Fig.6.5 and Fig.6.6 represents the Abrasion Resistance Test carried on SCC $_{HyFR\text{-}NA1.5}$ recipe at 7 days age.

6.6 Laval Beam Deflection Test(LBDT) at various ages of the selected SCC_{HyFRNA} recipe

The Laval Beam Deflection Test (LBDT) consists of an Aluminum angle of 1000mm length and having a size of 50mmX100mmX1.5mm thickness. A hole, of suitable size, at the centre of the aluminum angle to be made in order to permit the stem of the digital dial gauge and an arrangement of suitable clamp to be made available to seat the dial gauge firmly in to the hole of the angle. This test was intended to evaluate the performance of SCC_{HyFRNA} recipe against the deflection under self weight in a simply supported beam specimen ,casted to sizes of length 1000mmX 100mm width x 50mm thickness, during the various periods of age. 1 No. of such beam specimen was casted for each category of recipe. The specimens were covered with polythene sheet till the final setting time, as arrived and presented in Table 6.2, after this the polythene sheet was removed and the casted specimens were coated with thin paraffin wax coating on all the surfaces except top. After drying of the paraffin wax ,the specimens were placed on suitable supports to resemble a simply supported beam. All such beams were then left open to environment and observed for 56 days for failures, if any, like appearance of cracks, deflection. Fig.6.7 and Fig.6.8 represents SCC $_{HyFR-NA1.5}$ recipe as casted in this test and Table 6.8 shows the test results of LBDT.

Table 6.7

Abrasion resistance test at various ages of the selected SCC$_{HyFRNA}$ mix

Mix ID	Initial Depth Gauge Reading (mm)	Final Depth Gauge Reading (Average of 8 readings)(mm)					
		After Abrasion Test at various age after casting					
	Before test	16 Hrs	1Day	3Days	7Days	28 Days	56 Days
SCC $_{HyFR-NA0}$	0.0000	0.0792	0.0691	0.0618	0.0527	0.0238	0.0232
SCC $_{HyFR-NA0.5}$	0.0000	0.0623	0.0585	0.0512	0.0402	0.0389	0.0376
SCC $_{HyFR-NA1.0}$	0.0000	0.0476	0.0382	0.0317	0.0216	0.0198	0.0189
SCC $_{HyFR-NA1.5}$	0.0000	0.0382	0.0264	0.0162	0.0133	0.0130	0.0128
SCC $_{HyFR-NA2.0}$	0.0000	0.0379	0.0218	0.0160	0.0131	0.0127	0.0122

Fig. 6.5 Abrasion Resistance Test of SCC $_{HyFR-NA1.5}$ Mix at 7 days

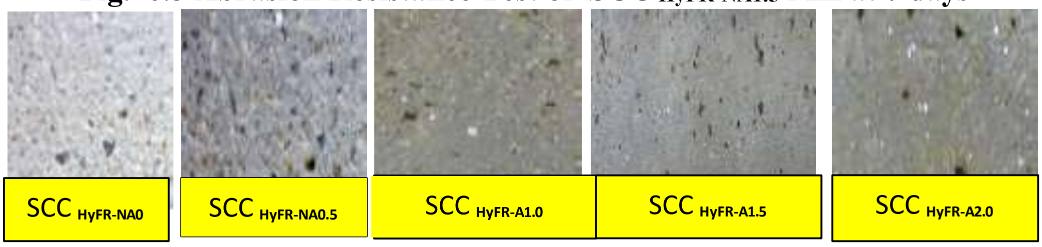


Fig. 6.6 Photo micrographs at 1000X magnification after Abrasion Resistance Test of SCC $_{HyFR-NA1.5}$ Mix at 7 days

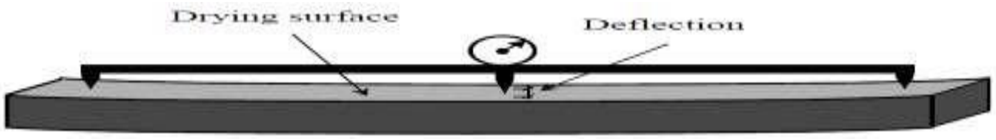


Fig. 6.7 Schematic view of Laval Beam Deflection Test(LBDT) of specimens

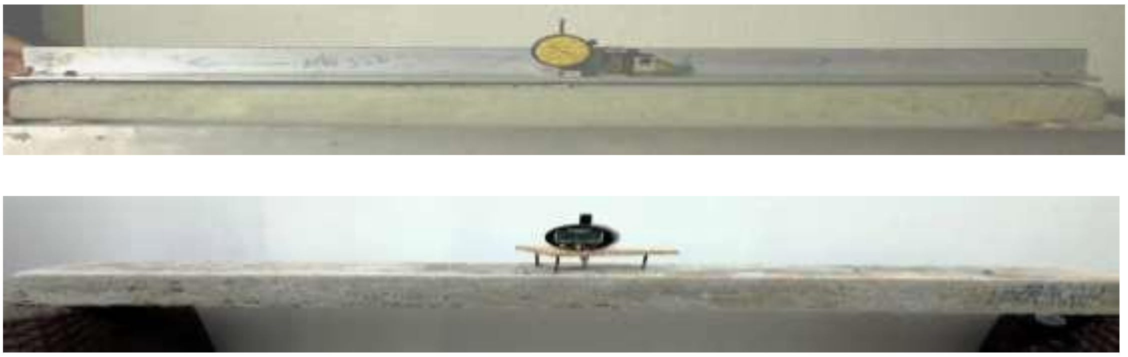


Fig. 6.8 Laval Beam Deflection Test(LBDT) of SCC_{HyFRNA} Mix specimens

Table 6.8
Laval Beam Deflection (LBD) at various ages of the selected SCC_{HyFRNA} mix

Mix ID	16 Hrs	1Day	3Days	7Days	28 Days	56 Days
	Observation for signs of debonding, cracks, Laval Beam Deflection (LBD)					
$SCC_{HyFR-NA0}$	0.00	0.00	0.00	0.09	0.09	0.09
$SCC_{HyFR-NA0.5}$	0.00	0.00	0.00	0.06	0.06	0.06
$SCC_{HyFR-NA1.0}$	0.00	0.00	0.00	0.06	0.06	0.06
$SCC_{HyFR-NA1.5}$	0.00	0.00	0.00	0.04	0.03	0.03
$SCC_{HyFR-NA2.0}$	0.00	0.00	0.00	0.03	0.03	0.03

It can be observed from the above table that all the mix categories passed this test satisfactorily as the tip deflection was negligible. No cracking was observed both in the initial ages and at 56 days.

6.7 Rate of Carbonation at various ages of the selected SCC_{HyFRNA} mix

The chemical response amongst CO_2 and forms of hydration out comes dissolved in the concrete pore water, particularly with $Ca(OH)_2$. Over a period of time, depending upon the porosity of concrete CO_2 concentrations in atmosphere or the subjected exposure conditions of concrete, carbonation reduces the P^H of concrete pore solution from approximately 13 to < 9. This change in P^H of concrete destabilises the passive oxide film, formed while casting of concrete, on the surface of the steel reinforcement, allowing the chances of reinforcement to corrode. A simple indicator spray test using phenolphthalein as indicator. If concrete's P^H< 8.5, there will be no colour change .If on spraying the phenolphthalein on the exposed concrete surface, if the colour turns out to be deep pink it indicates that P^H>8.5 . Phenolphthalein spray test was conducted on the core specimens that were extracted from the panels, which after casting were left open to atmosphere for 365 days. Carbonation depth study was conducted on the core specimen of 100mm diameter and depth of core was approximately 100mm. Concrete cores extracted from the casted specimen at various time intervals from 7 days to 365 days and immediately after taking out the core from the specimen Phynophthalene indicator solution was sprayed. If the concrete is not effected by carbonation, the colour of the core will turn into purple indicating and if there occurs any carbonation, the effected depth of carbonation will not have any change in colour and other sound concrete will turn into purple colour. The distance between the 'no change in colour' to 'purple colour' will be measured with Vernier callipers and recorded as carbonation depth for the particular period since the casted time. Test results of carbonation depth study of SCC_{HyFRNA} mix specimen is presented in Table.6.9 and in the Fig.6.9.

Fig. 6.9 Carbonation depth study of SCC_{HyFRNA} Mix specimens

Table 6.9

Carbonation depth study of SCC_{HyFRNA} Mix specimens

Mix ID	7 Days	28 Days	56Days	90Days	180Days	365 Days
	Carbonation depth ,mm					
$SCC_{HyFR-NA0}$	0.00	0.00	0.00	0.00	0.00	0.00
$SCC_{HyFR-NA0.5}$	0.00	0.00	0.00	0.00	0.00	0.00

Mix ID	7 Days	28 Days	56Days	90Days	180Days	365 Days
	Carbonation depth ,mm					
SCC $_{HyFR-NA1.0}$	0.00	0.00	0.00	0.00	0.00	0.00
SCC $_{HyFR-NA1.5}$	0.00	0.00	0.00	0.00	0.00	0.00
SCC $_{HyFR-NA2.0}$	0.00	0.00	0.00	0.00	0.00	0.00

It can be observed from the above Table 6.9 that all the mix categories passed this test satisfactorily as there was no carbonation effect on the concrete specimen.

6.8 Volume of permeable voids(VPV) at various ages of the selected SCC$_{HyFRNA}$ recipe

Volume of permeable voids (VPV) is a proportion of the volume of the bulk materials, such as solid and voids. The porosity of the concrete affects its mechanical strength but also its transfer properties. High porosity is detrimental to the strength and permeability of a concrete, particularly if the pores are of large diameter and connected. The hydration of the cement results in the formation of a gel, which reduces the size of these water holes and increases the water tightness of the concrete, although the voids are never completely eradicated. The VPV, a critical feature of concrete, influences the transport mechanisms through the concrete body, such as the entry of aggressive liquids and gases. Table 6.10 represents VPV of the selected SCC$_{HyFRNA}$ mix at various ages.

Table 6.10
Volume of permeable voids(VPV) at various ages of the selected SCC$_{HyFRNA}$ mix

Mix ID	16 Hrs	1Day	3Days	7Days	28 Days	56 Days
	Volume of permeable voids(VPV) tested as per ASTM C 642(%)					
SCC$_{HyFR-NA0}$	7.27	6.82	6.36	6.29	6.18	6.16
SCC $_{HyFR-NA0.5}$	7.16	6.67	6.22	6.14	6.07	6.06
SCC $_{HyFR-NA1.0}$	7.02	6.58	6.16	6.02	5.94	5.92
SCC $_{HyFR-NA1.5}$	6.87	6.46	6.09	5.97	5.91	5.87
SCC $_{HyFR-NA2.0}$	6.72	6.61	5.91	5.82	5.74	5.69

6.9 Water Absorption at various ages of the selected SCC_{HyFRNA} recipe

This test was carried out as per the ASTM C 642 on the concrete cylindrical specimens of size diameter 100mm X 200mm height and the test outcomes are provided under Table 6.11. It can be observed from the above Table 6.10 and Table 6.11 that all the mix categories of SCC_{HyFRNA} have demonstrated less VPV and less WA as compared to control sample. The microstructure development of the $SCC_{HyFRNA1.5}$ concrete mix at various ages ,as observed in SEM, is presented in Fig. and can be seen from the same due to the nano material additions besides the reactive MK in the concrete mix that the microstructure of was densified and hence the resulted in less VPA and WA for various periods of time.

Table 6.11
Water Absorption at various ages of the selected SCC_{HyFRNA} recipe

Mix ID	16 Hrs	1Day	3Days	7Days	28 Days	56 Days
	Water Absorption tested as per ASTM C-642(%)					
$SCC_{HyFR-NA0}$	6.89	6.62	6.25	6.12	5.09	5.07
$SCC_{HyFR-NA0.5}$	6.72	6.46	6.17	5.72	4.87	4.81
$SCC_{HyFR-NA1.0}$	6.51	6.37	6.04	5.61	4.72	4.68
$SCC_{HyFR-NA1.5}$	6.34	5.46	5.11	5.02	4.92	4.87
$SCC_{HyFR-NA2.0}$	6.09	5.31	4.99	4.84	4.46	4.40

6.10 Rate of Absorption of Water(Sorptivity) of the selected SCC_{HyFRNA} mix

The rate of absorption gauges the multi-dimensional rise of water in the concrete's capillaries. The amount of water that a concrete will absorb relies on the porosity and connection of those pores, the moisture content or levels of internal drying, and the water's temperature [. Since little water would enter the pores of the concrete, there would be little to no disintegration brought on by freezing or thawing or by aggressive waters, the absorption is thought to be related to the concrete's resistance to weathering. It looks like there's no real connection between total absorption and how long concrete will last, but there does seem to be a connection between how quickly it's absorbed and how long it'll last. Most concrete is only partially saturated, so the first time water and salts come in, they're mostly absorbed through capillaries instead of through water or ion diffusion. There are lots of different tests for measuring water absorption on concrete. You can measure how much weight a sample is gaining, how much water is coming in, how deep it's going, or a combination of all of these. You can do this by having dry samples soaked in water, exposing one face to it, or spraying it on the surface. You can measure either the weight gain at one time or the rate of absorption by measuring the change in mass. In all these tests, the amount of water absorbed is proportional to the amount of time over a certain amount of time, but the amount of positivity varies a lot depending on the test method. This test looked at the rate of absorption of water (sorption) at different ages of the SCC_{HyFRNA} mix in the sliced sample of concrete cores from the casted specimen. It was done according to ASTM C1585. The test results are shown in Tables 6.12, Table 6.13, and Fig.6.10.

Table 6.12

Initial absorption S_i (Sorptivity) at various ages of the selected SCC_{HyFRNA} recipe

Mix ID	**16 Hrs**	**1Day**	**3Days**	**7Days**	**28 Days**	**56 Days**
	Initial absorption S_i tested as per ASTM C 1585 in 10^{-4} mm/√s					
$SCC_{HyFR-NA0}$	7.01	6.89	6.72	6.58	6.47	6.42
$SCC_{HyFR-NA0.5}$	6.82	6.54	6.47	6.25	6.12	6.08
$SCC_{HyFR-NA1.0}$	6.73	6.42	6.34	6.17	6.09	6.04
$SCC_{HyFR-NA1.5}$	6.27	6.05	5.84	5.70	5.12	5.09
$SCC_{HyFR-NA2.0}$	6.10	5.87	5.67	5.46	4.98	4.91

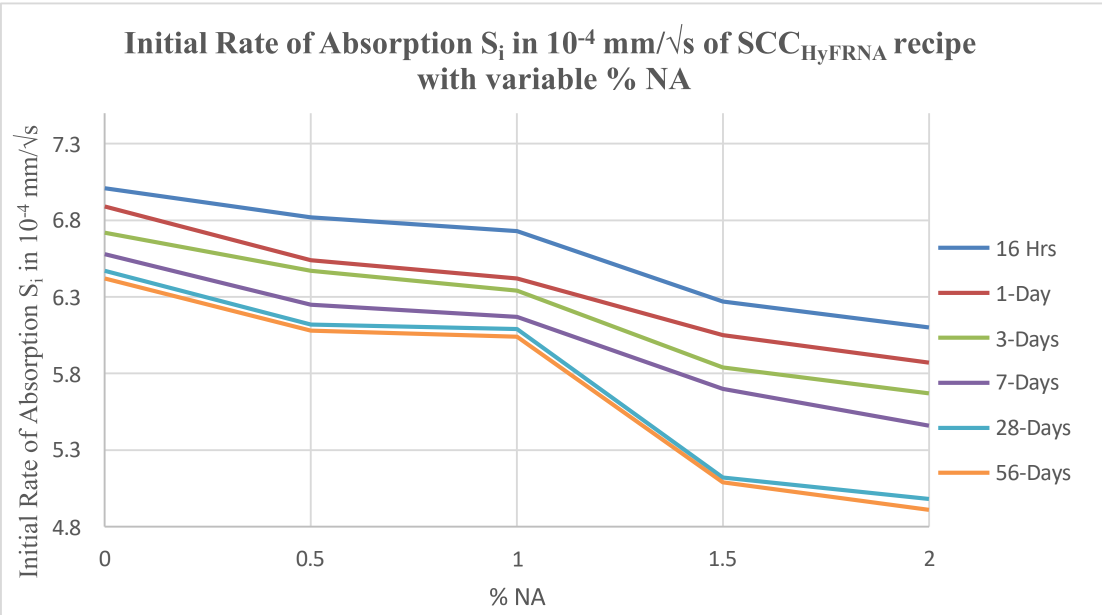
Table 6.13

Secondary absorption S_s (Sorptivity) at various ages of the selected SCC_{HyFRNA} recipe

Mix ID	**16 Hrs**	**1Day**	**3Days**	**7Days**	**28 Days**	**56 Days**
	Secondary absorption S_s tested as per ASTM C 1585 in 10^{-4} mm/√s					
$SCC_{HyFR-NA0}$	3.06	2.92	2.87	2.84	2.81	2.79
$SCC_{HyFR-NA0.5}$	3.01	2.84	2.73	2.75	2.70	2.67
$SCC_{HyFR-NA1.0}$	2.68	2.49	2.04	1.92	1.88	1.82

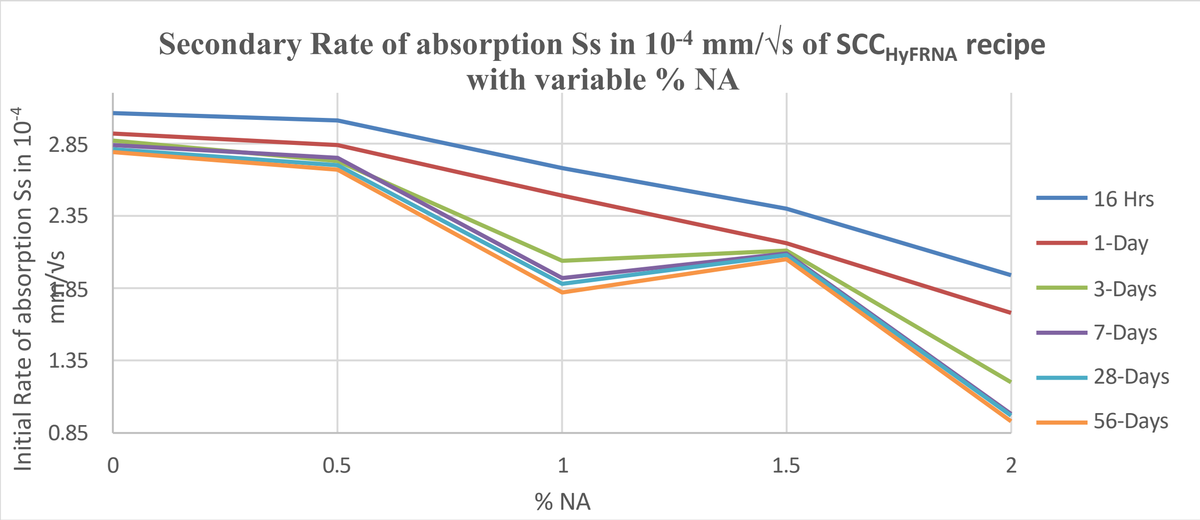
Mix ID	16 Hrs	1Day	3Days	7Days	28 Days	56 Days
	Secondary absorption S_s tested as per ASTM C 1585 in 10^{-4} mm/√s					
SCC $_{HyFR-NA1.5}$	2.40	2.16	2.11	2.09	2.08	2.05
SCC $_{HyFR-NA2.0}$	1.94	1.68	1.20	0.98	0.97	0.93

Fig. 6.10 Rate of Absorption of Water(Sorptivity) of the selected SCC$_{HyFRNA}$ recipe



Graph 6.2 Initial Rate of Absorption S_i of Hy$_{FRSCC}$ Mix with variable % NA

It can be observed from the above Table 6.12 and Table 6.13 that all the mix categories of SCC$_{HyFRNA}$ have demonstrated less initial as well as secondary Sorptivity as compared to control sample. The microstructure development of the SCC$_{HyFRNA1.5}$ concrete mix at various ages ,as observed in SEM, is presented in Fig. from this it can be observed that that due to the due to the nano material additions besides the reactive MK in the concrete mix that the microstructure of was densified and hence the resulted in less initial as well as secondary Sorptivity for various periods of time. Graph 6.2 and Graph 6.3 presents the Initial Rate of Absorption S_i and Secondary Rate of absorption Ss of Hy$_{FRSCC}$ Mix with variable % NA.



Graph 6.3 Secondary Rate of absorption Ss,in 10^{-4} mm/√s of Hy_{FRSCC} Mix with variable % NA

6.13 Field Trials of $SCC_{HyFR-NA1.0}$ and $SCC_{HyFR-NA1.5}$

(a) CC Pot Hole depth 60mmto80mm (b) CC Pot Hole depth 80mm to 100mm

Fig.6.11 Pot Holes of various depths in CC Pavements

(a)CC Pot Hole filled with $SCC_{HyFR-NA1.0}$ (b) Pot Hole filled with $SCC_{HyFR-NA1.5}$

Fig.6.12 Pot Holes repaired with two types of fast-setting $SCC_{HyFR-NA}$ recipes

Fig. 6.13 View of CC Pavement potholes repaired with SCC $_{HyFR-NA1.5}$ recipe at 356 days after repair- Patches were intact no damage observed

Fig.6.14 SCC $_{HyFR-NA1.5}$ panels and casted specimens placed by the side of study area to observe distress and maturity

Table 6.14

Field trials of SCC $_{HyFR-NA}$ recipe –Adiabatic Temperature Rise

Mix ID	MK %	NA %	Avg. Ambient Temperature ^0C	Maximum core Temperature ^0C	Time for reaching Maximum core Temperature Hrs	Temperature Gradient ^0C
(1)	(2)	(3)	(4)	(5)	(6)	(7) =(5)-(4)
SCC$_{HyFR-NA0}$	10.0	0.0	30.2	49.3	28.1	19.1
SCC$_{HyFR-A0.5}$	9.5	0.5	30.2	50.9	25.2	20.7
SCC$_{HyFR-A1.0}$	9.0	1.0	30.2	51.4	23.8	21.2
SCC $_{yFR-NA1.5}$	8.5	1.5	30.2	51.7	21.1	21.5
SCC$_{HyFR-A2.0}$	8.0	2.0	30.2	51.8	20.7	21.6

It can be observed from the above field trials and data presented in Table 6.13, that the mix category SCC $_{HyFR-NA1.0}$ and SCC $_{HyFR-NA1.5}$ performed well in terms of gain in temperature which was an indirect indication of hydration reactions. Two numbers of pot holes, in a CC pavement, having different depths ranging from 60mm-100mm was selected for evaluating two mixes i.e. SCC $_{HyFR-NA1.0}$ and SCC $_{HyFR-NA1.5}$ as a partial depth patch repair material. The selected study area was in an industrial location of an urban locality, having major traffic of 150-450 CVPD. The selected pot holes were filled with the above mix in the evening hours so that traffic disturbances will be less and after hardening of the patches (approximately at 16 hours after filling) traffic could be allowed to ply over the patches as filled with SCC $_{HyFR-NA1.0}$ and SCC $_{HyFR-NA1.5}$ in the pot holes in a CC pavement. Simultaneously all the mix as shown in the Table 6.14 were filled as patches in the slab panels to simulate the CC pavement slab panels and left open to atmosphere adjacent to the repaired CC pavement as above . All the samples of the above mix were also placed in moulds inserted with temperature sensor of recording sensitivity of 0.1^{0}C in order to estimate the maximum rise in temperature with reference to ambient temperature over a period of time 30 hours. The maximum rise in temperature for different experimented mix and the time to reach the maximum temperature is shown in Table 6.13 and as can be seen from the same that for the mix SCC $_{HyFR-NA1.0}$, SCC $_{HyFR-NA1.5}$ and SCC $_{HyFR-NA2.0}$ the maximum rise in temperature was fairly equal. This may be due to the reason that most of the highly reactive SCMs used in this study i.e. combination of MK+NA was actively participated in the hydration reactions and contributed to the fast setting and early strength gaining of the concerned mix as compared to control mix. The test results of studies conducted in this research like VPV,WA and Sorptivity are supporting the above logic. It was also observed from visual inspections conducted on the condition of above repaired CC pavement, from time to time to cover all the expected seasonal variations i.e. till 365 days after laying of the mix, performed satisfactorily. There were no signs of distress in the patches at 365 days of laying. Hence these mixes can be satisfactorily employed in fast track construction works.Fig.6.15 represents the field trials carried using SCC $_{HyFR-NA1.5}$ recipe for filling pot holes in a road as an emergency repair.

Fig. 6.15 View of CC Pavement potholes repaired with SCC $_{HyFR-NA1.5}$ recipe at 356 days after repair- Patches were intact no damage observed

6.11 Various site trials carried with SCC $_{\text{HyFR-NA1.5}}$ recipe

Upon the initial satisfactory performance of SCC $_{\text{HyFR-NA1.5}}$ recipe as a pot hole repair material for CC Pavements, the same recipe was tried in laboratory for casting of 80mm thick paver blocks. Laboratory trial demonstrated a satisfactory strength of 25-30 N/mm^2 at 1 Day compressive strength and yielded a satisfactory surface against abrasive forces . Thus the same recipe was provided to the nearby enthusiastic paver block manufacturer for using the recipe in catting few numbers of paver blocks at his plant under the supervision of the researcher scholar. These casted paver blocks after 1 day of casting were then used in a section of CC Paver Block Pavement at two different sites Site 1 being a colony road and Site 2 being a street road. Also the same recipe SCC $_{\text{HyFR-NA1.5}}$ was used for constructing a small panel CC Pavement in a municipality(Site 3). All the site trails(using SCC $_{\text{HyFR-NA1.5}}$ recipe) yielded satisfactory performance as observed after 6 months of laying of the same.Fig.6.16 and Fig.6.17 represents the laboratory and field trials.

Preparation of SCC $_{\text{HyFR-NA1.5}}$

Fresh State of SCC $_{\text{HyFR-NA1.5}}$ 1.5

Slump-Flow of SCC $_{\text{HyFR-NA1.5}}$ 1.5

Paver Block Moulds

SCC $_{\text{HyFR-NA1.5}}$ casted-T1

SCC $_{\text{HyFR-NA1.5}}$ casted-T2

Fig. 6.16 View of SCC $_{HyFR-NA1.5}$ recipe for site trials

Fig. 6.17 View of Precast Paver Block Pavement trials carried with SCC $_{HyFR-NA1.5}$

Site-3[Municipal Road] **SCC** $_{\mathbf{HyFR\text{-}NA1.5}}$ – Laying at site

Site-3[Municipal Road] **SCC** $_{\mathbf{HyFR\text{-}NA1.5}}$ – Quality Assessment

Site-3[Municipal Road] **SCC** $_{\mathbf{HyFR\text{-}NA1.5}}$ – CC Pavement after 6 months

Fig. 6.18 View of CC Pavement site- trials carried with SCC $_{\mathbf{HyFR\text{-}NA1.5}}$

CHAPTER 7

RESULTS AND DISCUSIONS

7.0 General

This chapter critically analyses the performance of various SCC recipes, both in laboratory condition and field conditions, as studied in this research work, and summarises the effect of following groupings

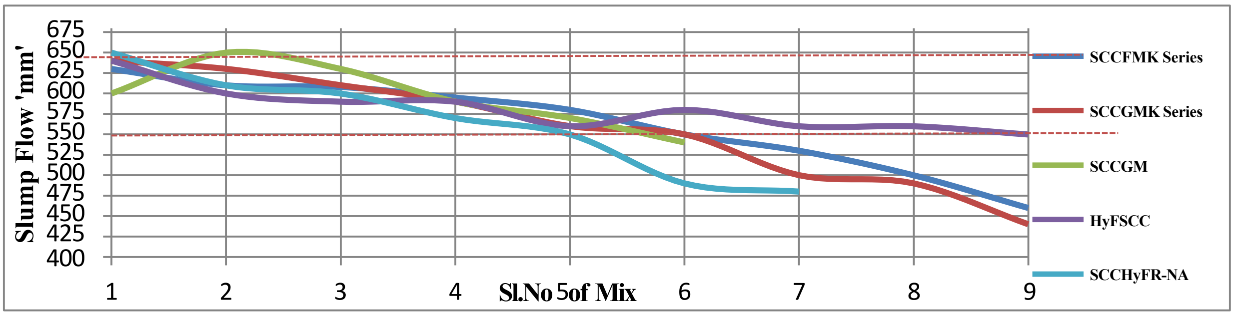
1. $SCC_{GMKseries}$ and $SCC_{FMKseries}$ recipes **-**Fixed quantity of moderately reactive SCMs i.e. flyash and GGBFS and variable quantity of reactive SCM i.e.MK as part replacement of OPC on properties of SCC
2. Effect of part replacement of OPC with GGBFS+MK on properties of SCC
3. Effect of part replacement of OPC with GGBFS+MK in groupings with PP-F and AR-F on properties of SCC Mix
4. Effect of part replacement of OPC with GGBFS in grouping with MK+NA in combination with 0.50% PP-F and 0.50% AR-F on properties of SCC

7.1 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Fresh-State Properties of SCC recipes

7.1.1 Fresh state characteristics of SCC

7.1.1.1 Slump-Flow

Observations as made in this research study presented in Chapter 5, expanded and discussed under section 5.1, 5.2, 5.3 and 5.4 wrf to the Slump-Flow ,a key characteristics of SCC, is presented below in Table 7.1 and Graph 7.1 for ready reference and the same is critically analysed in the subsequent paras.



Graph 7.1 Variation of Slump-Flow with Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

Table 7.1 Slump-Flow of various SCC recipes

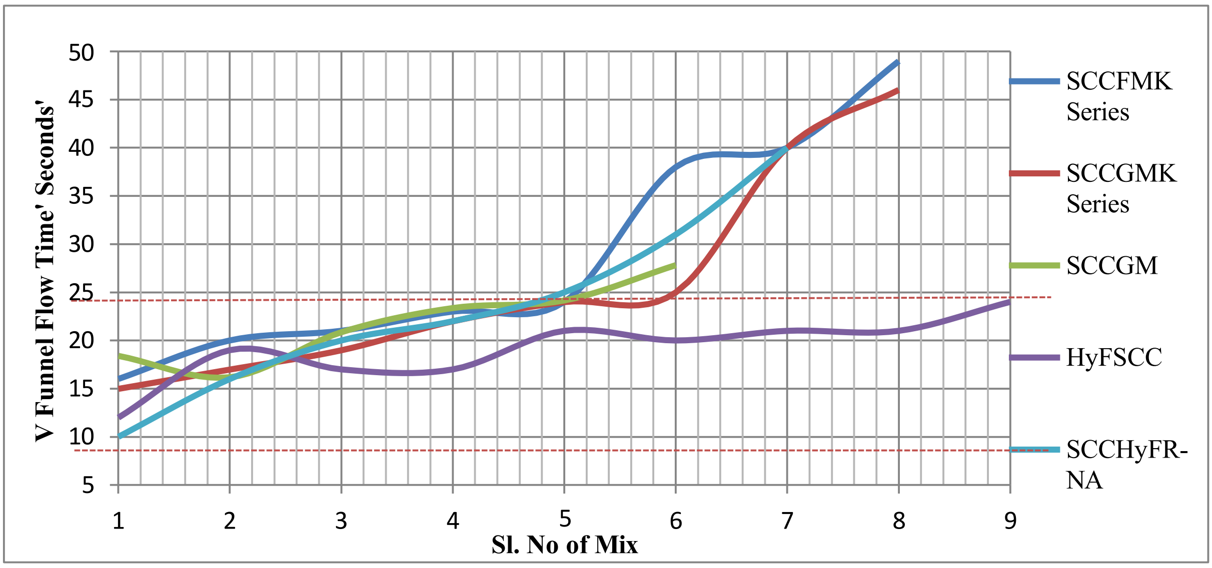
Mix Code Binder OPC+ Flyash+ MK	Slump -Flow mm	Mix Code Binder OPC+ GGBFS+ MK	Slump -Flow mm	Mix Code Binder OPC+ GGBFS+ MK	Slump -Flow mm	Mix Code Binder OPC+ GGBFS+ MK +Fibres	Slump -Flow mm	Mix Code Binder OPC+ GGBFS+ MK+NA +Fibres	Slump -Flow mm
$SCC_{FMK0.00}$	630	$SCC_{GMK0.00}$	640	$SCC_{0.00}$	600	$SCC_{Control}$	640	$SCC_{HyFR-NA0.00}$	650
$SCC_{FMK2.50}$	610	$SCC_{GMK2.50}$	630	$SCC_{GM0.00}$	650	$Hy_{FSCCType1-A}$	600	$SCC_{HyFR-NA0.50}$	610
$SCC_{FMK5.00}$	608	$SCC_{GMK5.00}$	610	$SCC_{GM5.00}$	630	$Hy_{FSCCType1-B}$	590	$SCC_{HyFR-NA1.00}$	600
$SCC_{FMK7.50}$	595	$SCC_{GMK7.50}$	590	$SCC_{GM10.00}$	590	$Hy_{FSCCType1-C}$	590	$SCC_{HyFR-NA1.50}$	570
$SCC_{FMK10.00}$	580	$SCC_{GMK10.00}$	560	$SCC_{GM15.00}$	570	$Hy_{FSCCType1-D}$	560	$SCC_{HyFR-NA2.00}$	550
$SCC_{FMK12.50}$	550	$SCC_{GMK12.50}$	550	$SCC_{GM20.00}$	540	$Hy_{FSCCType2-A}$	580	$SCC_{HyFR-NA2.50}$	490
$SCC_{FMK15.00}$	530	$SCC_{GMK15.00}$	500			$Hy_{FSCCType2-B}$	560	$SCC_{HyFR-NA3.00}$	480
$SCC_{FMK17.50}$	500	$SCC_{GMK17.50}$	490			$Hy_{FSCCType2-C}$	560		
$SCC_{FMK20.00}$	460	$SCC_{GMK20.00}$	440						

7.1.1.2 Discussion on variation of Slump-Flow wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.1 and the Graph 7.1 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, slump flow, as compared to control mix SCC_{FMK0} was decreased and was ranging from 610mm to 550mm and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, lessening in slump flow was observed to be ranging from 630mm to 550mm. Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50% and the rest 50% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the slump-flow for the recipe observed to be ranging from 630mm to 570mm.But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the slump-flow of $Hy_{FSCC\text{-}Type\ 1}$ recipe was reduced and the same was ranging from 600mm to 560mm, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, the slump-flow was decreased and was ranging from 580mm to 560mm, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the slump-flow was ranging from 550mm to 610mm .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes ,the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings ,the slump-flow reduces as compared to control SCC recipes and sophisticated slump-flow of SCC recipes can even be maintained by thoroughly understanding the individual characteristics of various materials forming SCC recipes and influences of the same on SCC characteristics and by proper refinement of mix ratios for meeting the SCC characteristics.

7.1.2 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Flow time through 'V' type funnel of SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under section 5.1, 5.2, 5.3 and 5.4 wrf to the 'V' funnel flow-time ,another key characteristics of SCC, is presented below in Table 7.2 and Graph 7.2 for ready reference and the same is critically analysed in the subsequent paras.



Graph 7.2 Variation of V Funnel-Flow Time with Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

7.1.2.1 Discussion on variation of V-Funnel Flow time wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

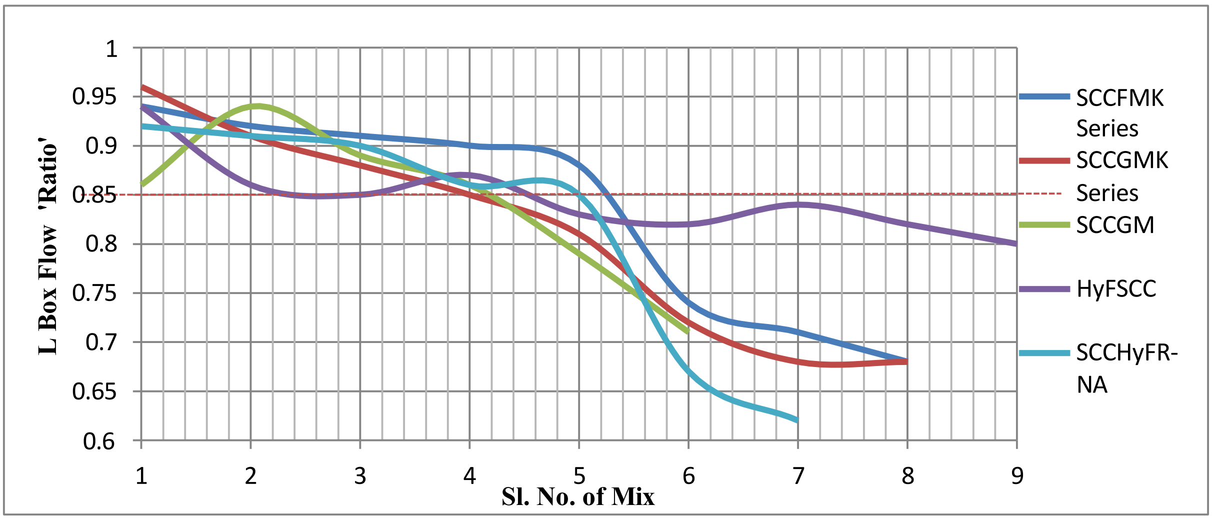
It can be seen from the Table 7.2 and the Graph 7.2 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, V-Funnel Flow Time, as compared to control mix SCC_{FMK0} was decreased and was ranging from 20 seconds to 38 seconds and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, lessening in V-Funnel Flow Time was observed to be ranging from 17 seconds to 25 seconds . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50% and the rest 50% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the V-Funnel Flow Time for the recipe observed to be ranging from 21 seconds to 24 seconds. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the V-Funnel Flow Time of $Hy_{FSCC-Type\ 1}$ recipe was reduced and the same was ranging from 19 seconds to 21seconds, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC-Type\ 2}$ recipe, V-Funnel Flow Time was decreased and was ranging from 20 seconds to 21 seconds, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the V-Funnel Flow Time was ranging from 16 seconds to 25 seconds .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes ,the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings ,the , V-Funnel Flow Time increases as compared to control SCC recipes and sophisticated , V-Funnel Flow Time of SCC recipes can even be maintained by thoroughly understanding the individual characteristics of various materials forming SCC recipes and influences of the same on SCC characteristics and by proper refinement of mix ratios for meeting the SCC characteristics.

Table 7.2 Flow time through 'V' type funnel of various SCC recipes

Mix Code	Flow time through 'V' type funnel 'Seconds'	Mix Code	Flow time through 'V' type funnel 'Seconds'	Mix Code	Flow time through 'V' type funnel 'Seconds'	Mix Code	Flow time through 'V' type funnel 'Seconds'	Mix Code	Flow time through 'V' type funnel 'Seconds'
$SCC_{FMK0.00}$	16	$SCC_{GMK0.00}$	15	$SCC_{0.00}$	18	$SCC_{Control}$	12	$SCC_{HyFR-NA0.00}$	10
$SCC_{FMK2.50}$	20	$SCC_{GMK2.50}$	17	$SCC_{GM0.00}$	16	$Hy_{FSCCType1-A}$	19	$SCC_{HyFR-NA0.50}$	16
$SCC_{FMK5.00}$	21	$SCC_{GMK5.00}$	19	$SCC_{GM5.00}$	21	$Hy_{FSCCType1-B}$	17	$SCC_{HyFR-NA1.00}$	20
$SCC_{FMK7.50}$	23	$SCC_{GMK7.50}$	22	$SCC_{GM10.00}$	23	$Hy_{FSCCType1-C}$	17	$SCC_{HyFR-NA1.50}$	22
$SCC_{FMK10.00}$	24	$SCC_{GMK10.00}$	24	$SCC_{GM15.00}$	24	$Hy_{FSCCType1-D}$	21	$SCC_{HyFR-NA2.00}$	25
$SCC_{FMK12.50}$	38	$SCC_{GMK12.50}$	25	$SCC_{GM20.00}$	28	$Hy_{FSCCType2-A}$	20	$SCC_{HyFR-NA2.50}$	31
$SCC_{FMK15.00}$	40	$SCC_{GMK15.00}$	40			$Hy_{FSCCType2-B}$	21	$SCC_{HyFR-NA3.00}$	40
$SCC_{FMK17.50}$	49	$SCC_{GMK17.50}$	46			$Hy_{FSCCType2-C}$	21		
$SCC_{FMK20.00}$	54	$SCC_{GMK20.00}$	52						

7.1.3 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Flow ratio in 'L' box in SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under section 5.1, 5.2, 5.3 and 5.4 wrf to the Flow ratio in 'L' box, another key characteristics of SCC, is presented below in Table 7.3 and Graph 7.3 for ready reference and the same is critically analysed in the subsequent paras.



Graph 7.3 Variation of Flow Ratio in L Box with Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

7.1.3.1 Discussion on variation of Flow Ratio in L Box wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

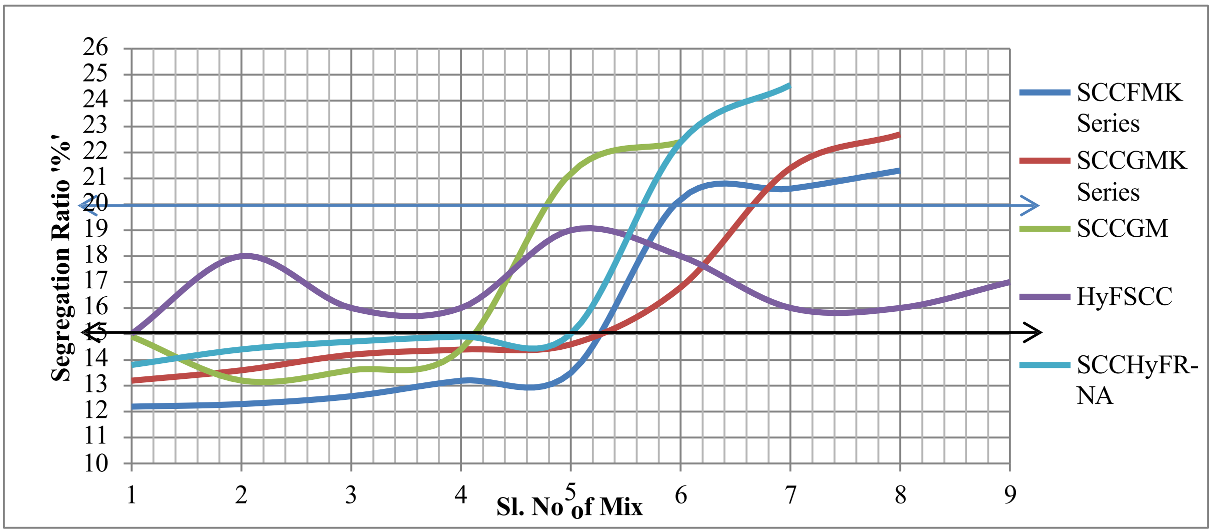
It can be seen from the Table 7.3 and the Graph 7.3 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, Flow Ratio in L Box, as compared to control mix SCC_{FMK0} was decreased and was ranging from 0.92 to 0.74 and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, lessening in Flow Ratio in L Box was observed to be ranging from 0.88 to 0.72 . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50% and the rest 50% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Flow Ratio in L Box for the recipe observed to be ranging from 0.88 to 0.72. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Flow Ratio in L Box of $Hy_{FSCC\text{-}Type\ 1}$ recipe was reduced and the same was ranging from 0.86 to 0.83, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, Flow Ratio in L Box was decreased and was ranging from 0.84 to 0.83, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Flow Ratio in L Box was ranging from 0.91 to 0.85 .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes ,the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings ,the Flow Ratio in L Box increased as compared to control SCC recipes and sophisticated Flow Ratio in L Box of SCC recipes can even be maintained by thoroughly understanding the individual characteristics of various materials forming SCC recipes and influences of the same on SCC characteristics and by proper refinement of mix ratios for meeting the SCC characteristics.

Table 7.3 Flow ratio in 'L' box of various SCC recipes

Mix Code	Flow ratio in 'L' box 'H_2/H_1'	Mix Code	Flow ratio in 'L' box 'H_2/H_1'	Mix Code	Flow ratio in 'L' box 'H_2/H_1'	Mix Code	Flow ratio in 'L' box 'H_2/H_1'	Mix Code	Flow ratio in 'L' box 'H_2/H_1'
$SCC_{FMK0.00}$	0.94	$SCC_{GMK0.00}$	0.96	$SCC_{0.00}$	0.86	$SCC_{Control}$	0.94	$SCC_{HyFR-NA0.00}$	0.92
$SCC_{FMK2.50}$	0.92	$SCC_{GMK2.50}$	0.91	$SCC_{GM0.00}$	0.94	$Hy_{FSCCType1-A}$	0.86	$SCC_{HyFR-NA0.50}$	0.91
$SCC_{FMK5.00}$	0.91	$SCC_{GMK5.00}$	0.88	$SCC_{GM5.00}$	0.89	$Hy_{FSCCType1-B}$	0.85	$SCC_{HyFR-NA1.00}$	0.90
$SCC_{FMK7.50}$	0.90	$SCC_{GMK7.50}$	0.85	$SCC_{GM10.00}$	0.86	$Hy_{FSCCType1-C}$	0.87	$SCC_{HyFR-NA1.50}$	0.86
$SCC_{FMK10.00}$	0.88	$SCC_{GMK10.00}$	0.81	$SCC_{GM15.00}$	0.79	$Hy_{FSCCType1-D}$	0.83	$SCC_{HyFR-NA2.00}$	0.85
$SCC_{FMK12.50}$	0.74	$SCC_{GMK12.50}$	0.72	$SCC_{GM20.00}$	0.71	$Hy_{FSCCType2-A}$	0.82	$SCC_{HyFR-NA2.50}$	0.67
$SCC_{FMK15.00}$	0.71	$SCC_{GMK15.00}$	0.68			$Hy_{FSCCType2-B}$	0.84	$SCC_{HyFR-NA3.00}$	0.62
$SCC_{FMK17.50}$	0.68	$SCC_{GMK17.50}$	0.68			$Hy_{FSCCType2-C}$	0.82		
$SCC_{FMK20.00}$	0.65	$SCC_{GMK20.00}$	0.68						

7.1.4 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Segregation Ratio(SR%) in SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under section 5.1, 5.2, 5.3 and 5.4 wrf to the Segregation Ratio, another key characteristics of SCC, is presented below in Table 7.4 and Graph 7.4 for ready reference and the same is critically analysed in the subsequent paras.



Graph 7.4 Variation of Segregation Ratio (SR%) with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.1.4.1 Discussion on variation of Segregation Ratio (SR%) wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

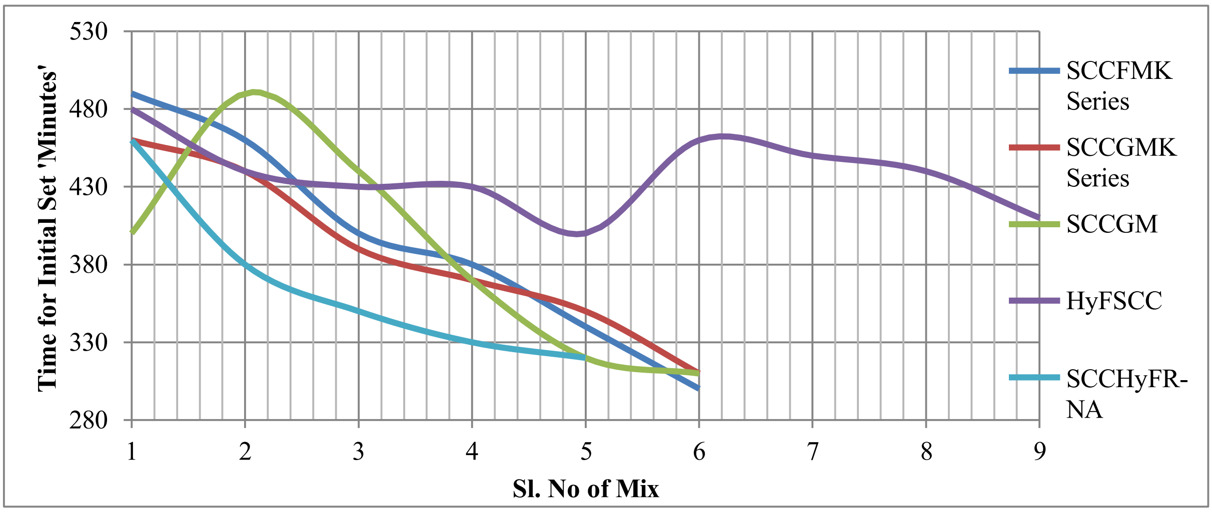
It can be seen from the Table 7.4 and the Graph 7.4 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, SR%, as compared to control mix SCC_{FMK0} was decreased and was ranging from 12.20% to 20.20% and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, lessening in SR% was observed to be ranging from 14.20% to 16.80% . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50% and the rest 50% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the SR% for the recipe observed to be ranging from 14.20% to 16.80%. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the SR% of $Hy_{FSCC-Type\ 1}$ recipe was reduced and the same was ranging from 18.00% to 19.00% , when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC-Type\ 2}$ recipe, SR% was decreased and was ranging from 16.00% to 18.00%, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the SR% was ranging from 14.40% to 15.00% .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes ,the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings ,the SR% increases as compared to control SCC recipes and sophisticated SR% of SCC recipes can even be maintained by thoroughly understanding the individual characteristics of various materials forming SCC recipes and influences of the same on SCC characteristics and by proper refinement of mix ratios for meeting the SCC characteristics.

Table 7.4 Segregation Ratio(SR%) of various SCC recipes

Mix Code	SR %	Mix Code	SR %	Mix Code	SR %	Mix Code	SR %	Mix Code	SR %
$SCC_{FMK0.00}$	12.20	$SCC_{GMK0.00}$	13.20	$SCC_{0.00}$	14.90	$SCC_{Control}$	15.00	$SCC_{HyFR-NA0.00}$	13.80
$SCC_{FMK2.50}$	12.30	$SCC_{GMK2.50}$	13.60	$SCC_{GM0.00}$	13.20	$Hy_{FSCCType1-A}$	18.00	$SCC_{HyFR-NA0.50}$	14.40
$SCC_{FMK5.00}$	12.60	$SCC_{GMK5.00}$	14.20	$SCC_{GM5.00}$	13.60	$Hy_{FSCCType1-B}$	16.00	$SCC_{HyFR-NA1.00}$	14.70
$SCC_{FMK7.50}$	13.20	$SCC_{GMK7.50}$	14.40	$SCC_{GM10.00}$	14.40	$Hy_{FSCCType1-C}$	16.00	$SCC_{HyFR-NA1.50}$	14.90
$SCC_{FMK10.00}$	13.50	$SCC_{GMK10.00}$	14.60	$SCC_{GM15.00}$	21.20	$Hy_{FSCCType1-D}$	19.00	$SCC_{HyFR-NA2.00}$	15.00
$SCC_{FMK12.50}$	20.20	$SCC_{GMK12.50}$	16.80	$SCC_{GM20.00}$	22.40	$Hy_{FSCCType2-A}$	18.00	$SCC_{HyFR-NA2.50}$	22.40
$SCC_{FMK15.00}$	20.60	$SCC_{GMK15.00}$	21.40			$Hy_{FSCCType2-B}$	16.00	$SCC_{HyFR-NA3.00}$	24.60
$SCC_{FMK17.50}$	21.30	$SCC_{GMK17.50}$	22.70			$Hy_{FSCCType2-C}$	16.00		
$SCC_{FMK20.00}$	22.70	$SCC_{GMK20.00}$	23.10						

7.1.5 Effect of moderately reactive SCMs, Reactive SCM, Fibres and Highly reactive SCM on Time Required for Initial Set of SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under section 5.1, 5.2, 5.3 and 5.4 wrf to the Time Required for Initial Set, a key characteristics of fast- setting SCC, is presented below in Table 7.5 and Graph 7.5 for ready reference and the same is critically analysed in the subsequent paras.



Graph 7.5 Variation of Time Required for Initial Set with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.1.5.1 Discussion on variation of Time required for Initial Set wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.5 and the Graph 7.5 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Time required for Initial Set, as compared to control mix SCC_{FMK0} was decreased and was ranging from 460 minutes to 300 minutes and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight lessening in Time required for Initial Set was observed to be ranging from 440 minutes to 310 minutes . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50% and the rest 50% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Time required for Initial Set for the recipe slightly varied and the same was observed to be ranging from 440 minutes to 320 minutes. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Time required for Initial Set of $Hy_{FSCC-Type\ 1}$ recipe was reduced and the same was ranging from 440 minutes to 320 minutes, when %PP-F increased from 0.00%

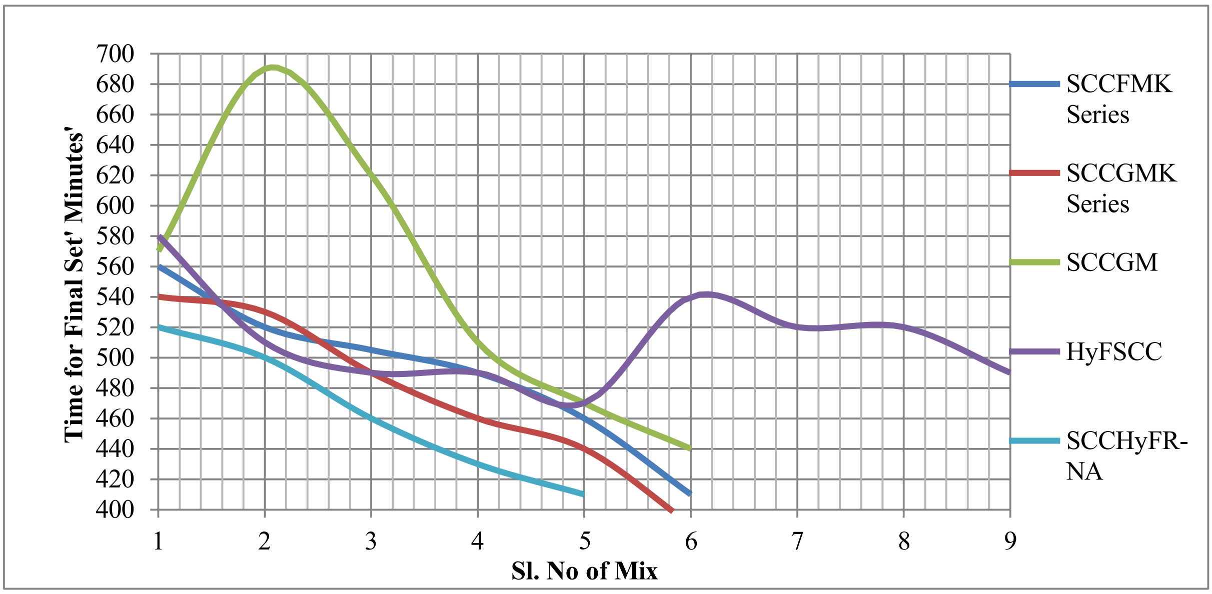
to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, Time required for Initial Set was slightly varied and the same was ranging from 460 minutes to 440 minutes , as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Time required for Initial Set was decreased and the same was observed to be ranging from 380 minutes to 320 minutes .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes ,the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings ,the Time required for Initial Set as compared to control SCC recipes and yield fast-setting recipes.

Table 7.5 Time required for initial set of various SCC recipes

Mix Code	Time required for initial set 'Minutes'	Mix Code	Time required for initial set 'Minutes'	Mix Code	Time required for initial set 'Minutes'	Mix Code	Time required for initial set 'Minutes'	Mix Code	Time required for initial set 'Minutes'
$SCC_{FMK0.00}$	490	$SCC_{GMK0.00}$	460	$SCC_{0.00}$	400	$SCC_{Control}$	480	$SCC_{HyFR-NA0.00}$	460
$SCC_{FMK2.50}$	460	$SCC_{GMK2.50}$	440	$SCC_{GM0.00}$	490	$Hy_{FSCCType1-A}$	440	$SCC_{HyFR-NA0.50}$	380
$SCC_{FMK5.00}$	400	$SCC_{GMK5.00}$	390	$SCC_{GM5.00}$	440	$Hy_{FSCCType1-B}$	430	$SCC_{HyFR-NA1.00}$	350
$SCC_{FMK7.50}$	380	$SCC_{GMK7.50}$	370	$SCC_{GM10.00}$	370	$Hy_{FSCCType1-C}$	430	$SCC_{HyFR-NA1.50}$	330
$SCC_{FMK10.00}$	340	$SCC_{GMK10.00}$	350	$SCC_{GM15.00}$	320	$Hy_{FSCCType1-D}$	400	$SCC_{HyFR-NA2.00}$	320
$SCC_{FMK12.50}$	300	$SCC_{GMK12.50}$	310	$SCC_{GM20.00}$	310	$Hy_{FSCCType2-A}$	460	$SCC_{HyFR-NA2.50}$	Not carried
$SCC_{FMK15.00}$	Not carried	$SCC_{GMK15.00}$	Not carried			$Hy_{FSCCType2-B}$	450	$SCC_{HyFR-NA3.00}$	Not carried
$SCC_{FMK17.50}$	Not carried	$SCC_{GMK17.50}$	Not carried			$Hy_{FSCCType2-C}$	440		
$SCC_{FMK20.00}$	Not carried	$SCC_{GMK20.00}$	Not carried						

7.1.6 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Time Required for Final Set of SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under section 5.1, 5.2, 5.3 and 5.4 wrf to the Time Required for Final Set, a key characteristics of fast- setting SCC, is presented below in Table 7.6 and Graph 7.6 for ready reference and the same is critically analysed in the subsequent paras.



Graph 7.6 Variation of Time Required for Final Set with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.1.6.1 Discussion on variation of Time Required for Final Set wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.6 and the Graph 7.6 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Time Required for Final Set, as compared to control mix SCC_{FMK0} was decreased and was ranging from 520 minutes to 410 minutes and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in Time required for Final Set was observed to be ranging from 530 minutes to 390 minutes . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50% and the rest 50% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Time required for Final Set for the recipe varied and the same was observed to be ranging from 620 minutes to 440 minutes. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Time required for Final Set of $Hy_{FSCC\text{-}Type\ 1}$ recipe was varied and the same was ranging from 510 minutes to 470 minutes, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC-Type\ 2}$ recipe, Time required for Final Set was slightly varied and the same was ranging from 540 minutes to 520 minutes , as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Time required for Final Set was decreased and the same was observed to be ranging from 500 minutes to 410 minutes .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings, the Time required for Initial Set as compared to control SCC recipes and yield fast-setting recipes.

Table 7.6 Time required for Final set of various SCC recipes

Mix Code	Time required for Final set 'Minutes'	Mix Code	Time required for Final set 'Minutes'	Mix Code	Time required for Final set 'Minutes'	Mix Code	Time required for Final set 'Minutes'	Mix Code	Time required for Final set 'Minutes'
$SCC_{FMK0.00}$	560	$SCC_{GMK0.00}$	540	$SCC_{0.00}$	570	$SCC_{Control}$	580	$SCC_{HyFR-NA0.00}$	520
$SCC_{FMK2.50}$	520	$SCC_{GMK2.50}$	530	$SCC_{GM0.00}$	690	$Hy_{FSCCType1-A}$	510	$SCC_{HyFR-NA0.50}$	500
$SCC_{FMK5.00}$	505	$SCC_{GMK5.00}$	490	$SCC_{GM5.00}$	620	$Hy_{FSCCType1-B}$	490	$SCC_{HyFR-NA1.00}$	460
$SCC_{FMK7.50}$	490	$SCC_{GMK7.50}$	460	$SCC_{GM10.00}$	510	$Hy_{FSCCType1-C}$	490	$SCC_{HyFR-NA1.50}$	430
$SCC_{FMK10.00}$	460	$SCC_{GMK10.00}$	440	$SCC_{GM15.00}$	470	$Hy_{FSCCType1-D}$	470	$SCC_{HyFR-NA2.00}$	410
$SCC_{FMK12.50}$	410	$SCC_{GMK12.50}$	390	$SCC_{GM20.00}$	440	$Hy_{FSCCType2-A}$	540	$SCC_{HyFR-NA2.50}$	Not Carried
$SCC_{FMK15.00}$	Not carried	$SCC_{GMK15.00}$	Not carried			$Hy_{FSCCType2-B}$	520	$SCC_{HyFR-NA3.00}$	Not Carried
$SCC_{FMK17.50}$	Not carried	$SCC_{GMK17.50}$	Not carried			$Hy_{FSCCType2-C}$	520		
$SCC_{FMK20.00}$	Not carried	$SCC_{GMK20.00}$	Not carried						

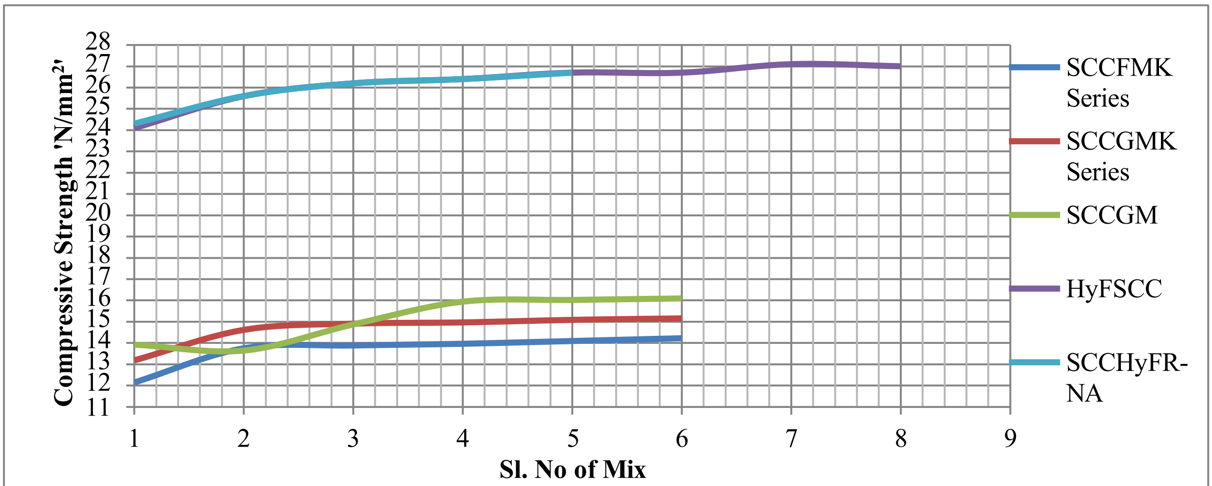
7.2 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Compressive-Strength of SCC recipes

7.2.1 Compressive-Strength (At Early age, At Maturity & at Post Maturity Ages)

Observations as made in this research study presented in Chapter 5, expanded and discussed under sections 5.1, 5.2, 5.3 and 5.4 wrf to the Compressive-Strength (At Early age, At Maturity & at Post Maturity Ages),a key characteristics of SCC, is presented in below sections.

7.2.1.1 Compressive-Strength (At Early age)

Observations made on the effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Early-Age Compressive-Strength is presented in Table 7.7 and Graph 7.7 and the same is critically analysed in the subsequent paras.



Graph 7.7 Variation of Early-Age Compressive-Strength with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.2.1.1.1 Discussion on variation of Early-Age Compressive-Strength wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

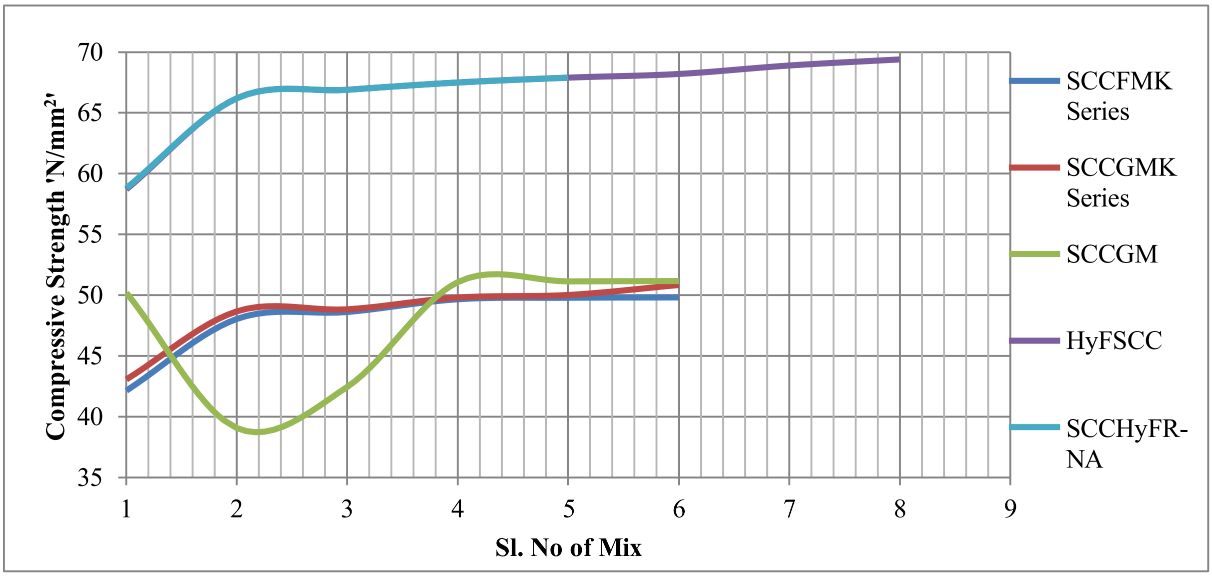
It can be seen from the Table 7.7 and the Graph 7.7that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Early-Age Compressive-Strength, as compared to control mix SCC_{FMK0} was increased and was ranging from 13.75 N/mm^2 to 14.22 N/mm^2 and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in Early-Age Compressive-Strength was observed to be ranging from 14.62 N/mm^2 to 15.16 N/mm^2 . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50% and the rest 50% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Early-Age Compressive-Strength was observed to be ranging from 14.87 N/mm^2 to 16.02 N/mm^2. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Early-Age Compressive-Strength of $Hy_{FSCC-Type\ 1}$ recipe was varied and the same was ranging from 25.60 N/mm^2 to 26.70 N/mm^2, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC-Type\ 2}$ recipe, Early-Age Compressive-Strength was slightly varied and the same was ranging from 26.70 N/mm^2 to 27.00 N/mm^2, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Early-Age Compressive-Strength was increased and the same was ranging from 26.70 N/mm^2 to 27.00 N/mm^2 .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the compressive strength as compared to control SCC recipes and yield early-strength characteristics.

Table 7.7 Compressive-Strength (At Early age) of various SCC recipes

Mix Code	Compressive-Strength (At Early age) N/mm^2	Mix Code	Compressive-Strength (At Early age) N/mm^2	Mix Code	Compressive-Strength (At Early age) N/mm^2	Mix Code	Compressive-Strength (At Early age) N/mm^2	Mix Code	Compressive-Strength (At Early age) N/mm^2
$SCC_{FMK0.00}$	12.14	$SCC_{GMK0.00}$	13.18	$SCC_{0.00}$	13.92	$SCC_{Control}$	24.10	$SCC_{HyFR-NA0.00}$	24.30
$SCC_{FMK2.50}$	13.75	$SCC_{GMK2.50}$	14.62	$SCC_{GM0.00}$	13.64	$Hy_{FSCCType1-A}$	25.60	$SCC_{HyFR-NA0.50}$	25.60
$SCC_{FMK5.00}$	13.88	$SCC_{GMK5.00}$	14.91	$SCC_{GM5.00}$	14.87	$Hy_{FSCCType1-B}$	26.20	$SCC_{HyFR-NA1.00}$	26.20
$SCC_{FMK7.50}$	13.96	$SCC_{GMK7.50}$	14.97	$SCC_{GM10.00}$	15.94	$Hy_{FSCCType1-C}$	26.40	$SCC_{HyFR-NA1.50}$	26.40
$SCC_{FMK10.00}$	14.09	$SCC_{GMK10.00}$	15.09	$SCC_{GM15.00}$	16.02	$Hy_{FSCCType1-D}$	26.70	$SCC_{HyFR-NA2.00}$	26.70
$SCC_{FMK12.50}$	14.22	$SCC_{GMK12.50}$	15.16	$SCC_{GM20.00}$	16.09	$Hy_{FSCCType2-A}$	26.70	$SCC_{HyFR-NA2.50}$	
$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2-B}$	27.10	$SCC_{HyFR-NA3.00}$	
$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2-C}$	27.00		
$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.2.1.2 Compressive-Strength at Maturity(28 days)

Observations made on the effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Compressive-Strength at Maturity is presented in Table 7.8 and Graph 7.8 and the same is critically analysed in the subsequent paras.



Graph 7.8 Variation of Compressive-Strength at Maturity(28 days) with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.2.1.2.1 Discussion on variation of Compressive-Strength at Maturity(28 days) wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.8 and the Graph 7.8 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Compressive-Strength at Maturity(28 days), as compared to control mix SCC_{FMK0} was increased and was ranging from 48.04 N/mm^2 to 49.81 N/mm^2 and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in Compressive-Strength at Maturity(28 days) was observed to be ranging from 48.67 N/mm^2 to 50.84 N/mm^2 . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Compressive-Strength at Maturity(28 days) was observed to be ranging from 42.46 N/mm^2 to 51.14 N/mm^2. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Compressive-Strength at Maturity(28 days) of $Hy_{FSCC\text{-}Type\ 1}$ recipe was varied and the same was ranging from 66.20 N/mm^2 to

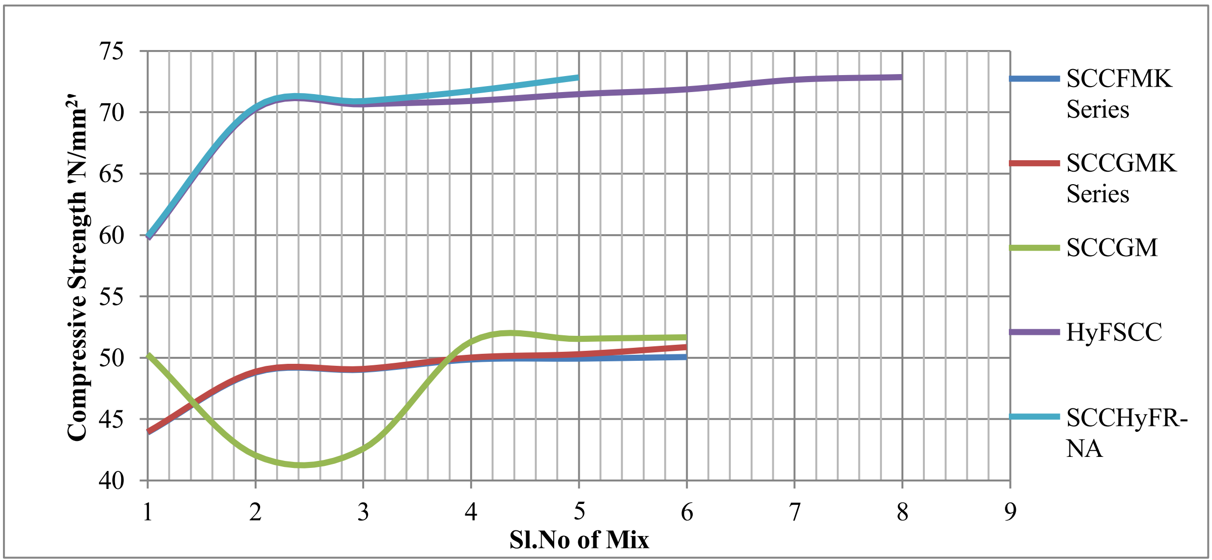
67.90N/mm^2, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, Compressive-Strength at Maturity(28 days) was slightly varied and the same was ranging from 68.20 N/mm^2 to 69.40 N/mm^2, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Compressive-Strength at Maturity(28 days)was increased and the same was ranging from 66.20N/mm^2 to 67.90 N/mm^2 .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the compressive strength as compared to control SCC recipes and not only yield early-strength characteristics but also satisfy the target mean strengths at maturity i.e 28 days.

Table 7.8 Compressive-Strength (at Maturity(28Days)) of various SCC recipes

Mix Code	Compressive-Strength (At Maturity) N/mm^2	Mix Code	Compressive-Strength (At Maturity) N/mm^2	Mix Code	Compressive-Strength (At Maturity) N/mm^2	Mix Code	Compressive-Strength (At Maturity) N/mm^2	Mix Code	Compressive-Strength (At Maturity) N/mm^2
$SCC_{FMK0.00}$	42.14	$SCC_{GMK0.00}$	43.06	$SCC_{0.00}$	50.20	$SCC_{Control}$	58.70	$SCC_{HyFR-NA0.00}$	58.80
$SCC_{FMK2.50}$	48.04	$SCC_{GMK2.50}$	48.67	$SCC_{GM0.00}$	39.06	$Hy_{FSCCType1-A}$	66.20	$SCC_{HyFR-NA0.50}$	66.20
$SCC_{FMK5.00}$	48.61	$SCC_{GMK5.00}$	48.84	$SCC_{GM5.00}$	42.46	$Hy_{FSCCType1-B}$	66.90	$SCC_{HyFR-NA1.00}$	66.90
$SCC_{FMK7.50}$	49.66	$SCC_{GMK7.50}$	49.81	$SCC_{GM10.00}$	51.08	$Hy_{FSCCType1-C}$	67.50	$SCC_{HyFR-NA1.50}$	67.50
$SCC_{FMK10.00}$	49.78	$SCC_{GMK10.00}$	50.02	$SCC_{GM15.00}$	51.14	$Hy_{FSCCType1-D}$	67.90	$SCC_{HyFR-NA2.00}$	67.90
$SCC_{FMK12.50}$	49.81	$SCC_{GMK12.50}$	50.84	$SCC_{GM20.00}$	51.17	$Hy_{FSCCType2-A}$	68.20	$SCC_{HyFR-NA2.50}$	
$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2-B}$	68.90	$SCC_{HyFR-NA3.00}$	
$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2-C}$	69.40		
$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.2.1.3 Compressive-Strength at Post Maturity(>28Days)

Observations made on the effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Compressive-Strength at Post Maturity Ages is presented in Table 7.9 and Graph 7.9 and the same is critically analysed in the subsequent paras.



Graph 7.9 Variation of Compressive-Strength at Post Maturity(>28Days) with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.2.1.3.1 Discussion on variation of Compressive-Strength at Post Maturity(>28Days) wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.9 and the Graph 7.9 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Compressive-Strength at Post Maturity(>28Days), as compared to control mix SCC_{FMK0} was increased and was ranging from 48.79 N/mm^2 to 50.05 N/mm^2 and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in Compressive-Strength at Post Maturity(>28Days) was observed to be ranging from 48.67 N/mm^2 to 50.84 N/mm^2 . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK, wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Compressive-Strength at Post Maturity(>28Days) was observed to be ranging from 42.05 N/mm^2 to 51.54 N/mm^2. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Compressive-Strength at Post Maturity(>28Days) of $Hy_{FSCC\text{-}Type\ 1}$ recipe was varied and the same was ranging from 70.26 N/mm^2 to 71.47N/mm^2, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, Compressive-Strength at Post Maturity(>28Days) was slightly varied and the same was ranging from 71.86 N/mm^2 to 72.90 N/mm^2, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Compressive-Strength at Post Maturity(>28Days) was increased and the same was ranging from 70.42 N/mm^2 to 72.84 N/mm^2 .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the compressive strength as compared to control SCC recipes and not only yield early-strength characteristics , satisfy the target mean strengths at maturity i.e. 28 days and perform well at post maturity ages i.e. >28 days also.

Table 7.9 Compressive-Strength (At Post Maturity Ages) of various SCC recipes

Mix Code	Compressive-Strength (At Post Maturity Ages N/mm^2	Mix Code	Compressive-Strength (At Post Maturity Ages N/mm^2	Mix Code	Compressive-Strength (At Post Maturity Ages N/mm^2	Mix Code	Compressive-Strength (At Post Maturity Ages N/mm^2	Mix Code	Compressive-Strength (At Post Maturity Ages N/mm^2
$SCC_{FMK0.00}$	43.91	$SCC_{GMK0.00}$	43.96	$SCC_{0.00}$	50.29	$SCC_{Control}$	59.69	$SCC_{HyFR-NA0.00}$	59.88
$SCC_{FMK2.50}$	48.79	$SCC_{GMK2.50}$	48.87	$SCC_{GM0.00}$	42.05	$Hy_{FSCCType1-A}$	70.26	$SCC_{HyFR-NA0.50}$	70.42
$SCC_{FMK5.00}$	49.02	$SCC_{GMK5.00}$	49.09	$SCC_{GM5.00}$	42.58	$Hy_{FSCCType1-B}$	70.64	$SCC_{HyFR-NA1.00}$	70.91
$SCC_{FMK7.50}$	49.85	$SCC_{GMK7.50}$	50.02	$SCC_{GM10.00}$	51.31	$Hy_{FSCCType1-C}$	70.92	$SCC_{HyFR-NA1.50}$	71.73
$SCC_{FMK10.00}$	49.92	$SCC_{GMK10.00}$	50.29	$SCC_{GM15.00}$	51.54	$Hy_{FSCCType1-D}$	71.47	$SCC_{HyFR-NA2.00}$	72.84
$SCC_{FMK12.50}$	50.05	$SCC_{GMK12.50}$	50.87	$SCC_{GM20.00}$	51.67	$Hy_{FSCCType2-A}$	71.86	$SCC_{HyFR-NA2.50}$	
$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2-B}$	72.64	$SCC_{HyFR-NA3.00}$	
$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2-C}$	72.90		
$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

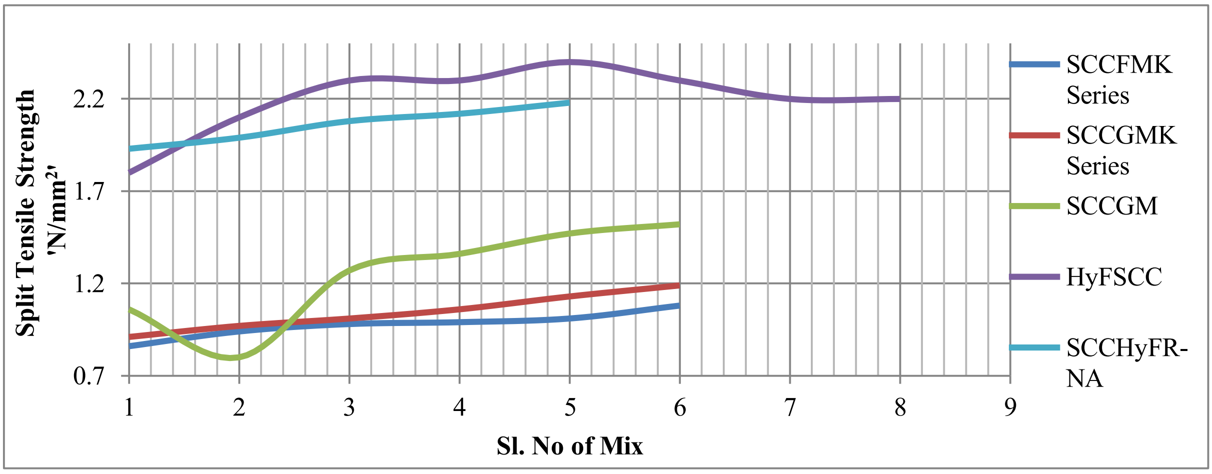
7.3 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Splitting-Tensile Strength of in SCC recipes

7.3.1 Splitting-Tensile Strength (At Early age, At Maturity & at Post Maturity Ages)

Observations as made in this research study presented in Chapter 5, expanded and discussed under sections 5.1, 5.2, 5.3 and 5.4 wrf to the Splitting-Tensile Strength (At Early age, At Maturity & at Post Maturity Ages),a key characteristics of SCC, is presented in below sections.

7.3.1.1 Splitting-Tensile Strength (At Early age)

Observations made on the effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Early-Age Splitting-Tensile Strength is presented in Table 7.10 and Graph 7.10 and the same is critically analysed in the subsequent paras.



Graph 7.10 Variation of Early-Age Splitting-Tensile Strength with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.3.1.1.1 Discussion on variation of Early-Age Splitting-Tensile Strength wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.10 and the Graph 7.10 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Early-Age Splitting-Tensile Strength, as compared to control mix SCC_{FMK0} was increased and was ranging from 0.94 N/mm^2 to 1.08 N/mm^2 and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in Early-Age Splitting-Tensile Strength was observed to be ranging from 1.01 N/mm^2 to 1.19 N/mm^2 . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of

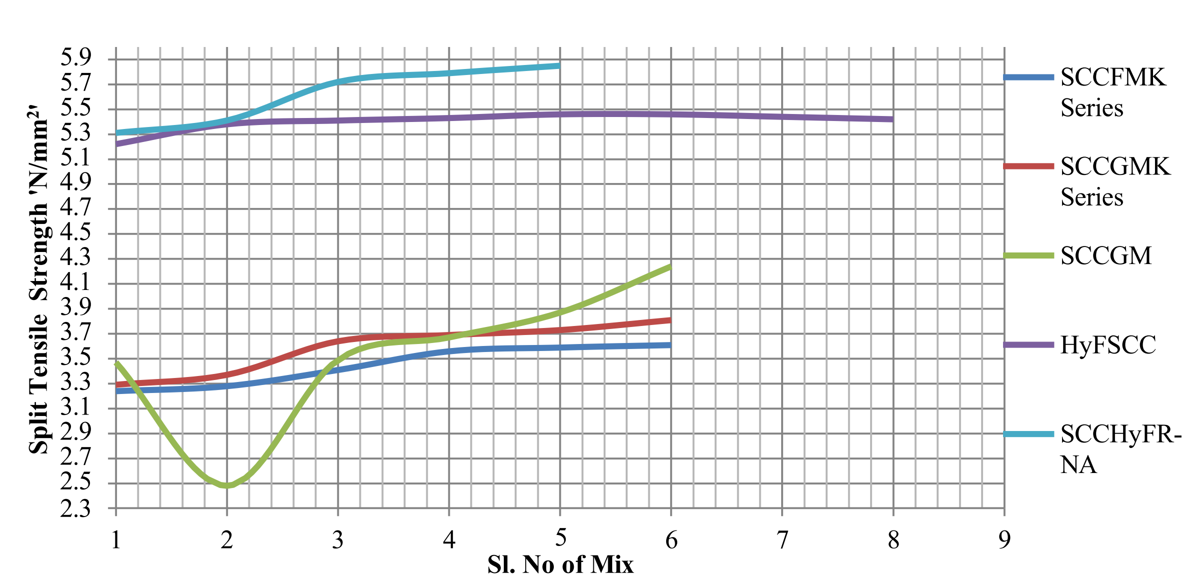
GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Early-Age Splitting-Tensile Strength was observed to be ranging from 1.27 N/mm^2 to 1.52 N/mm^2. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Early-Age Splitting-Tensile Strength of $Hy_{FSCC\text{-}Type\ 1}$ recipe was varied and the same was ranging from 2.10 N/mm^2 to 2.40N/mm^2, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, Early-Age Splitting-Tensile Strength) was slightly varied and the same was ranging from 2.30 N/mm^2 to 2.20 N/mm^2, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Early-Age Splitting-Tensile Strength was increased and the same was ranging from 1.99 N/mm^2 to 2.18 N/mm^2 .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the Early-Age Splitting-Tensile Strength as compared to control SCC recipes and yielded early-tensile strength characteristics.

Table 7.10 Splitting-Tensile Strength (At Early age) of various SCC recipes

Mix Code	Splitting-Tensile Strength (At Early age) N/mm²	Mix Code	Splitting-Tensile Strength (At Early age) N/mm²	Mix Code	Splitting-Tensile Strength (At Early age) N/mm²	Mix Code	Splitting-Tensile Strength (At Early age) N/mm²	Mix Code	Splitting-Tensile Strength (At Early age) N/mm²
$SCC_{FMK0.00}$	0.86	$SCC_{GMK0.00}$	0.91	$SCC_{0.00}$	1.06	$SCC_{Control}$	1.80	$SCC_{HyFR\text{-}NA0.00}$	1.93
$SCC_{FMK2.50}$	0.94	$SCC_{GMK2.50}$	0.97	$SCC_{GM0.00}$	0.80	$Hy_{FSCCType1\text{-}A}$	2.10	$SCC_{HyFR\text{-}NA0.50}$	1.99
$SCC_{FMK5.00}$	0.98	$SCC_{GMK5.00}$	1.01	$SCC_{GM5.00}$	1.27	$Hy_{FSCCType1\text{-}B}$	2.30	$SCC_{HyFR\text{-}NA1.00}$	2.08
$SCC_{FMK7.50}$	0.99	$SCC_{GMK7.50}$	1.06	$SCC_{GM10.00}$	1.36	$Hy_{FSCCType1\text{-}C}$	2.30	$SCC_{HyFR\text{-}NA1.50}$	2.12
$SCC_{FMK10.00}$	1.01	$SCC_{GMK10.00}$	1.13	$SCC_{GM15.00}$	1.47	$Hy_{FSCCType1\text{-}D}$	2.40	$SCC_{HyFR\text{-}NA2.00}$	2.18
$SCC_{FMK12.50}$	1.08	$SCC_{GMK12.50}$	1.19	$SCC_{GM20.00}$	1.52	$Hy_{FSCCType2\text{-}A}$	2.30	$SCC_{HyFR\text{-}NA2.50}$	
$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2\text{-}B}$	2.20	$SCC_{HyFR\text{-}NA3.00}$	
$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2\text{-}C}$	2.20		
$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.3.1.2 Splitting-Tensile Strength - at Maturity(28days)

Observations made on the effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Splitting-Tensile Strength at Maturity is presented in Table 7.11 and Graph 7.11 and the same is critically analysed in the subsequent paras.



Graph 7.11 Variation of Splitting-Tensile Strength at Maturity(28days) with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.3.1.2.1 Discussion on variation of Splitting-Tensile Strength at Maturity(28days) wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.11 and the Graph 7.11 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Splitting-Tensile Strength at Maturity(28days), as compared to control mix SCC_{FMK0} was increased and was ranging from 3.28 N/mm^2 to 3.61 N/mm^2 and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in Splitting-Tensile Strength at Maturity(28days)was observed to be ranging from 3.37 N/mm^2 to 3.81 N/mm^2 . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK, wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Early-Age Splitting-Tensile Strength was observed to be ranging from 3.49 N/mm^2 to 3.87 N/mm^2. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Splitting-Tensile Strength at Maturity(28days) of $Hy_{FSCC-Type\ 1}$ recipe was varied and the same was ranging from 5.38 N/mm^2 to 5.46N/mm^2, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC-Type\ 2}$ recipe, Splitting-Tensile Strength at

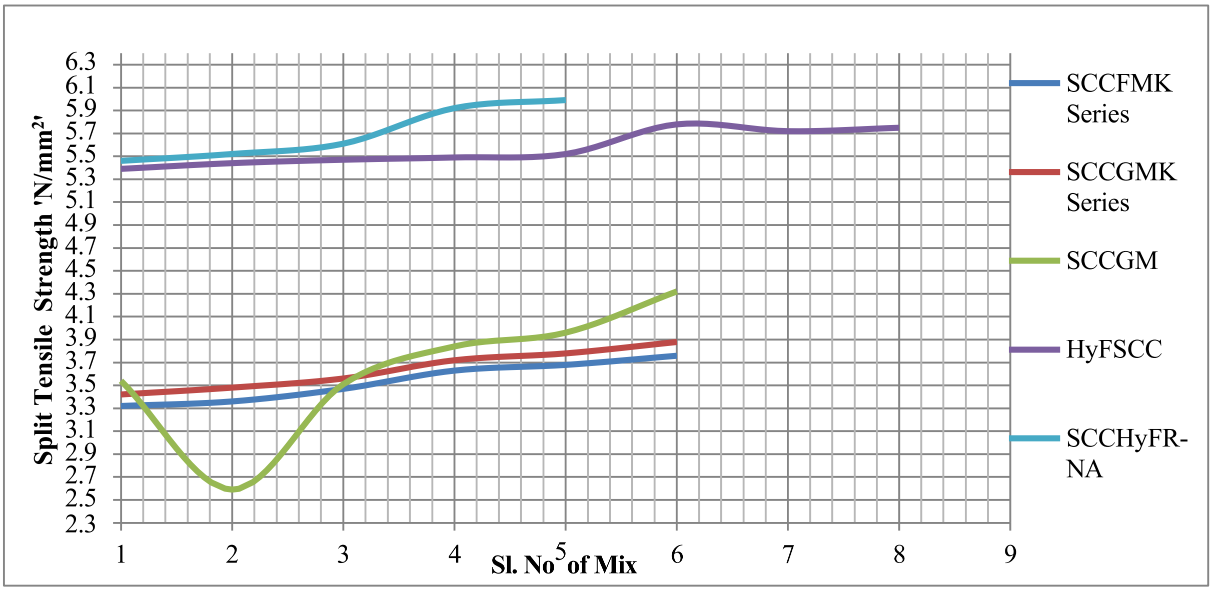
Maturity(28days) was slightly varied and the same was ranging from 5.42 N/mm^2 to 5.46 N/mm^2, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Early-Age Splitting-Tensile Strength was increased and the same was ranging from 5.41 N/mm^2 to 5.85 N/mm^2 .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the Splitting-Tensile Strength as compared to control SCC recipes and yielded early-tensile strength characteristics but also demonstrated tensile strength characteristics at maturity (28days).

Table 7.11 Splitting-Tensile Strength At Maturity(28days)of various SCC recipes

Mix Code	**Splitting-Tensile Strength (At Maturity) N/mm²**	**Mix Code**	**Splitting-Tensile Strength (At Maturity) N/mm²**	**Mix Code**	**Splitting-Tensile Strength (At Maturity) N/mm²**	**Mix Code**	**Splitting-Tensile Strength (At Maturity) N/mm²**	**Mix Code**	**Splitting-Tensile Strength (At Maturity) N/mm²**
$SCC_{FMK0.00}$	3.24	$SCC_{GMK0.00}$	3.29	$SCC_{0.00}$	3.47	$SCC_{Control}$	5.22	$SCC_{HyFR-NA0.00}$	5.31
$SCC_{FMK2.50}$	3.28	$SCC_{GMK2.50}$	3.37	$SCC_{GM0.00}$	2.48	$Hy_{FSCCType1-A}$	5.38	$SCC_{HyFR-NA0.50}$	5.41
$SCC_{FMK5.00}$	3.41	$SCC_{GMK5.00}$	3.64	$SCC_{GM5.00}$	3.49	$Hy_{FSCCType1-B}$	5.41	$SCC_{HyFR-NA1.00}$	5.72
$SCC_{FMK7.50}$	3.56	$SCC_{GMK7.50}$	3.69	$SCC_{GM10.00}$	3.67	$Hy_{FSCCType1-C}$	5.43	$SCC_{HyFR-NA1.50}$	5.79
$SCC_{FMK10.00}$	3.59	$SCC_{GMK10.00}$	3.73	$SCC_{GM15.00}$	3.87	$Hy_{FSCCType1-D}$	5.46	$SCC_{HyFR-NA2.00}$	5.85
$SCC_{FMK12.50}$	3.61	$SCC_{GMK12.50}$	3.81	$SCC_{GM20.00}$	4.24	$Hy_{FSCCType2-A}$	5.46	$SCC_{HyFR-NA2.50}$	
$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2-B}$	5.44	$SCC_{HyFR-NA3.00}$	
$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2-C}$	5.42		
$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.3.1.3 Splitting-Tensile Strength -At Post Maturity Ages(>28 Days)

Observations made on the effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Splitting-Tensile Strength at Post Maturity Ages is presented in Table 7.12 and Graph 7.12 and the same is critically analysed in the subsequent paras.



Graph 7.12 Variation of Splitting-Tensile Strength at Post Maturity(>28 Days) with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.3.1.3.1 Discussion on variation of Splitting-Tensile Strength at Post Maturity(>28 Days) wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.12 and the Graph 7.12 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Splitting-Tensile Strength at Post Maturity(>28 Days), as compared to control mix SCC_{FMK0} was increased and was ranging from 3.36 N/mm^2 to 3.76 N/mm^2 and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in the Splitting-Tensile Strength at Post Maturity(>28 Days)was observed to be ranging from 3.48 N/mm^2 to 3.88 N/mm^2 . Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Splitting-Tensile Strength at Post Maturity(>28 Days)was observed to be ranging from 3.51 N/mm^2 to 4.32 N/mm^2. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Splitting-Tensile Strength at Post Maturity(>28 Days)of $Hy_{FSCC-Type\ 1}$ recipe was varied and the same was ranging from 5.44 N/mm^2 to 5.52N/mm^2, when %PP-F increased from 0.00% to 1.00%, while for Hy$_{FSCC\text{-}Type\ 2}$ recipe, the Splitting-Tensile Strength at Post Maturity(>28 Days)was slightly varied and the same was ranging from 5.78 N/mm^2 to 5.75 N/mm^2, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Splitting-Tensile Strength at Post Maturity(>28 Days)was increased and the same was ranging from 5.52 N/mm^2 to 5.99 N/mm^2 .The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the Splitting-Tensile Strength as compared to control SCC recipes and yielded early-tensile strength characteristics , demonstrated tensile strength characteristics at maturity (28days) and also the Splitting-Tensile Strength at Post Maturity(>28 Days).

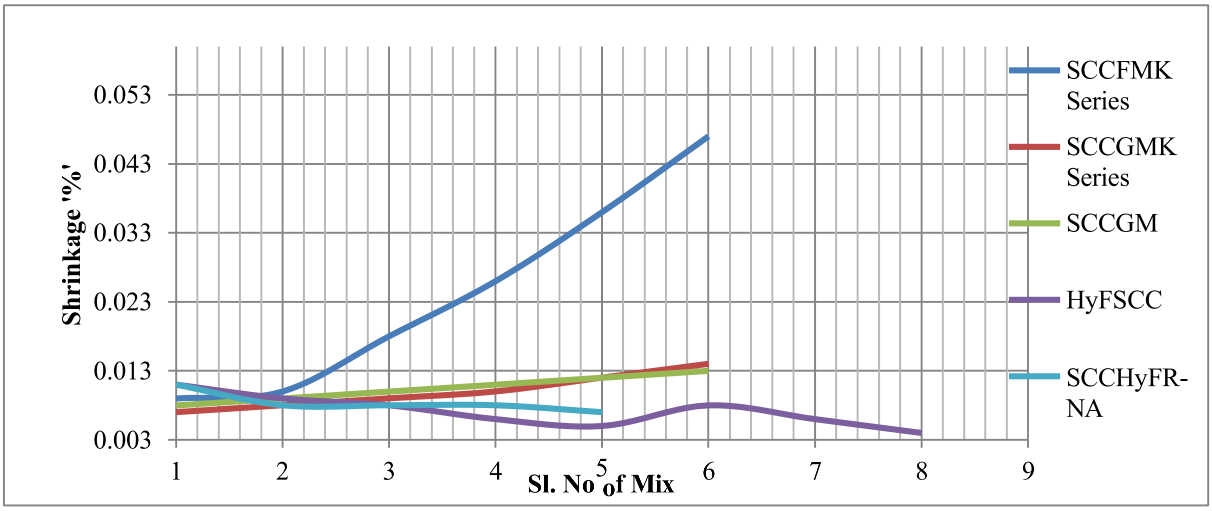
Table 7.12 Splitting-Tensile Strength (At Post Maturity Ages) of various SCC recipes

Mix Code	Splitting-Tensile Strength (At Post Maturity Ages N/mm^2	Mix Code	Splitting-Tensile Strength (At Post Maturity Ages N/mm^2	Mix Code	Splitting-Tensile Strength (At Post Maturity Ages N/mm^2	Mix Code	Splitting-Tensile Strength (At Post Maturity Ages N/mm^2	Mix Code	Splitting-Tensile Strength (At Post Maturity Ages N/mm^2
$SCC_{FMK0.00}$	3.32	$SCC_{GMK0.00}$	3.42	$SCC_{0.00}$	3.54	$SCC_{Control}$	5.39	$SCC_{HyFR-NA0.00}$	5.46
$SCC_{FMK2.50}$	3.36	$SCC_{GMK2.50}$	3.48	$SCC_{GM0.00}$	2.59	$Hy_{FSCCType1-A}$	5.44	$SCC_{HyFR-NA0.50}$	5.52
$SCC_{FMK5.00}$	3.47	$SCC_{GMK5.00}$	3.56	$SCC_{GM5.00}$	3.51	$Hy_{FSCCType1-B}$	5.47	$SCC_{HyFR-NA1.00}$	5.61
$SCC_{FMK7.50}$	3.63	$SCC_{GMK7.50}$	3.72	$SCC_{GM10.00}$	3.84	$Hy_{FSCCType1-C}$	5.49	$SCC_{HyFR-NA1.50}$	5.92
$SCC_{FMK10.00}$	3.68	$SCC_{GMK10.00}$	3.78	$SCC_{GM15.00}$	3.96	$Hy_{FSCCType1-D}$	5.52	$SCC_{HyFR-NA2.00}$	5.99
$SCC_{FMK12.50}$	3.76	$SCC_{GMK12.50}$	3.88	$SCC_{GM20.00}$	4.32	$Hy_{FSCCType2-A}$	5.78	$SCC_{HyFR-NA2.50}$	
$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2-B}$	5.72	$SCC_{HyFR-NA3.00}$	
$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2-C}$	5.75		
$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.4 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Linear Shrinkage(LS) at Early-Age of in SCC recipes

7.4.1 Linear Shrinkage(LS) at Early-Age

Observations as made in this research study presented in Chapter 5, expanded and discussed under sections 5.1, 5.2, 5.3 and 5.4 wrf to the Linear Shrinkage(LS) at Early-Age ,a key characteristics of repair material , is presented in Table 7.13 and Graph 7.13 and the same is critically analysed in the subsequent paras.



Graph 7.13 Variation of Early Age Drying Shrinkage(Linear) with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.4.1.1 Discussion on variation of Early Age Drying Shrinkage(Linear) wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

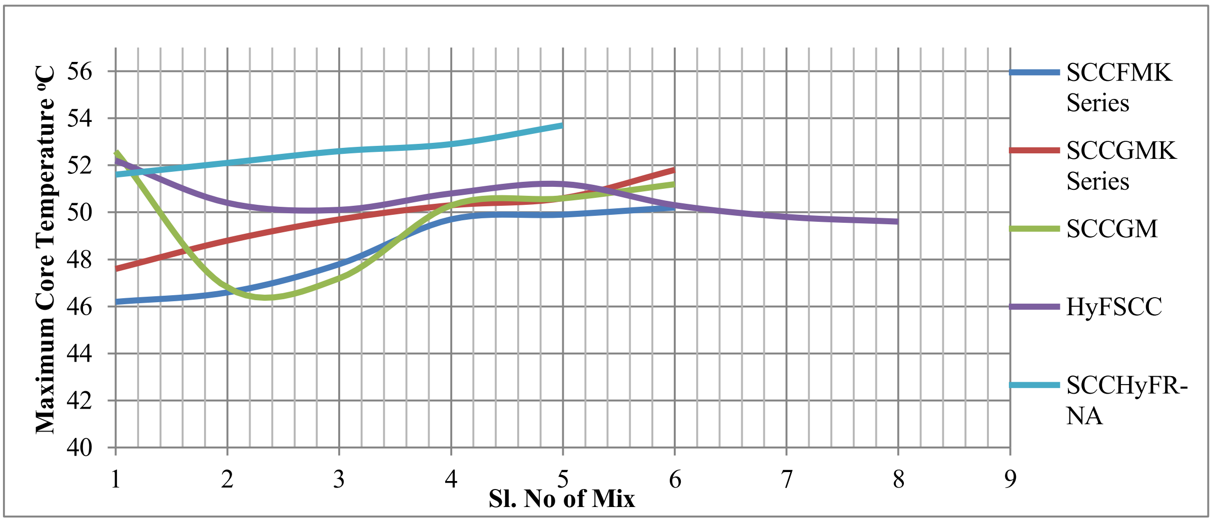
It can be seen from the Table 7.13 and the Graph 7.13 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Early Age Drying Shrinkage(Linear), as compared to control mix SCC_{FMK0} was increased and was ranging from 0.0100 to 0.0470 and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in the Early Age Drying Shrinkage(Linear) was observed to be ranging from 0.0080 to . 0.0140. Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Early Age Drying Shrinkage(Linear) was observed to be ranging from 0.0100 to 0.0130. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Early Age Drying Shrinkage(Linear) of $Hy_{FSCC\text{-}Type\ 1}$ recipe was varied and the same was ranging from 0.0090 to 0.0050, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, the Early Age Drying Shrinkage(Linear) was slightly varied and the same was ranging from 0.0050 to 0.0040, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Early Age Drying Shrinkage(Linear) was increased and the same was ranging from 0.0080 to0.0070.The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the Early Age Drying Shrinkage(Linear) as compared to control SCC recipes and the shrinkage was observed to be well within limits.

Table 7.13 Linear Shrinkage(LS)at Early-Age of various SCC recipes

Mix Code	LS at Early-Age	Mix Code	LS at Early-Age	Mix Code	LS at Early-Age	Mix Code	LS at Early-Age	Mix Code	LS at Early-Age
$SCC_{FMK0.00}$	0.0090	$SCC_{GMK0.00}$	0.0070	$SCC_{0.00}$	0.0080	$SCC_{Control}$	0.0110	$SCC_{HyFR-NA0.00}$	0.0110
$SCC_{FMK2.50}$	0.0100	$SCC_{GMK2.50}$	0.0080	$SCC_{GM0.00}$	0.0090	$Hy_{FSCCType1-A}$	0.0090	$SCC_{HyFR-NA0.50}$	0.0080
$SCC_{FMK5.00}$	0.0180	$SCC_{GMK5.00}$	0.0090	$SCC_{GM5.00}$	0.0100	$Hy_{FSCCType1-B}$	0.0080	$SCC_{HyFR-NA1.00}$	0.0080
$SCC_{FMK7.50}$	0.0260	$SCC_{GMK7.50}$	0.0100	$SCC_{GM10.00}$	0.0110	$Hy_{FSCCType1-C}$	0.0060	$SCC_{HyFR-NA1.50}$	0.0080
$SCC_{FMK10.00}$	0.0360	$SCC_{GMK10.00}$	0.0120	$SCC_{GM15.00}$	0.0120	$Hy_{FSCCType1-D}$	0.0050	$SCC_{HyFR-NA2.00}$	0.0070
$SCC_{FMK12.50}$	0.0470	$SCC_{GMK12.50}$	0.0140	$SCC_{GM20.00}$	0.0130	$Hy_{FSCCType2-A}$	0.0080	$SCC_{HyFR-NA2.50}$	
$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2-B}$	0.0060	$SCC_{HyFR-NA3.00}$	
$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2-C}$	0.0040		
$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.5 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Maximum Core Temperature , °C, in 24-30 Hours of in SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under sections 5.1, 5.2, 5.3 and 5.4 wrf to the Maximum Core Temperature , °C, in 24-30 Hours, a key characteristics of repair material , is presented in Table 7.14 and Graph 7.14 and the same is critically analysed in the subsequent paras.



Graph 7.14 Variation of Maximum Core Temperature , °C, in 24-30 Hours with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.5.1.1 Discussion on variation of Maximum Core Temperature , °C, in 24-30 Hours wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.14 and the Graph 7.14 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the Maximum Core Temperature , °C, in 24-30 Hours, as compared to control mix SCC_{FMK0} was increased and was ranging from 46.6 °C to 50.2 °C and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in the Maximum Core Temperature , °C, in 24-30 Hours was observed to be ranging from 48.8 °C to 51.8 °C. Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Maximum Core Temperature , °C, in 24-30 Hours was observed to be ranging from 46.8 °C to 51.2 °C. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Maximum Core Temperature , °C, in 24-30 Hours of $Hy_{FSCC\text{-}Type\ 1}$ recipe was varied and the same was ranging from 50.4 °C to 51.2 °C, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, the Maximum Core

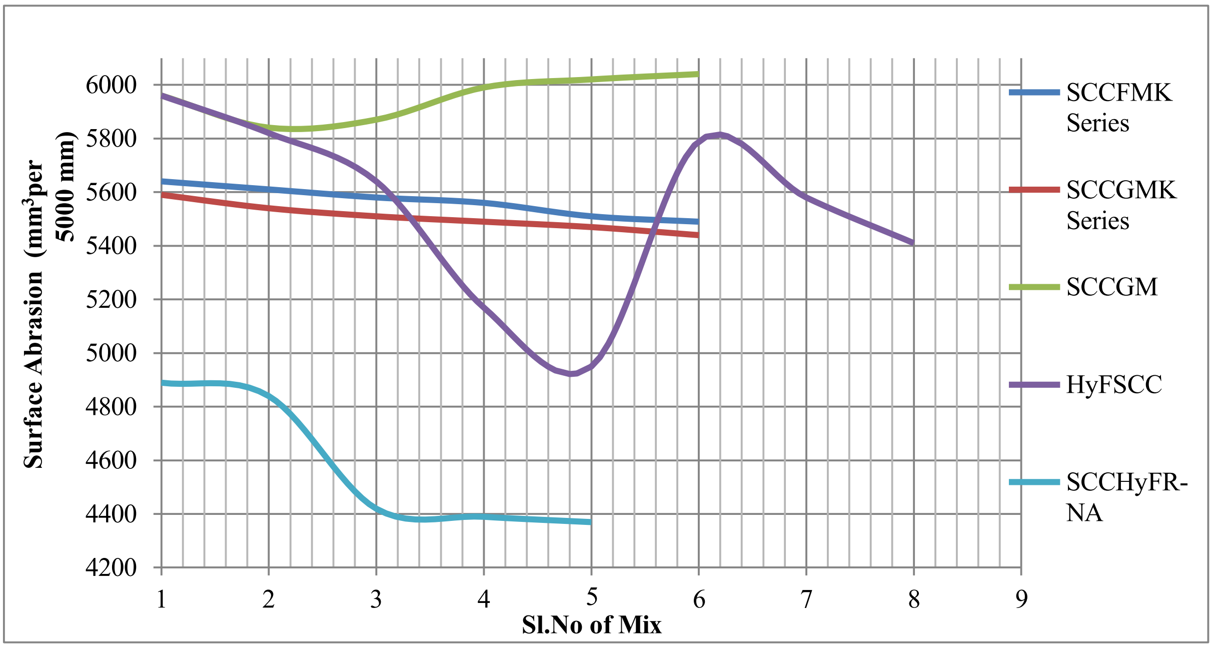
Temperature , ºC, in 24-30 Hours was slightly varied and the same was ranging from 50.3 ºC to 49.6 ºC, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Maximum Core Temperature , ºC, in 24-30 Hours was increased and the same was ranging from 52.1 ºC to 53.7 ºC. The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the development and built up of Core Temperature, ºC, in 24-30 Hours, a indirect indication of heat of hydration and early age reactions as compared to control SCC recipes and the temperature gradient i.e. difference in core temperature and near surface temperature was observed to be well within limits of <22 ºC. The recipes were found to be useful for use in fast-track construction, precast construction and repair works wherein early age strength gain is of predominant importance.

Table 7.14 Maximum Core Temperature in 24-30 Hours , ^{o}C ,of various SCC recipes

Sl. No	Mix Code	Maximum Core Temperature in 24-30 Hours ^{o}C	Mix Code	Maximum Core Temperature in 24-30 Hours ^{o}C	Mix Code	Maximum Core Temperature in 24-30 Hours ^{o}C	Mix Code	Maximum Core Temperature in 24-30 Hours ^{o}C	Mix Code	Maximum Core Temperature in 24-30 Hours ^{o}C
1	$SCC_{FMK0.00}$	46.2	$SCC_{GMK0.00}$	47.6	$SCC_{0.00}$	52.6	$SCC_{Control}$	52.2	$SCC_{HyFR\text{-}NA0.00}$	51.6
2	$SCC_{FMK2.50}$	46.6	$SCC_{GMK2.50}$	48.8	$SCC_{GM0.00}$	46.8	$Hy_{FSCCType1\text{-}A}$	50.4	$SCC_{HyFR\text{-}NA0.50}$	52.1
3	$SCC_{FMK5.00}$	47.8	$SCC_{GMK5.00}$	49.7	$SCC_{GM5.00}$	47.2	$Hy_{FSCCType1\text{-}B}$	50.1	$SCC_{HyFR\text{-}NA1.00}$	52.6
4	$SCC_{FMK7.50}$	49.7	$SCC_{GMK7.50}$	50.3	$SCC_{GM10.00}$	50.3	$Hy_{FSCCType1\text{-}C}$	50.8	$SCC_{HyFR\text{-}NA1.50}$	52.9
5	$SCC_{FMK10.00}$	49.9	$SCC_{GMK10.00}$	50.6	$SCC_{GM15.00}$	50.6	$Hy_{FSCCType1\text{-}D}$	51.2	$SCC_{HyFR\text{-}NA2.00}$	53.7
6	$SCC_{FMK12.50}$	50.2	$SCC_{GMK12.50}$	51.8	$SCC_{GM20.00}$	51.2	$Hy_{FSCCType2\text{-}A}$	50.3	$SCC_{HyFR\text{-}NA2.50}$	
7	$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2\text{-}B}$	49.8	$SCC_{HyFR\text{-}NA3.00}$	
8	$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2\text{-}C}$	49.6		
9	$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.6 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Surface resistance in SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under sections 5.1, 5.2, 5.3 and 5.4 wrf Surface resistance to the Abrasive forces At 28 Days ,mm^{3}per 5000 mm, a key characteristics of repair material , is presented in Table 7.15 and Graph 7.15 and the same is critically analysed in the subsequent paras.



Graph 7.15 Variation of Surface resistance to Abrasive forces At 28 Days(mm^{3}per 5000 mm) with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.6.1.1 Discussion on variation of Surface resistance to Abrasive forces At 28 Days(mm^{3}per 5000 mm) wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.15 and the Graph 7.15 that for SCC$_{FMK\ Series}$ recipes, as related to control SCC recipe SCC$_{FMK0.00}$,once the %MK in SCC$_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes SCC$_{FMK2.50}$ to SCC$_{FMK12.50}$, the Surface resistance to Abrasive forces At 28 Days(mm^{3}per 5000 mm), as compared to control mix SCC$_{FMK0}$ was increased and was ranging from 5610 to 5490 and for the alike variation of % MK in SCC$_{GMK\ Series}$ recipes, slight variation in the Surface resistance to Abrasive forces At 28 Days(mm^{3}per 5000 mm)was observed to be ranging from 5540 to 5440. Whereas for the SCC$_{GM}$ recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the Surface resistance to Abrasive forces At

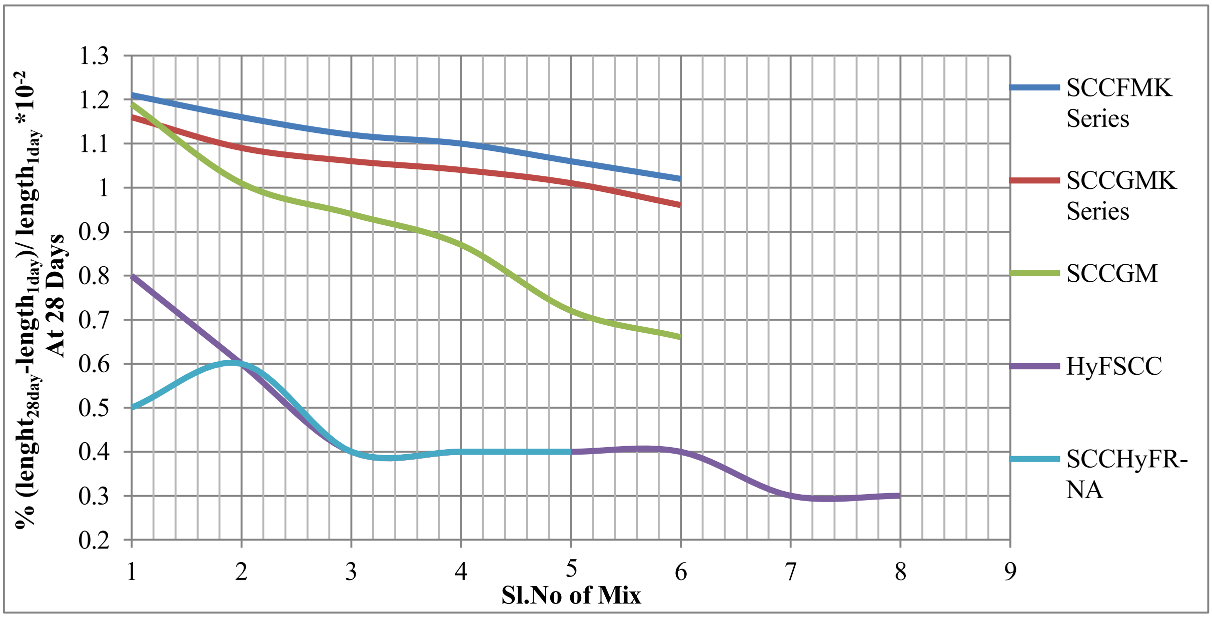
28 Days(mm^{3}per 5000 mm) as observed to be ranging from 5840 to 6020. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the Surface resistance to Abrasive forces At 28 Days(mm^{3}per 5000 mm) of $Hy_{FSCC-Type\ 1}$ recipe was varied and the same was ranging from 5820 to 4950, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC-Type\ 2}$ recipe, the Surface resistance to Abrasive forces At 28 Days(mm^{3}per 5000 mm)was slightly varied and the same was ranging from 5790 to 5410, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , the Surface resistance to Abrasive forces At 28 Days(mm^{3}per 5000 mm) as increased and the same was ranging from 4840 to 4370. The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the Surface resistance to Abrasive forces At 28 Days(mm^{3}per 5000 mm), an indirect indication of wear resistance of concrete, as compared to control SCC recipes. The recipes were found to be useful for use in fast-track construction, precast construction and repair works wherein not only early age strength gain is of predominant importance but resistance to abrasion also warranted.

Table 7.15 Surface resistance to Abrasive forces At 28 Days of various SCC recipes

Sl. No	Mix Code	Surface resistance To Abrasive forces At 28 Days mm^{3}per 5000 mm	Mix Code	Surface resistance To Abrasive forces At 28 Days mm^{3}per 5000 mm	Mix Code	Surface resistance To Abrasive forces At 28 Days mm^{3}per 5000 mm	Mix Code	Surface resistance To Abrasive forces At 28 Days mm^{3}per 5000 mm	Mix Code	Surface resistance To Abrasive forces At 28 Days mm^{3}per 5000 mm
1	$SCC_{FMK0.00}$	5640	$SCC_{GMK0.00}$	5590	$SCC_{0.00}$	5960	$SCC_{Control}$	5960	$SCC_{HyFR-NA0.00}$	4890
2	$SCC_{FMK2.50}$	5610	$SCC_{GMK2.50}$	5540	$SCC_{GM0.00}$	5840	$Hy_{FSCCType1-A}$	5820	$SCC_{HyFR-NA0.50}$	4840
3	$SCC_{FMK5.00}$	5580	$SCC_{GMK5.00}$	5510	$SCC_{GM5.00}$	5870	$Hy_{FSCCType1-B}$	5640	$SCC_{HyFR-NA1.00}$	4420
4	$SCC_{FMK7.50}$	5560	$SCC_{GMK7.50}$	5490	$SCC_{GM10.00}$	5990	$Hy_{FSCCType1-C}$	5170	$SCC_{HyFR-NA1.50}$	4390
5	$SCC_{FMK10.00}$	5510	$SCC_{GMK10.00}$	5470	$SCC_{GM15.00}$	6020	$Hy_{FSCCType1-D}$	4950	$SCC_{HyFR-NA2.00}$	4370
6	$SCC_{FMK12.50}$	5490	$SCC_{GMK12.50}$	5440	$SCC_{GM20.00}$	6040	$Hy_{FSCCType2-A}$	5790	$SCC_{HyFR-NA2.50}$	
7	$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2-B}$	5580	$SCC_{HyFR-NA3.00}$	
8	$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2-C}$	5410		
9	$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.7 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on resistance against ingression of SO_3^- Ions in SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under sections 5.1, 5.2, 5.3 and 5.4 wrf resistance against ingression of SO_3^- ions, measured as enlargement in length of specimen-dipped in sulphate ion rich solution, at 28 Days , against original length, a key characteristics of durability of concrete , is presented in Table 7.16 and Graph 7.16 and the same is critically analysed in the subsequent paras.



Graph 7.16 Variation of resistance against ingression of SO_3^- Ions % ($lenght_{28day}$-$length_{1day}$)/ $length_{1day}$, At 28 Days with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.7.1.1 Discussion on variation of resistance against ingression of SO_3^- Ions -% ($lenght_{28day}$-$length_{1day}$)/ $length_{1day}$, At 28 Days wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

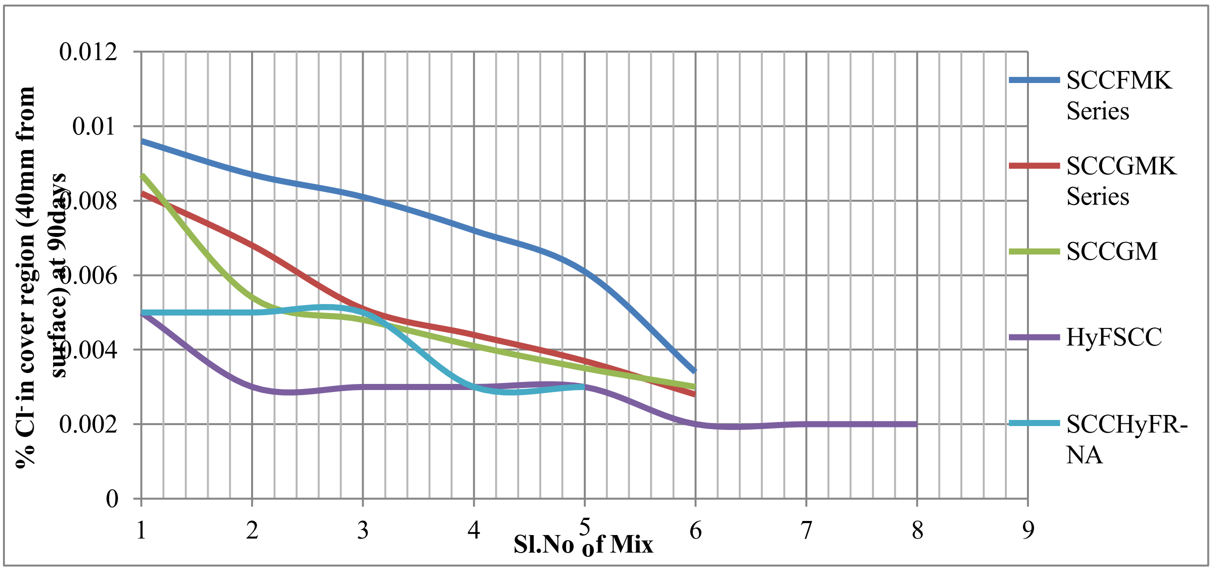
It can be seen from the Table 7.16 and the Graph 7.16 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the resistance against ingression of SO_3^- Ions -% ($lenght_{28day}$-$length_{1day}$)/ $length_{1day}$, At 28 Days , as compared to control mix SCC_{FMK0} was increased and was ranging from 1.16% to 1.02% and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in the same was observed to be ranging from 1.09% to 0.96%. Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the resistance against ingression of SO_3^- Ions -% ($lenght_{28day}$-$length_{1day}$)/ $length_{1day}$, At 28 Days was observed to be ranging from 1.01% to 0.72%. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, the resistance against ingression of SO_3^- Ions -% ($lenght_{28day}$-$length_{1day}$)/ $length_{1day}$, At 28 Days of $Hy_{FSCC-Type\ 1}$ recipe was varied and the same was ranging from 0.60% to 0.40%, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC-Type\ 2}$ recipe, the same was slightly varied and the same was ranging from 0.40% to 0.30%, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , resistance against ingression of SO_3^- Ions -% ($lenght_{28day}$-$length_{1day}$)/ $length_{1day}$, At 28 Days was increased and the same was ranging from 0.60% to 0.40%. The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the resistance against ingression of SO_3^- Ions -% ($lenght_{28day}$-$length_{1day}$)/ $length_{1day}$, At 28 Days , an indirect indication of durability of concrete, as compared to control SCC recipes. The recipes were found to be useful for use in fast-track construction, precast construction and repair works wherein not only early age strength gain is of predominant importance but durability of concrete also warranted.

Table 7.16 Resistance against ingression of SO_3^- ions. at 28 Days, of various SCC recipes

Mix Code	Enlargement in length $(l_{28day}-l_{1day})/l_{1day}$ %	Mix Code	Enlargement in length $(l_{28day}-l_{1day})/l_{1day}$ %	Mix Code	Enlargement in length $(l_{28day}-l_{1day})/l_{1day}$ %	Mix Code	Enlargement in length $(l_{28day}-l_{1day})/l_{1day}$ %	Mix Code	Enlargement in length $(l_{28day}-l_{1day})/l_{1day}$ %
$SCC_{FMK0.00}$	1.21	$SCC_{GMK0.00}$	1.16	$SCC_{0.00}$	1.19	$SCC_{Control}$	0.80	$SCC_{HyFR-NA0.00}$	0.50
$SCC_{FMK2.50}$	1.16	$SCC_{GMK2.50}$	1.09	$SCC_{GM0.00}$	1.01	$Hy_{FSCCType1-A}$	0.60	$SCC_{HyFR-NA0.50}$	0.60
$SCC_{FMK5.00}$	1.12	$SCC_{GMK5.00}$	1.06	$SCC_{GM5.00}$	0.94	$Hy_{FSCCType1-B}$	0.40	$SCC_{HyFR-NA1.00}$	0.40
$SCC_{FMK7.50}$	1.10	$SCC_{GMK7.50}$	1.04	$SCC_{GM10.00}$	0.87	$Hy_{FSCCType1-C}$	0.40	$SCC_{HyFR-NA1.50}$	0.40
$SCC_{FMK10.00}$	1.06	$SCC_{GMK10.00}$	1.01	$SCC_{GM15.00}$	0.72	$Hy_{FSCCType1-D}$	0.40	$SCC_{HyFR-NA2.00}$	0.40
$SCC_{FMK12.50}$	1.02	$SCC_{GMK12.50}$	0.96	$SCC_{GM20.00}$	0.66	$Hy_{FSCCType2-A}$	0.40	$SCC_{HyFR-NA2.50}$	0.40
$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2-B}$	0.30	$SCC_{HyFR-NA3.00}$	
$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2-C}$	0.30		
$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.8 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on resistance against ingression of Cl^- Ions in SCC recipes

Observations as made in this research study presented in Chapter 5, expanded and discussed under sections 5.1, 5.2, 5.3 and 5.4 wrf resistance against ingression of Cl^- ions, measured as % Cl^- present in concrete specimen-subjected to surface ponding with Cl^- rich solution, at 28 Days , against original length, a key characteristics of durability of concrete , is presented in Table 7.17 and Graph 7.17 and the same is critically analysed in the subsequent paras.



Graph 7.17 Variation of resistance against ingression of Cl^- Ions : % Cl^- in cover region (40mm from surface) at 90days with Reactive SCM, Fibres and Highly reactive SCMs in SCC Recipes

7.8.1.1 Discussion on variation of resistance against ingression of Cl^- Ions : % Cl^- in cover region (40mm from surface) at 90days wrf to the presence of Reactive SCM ,Fibres and Highly reactive SCMs in SCC Recipes

It can be seen from the Table 7.17 and the Graph 7.17 that for $SCC_{FMK\ Series}$ recipes, as related to control SCC recipe $SCC_{FMK0.00}$,once the %MK in $SCC_{FMKseries}$ changed from 2.50% to 12.50% i.e. for the recipes $SCC_{FMK2.50}$ to $SCC_{FMK12.50}$, the resistance against ingression of Cl^- Ions : % Cl^- in cover region (40mm from surface) at 90days , as compared to control mix SCC_{FMK0} was increased and was ranging from 0.0087% to 0.0034% and for the alike variation of % MK in $SCC_{GMK\ Series}$ recipes, slight variation in the same was observed to be ranging from 0.0068 % to 0.0028 %. Whereas for the SCC_{GM} recipes ,in the total binder content when % of OPC was maintained at 50.00% and the rest 50.00% was consisting of grouping of GGBF+MK,wherein GGBFS was varied from 30.00% to 50.00% and % MK was varied from 5.00% to 15.00%, the resistance against ingression of Cl^- Ions : % Cl^- in cover region (40mm from surface) at 90days was observed to be ranging from 0.0054% to 0.0030%. But when AR-F Fibres and GR-F Fibres were incorporated in the SCC recipes, resistance against ingression of Cl^- Ions : % Cl^- in cover region (40mm from surface) at 90days of $Hy_{FSCC\text{-}Type\ 1}$ recipe was varied and the same was observed to be 0.003%, when %PP-F increased from 0.00% to 1.00%, while for $Hy_{FSCC\text{-}Type\ 2}$ recipe, the same was slightly varied and the same was 0.002%, as AR-F% was varied from 0.00% to 1.00% .Yet again in the SCC recipes, that consisted of groupings of 0.50% AR-F Fibres + 0.50% of PP-F Fibres ,when NA was incorporated from 0.50% to 2.00% , resistance against ingression of Cl^- Ions : % Cl^- in cover region (40mm from surface) at 90days was increased and the same was ranging from 0.005% to 0.003%. The recipe terminated to confirm SCC characteristics when %NA exceeded 2.00%. From the above discussions it can be summarised that in the SCC recipes, the presence of highly reactive SCM in addition to reactive SCM and Fibre groupings effected the resistance against ingression of Cl^- Ions : % Cl^- in cover region (40mm from surface) at 90days , an indirect indication of durability of concrete, as compared to control SCC recipes. The recipes were found to be useful for use in fast-track construction, precast construction and repair works wherein not only early age strength gain is of predominant importance but durability of concrete also warranted.

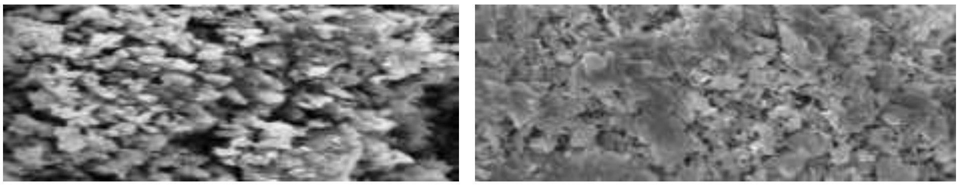
Table 7.17 Resistance against ingression of Cl^- at 28 Days, of various SCC recipes

Sl. No	Mix Code	Cl^- in cover region (40mm from surface) at 90days %	Mix Code	Cl^- in cover region (40mm from surface) at 90days %	Mix Code	Cl^- in cover region (40mm from surface) at 90days %	Mix Code	Cl^- in cover region (40mm from surface) at 90days %	Mix Code	Cl^- in cover region (40mm from surface) at 90days %
1	$SCC_{FMK0.00}$	0.0096	$SCC_{GMK0.00}$	0.0082	$SCC_{0.00}$	0.0087	$SCC_{Control}$	0.005	$SCC_{HyFR\text{-}NA0.00}$	0.005
2	$SCC_{FMK2.50}$	0.0087	$SCC_{GMK2.50}$	0.0068	$SCC_{GM0.00}$	0.0054	$Hy_{FSCCType1\text{-}A}$	0.003	$SCC_{HyFR\text{-}NA0.50}$	0.005
3	$SCC_{FMK5.00}$	0.0081	$SCC_{GMK5.00}$	0.0051	$SCC_{GM5.00}$	0.0048	$Hy_{FSCCType1\text{-}B}$	0.003	$SCC_{HyFR\text{-}NA1.00}$	0.005
4	$SCC_{FMK7.50}$	0.0072	$SCC_{GMK7.50}$	0.0044	$SCC_{GM10.00}$	0.0041	$Hy_{FSCCType1\text{-}C}$	0.003	$SCC_{HyFR\text{-}NA1.50}$	0.003
5	$SCC_{FMK10.00}$	0.0061	$SCC_{GMK10.00}$	0.0037	$SCC_{GM15.00}$	0.0035	$Hy_{FSCCType1\text{-}D}$	0.003	$SCC_{HyFR\text{-}NA2.00}$	0.003
6	$SCC_{FMK12.50}$	0.0034	$SCC_{GMK12.50}$	0.0028	$SCC_{GM20.00}$	0.0030	$Hy_{FSCCType2\text{-}A}$	0.002	$SCC_{HyFR\text{-}NA2.50}$	
7	$SCC_{FMK15.00}$		$SCC_{GMK15.00}$				$Hy_{FSCCType2\text{-}B}$	0.002	$SCC_{HyFR\text{-}NA3.00}$	
8	$SCC_{FMK17.50}$		$SCC_{GMK17.50}$				$Hy_{FSCCType2\text{-}C}$	0.002		
9	$SCC_{FMK20.00}$		$SCC_{GMK20.00}$							

7.9 Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on Microstructure development at early ages(1-Day and 3-Days)in SCC recipes

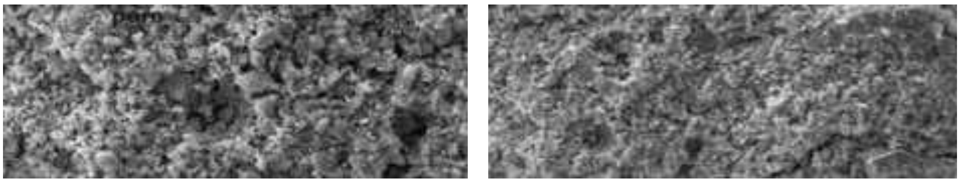
7.9.1 Microstructure Development

Effect of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM on microstructure development at early ages(1-Day and 3-Days)in SCC recipes was studied in SEM for morphology and denseness of reacted matrix. Fig.7.1 presents the extracts of images of SEM acquired from the fragmented surfaces of the specimens of various SCC recipes ,after the compressive strength test, at 1-Day and 3-Days .The micro-structure of hydrated matrix of SCCControl was categorised by incidence of 'C-S-H'gel, 'C-H plates', ettringite, different pore spaces etc. and could be understood, by glancing the Fig.7.1 (a) and (b) ,by the presence of sloppily filled inner matrix space. By glancing the Fig.7.1 (c) and (d) , where the recipe was modified with 25.00%Flyash+12.00%MK(i.e $SCC_{FMK12.50}$ recipe),it could be understood that moderately compact, close, encrusted crystal-like micro-structure with inter-layer pore-spaces, scattered void spaces were developed in the matrix and thus lead to improved mechanical and durability characteristics of $SCC_{FMK12.50}$ recipe wrf to $SCC_{Control}$ recipe. Upon glancing the Fig.7.1 (e) and (f) , where the recipe was modified with 25.00% GGBFS+ 12.50% MK(i.e$SCC_{GMK12.50}$ recipe),it could be understood that ascetically compressed, close by, enveloped crystal-like micro-structure, scattered void spaces were developed in the matrix and thus lead to improved mechanical and durability characteristics of $SCC_{GMK12.50}$ recipe wrf to $SCC_{FMK12.50}$ recipe. Upon glancing the Fig.7.1 (g) and (h) , where the recipe was modified with 40.00%GGBFS+10.00%MK(i.e$SCC_{GM10.00}$ recipe),it could be understood that well compressed, closely packed, enclosed crystal-like micro-structure with less scattered void-spaces were developed in the matrix and thus lead to further improved mechanical and durability characteristics of $SCC_{GM10.00}$ recipe wrf to $SCC_{GMK12.50}$ recipe.



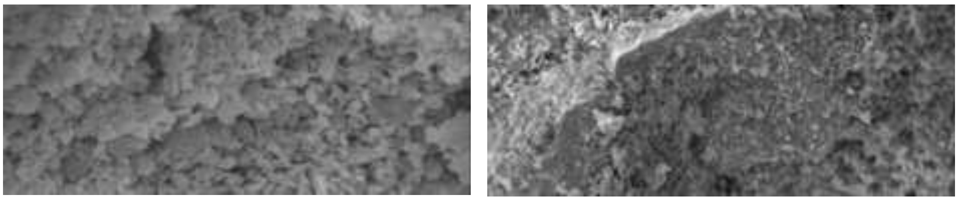
(a)1-Day **(b)3-Days**

SEM-SCC$_{Control}$



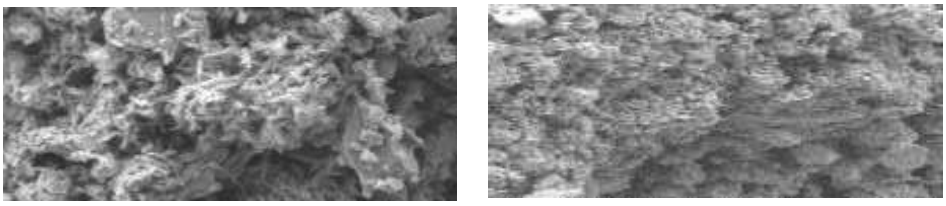
(c)1-Day **(d)3-Days**

SEM-SCC$_{FMK12.50}$



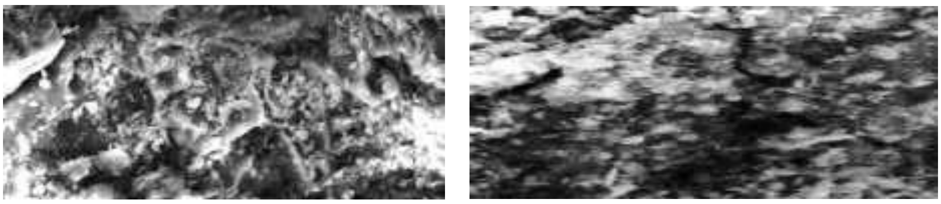
(e)1-Day **(f)3-Days**

SEM-SCC$_{GMK12.50}$



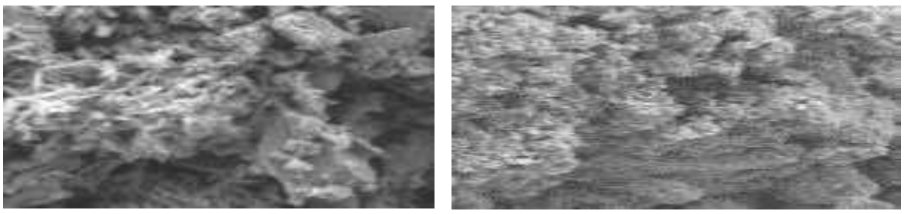
(g)1-Day **(h)3-Days**

SEM-SCC$_{GM10.00}$



(i)1-Day **(j)3-Days**

SEM- Hy$_{FSCCType1-D}$



(k)1-Day **(l)3-Days**

SEM- SCC$_{HyFR-NA1.00}$

Fig.7.1 (g-l) Microstructure development at early ages(1-Day and 3-Days)in SCC recipes

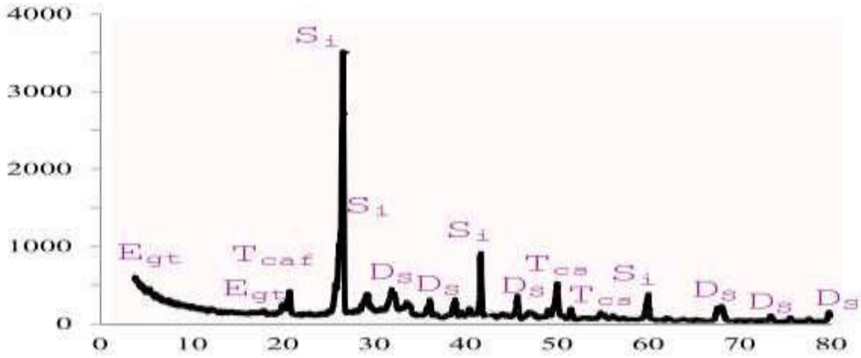
Again, upon examining the Fig.7.1(i) and (j) ,where the recipe was modified with 0.50% AR-F +0.50% PP-F in the earlier above modified recipe $SCC_{GM10.00}$,it could be implicit that spartanly compacted crystal-like micro-structure, with few scattered void-spaces were developed in the matrix and thus lead to further varied mechanical and durability characteristics of $Hy_{FSCCType1-D}$ recipe wrf to recipe wrf to $SCC_{GM10.00}$ recipe. When closely observing the Fig.7.1(k) and (l),wherein the recipe $Hy_{FSCCType1-D}$ was modified as 8.50% of MK+1.50% NA (i.e $SCC_{HyFR-NA1.00}$ recipe) ,it could be understood that well-compacted, further dense micro-structure with very few void-spaces were developed in the matrix and thus lead to further improved mechanical and durability characteristics of $SCC_{HyFR-NA1.00}$ recipe wrf to $Hy_{FSCCType1-D}$ recipe.

7.9.2 XRD patterns of various SCC Recipes at 7-Days

Fig.7.2(a-f) demonstrates the XRD forms of the of various SCC Recipes at 7-Days. The crystal-like segments of present in various SCC recipes were deliberated by XRD wherein peaks are influenced by reactive phases in the matrix. The passion of the unique crests in their XRD spectrum was pliably related to the extent of reactiveness material present after hydration effects. The dissemination of summits in the $SCC_{Control}$, $SCC_{GMK12.50}$, $SCC_{FMK12.50}$, $SCC_{GM10.00,}$ $Hy_{FSCCType1-D}$ and $SCC_{HyFR-NA1.50}$ recipes, at 7-days, after XRD in the $2\theta^{0}$-ranged from 22° to 41°.The Quartz (S_i)crest in the $SCC_{HyFR-NA1.50}$ with GGBFS ,MK and NA addition ,fallen, indicating the consumption of 'C-H' due to higher pozzolonic reactions in the concerned recipe. The Quartz (S_i)crest level of the experimented recipes were $SCC_{Control}$ < $SCC_{GMK12.50}$ < $SCC_{FMK12.50}$ <$SCC_{GM10.00}$ < $Hy_{FSCCType1-D}$ < $SCC_{HyFR-NA1.50}$.This diminishing crest level of Quartz (S_i)crest indirectly hints towards the early age reactiveness of the recipes where in $SCC_{HyFR-NA1.50}$ recipe was highly reactive while $SCC_{Control}$ recipe was slightly less reactive. This trend of reactiveness was confirmed by the compressive strength as well as the split tensile strength test of the specimens at 7-days age of the above recipes.

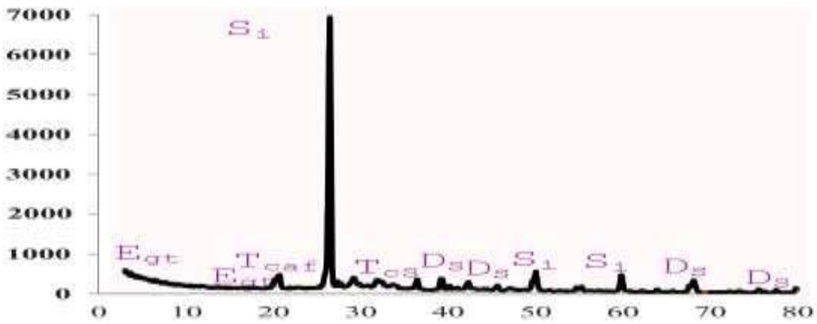
S_1 :Quartz
D_{s1} :C_2S
T_{cs} :C_3S
T_{caf} :C_4AF
E_{gt} :Ettringite

Notations



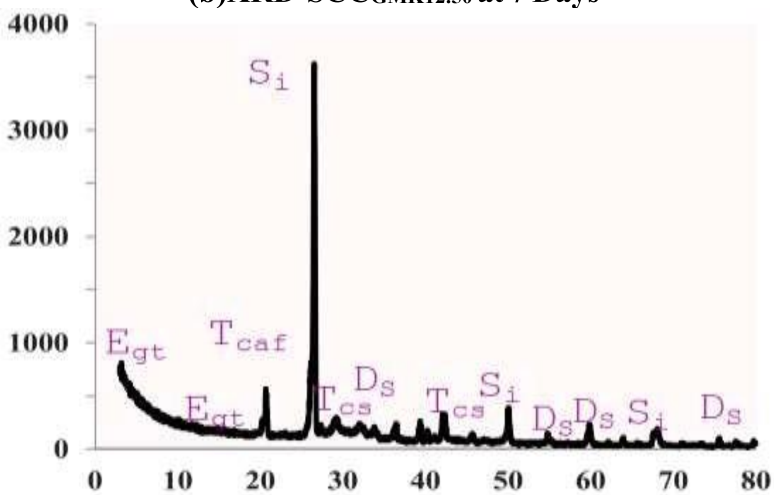
Diffraction Angle 2θ^0

(a) XRD-SCC$_{Control}$ at 7 Days



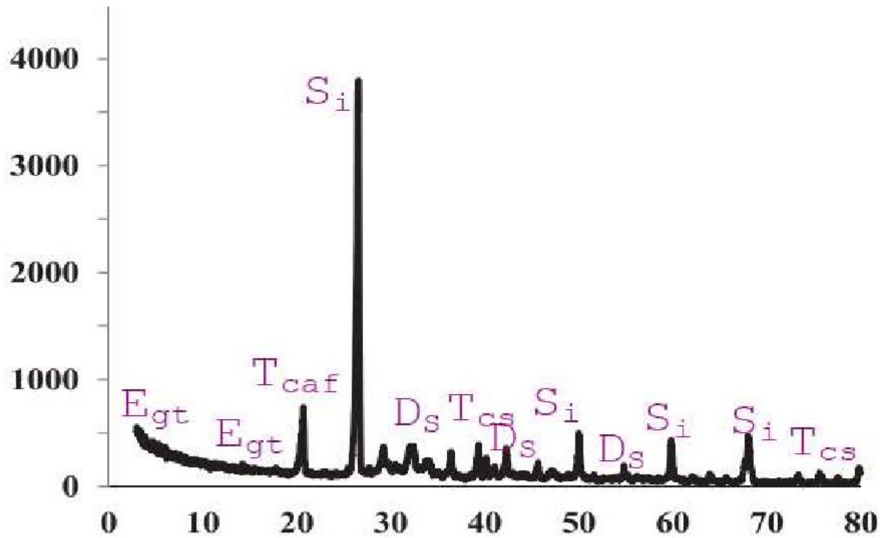
Diffraction Angle 2θ^0

(b)XRD-SCC$_{GMK12.50}$ at 7 Days



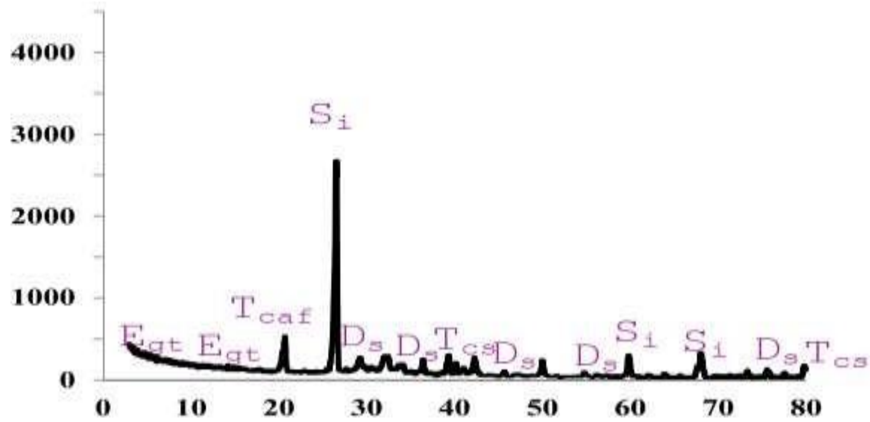
Diffraction Angle 2θ^0

(c)XRD-SCC$_{FMK12.5}$ at 7 Days



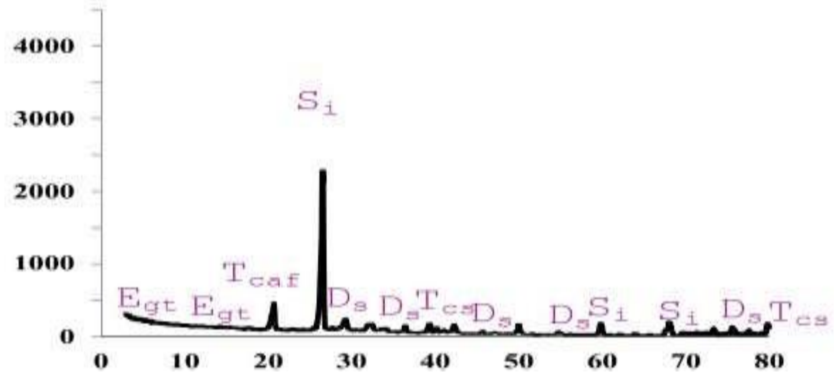
Diffraction Angle $2\theta^0$

(d)XRD-SCC$_{GM10.00}$ at 7 Days



Diffraction Angle $2\theta^0$

(e)XRD-Hy$_{FSCCType1-D}$ at 7 Days



Diffraction Angle $2\theta^0$

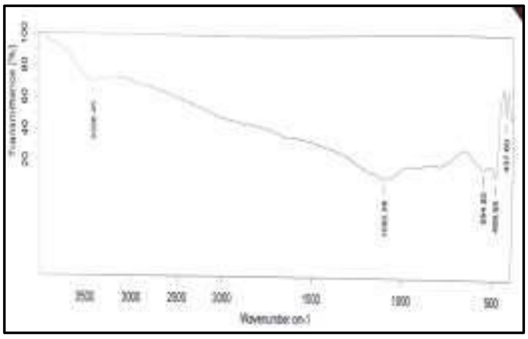
(f)XRD- SCC$_{HyFR-NA1.50}$ at 7 Days

Graph 7.18 (a-f) XRD at 7-Days) of various SCC recipes

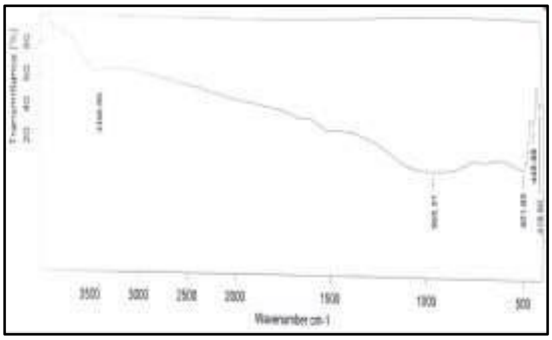
7.9.3 FT-IR patterns of various SCC Recipes at 7-Days

Graph 7.19 (a-f) presents FT-IR at 7-Days of various SCC recipes studied in this research work is presented. The spectrum of the $SCC_{FMK12.5}$ sample shows that the OH stretching vibrations in the defined highest point at 3398 cm^{-1}. Furthermore, the highest points in the 1200cm^{-1} to 400cm^{-1} range are a confirmation of the presence of kaolinite in the sample.

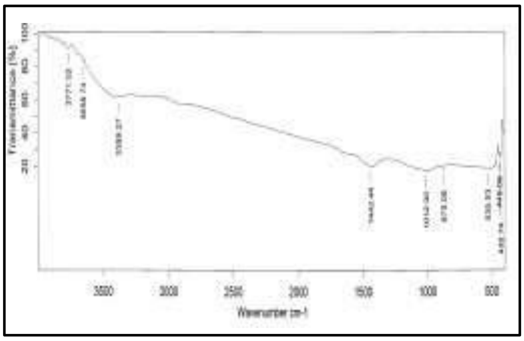
The spectrum of the $SCC_{GMK12.5}$ sample shows that the OH stretching vibrations in the defined highest point at 3396 cm^{-1}. Furthermore, the highest points in the 1300cm^{-1} to 400cm^{-1} range are a confirmation of the presence of alumina and silica based compounds in the sample.



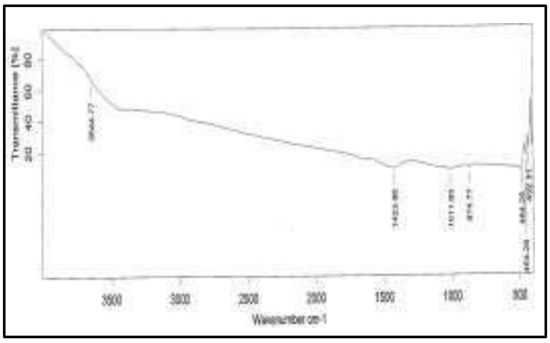
(a) FT-IR –$SCC_{FMK12.5}$



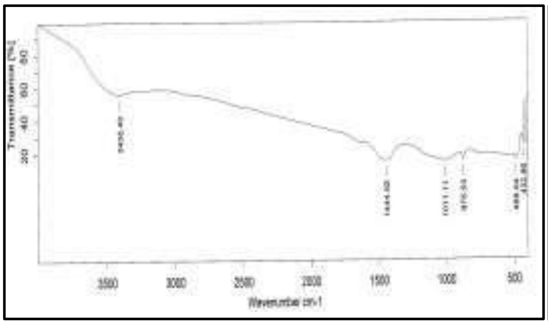
(b) FT-IR –$SCC_{GMK12.5}$



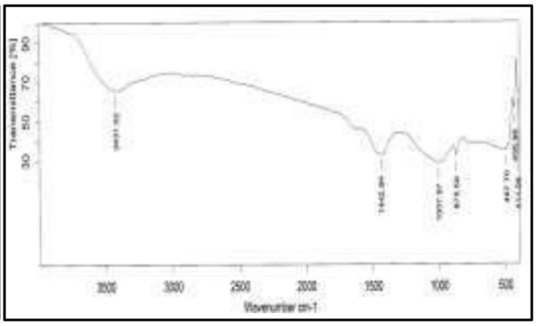
© FT-IR –SCC_{GM10}



(d) FT-IR –$Hy_{FSCC\ Type\text{-}1D}$



(e) FT-IR – **$SCC_{HyFR\text{-}NA0.0}$**



(f) FT-IR **$SCC_{HyFR\text{-}NA1.50}$**

Graph 7.19 (a-f) FT-IR at 7-Days of various SCC recipes

The spectrum of the SCC_{GMK10} sample shows that the OH stretching vibrations in the defined highest point at 3771 cm^{-1}. Furthermore, the highest points in the 1400cm^{-1} to 400cm^{-1} range are a confirmation of the presence of kaolinite in the sample. The spectrum of the $Hy_{FSCC\ Type\text{-}1D}$ sample shows that the OH stretching vibrations in the defined highest point at 3396 cm^{-1}. Furthermore, the highest points in the 1300cm^{-1} to 400cm^{-1} range are a confirmation of the presence of alumina and silica based compounds in the sample.

7.10 Cost comparison of SCC Recipes consisting of moderately reactive SCMs, Reactive SCM ,Fibres and Highly reactive SCM

7.10.1 Cost of 1m^3 of $SCC_{FMK12.5}$ Recipe

The market cost of various constituents forming SCC recipe, for the financial year 2022-23, and cost of 1m^3 $SCC_{FMK12.5}$ Recipe at the place of mixing is presented in Table 7.17. From the above Table 7.17, it can be observed that the cost of $SCC_{FMK12.5}$ recipe for 1m^3 was Rs.6621 and the cost same for 1m^3 $SCC_{Conventional}$ recipe was Rs.5587.

7.10.2 Cost of 1m^3 of $SCC_{GMK12.5}$ Recipe

The market cost of various constituents forming SCC recipe, based on the market cost of materials for the financial year 2022-23, and cost of 1m^3 $SCC_{GMK12.5}$ recipes at the place of mixing is presented in Table 7.18. From the above Table 7.17, it can be observed that the cost of $SCC_{GMK12.5}$ recipe for 1m^3 was Rs.7142 and the cost same for 1m^3 $SCC_{Conventional}$ recipe was Rs.6718.

7.10.3 Cost of 1m^3 of SCC_{GM10} Recipe

The market cost of various constituents forming SCC recipe, based on the market cost of materials for the financial year 2022-23, and cost of 1m^3 SCC_{GM10} recipe at the place of mixing is presented in Table 7.19. From the above Table 7.17, it can be observed that the cost of SCC_{GM10} recipe for 1m^3 was Rs.6445 and the cost same for 1m^3 $SCC_{Conventional}$ recipe was Rs.5503.

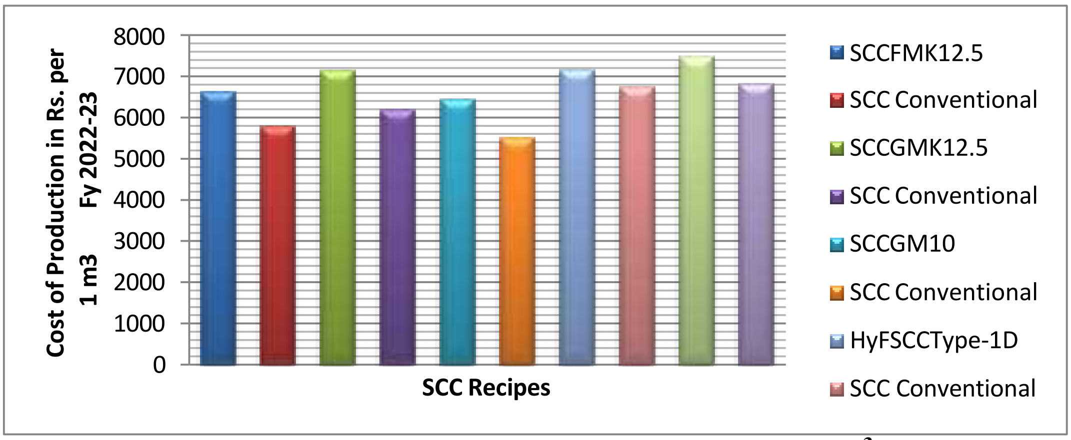
7.10.4 Cost of 1m^3 of $Hy_{FSCC\ Type1\text{-}D}$ Recipe

The market cost of various constituents forming SCC recipe, based on the market cost of materials for the financial year 2022-23, and cost of 1m^3 $Hy_{FSCC\ Type1\text{-}D}$ recipes at the place of mixing is presented in Table 7.19. From the above Table 7.17, it can be observed that the cost of $Hy_{FSCC\ Type1-D}$ recipe for $1m^3$ was Rs.7154 and the cost same for $1m^3$ $SCC_{Conventional}$ recipe was Rs.6753.

7.10.5 Cost of $1m^3$ of $SCC_{HyFR-NA1.50}$ Recipe

The market cost of various constituents forming SCC recipe, based on the market cost of materials for the financial year 2022-23, and cost of $1m^3$ $SCC_{HyFR-NA1.50}$ recipe at the place of mixing is presented in Table 7.20. From the above Table 7.17, it can be observed that the cost of $SCC_{HyFR-NA1.50}$ recipe for $1m^3$ was Rs.7475 and the cost same for $1m^3$ $SCC_{Conventional}$ recipe was Rs.6815.

Based on the comparison of cost of $1m^3$ of SCC recipes $SCC_{FMK12.5}$, $SCC_{GMK12.5}$, SCC_{GM10}, $Hy_{FSCCType-1D}$ and $SCC_{HyFR-NA\ 2.0}$ against the cost of $1m^3$ of respective $SCC_{Conventional}$ recipes , it can be seen that there was an increase of 12.59% in the cost of $SCC_{FMK12.5}$; an increase of 13.49% in the cost of $SCC_{GMK12.5}$; an increase of 14.61% in the cost of SCC_{GM10} ; an increase of 5.74% in the cost of $Hy_{FSCCType-1D}$; an increase of 8.83% in the cost of $SCC_{HyFR-NA\ 1.50}$ **.** Graph 7.18 represents the cost of production of various SCC recipes as proportioned in this research study, per $1m^3$ for the Fy2022-23.



Graph 7.20 Cost of production of various SCC Recipes per $1m^3$ for the Fy2022-23

Table 7.18

Cost of 1m^3 of SCC$_{FMK12.5}$ Recipe(based on the market cost of materials for the financial year 2022-23)

Material	Units	Approx. Cost per Unit	Quantity Required for 1m3 (Total Binding Material 540 Kg/m3)	Cost of Recipe SCC FMK12.5 (C 62.50%+MK 12.50% +Flyash 25.00%)	SCC Conventional (C 75.00+Flyash 25.00%) for 1m3 (Total Binding Material 540 Kg/1m3)	Cost of Recipe SCCConventional
		Rs.	Kgs	Rs.	Kgs	Rs.
Cement	Kgs	8.00	338	2700	405	3240
Metakaolin	Kgs	20.00	68	1350	0	0
Flyash	Kgs	0.10	135	14	135	13.5
GGBFS	Kgs	3.00	0	0	0	0
Nano Alumina	Kgs	50.00	0	0	0	0
Sand	Kgs	1.60	915	1464	915	1464
CA 10mm	Kgs	1.00	750	750	750	750
Water	Kgs	0.10	190	19	190	19
Admixture PCE	Kgs	60.00	5	324	5	300
AR-F Fibre	Kgs	100.00	0	0	0	0
PP-F Fibre	Kgs	100.00	0	0	0	0
Total cost of SCC Recipe per 1m^3 Rs.				6621		5587

Table 7.19

Cost of 1m^3 of SCC$_{GMK12.5}$ Recipe(based on the market cost of materials for the financial year 2022-23)

Material	Units	Approx. Cost per Unit	Quantity Required for 1m^3 (Total Binding Material 540 Kg/m^3)	SCC GMK12.5 (C 50%+MK 12.50% +GGBFS 25%)	SCC Conventional for 1m3 (Total Binding Material 540 Kg/1m3)	Cost of SCC Conventional
		Rs.	Kg	Rs	Kg	Kg
Cement	Kgs	8.00	354	2830	405	3240
Metakaolin	Kgs	20.00	68	1350	0	0
Flyash	Kgs	0.10	0	0	0	0
GGBFS	Kgs	3.00	135	405	135	405
NA	Kgs	50.00	0	0	0	0
Sand	Kgs	1.60	915	1464	915	1464
CA 10mm	Kgs	1.00	750	750	750	750
Water	Kgs	0.10	190	19	190	19
Admixture PCE	Kgs	60.00	5	324	5	300

Material	Units	Approx. Cost per Unit	Quantity Required for 1m³ (Total Binding Material 540 Kg/m³)	SCC GMK12.5 (C 50%+MK 12.50% +GGBFS 25%)	SCC Conventional for 1m3 (Total Binding Material 540 Kg/1m3)	Cost of SCC Conventional
		Rs.	Kg	Rs	Kg	Kg
AR Fibre 6mm	Kgs	100.00	0	0	0	0
AR Fibre 12mm	Kgs	100.00	0	0	0	0
Total cost of SCC Recipe per 1m³ Rs.				7142	6178	

Table 7.20

Cost of 1m³ of SCC$_{GM10}$ Recipe(based on the market cost of materials for the financial year 2022-23)

Material	Units	Approx. Cost per Unit	Quantity Required for 1m3 (Total Binding Material 540 Kg/m3)	Cost of Recipe SCC GM10 (C 50.00%+MK 10.00% +GGBFS 40.00%)	SCC Conventional (C 75.00+Flyash 25.00%) for 1m3 (Total Binding Material 540 Kg/1m3)	Cost of Recipe SCCConventional
		Rs.	**Kgs**	**Rs.**	**Kgs**	**Rs.**
Cement	Kgs	8.00	270	2160	270	2160
Metakaolin	Kgs	20.00	54	1080	0	0
Flyash	Kgs	0.10	0	0	0	0
GGBFS	Kgs	3.00	216	648	270	810
NA	Kgs	50.00	0	0	0	0
Sand	Kgs	1.60	915	1464	915	1464
CA 10mm	Kgs	1.00	750	750	750	750
Water	Kgs	0.10	190	19	190	19
Admixture PCE	Kgs	60.00	5	324	5	300
AR Fibre 6mm	Kgs	100.00	0	0	0	0
Cement	Kgs	100.00	0	0	0	0
Total cost of SCC Recipe per 1m³ Rs.				6445	5503	

Table 7.21

Cost of 1m³ of Hy_{FSCCType-1D} Recipe (based on the market cost of materials for the financial year 2022-23)

Material	Units	Approx. Cost per Unit	Quantity Required for 1m³ (Total Binding Material 550 Kg/m³)	HyFSCCType-1D (C 50.00%+MK 10.00% +GGBFS 40.00%+ARF 0.50% +PPF 0.50%)	SCC Conventional for 1m3 (Total Binding Material 550 Kg/1m3)	Cost of SCC Conventional
		Rs.	Kg	Rs	Kg	Kg
Cement	Kgs	8.00	275	2200	412.5	3300
Metakaolin	Kgs	20.00	55	1100	0	0
Flyash	Kgs	0.10	0	0	0	0
GGBFS	Kgs	3.00	220	660	275	825
NA	Kgs	50.00	0	0	0	0
Sand	Kgs	1.60	900	1440	900	1440
CA 10mm	Kgs	1.00	740	740	740	740
Water	Kgs	0.10	181	18	181	18.1
Admixture PCE	Kgs	60.00	7	396	7	420
AR Fibre 6mm	Kgs	100.00	3	300	0	0
AR Fibre 12mm	Kgs	100.00	3	300	0	0
Total cost of SCC Recipe per 1m³ Rs.				7154	6753	

Table 7.22

Cost of 1m³ of SCC_{HyFR-NA 1.50} Recipe (based on the market cost of materials for the financial year 2022-23)

Material	Units	Approx. Cost per Unit	Quantity Required for 1m³ (Total Binding Material 560 Kg/m³)	SCCHyFR-NA 1.50 (C 50.00%+MK 8.50% +NA 1.50%+GGBFS 40.00%+ARF 0.50% +PPF 0.50%)	SCC Conventional for 1m3 (Total Binding Material 560 Kg/1m3)	Cost of SCC Conventional
		Rs.	Kg	Rs	Kg	Kg
Cement	Kgs	8.00	280	2240	420	3360
Metakaolin	Kgs	20.00	48	952	0	0
Flyash	Kgs	0.10	0	0	0	0
GGBFS	Kgs	3.00	224	672	280	840
NA	Kgs	50.00	8	420	0	0
Sand	Kgs	1.60	910	1456	910	1456
CA 10mm	Kgs	1.00	720	720	720	720
Water	Kgs	0.10	185	19	185	18.5
Admixture PCE	Kgs	60.00	7	396	7	420
AR Fibre 6mm	Kgs	100.00	3	300	0	0
AR Fibre 12mm	Kgs	100.00	3	300	0	0
Total cost of SCC Recipe per 1m³ Rs.				7475	6815	

CHAPTER 8

OUTCOME OF THE STUDY

8.0 General

After accomplishment of experiments that were carried in this research and comprehensive studies made and analysis, of the same -both in laboratory and field trials, on fast setting and early strength hybrid fibre reinforced self compacting concrete(FSESHFRSCC), the following inferences can be drawn ,presented hereunder.

8.1 Outcome from the study

1) In SCC recipes ,proportioned with part replacement of OPC with variable proportions of MK and at constant proportions of 25% with GGBFS and flyash, fast reactions of MK was observed in association of GGBFS than the similar reactions of MK in association of Flyash.

2) MK's incorporation in SCC recipes -as a high reactive SCM, increases the water demand but results in an increased cohesiveness of the mix.

3) In SCC recipes- proportioned with part replacement of OPC with MK and at constant 40% of GGBFS, replacement of OPC with 10% MK observed to result in satisfactory fresh state properties of SCC like SF and VFT.

4) Time required for final set of SCC recipes proportioned with part replacement of OPC with MK and at constant 40% of GGBFS, there was continues decrease in final setting time with an increase in %MK(up 10% replacement levels) and beyond 10% MK content, there was a marginal decrease in final setting time in all the experimented SCC recipes.

5) In SCC recipe, containing weighted proportions of OPC as 50%,proportion of GGBFS as 40% and proportion of MK as 10%, the hybrid fibre combinations of PP-F at 0.5% and AR-F at 0.5% resulted into an acceptable mix in fresh state, hardened state and also demonstrated satisfactory durability characteristics.

6) In of SCC $_{HyFR-NA}$ recipe with proportions of OPC as 50%,proportion of GGBFS as 40% and proportion of MK as 10%, when MK was marginally replaced in a proportion of 0.5% to 2.0% by NA, to make total combination of MK+NA to 10%, the time required for final set was further decreased indicating quicker hydration reactions. The recipe ceases to have SCC characteristics beyond 2.0% of NA.

7) As the NA proportion increased from 0.5% to 2.0% in the SCC $_{HyFR-NA}$ recipe, early age and later age compressive strength and split tensile strength observed to be increased

8) In SCC $_{HyFR-NA}$ recipe, as the NA proportion increased from 0.5% to 2.0%, durability characteristics of the SCC $_{HyFR-NA}$ recipe like linear shrinkage, resistance to SO_3^- and Cl^- ion ingression were observed to be decreased

9) Optimized concrete recipes of SCC $_{HyFR-NA1.0}$ and SCC $_{HyFR-NA1.5}$ can be used for quick construction as well as repairs to concrete, where early operation time is required to meet.

10) The XRD, SEM, Photo micrograph and FTIR analyses on optimized mixes support the results of early age hydration, compact microstructure etc., which are very useful for similar kind of studies.

8.2 Consequences of the Study

The consequence of this research covers all the props of sustainability like economy, environment and society and helps the construction sector in light of achieving reduced carbon footprint and to achieve sustainability and durability, an imperative prerequisites of long-lasting infrastructures. This research in future may be a significant implement in the field of fast track construction and will be very helpful for construction engineers and researchers in understanding the effects and behaviour of various highly reactive supplementary cementitious materials and fibres for developing the tailor made proportions to suit various construction requirement.

CHAPTER 9

FUTURE SCOPE

9.0 General

This detailed research work was carried out in an assumed scope and objectives with certain suppositions. During the research and after concluding the same it had been instituted that there are quiet definite research gaps which can be further explored by impending researchers to explore on to treasure more meticulous study on certain outcomes.

9.1 Future scope for research

The future scope of research that can be investigated further, is itemized in the following themes

9.1.1 The mix proportioning methods for hybrid fibre reinforced self-compacting to be analyzed in detail so that it can be used at site to proportion the recipes conveniently and use the same .

9.1.2 The various fast reacting cementitious materials like micro silica, rice husk ash, nano clays etc., can be explored in the optimum recipes to develop compatible recipes resulting in early strength recipes as well as maintaining durability.

9.1.3 The optimized mixes can be verified for its performance in dynamic loading conditions , pre-stressed and post tensioned concrete elements.

9.1.4 The optimized mixes can be verified for its performance in fracture mechanics investigations.

9.1.5 The optimized mixes can be modified and verified for the possible use in 3-D printable concrete works

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