EXPERIMENTAL ANALYSIS ON PROPERTIES OF CONCRETE USING ALCCOFINE AND BOTTOM ASH

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dedicated to my Wife, Parents

and

my lovable brother Abhitesh

Declaration

The research work presented in this dissertation was carried out at School of Civil Engineering, Lovely Professional University, Punjab, India between August 2016 to January 2022 under the supervision of Dr. Pushpendra Kumar Sharma and Dr. Abhinav Kumar.

I hereby declare that, except for where specific references are made to the work of other authors or specially indicated in the text, the contents of this dissertation are his own work. This report has not been submitted in parts, or in whole to any other university for a degree, diploma or other qualification. The work is purely done by me and includes nothing which is the outcome of work done in collaboration. This dissertation is within the word limit of 40,000 words, including bibliography, appendices, table and equations, and does not contain more than 80 figures.

Abhishek Sachdeva

February 2022

Certificate

This is to certify that **Mr. Abhishek Sachdeva** has completed the Ph.D. Civil Engineering titled, **“Experimental Analysis on properties of concrete using Alccofine and Bottom Ash”** under my guidance and supervision. To the best of my knowledge, the present work is the result of his original investigation and study. No part of this thesis work has ever been submitted for any degree.

This thesis is fit for the submission for the complete fulfilment of the condition for the award of degree of Ph.D. in Civil Engineering.

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Abstract

Problems associated with environmental pollution are escalating and in the current scenario, various strategies have to be worked, in order to curtail the adverse impacts occurring due to the rising pollution. Due to the urbanization, infrastructure and industrial developments, waste management also presents a host of challenges now-a-days. Human and environment is prone to the irreparable damages due to the lack of proper waste collection and disposal approaches in industries. Coal fired thermal power plants are the major source of electricity generation in the country. By-products of these thermal power plants cause various environmental hazards to the surrounding community. It is a well-known fact that natural resources are depleting at very rapid rate, while simultaneously industrial waste is increasing substantially. In order to achieve goal of sustainable environment and green construction, there is a need to find the suitable alternative non-conventional and innovative materials along with the recycling of the wastage with a view to tackle the depletion of naturally existing resources. With this approach, the present exploration work is planned where fine aggregates were partially replaced with coal bottom ash and simultaneously Alccofine is introduced as an alternative to cement in coal bottom ash concrete mixture.

The research program has been divided into two phases. In the Phase-I, a controlled concrete mix of M40 grade was designed as per IS 10262:2009 and IS 456:2000. Coal bottom ash was utilized as replacement of fine aggregates in incremental percentage of 10 % up to 50 % and strength properties was evaluated. In the Phase-II, the effect of Alccofine on properties of bottom ash concrete was evaluated. Concrete's flowability was evaluated by executing the slump test on fresh concrete. Tests for compressive strength split tensile strength and flexural strength was carried out to assess mechanical properties of concrete. Rapid Chloride Penetration Test (RCPT) and Initial Surface Absorption Test (ISAT) were conducted on varied concrete mixtures to evaluate the durability of concrete. Non Destructive Testing (NDT) was also conducted on concrete specimens, which includes Rebound Hammer Test and Ultrasonic Pulse Velocity (UPV) test. All the tests were performed up to the age of 180 days. Scanning Electron Microscopy (SEM) technique was employed to analysis the morphological behavior of various hardened concrete mixtures.

Phase-I results showed that coal bottom ash addition as a partial replacement of fine aggregates has affected the properties and durability of concrete significantly for all percentage replacements. moreover, the central idea of this research study was to utilize maximum waste i.e. coal bottom ash along with conceiving green environment strategies by keeping the superplasticizer dosage within 2%. Thus, to improve the concrete properties, Alccofine has been introduced as an alternative to cement in bottom ash concrete. Phase-II studies have revealed that the usage of Alccofine in bottom ash concrete has improve the strength and durability parameters of concrete. Properties improved after inclusion of Alccofine and maximum increase in strength was achieved on substitution of 15% of cement with Alccofine in comparison to the controlled concrete and lone bottom ash concrete mixture. SEM analysis revealed the enhanced formation of C-S-H and dense non-porous microstructure resulting in development of bottom ash based high performance concrete in combination with Alccofine. Determination coefficient (R^2) has been evaluated for the developed empirical equations for correlating the concrete properties. It has been concluded form this research work that to achieve green environment and to restore natural reserves, the combination of coal bottom ash and Alccofine has enough potential to be used as partial replacement of fine aggregates and cement respectively.

List of Publications

Journal Papers

1. “Replacement of Portland Cement with Alccofine” International Journal for Research in Applied Science and Engineering Technology (IJRASET), Volume 6 (3), March 2018, Pages 1285-1288.
2. “Strength and Durability Properties Improvement of Bottom Ash Concrete using Ultra-Fine Slag Cementitious Material” Journal of Mechanical Engineering Research and Developments, Volume 44 (10), Pages 57-65.

Conference Papers

1. “Utilization of Alccofine and Bottom Ash in Concrete”, ICSWMD, 2018, Pages 233-240.
2. “Effective Waste Utilization in Production of Concrete”, EIAETM, September 2019, Pages 501-511.
3. “Utilization of Waste and Production of Green Concrete”, ICATE, March 2020, Pages 513-517.

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Nomenclature

RCPT	Rapid Chloride Penetration Test
ISAT	Initial Surface Absorption Test
NDT	Non-Destructive Testing
UPV	Ultrasonic Pulse Velocity
SEM	Scanning Electronic Microscopy
R^2	Determination Coefficient
MMT	Million Metric Ton
CBA	Coal Bottom Ash
SCMs	Supplementary Cementing Materials
OPC	Ordinary Portland Cement
HRWR	High-Range Water Reducers
GGBS	Ground Granulated Blast Furnace Slag
SCC	Self-compacting Concrete
UHS	Ultra High Strength
RCA	Recycled Coarse Aggregate
HSC	High Strength Concrete
EFC	Eco-Friendly Concrete
BIS	Bureau of Indian Standards
ASTM	American Society for Testing and Materials
MB0	Controlled Concrete Mix
MB1	Concrete Mix with 10% CBA as a partial replacement of Fine Aggregates
MB2	Concrete Mix with 20% CBA as a partial replacement of Fine Aggregates
MB3	Concrete Mix with 30% CBA as a partial replacement of Fine Aggregates
MB4	Concrete Mix with 40% CBA as a partial replacement of Fine

	Aggregates
MB5	Concrete Mix with 50% CBA as a partial replacement of Fine Aggregates
MB4A5	Concrete Mix with 5% Alccofine as a partial replacement of Cement in MB4
MB4A10	Concrete Mix with 10% Alccofine as a partial replacement of Cement in MB4
MB4A15	Concrete Mix with 15% Alccofine as a partial replacement of Cement in MB4
MB4A20	Concrete Mix with 20% Alccofine as a partial replacement of Cement in MB4
RCC	Reinforced Cement Concrete
C-S-H	Calcium-Silicate-Hydrate

CHAPTER
1 INTRODUCTION

This chapter aims to present the concise preface to concrete and its constituents i.e. cement, alccofine and coal bottom ash along with their importance as a construction material. The challenges involved in the production of cement has been addressed and it has been found that excessive amount of CO_2 *release has been associated in cement production which further leads in global warming potential increase. In order to preserve the clean environment, other alternatives have been identified and it has been found that alccofine has a positive potential in replacing the main constituent of cement. Industrial waste, coal bottom ash, properties have been studied and it has been concluded that it can be used as fine aggregate. Therefore, in this investigation, an effort was put forward to partially replace cement with Alccofine and fine aggregate with coal bottom ash at the same time.*

Keywords: Concrete, coal bottom ash, alccofine, cement, industrial waste.

1.1 Basic Overview

Current era is dealing with the enormous development in infrastructure to meet the requirements and living standards of the society. Construction activities have drastically increased in the past few years. Increased rate of construction activity enhanced the production of concrete and thus, resulting in increased manufacturing of cement. Transportation infrastructure is an essential component for the economic growth of any country that helps in developing sound industrial, commercial and societal connects among the globe. Transportation infrastructure helps in GDP growth and offering a quality life style to the people. Globally, countries are spending a huge amount of money in developing intelligent infrastructure that can handle traffic efficiently which includes more roads and highways along with the introduction of artificial intelligence and machine learning approach.

It has been reported by Global Infrastructure Outlook that to attain higher income levels along with economic prosperity or balance in India, there is a need to invest about USD 4.5 trillion by 2040 [1]. In recent years, in order to achieve economic growth and community well-being, India has started to construct Economic Corridors (EC) where modern techniques have been incorporated in order to ensure the durability of the structure and speed of construction with minimal maintenance.

As per Compound Annual Growth Rate, Indian freight transport market has grown by 13.55% in 2020 due to the growth in manufacturing, FMCG, retail and e-commerce sector. Freight transport sector in India has a worth of USD 307.77 billion in 2020 [2]. 14.4% of our country's GDP is exhausted on transportation and logistics in comparison to other developing countries. These machines cover around 18 lakh kilometres distance and carry around 3000 MMT (million metric ton) of load annually. This indicates the importance of roads and highways and need to construct robust transport infrastructure.

Many studies have been found where it has been recommended that concrete roads are the most suitable contender in the modern era for road construction and it is most sustainable material for construction compared to the other alternatives present. Concrete is a multipurpose and durable construction material which has been employed in many sectors including building, dams, bridges, roads and highways etc. As per the available records, it has been stated that roughly 1-ton per capita is the World's concrete consumption.

Concrete consists mainly four ingredients; cement, coarse aggregates, fine aggregates and water. It has been reported that cement, coarse and fine aggregates are depleting with a faster rate thus alternatives have been introduced and emphasis has been laid on the usage of recycled aggregates.

Presently, concrete has been used for paving highways, city roads and airport runways. Almost all the construction duties are accomplished with varied types of concrete and this has become the basic necessity for the nation's growth and enhancement in almost about all the sectors.

The other major concern in using concrete is related to production of cement which involves extensive environmental pollution. According to International Energy Agency (IEA), due to cement production, the direct CO_2 intensity has been increased by 0.5% per year during 2014-18. In order to preserve Sustainable Development Scenario (SDS) by 2030, it has been reported that a 0.8% annual decline is required. Careful investigation is required on two key aspects: (i) reduction in clinker-to-cement ratio and (ii) finding other alternative technologies to replace cement. It has been found that out of various strategies using alternative material is best option that can provide similar strength and other characteristics as that of cement. Keeping such views in mind, in the present work Alccofine manufactured by Ambuja Cement has been has been proposed as a proportional binder in place of cement.

Due to extensive usage and mining of fine aggregates, it has been reported that such materials depleting at very faster rate and immediate steps are required in order to stop such activities by innovating alternative techniques. The suitable and well deserved alternative for such issues is an effective way out in order to deal with waste management issues and depletion of sand reserves. The present proposal explains that coal bottom ash (CBA), which is waste matter given via power plants, can be helpful in curtailment of usage fine aggregates. Thus, in this dissertation work, effect of CBA and Alccofine, which are used as a fractional change in place of fine aggregates and cement have been studied, where physical and mechanical characteristics of concrete has been evaluated.

1.2 Basic Introduction Concrete and its Constituents

Concrete is a widely used construction material on the planet Earth which has actively contributed in the urbanization of the building infrastructure, roads and highways etc. Concrete is a blend of cement, fine/ coarse aggregates, mineral and chemical admixtures and water which is generally employed in construction projects.

1.2.1 Cement

The active component of concrete is its cement paste and the concrete's workability is highly dependent upon the nature and properties of the developed binder paste. OPC is one of the major constituents employed in the cement. Cement is a powder which holds adhesive and cohesive properties and when mixed with other ingredients along with water it provides a binding medium that generate strength. Trade of cement embroils burning together the blend of naturally occurring argillaceous/alumina and calcareous/lime resources in a fixed fraction to a fractional fusion at high temperature (about 1450°C). It contains Tricalcium Silicates (C_3S), Dicalcium Silicates (C_2S), Tricalcium Aluminates (C_3A), and Tetracalcium Alumino Ferrite (C_4AF).

1.2.2 Course Aggregates

Coarse aggregates are considered to be those which are retained on 4.75 mm IS sieve and contain solitary that copious of fine material as is legitimate by IS: 383 (1970) – Specification for coarse and fine aggregates from natural sources for concrete, in a definite proportion are termed as coarse aggregates.

Coarse aggregate properties greatly influence the mix design strength. Maximum size of aggregate affects concrete's workability and strength. It, otherwise, leads a vital parameter of providing bulk to the mix, resulting in cost cutting since it occupies major capacity.

1.2.3 Fine Aggregates

Fine aggregates are those which passes through 4.75 mm sieve and possesses the amount of coarser material permitted by IS 383 in a definite proportion. The aggregates can be classified into three categories; coarse, medium and fine particles as per the size distribution. Effectively, the usage may be co-related with the filling of voids within the blend to different materials.

1.2.4 Water

Water is an essential and least affluent constituent of concrete. A large portion of water is exploited in cement hydration in order to achieve binding matrix where the sluggish aggregates are kept in deferment while waiting for the matrix becomes hard. The other part of the liquid component plays oiling influence among aggregates and makes concrete workable. It is desirable that water used should be clean and sugar free, acids, oils, salts, organic materials etc. The pH of water shall not be minus 6. Following reactions have been take place during hydration process:

$$2(3CaO.SiO_2)+6H_2O=3CaO.2SiO_2.3H_2O+3Ca(OH)_2$$

Or symbolically,

$$2C_3S+6H=C_3S_2H_3+3Ca(OH)_2$$

$$2(2CaO.SiO_2)+4H_2O=3CaO.2SiO_2.3H_2O+Ca(OH)_2$$

$$2C_2S+4H=C_3S_2H_3+Ca(OH)_2$$

$$2C_3A+21H=C_4AH_{13}+C_2AH_8=2C_3AH_6+9H$$

$$C_4AF+7H=C_3AH_6+CFH$$

1.3 Admixtures

In order to modify or control certain concrete's properties either in flow-able or compacted state, few additional chemical compounds are generally mixed in the concrete. Such compounds have framed chemical compositions and predefined chemical action which helps in modifying concrete properties like hydration rate, dispersion, workability, air-entrainment etc.

There is two type of admixture:

- ✓ Mineral admixture (rice husk, fly ash, silica fume, metakaolin etc).
- ✓ Chemical admixture (super plasticizer, plasticizer etc.)

Admixtures are the chemical additives, generally added to obtain few desirable parameters like high strength, durability, air entrainment, better workability, water reduction, acceleration, retardation, plasticity etc.

In order to enhance the class of the concrete, mineral admixtures such as fly ash, silica fume, blast furnace slag, and others are widely used. The performance of any concrete structure is significantly dependent upon the quality of the constituents, their proportions, and exposure conditions. For instance, the raw material quality used to manufacture clinker, the refinement and particle size of the binder, comparative shares of the binder phases, the calcining conditions, and portion of mixing of water influence the behaviour, both physically and chemically, of the hardened cement paste in concrete. Also, cement variety, temperature of mixing, admixture, type of fine and coarse aggregates, water and the working environment will define the physical chemical and durability properties of the concrete. In order to examine the physico-chemical behaviour of the concrete, cement and cement compounds subjected to various conditions, thermal techniques are extensively used. It has also been found that when admixtures added in a small amount may influence the various characteristics of the concrete starting from the time when it first comes in contact of the water to its long term behaviour.

1.3.1 Mineral Admixtures

These are finely crushed siliceous materials generally added into concrete mixes in relatively large amount in the range 20 to 70% by mass of the total cementitious material. Depending upon the desired properties such as workability, strength or compactability of the concrete, such additives can be used in addition or as replacement of OPC.

Portland cement is a primary cementitious constituent of the concrete however, in modern construction works concrete mixtures having Supplementary Cementitious Materials (SCM) are widely used which take care of cementitious component in concrete. Such pozzolanic materials can be gathered as a by-product from other processes. Fly Ash, GGBS, Rice husk ash, Metakaolin, Silica fume, Alccofine are a few examples of such parts.

Alccofine and Silica fumes are generally by –products of the industries, and due to this reason these two are promising contenders and can be helpful to offer better supplement when compared with others. Moreover, various studies have been performed and going in India and abroad where such pozzolanic materials utilized as replacement of cement and it has been found that the obtained results are encouraging. Properties of various ingredients, method of compaction, proportion of mix and other controls while placing and curing decides the strength, durability and other important characteristics of the concrete. It has been noticed during literature survey that many scholars and academicians have put in their best efforts to probe the properties of concrete using OPC where silica, fly ash, rise husk ash, GGBS etc. has been tried as cement replacement materials. However, very few studies have been found where Alccofine 1203 has been employed as cement replacement material.

1.3.2 Chemical Admixtures

These are ingredients those are generally mixed to mixture instantaneously before or throughout concrete's mixing. Implementation of such supplements (chemical retarders, reducers, HRWR's or superplasticizer (SP) and other viscosity controlled admixtures) is done in order to improve or control a few fundamental assets of fresh and hardened concrete. Implementation of such admixtures increase the adaptability of the concrete as such materials enhance the strength and self-compacting properties of the concrete and promote the lowest practical water to cementing materials ratio.

1.3.3 Need for Supplementary Cementitious Materials

Concrete is a mixture of OPC, water and aggregates where a fixed proportion of such ingredients is used to create a concrete of specific grade depending upon the type of application. Cement has been invented in Britain (1824) and for its 1 tonne production approximately 2 tonnes of raw material is required. Consequently, 0.95 tonne of CO_2 has been released during such conversion. It has been drawn that nearly around 23 billion tonnes CO_2 has been released in the OPC production per year which constitutes around 7% of the total CO_2 emissions globally. It is a prominent reality that CO_2 gas is a key contributor to global warming, hence, it is inevitable either completely replace cement with alternate compatible material for the sustainable development or partial replacement until suitable replacement will be found. Thus, for a fractional change of the cement, in this study an engineered material Alccofine 1203 has been proposed to judge and conclude the strength and durability parameters of concrete blended with Alccofine 1203.

1.4 Alccofine

Ambuja Cement Pvt. Ltd. is manufacturing Alccofine 1203 which is an innovative ultra-fine slag material, low calcium silicate and ultrafine product (Figure 1-1). It has distinctive properties to augment the "performance of concrete" in hardened and fresh platforms. It is a specifically manufactured invention which composes low calcium silicates. The interaction with supplementary matter ends in controlled PSD. Based on PSD, the evaluated blains' value is about 12000 cm^2/gm, which indicates it is a truly fine material.

For a fixed or known workability, Alccofine 1203 offers reduced water demand depending upon the concrete performance. It can also be employed to recover the compressive strength and concrete flow. Compared to all existing mineral admixtures used in concrete within India, it is expected that Alccofine1203 may perform in better way.

$$\underset{(By\ product\ of\ Cement\ \&\ Water\ reaction)}{3[Ca(OH)_2]} + \underset{(From\ SCM)}{2[SiO_2]} = \underset{(Cementetious\ Gel)}{[3(CaO)2SiO_2)3H_2O]}$$

Figure 1-1 Alccofine bag

1.4.1 Technical benefits of Alccofine

Manufacturer has claimed a few advantages of Alccofine over other commercial competitors:

Fresh State

- Improves workability retention
- Improves flow ability
- Improves rheology
- Reduces segregation
- Reduces heat of hydration

Hardened State

- Improves durability
- Improves resistance to ASR
- Improves strength at all ages
- Improves resistance to chemical attack/corrosion
- Impart light colour
- Lowers permeability

1.5 Need for Aggregate Replacement

It is a well-known fact that natural resources are depleting at very rapid rate, while simultaneously industrial waste is increasing substantially. For the attainment of the sustainable improvement, it is must to find the suitable alternative non-conventional and innovative materials along with the recycling of the wastage in order to tackle the depletion of natural resources.

The critical issues for the construction engineering are associated with the development of high-tech buildings and highways that leads to the sustainable technical advancement which involves the implications of high performance materials at realistic cost with minimal environment impact.

Industrial waste management can be achieved easily by using such wastage in concrete which will result in green environment. There is a vast variety of waste materials that can be used in concrete as a replacement of sand and cement such as rice husk ash, fly ash, blast furnace slag, gypsum, red mud and phosphor, eggshells, crushed glass and silica fume.

1.6 Coal Bottom Ash

Coal burning, in thermal power plants, is a key foundation of energy (electrical energy) for India and about 70% of electrical energy is produced using fossil fuels which results in production of roughly 100 ton of ash. Consequently, it causes water pollution and infertility of productive land.

The by-products of crushed coal combustion are bottom ash and numerous research works have been performed to find an effective use of fly ash in civil construction activities due the fine nature of particles and its pozzolanic characteristics. It has been found after comprehensive literature survey that the studies on the usage of bottom ash were limited. However, it has been well defined that bottom ash has potential to be incorporated as fine aggregate in concrete as they are coarser in size and less Pozzolanic than fly ash.

In lieu of the matter size ranging from fine sand to fine gravel, they consist mainly silica, Al_2O_3 and iron with minor range of $MgSO_4$, calcium etc. PSD and look of CBA is somewhat analogous to natural river sand. Such properties of CBA are useful if one wants to use as a part of fine aggregate in concrete. Research studies done previously showed that CBA usage has indicated promising results when it was employed as a fractional change in lieu of natural sand. Recipient's electrostatics is used to capture the fly ash and sand dirt soaring in the atmosphere. Coal bottom ash is generally collected by means of electricity. This ash is coarser in nature, glassy, porous, greyish, granular and incombustible material.

The bottom ash type is depending upon the furnace type and coal sources. In general, coal burning produces about 80% of fly ash and 20% of bottom ash. At the bottom of the combustion chamber, bottom ash is collected in liquid-bound hopper which is detached using intense water jets and transported by sluiceways to a transferring basin for dewatering in a sequence after stockpiling and probably crushing (Steam, 1978). In this work, CBA (Figure 1-2) is collected from Guru Gobind Singh Super Thermal Power Plant, Roopnagar, Punjab.

Figure 1-2 Coal Bottom Ash at dump

CHAPTER

2 LITERATURE REVIEW

This chapter grants an extensive assessment of published works related to the recent development in the area of concrete research. Here, we have discussed about the existing methods, technologies and opportunities available to explore in the field of concrete research so that better constituents can be discovered that can replace the cement as its production is unhygienic to the environment. Also, in this chapter, we have tried to cover all related studies those are very much helpful in defining the problem more evidently.

Keywords: Concrete, Alccofine, Coal bottom ash, Cement, Construction.

2.1 Waste Material Management

Due to population growth, speedy industrialization has ended into the increase in the waste production and it will seem to be increased in future. Solid waste management has become a critical challenge for all the industries as government policies are so stringent. Therefore, it is always desirable to manage such solid wastes in an appropriate way so that it can create minimum environmental issues. Productive use of such industrial wastes is a significant aspect for any country as it can affect the economy. Depending upon their physical and chemical characteristics, the solid waste materials can be utilized in many ways and applications. Waste materials can be employed as a potential building material which further helps in disposing of industrial waste in a constructive way thus playing an imperative role in achieving clean environment.

There are three categories where waste materials can be practiced efficiently; as auxiliary commentating material, aggregate replacement in concrete or as a mortar. Depending upon the properties of the solid waste, they can be used accordingly. There is initiative needed from the Government side in order to promote such activities so that a pollution free environment can be achieved.

After the extensive literature survey, it has been found that solid wastes like rice husk ash, baggase fly ash, fly ash, sewage sludge ash, titanium fume, silica fume, glass residue, municipal solid waste incineration FA and GGBS are widely employed as an alternative of binder content in the production of concrete/mortar. Industrial wastes like CBA, neglected foundry sand, ceramic left-over, recycled aggregate, marble powder, copper slag and plastic waste are enlisted as alternative for the aggregate in concrete's manufacturing. A brief overview of such waste material as an alternative for cement and as aggregate in concrete has been given below:

2.1.1 Solid Waste as a Substitute for Supplementary Cementitious Material

The first use of waste material has been done by Roman people where they have utilized volcano ash as pozzolanic constituent in the manufacturing of concrete which was further employed for construction of structures. In 1937, a study has been reported where fly ash has been used as pozzolanic ingredient. In 1981-82, the fly ash has been used as cement alternative in concrete for the building of infrastructures and RCC tanks in power station of USA, Dustan, (1985) [3]. Though, in our country, FA has been used as an alternative of cement in early 90's.

Mishra et al. (1994) [4] investigated the influence of fly ash (FA), blast silica fume and furnace slag on the concrete permeability and the authors have established that with the inclusion of such materials, chloride permeability is found to decline.

Khan et al. (2002) [5] examined the performance of the concrete using FA and SF as an alternative supplementary binder material. Authors have concluded that having 8-12% addition of SF, mixture yielded optimum strength and permeability. They have reported that the compressive strength of concrete is found to decline with the addition of fly ash, however, it has been increased when the mixture was blended with 10% silica fume. Also, authors have concluded that addition of silica fume more than 10% has no significant effect on the compressive strength of the concrete.

Khan (2003) [6] examined the effect of FA and micro-silica as alternative materials for cement on the permeation related characteristics. Authors have found that with the addition of 8-12% of micro-silica as binder alternative, concrete showed best permeability, sorptivity and porosity. Khatib (2008) [7] has examined that with the addition 60% fly ash as an alternative of cement for SCC has caused in surge in compressive strength, however, having 80% FA, there is a sharp 67% drop in shrinkage and 2% diminution in absorption value when compared at 56 days of curing age with the reference concrete.

Cyr et al. (2006) [8] investigated resultant of the addition of waste materials (25%) like SSA, Bag, MSWIFA and TF to be recycled as a option to cement in concrete indicating the strength activity index 90, 70, 60 and 90% respectively. Addition of 25 and 50% SSA in the mortars as an alternative caused in the reduction in workability plus rise in the settling time (Cyr et al. 2007) [9]. Behim et al. (2011) [10] examined that the fineness of slag has significant influence on the strength. For a very high degree of fineness (4000 cm^2/g) and for all ages, mortars comprising up to 40% of slag indicated strength merely equal to the reference mortar. Tripathi and Barai (2006) [11] found that for a 40% replacement of cement by crusher stone powder, the compressive strength of autoclave preserved mortar was either equal or less than of reference normal preserved mortar.

Cwirzen (2008) [12] used silica fume to develop ultra-high strength (UHS) concrete and performed 28-day compressive strength studies for both heat treated (90^{o}C) and non-heat treated (20^{o}C) samples. Author has observed a compressive strength of 170-202 MPa for heat treated and 30-150 MPa for non-heat treated specimens. It has been reported that the shrinkage value for UHS mortars was two times higher than UHS concretes. Moreover, there was no significant effect on the micro level structure morphology of heat treated/non-heat treated samples was inspected. Similar outcomes have been reported by Scott and Singh (2011) [13] for ultra-high performance silica fume concretes.

Esteves et al. (2010) [14] analysed the impact on the rheological characteristics of the high routine cement-silica systems due to the inclusion of fine aggregates. Authors have found that fine aggregates having particle's surface area (75 and 1000 μm) behaved as water fixation point. For the higher diameter particles, flow resistance appeared which may be due to surface frictional forces.

Younsi et al. (2013) [15] examined that with the addition of blast furnace slag or FA as a replacement of cement in concrete, the hydration diminishes. Further, such additions showed lower portlandite content in concrete. Hemalatha et al. (2015) [16] have suggested a mix design for a 28 days curing age where SCC has been produced using FA and silica fume.

Khatib et al. (2014) [17] has examined that with the 10% replacement of cement by means of MK, the compressive strength of mortar was found to maximum and this concentration was found to optimum. It has been observed by the authors that for a replacement of more than 20%, no impression on the compressive strength was seen. It has also been found by the authors that gain in strength of the mortar was 50% than that of with control mortar (Khatib et al. 2012) [18] when 20% MK added. It has been found that during initial curing age, compressive strength of the samples decreased when GGBFS is added as an alternative of cement. In order to compensate the reduction in compressive strength, 10% metakaolin has been added (Khatib and Hibbert, 2005) [19] and the final opinion was that the strength was increased by adding metakaolin for the first 14 days due to hydration. Authors have concluded that the development in strength parameters of concrete specimens may be featured to the filling effect, quickening of cement hydration and pozzolanic reaction of MK (Wild et al. 1996) [20].

Paiva et al. (2012) [21] studied flowable and hard state parameter of concrete where authors have examined the influence of the metakaolin dispersion. They have found that due to the insertion of metakaolin in concrete as alternative of cement, the water consumption has been increased which further enhanced the concrete's porosity. Hydrated chemical activities of the metakaolin has developed nil hostile influence on the concrete's strength aspects due to the presence of agglomerate. However, authors found that the dispersion of metakaolin was more significant after incorporating water reducing proxies, and porosity found to decrease. Moreover, an increase of 30% has been detected in compressive strength after using metakaolin as alternative of cement. Figueiredo et al. (2014) [22] drawn the interest on the performance of metakaolin as cement alternative in the concrete and after the study authors have concluded that metakaolin has a significant potential in preventing concrete against the chlorides action. Hemalatha et al. (2015) [23] found that with the existence of more fines in SCC leads to smaller interfacial transitional regions at all curing ages. Momentarily changes in the micro and macro characteristics have been realized after 28 days of curing age in SCC formed through FA and silica fume, however, no influential change in the properties of SCC has been observed without FA and silica fume.

2.1.2 Waste Material as Aggregate

Khatib and Ellis (2001) [24] calculated the mechanical properties of the concrete when foundry sand was used as FA. Authors have found that drying shrinkage has increased and compressive strength of concrete has established to reduce on usage of foundry sand as fine aggregate.

Siddique (2003) [25] examined the influence of FA as fine aggregate replacement in concrete and concluded that by increasing the degree of replacement level of sand via FA, there is an growth in the concrete compressive strength and simultaneously decline in the abrasion resistance of concrete. Sahu et al. (2003) [26] investigated the consequence of 40% stone powder inclusion as fine aggregate in concrete and the authors have described that there is growth in modulus of elasticity and strength parameters.

Khatib (2005) [27] investigated the concrete's mechanical strength variations with recycled aggregate as fine aggregate. Authors have concluded that for the reused aggregate, the level of growth of strength comprising re-fabricated used aggregate after 28 days of curing age was greater in comparison with base sample. Cyr et al. (2006) [28] examined that sand can be replaced with MBM bottom ash in mortars. It has been found that there was no noteworthy influence on mortars' strength when 17% of BA has been added in place of sand. Cyr et al. (2006) [8] investigated the influence of rubber sand on concrete and authors have concluded that there was a 25% improvement in strain of concrete however, adverse effects have been noticed on compressive strength. Yuksel et al. (2006) [29] studied the effect of GGBFS/sand ratio on the durability and strength of concrete. Authors have found that durability properties have shown a significant increase on inclusion of GGBFS while strength decreased.

Rao et al. (2007) [30] observed that by using recycled aggregate, a good quality concrete can be prepared. Rakshvir and Barai (2006) [31] found that with the use of RCA, 10% drop in strength of concrete and water consumption has been increased than natural aggregates. Evangelista and Brito (2007) [32] examined that with 30% inclusion of FRA, there was not any adverse consequences on the concrete's mechanical characteristics.

Cachim (2009) [33] studied the strength and stiffness studies of concrete blend through 15% substitution of the natural aggregates with crushed bricks and authors have found that there was no significant effect on such properties and they are same as that of traditional concrete. Researchers have established that replacement of 30% natural aggregates can significantly affect the properties. Menadi et al. (2009) [34] testified that compressive strength decreased on 15% mixing of limestone dust in place of fine aggregate and there is significant rise in gas permeability and chloride ion penetration of concrete. Though, authors have noticed insignificant effect on capillary water absorption and decline in water permeability on the inclusion of 15% lime dust in concrete.

Chakradhara Rao et al. (2011) [35] explored the impressions of recycled coarse aggregate on the modulus of elasticity, indirect tensile strength, compressive strength, chloride penetration and water absorption of concrete. Conclusion reached that the water absorption of recycled concrete and volume of voids was 1.82% and 2.61% higher than normal concrete. Authors have found that for 7 days of wet curing, the concrete cured in air hold better strength than the concrete cured with 28 days of curing period. Cachim et al. (2014) [36] claimed that waste materials for instance ceramic wastes, copper slag, recycled collection from building and devastation wastes and plastic wastes be able to engaged in place of aggregate, in concrete's production.

2.1.3 Coal Bottom Ash as Fine Aggregate

From literature studies, various waste materials like SF, FA, GGBS etc. are widely employed in the production of either concrete or cement. Cement is extensively exploited as a building material and it has revolutionized the construction industry since the day it was discovered. It is one of the main constituents in the concrete and act as a binding agent. River sand is one the natural resources which is widely employed in construction is depleted because of excess usage. The depletion of such natural resources has increased the overall cost of the construction. In Punjab (India), the construction cost has increased steeply in past 4 to 5 years due to insufficiency and high price of river sand. Therefore, alternative materials need to be identified in order to lower the construction cost without compensating much with the strength parameters concluded on concrete.

On the other hand, huge amount of CBA, gathered as a waste in the dump yard of thermal power plants, has become an environmental hazard for the local Society. In order to reduce such environmental issues, many researchers have proposed to manage the CBA as substitute of sand in the concrete. Researchers have strongly recommended using CBA as a partial or complete alternate of river sand.

Cheriaf et al. (1999) [37] inspected the consequences of CBA which was used as an alternative (100%) of river sand, resultant of which the authors realised the strength activity index (SAI) of CBA when used with OPC was 0.88 and 0.97 after 28 and 90 days of hydration. These values are quite greater than 0.75 for 28 days and 0.85 for 90 days, specified upper limits by European standard EN 450 which indicates that CBA is appropriate to be employed as construction material in concrete. Such higher values of

SAI indicate the pozzolanic activity of CBA which starts at 14th day and consume significant amount of $Ca(OH)_2$ after 90 days of hydration.

In general, CBA particles ranging from fine sand to fine gravel and it looks analogous to river sand. Such properties of CBA fascinated the researchers from the global research institutions to identify the potential of CBA as fine aggregate material that can be utilized as a good building material as a place of cement. A set of framework have been established where CBA has been considered as fractional or complete replacement of river sand. In the coming section, the effect of CBA on concrete properties when considered with natural sand has been studied.

Bai et al. (2005) [38] examined drying shrinkage parameter and strength property of the concrete at permanent w/c ratio and slump ranges where river sand has been swapped with furnace bottom ash (FBA) by mass which has been taken from Kilroot Power Station, Northern Ireland, UK. Class 42.5N OPC manufactured by Blue Circle has been utilized. The experimental work has been divided into two parts, where in the both parts, the cement content used was 382 kg/m^3 and ordinary sand substituted through FBA ranging from 0%, 30%, 50%, 70% and 100% by mass. First part has been designed for constant w/c ratio 0.45 and 0.55. Second part has been designed for controlled slump ranging from 0-10 mm and 30-60 mm. The aim of targeting designed workability for desired slump values, the free water content has been adjusted. It has been concluded that the strength as well as drying shrinkage parameters dropped at stable w/c ratio with escalation in the FBA amount. Also, it has been observed that for a fixed slump value, the compressive strength has been found similar with control concrete however, drying shrinkage increased with FBA content beyond replacement level. It has been observed that for both the parts, the results predicted that with addition of FBA as a part of natural sand, the concrete's water demand decreased. It has been concluded by the authors that it is good practice to switch 30% sand with FBA sand without affecting the drying shrinkage and permeation properties of the concrete in order to yield concrete's compressive strength ranging from 40 to 60 N/mm^2.

Aggarwal et al. (2007) [39] examined influence of CBA on the properties of the concrete includes compressive strength, splitting tensile strength and flexural strength which is used as a portioned supplement of natural sand. OPC 43 grade has been used for the analysis where bottom ash (specific gravity=1.68) collected from thermal power plant, Panipat, Haryana, India, has been united in place of fine aggregates in 20%, 30%, 40% and 50% proportions. Natural river sand (conforming to zone III) has been used whose fineness modulus was 2.36 and specific gravity 2.65. The specific gravity and fineness modulus were 2.67 and 6.9 respectively. In order to evaluate compressive strength, standard 150 mm cubical specimens were prepared, for splitting tensile strength 150 *300 mm cylindrical specimens were generated and for flexural strength 101.4*101.4*508 mm beams samples were made. It has been concluded that with the increase in the bottom ash content, the workability of the concrete decreased. Also, all three strength parameters were decreased compared to control concrete at all ages.

Sani et al. (2010) [40] have studied the special concrete properties when Washed Bottom Ash (WBA) is employed as a fine aggregate. WBA is among waste materials generally occupied form electric power plants where the basis substantial is bottom ash. In order to maintain a certain quantity of carbon in the concrete, WBA was employed entirely dipped in water for three days in order to harvest WBA with low carbon configuration. Prime objective of the analysis was to examine the viability and prospective use of WBA in concrete applications. The bottom ash has been collected from the coal power station situated in Perak. With the substitution of BA by weight, total 5 types of concrete were prepared by mixing into natural river sand in proportions 10 to 50%. For the experimental analysis, a standard cube size of (150*150*150) mm has been used. It has been resolved that the compressive strength of the mixture was far less than the control mix for all ages.

Singh and Siddique (2013) [41] studied the effect of CBA on the properties of the concrete for instance bleeding, workability, splitting time, compressive, split tensile, flexural strength drying shrinkage and durability. It has been reported that addition of CBA in the concrete influence the properties of hardened mass. Authors have concluded form the literature that similar pattern can be found in the strength development among CBA concrete mix and conventional concrete mix. Also, it has been found that there was diminution in the strength at all ages. It has found that higher porosity and water demand while using CBA has resulted in decrease in strength. It has been reported that by incorporating superplasticizers, the water demand can be controlled and thus compressive strength can be improved. It has been claimed that CBA is a potential component that can be used as fine aggregate to produce durable concrete. It will help managing the waste effectively.

Soman et. al (2014) [42] studied the strength of concrete when 10% to 50% manufactured sand has been replaced by bottom ash. Analysis was carried out on samples, tested to evaluate the strength properties of the concrete. CBA following to Zone II used as fine aggregate and manufactured sand were mixed together for experimental analysis. OPC 53 grade of cement has been undertaken for this research. IS:2386 standards have been incorporated for the sieve analysis of fine aggregate (bottom ash). Coarse aggregates of dimension 20 mm were employed for the experimental study. A polycarboxylic ether based high-performance super plasticizer (Glenium SKY 8233) for specific gravity of 1.08 was bought. Compaction and intensive slump flow testing was undergone to conclude the flow of fresh concrete. A compacting factor of 0.93 has been obtained for a control mix which is matching with a slump of 100 mm. M30 mix has been chosen for the study using super plasticiser and a w/c ratio of 0.45. The tests were performed on the standard sized specimens where a control mix has been used for the analysis along with the replacement of manufactured sand with CBA (10, 20, 30 and 50 %). After the analysis, it has been concluded that strength diminutions for CBA mixes when equalled to the controlled concrete. This study shows that the strength for 30% replacement is the most optimum in relations to compressive strength and split tensile strength.

Using the volume replacement approach, Hasim et al. (2021) [43], CBA was used to replace 50 percent, 60 percent, 70 percent, 80 percent, 90 percent, and 100 percent of fine and coarse aggregate in concrete. Fresh concrete workability and mechanical qualities in terms of CS, TS, and FS were tested on concrete. The association models between each of the mechanical strengths were established when all of this strength was achieved. The large amount of CBA had the greatest impact on slump reduction and the weakest flexural strength, according to the findings. Furthermore, after 28 days of curing, concrete with a large volume of CBA material had acquired the desired compressive strength. The acceptable strength performance of concrete having a high percentage of CBA could lead to its widespread adoption in the construction industry.

Bheel et al. [44] that rice husk ash can be used to substitute cement ingredients like 5 percent, 10 percent, and 15 percent, as well as fine aggregates like 10 percent, 20 percent, 30 percent, and 40 percent in concrete. In this case, 180 concrete samples were made with a 1:2:4 mix proportion and a 0.50 water/cement ratio, and they were cured for 28 days. The major goal of this research is to separate and combine slump tests, compressive strength, split tensile strength, and water absorption of concrete with varying amounts of rice husk ash as a cement substitute and fine particles replaced with coal bottom ash. As the dosages of rice husk ash and coal bottom ash in concrete grow, the workability and water absorption of the concrete decreases. Furthermore, using 5% RHA and 30% fine aggregate replaced with coal bottom ash in concrete for 28 days consistently increased compressive and split tensile strength by 9.10 percent and 7.73 percent, respectively.

Table 2-1 shows the various studies performed in literature where effect of CBA on mechanical properties (compressive strength and flexural strength) of the concrete has been explored.

Table 2-1 Effect of CBA on mechanical properties of concrete

Coal bottom ash content (%)	**Variation in mechanical properties**	
	Compressive strength	**Flexural strength**
0, 20, 30, 40, 50[45], 20 to 50[46], 10 to 50 [47], [48], 0 to 100 [49], 25 to 100 [50]	Reduced for all replacement	
0 to 100 [51], 0 to 30 [41], 10 to 50 [40], [52], 0 to 100 [53], 25, 50, 75, 100 [54]	Reduced for all replacement	-
0 to 25 [55], 10 to 30 [56]	Increased at 10% replacement	
0 to 50 [57]	Increased at 20% replacement	

2.2 Alccofine as a Cement Alternative

Suthar et al. (2013) [58] investigated experimentally the strength parameters of M-70 grade concrete. Intensive testing was undertaken. Fractional change of cement has been done with FA (class F fly ash used in 20 to 35% proportion by weight of cement), alccofine (4 to 14%) and silica fume (4 to 14%) in order to obtain high performance concrete. A water binder ratio of 0.30 has been used for Alccofine mix concrete and 0.32 for silica-fume mix concrete. Silica fume and Alccofine having 4 to 14% content of each has been added in the mix separately. With a view to examine the compressive strength, cube specimens have been incorporated and for flexural strength, a beam specimen of size (150*150*700) mm has been used. Authors have found that in comparison to fume mixes, the slump value for all alccofine mixes was superior. It has been concluded that due to the increase in the particle packing by the addition of the Alccofine, it increases the overall strength of the concrete. It has been concluded that with the inclusion of 8% Alccofine in place of fly ash has better compressive strength than 10% silica fume. Also, it has been reported that in order to obtain optimum and high strength concrete 8% Alccofine and 20% fly ash can be used.

Suthar and Shah (2013) [59] studied the compressive strength of high strength concrete (HS) experimentally. HSC has been obtained by adding fly-ash and Alccofine as a fractional change in lieu of cement. A proportion 0, 20, 25, 30 and 35% of class F fly ash and 0, 4, 6, 8, 10, 12 and 14% of Alccofine by weight of cement (OPC 53 grade) has been used along with a fixed water binder ratio of 0.4. Local natural sand has been used as fine aggregate and crushed gravels have been used as coarse aggregate. A total 24 concrete mixtures have been prepared where fly ash (C+F), Alccofine (C+A) and mixed proportions of both (C+F+A) have been used as a replacement of cement. It has been concluded that the maximum compressive strength can be obtained for a cement-Alccofine mixture having 7% Alccofine and for a (C+F+A) mixture, mixture having 7% Alccofine and 25% Fly ash resulted in maximum compressive strength. It has been concluded that on the one side, Alccofine helps in improving the early age recital of concrete with FA unceasingly polishing the characteristics of the hardened concrete as it matures.

Soni et al. (2013) [60] studied the performance of HPCs having additional cementitious materials. In the study, authors have prepared a concrete of M80 grade using local elements and afterwards in order to evaluate impact of varied samples of FA and Alccofine on strength of concrete, the experimental studies have been performed. Also, attempts have been made to identify the optimum proportions (by weight of the cement) of the fly ash and Alccofine in the mix. Coarse aggregates of size 10mm and 20mm crushed type has been employed however, for fine aggregates, natural river sand has been used in order to prepare M80 grade of concrete. A total binder content of 582 kg has been used where for the trial purposes, a mix of 76% cement has been incorporated and a proportion of Alccofine varying from 6% to 10% by mass and of fly ash ranging from 14% to 18% has been used in the mix and a water binder ratio of 0.25 has been used. For testing purpose, standard testing specimens were undertaken and sampling was done accordingly to justify the parameters concluded after detailed analysis. It has been concluded that Alccofine showed superior performance that other slag materials. After the rigorous analysis, it has been found that with 8% Alccofine and 16% Fly ash, better results has been obtained where Alccofine helps in enhancing overall parameters of concrete.

Ansari et al. (2015) [61] prepared M70 grade concrete by infusing Alccofine in place of cement and fly ash where OPC 53 grade has been used compatible to BIS 1269-1987 standards. Fly ash or pulverized ash is employed in this study which has been obtained from the mechanical separators collected after the combustion of pulverized coal. Compared to conventional concretes, in HPCs the coarse aggregates have been used having round shape, well graded and smaller in size. Superplasticizers like Poly-carboxylate ether (PCE) has been used which are very effective dispersants for Calcium Aluminate cement based constables and it has been reported that such superplasticizers advances the workability of flow-able plastic stage concrete and strength judgement in the hard stage. Authors have used Alccofine 1203 which is manufactured by Ambuja® industries. A total three mixtures have been prepared where first concrete mix represents control mixture, second represents 27% OPC replaced with PFA and third represents, a mix where 16% PFA has been incorporates in place of binders and 8% includes Alccofine. Authors have concluded the addition of Alccofine and fly ash up to a proportion of 15-20% has increased the compressive strength of the HPC. It has also been reported that higher packing value along with high density of the mix has been attained. Also, authors claimed that as Alccofine is cheaper than cement and provides better strength and durability to the concrete thus it should be sponsored as an alternative in the Indian construction industry.

Reddy and Meena (2017) [62] has premeditated the strength of M30 grade concrete where cement has been replaced with 0 to 25% of fly ash by weight. In order to identify the optimum content of fly ash, compression test has been performed. After achieving the optimum content of fly ash, cement has been replaced with Alccofine in the range of 8, 10, 12 and 14%. The split tensile, compressive and flexural strengths have been computed for 7, 14 and 28 days where OPC grade 53 has been used as per IS 12269:1987 employed for all type of mixes. F-type fly ash has been used in the study which was obtained from Vijayawada thermal power station, Andhra Pradesh. In this study, Alccofine used for the analysis has been manufactured by CMPP, Alcon organization, Goa, India. Local river sand is used in place of aggregate and rounded uncrushed gravel is used in place of CA which were usually passed through a 20 mm sieve and retained in 12 mm locally. The concrete mix has been designed for 30 grade as per IS 10262-2009 and w/c ratio for all mixes was retained to 0.43. Authors have found supreme strength of the concrete mix when 15% cement has been replaced with fly ash. It has been reported that when compression test results of Eco-Friendly Concrete (EFC) with Alccofine and fly ash have been compared with control concrete mix, the earlier showed superior results. It has been concluded that the maximum compression strength has been achieved with the fly ash (15%) and Alccofine (10%) combination, similarly, this combination showed maximum split tensile and flexural strength. It has been found that about 24.7% compression, 23.2% split tensile and 14.28% flexural strength has been increased at the 28 days curing age when compared with controlled mix.

The impact of alccofine-1203 (alccofine) on the mechanical and microstructure features of High Strength Concrete is presented in this study (HSC). The Standard Consistency (SC), Initial Setting Time (IST), and Final Setting Time (FST) of the binders, as well as the mechanical properties of HSC, were evaluated using a total of seven binder mixtures [63]. The microstructure properties of binder pastes were studied using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy analysis (EDS), and X-ray diffraction (XRD). Alccofine is used to replace cement in the control mix at a rate of 4–14 percent. The results showed that increasing alccofine replacement levels enhanced the SC marginally but decreased the IST and FST when compared to the control mix binder. The compressive and tensile strengths of concrete increased when alccofine replacement levels climbed from 4 to 10%, but 12 and 14 percent replacement levels lowered the concrete's strength. All of the alccofine-based mixes had higher compressive and tensile strengths than the control mix. SEM and EDS research revealed that the mix with 10% alccofine had a higher amount of C-S-H gel formation, a stronger dense matrix with fewer holes and micro-cracks, and a lower Ca/Si ratio than the other mix binders. When compared to other mixes, XRD examination demonstrated that the M-10 percent AF mix had higher quantification of Alites and Larnites, resulting in higher early as well as later strengths.

To create UHPC mixes, quartz powder and crushed granulated blast furnace slag are utilised individually, along with Alccofine and silica fume, Reddy et al. (2021) [64]. To lower the amount of binder, coarse aggregates with diameters of 6 mm and 10 mm are additionally added to UHPC. Mechanical strength parameters of eight UHPC blends were tested as part of the performance evaluation. The results of the study show that UHPC with Alccofne provided better mechanical performance than UHPC with silica fume added. At 28 days of normal curing, the UHPC combination comprising Alccofne and ground granulated blast furnace slag achieved cumulative compressive strength, splitting tensile strength, and flexural strength of 136.67 MPa, 15.2 MPa, and 31.88 MPa, respectively. The use of coarse particles in UHPC resulted in a steady loss in mechanical performance and an increase in concrete slump values. To forecast compressive strength values, compare them to experimental results, and assess their validity, a response surface model was used for mathematical modelling and statistical analysis. The findings of this study show that UHPC created by combining Alccofine has a better overall performance.

Furthermore, various strategies have been established to work out an effective alternative to cement with fly ash [65], [66], blast furnace slag [67], [68], silica fume [69], [70], Alccofine [49][50][73] and metakaolin [74], [75] have been used as an alternative for supplementary cementitious material. Table 2-2 shows the effect of various supplementary materials, as a proportional alternative to cement, on the mechanical properties of the concrete mix.

Table 2-2 Effect of various additives used as partial replacement of cement on mechanical properties of concrete

Additives	Influence on mechanical properties
OPC, rice husk ash, fly ash [76]	Significant surge in compressive strength and corrosion resistance
Fly ash and slag [77]	Increase in mechanical strength and reduction in workability
Fly ash and Alccofine[71], [78], [79]	Significant increase in compressive and splitting tensile strength, reduction in workability
Fly ash and GGBFS[80]	Compressive strength increased up to 180 days
Low calcium FA and nano-silica [81]	Significant increase in compressive, splitting tensile and flexural strength

2.3 Properties of Fresh Bottom Ash Concrete

2.3.1 Workability

The properties of the fine aggregates decide the water requirement for desired workability of concrete. CBA particles are angular in shape and generally rough textured thus having interlocking properties. Few of them similar to popcorn and are porous. CBA usually having very fine particles whose size is less than 75 µm compared to sand. Compared to CBA, sand particles are having regular shape, dense and smoothly textured. This implies, the number of fine particles (less than 75 µm) have been increased due to the inclusion of CBA by replacing river sand. Due to increase in irregular shaped particles in the mixture, interlocking properties increased which further increases the inter-particle friction. Such frictional behaviour can affect the flow characteristics of the mixture. Moreover, the water poured to the mixture absorbed by the porous CBA particles which further reduce the water availability for lubrication. Subsequently, for a fixed cement-water ratio, the workability was found to degraded due to the inclusion of CBA as sand replacement. It has been reported that the water required to achieve the similar slump index as that of conservative concrete has raised with the partly changing of sand with CBA. The studies discussing about the decrease in workability after the inclusion of CBA as naturally occurring sand in concrete by replacing sand are written below.

Ghafoori and Bucholc (1996) [82] has investigated the fresh concrete properties when high calcium CBA is added in concrete. Authors have designed control concrete blends in order to develop 28-days compressive strength test. Authors have found that the water required to achieve the similar slump index as that of conventional concrete has improved with the replacement of sand with CBA. In the study, 7% of water absorption has been observed and it has also been reported that for a mixture of 50% CBA and 50% sand, the water requirement significantly reduced however, this value is still higher than the control concrete. This issue can still be handled by using water reducing admixtures (WRA) however, study explained the sample's absorption was much on a higher side when equated to control concrete. For a mixture of CBA and concrete having 474 kg/m^3 cement, it has been found that the water requirement was 189.6 kg/m^3 equated to base mix after the usage of higher dosage of WRA. Authors have concluded that in order to preserve same slump, with the addition of more cement content, the difference among the water requirement depleted for CBA concrete mixture and control concrete mixture.

Bai et al. (2005) [38] has investigated the consequence of use of CBA in place of natural sand for a permanent w/c value 0.45 and 0.55 and it has been found that the slump of the bottom ash mixtures improved with the inclusion of more and more CBA content. In order to preserve a controlled slump 0-10 mm and 30-60 mm, demand for water fallen with the addition of CBA as fine aggregate. As cement content was unaltered for all samples, freely available water decreased. Authors concluded that the ball bearing influence of the spherical shaped CBA particles predominated in increase of slump against the irregular shaped natural sand particles.

Aramraks (2006) [83] investigated the effect on water requirement on the concrete mixture when half and complete replacement of sand is achieved with CBA. For the study, Lignite based CBA particles (moving through Sieve No.4) have been incorporated as FA. Authors have used 5.45% of water absorption content for CBA. They have noticed that in order to achieve suitable workability, the mixing quantity of water required in case of CBA concrete was 25 to 50% more than the normal concrete blends. Aggarwal et al. (2007) [39] examined the influence of CBA concentration in concrete using compaction factor and the authors have observed that the CF value for workability deteriorated on inclusion of CBA in place of natural river sand.

Though, there are few conflicting articles available in the literature which indicate the reverse trend i.e. increased value of workability when CBA was preferred as a portion or full change in place of sand. Such reports have been summarized below:

Yuksel and Genc (2007) [47] discovered the consequence of CBA on concrete samples where 10 to 50% of sand has been replaced by CBA. Consequently, the slump values increased up to 40% for the fresh CBA and then a marginal decline has been found. Authors have used 6.10% water absorption level for CBA. It has been found that for 50% sand replacement with CBA in concrete, slump of 50 mm has been evaluated equated to 60 mm for control concrete. Conversely, when CBA was employed in association with natural sand, BA and GBFS, an improved workability has been observed for all sand replacement levels.

Kou and Poon (2009) [84] investigated the influence of sand replacement with CBA by 0:25:100% mass at a set W/c value and slump on concrete workability. Authors have employed saturated surface dried CBA in concrete with a water absorption of 28.9%. It has been noticed that slump values increased with the inclusion of more and more CBA in the concrete. The reason behind such behaviour was the higher affinity to absorb water and lower water retention capabilities of CBA than natural sand. Authors have identified that more water availability was there when CBA was introduced and it further improve the fluidity of the fresh concrete.

2.3.2 Bleeding

The water-cement ratio decides the amount of bleeding water in bottom ash concrete. Bleeding is significantly depending upon the properties of cement, size of fine aggregate particles and water absorption. Addition of CBA, in a small or full quantity of sand, in bottom ash samples significantly disturbed the bleeding of flowable concrete. It has also been reported that addition of CBA in concrete would result in porous particles which absorbs a portion of water inherently during the mixing along with the water absorbed by the voids among the particles available in the concrete mixture. Intend of CBA may be attributed that the quality fallen as equated to base mixture. Also, it has been found that natural river sand has more affinity for water retention compared to CBA particles. CBA particles generally discharge the absorbed water in to the bottom ash concrete as the time elapsed which indicates that the bleeding results in high loss of water in comparison with natural sand concrete. It has been reported that the water reducing admixtures can affect the extent and amount of bleeding significantly in CBA concrete.

Ghafoori and Bucholc (1996) [82] have established that the CBA mixture concrete has a great affinity to generate higher grade of bleeding than control concrete. It has been reported that the water quantity added in CBA concrete mixtures was varied from 251.2 kg/m^3 to 269.6 kg/m^3 equated to 182.7 kg/m^3 and 194.3 kg/m^3 for control concrete. It has been found that with the usage of small quantity of water reducing admixtures, the bleeding water content decreased by 50% than the CBA concrete mixture without admixtures and authors have concluded that with higher dosage of WRA, water bleeding can be controlled to a significant level.

Andrade et al. (2009) [85] drawn the consequence of CBA on a fractional change in place of sand and the authors have drawn that due presence of CBA, the bleeding time, the amount of bleeding water and the water release rate has been increased and for higher concentration of CBA in concrete, higher effects will be there. Authors have evaluated that for 25 and 50% of CBA in concrete mixture, the bleeding water quantity was comparably same as that of base sample. In contrary to the concrete mixture comprising 75 and 100% of CBA, authors have found higher bleeding water content than control concrete mixture.

2.3.3 Setting times

It is the time required by the concrete to indicate certain level of stiffness. It has been drawn that on usage of CBA in place of natural sand, overall setting times compared to natural sand concrete mixtures. This may be owing to the reason of increased claim of mixing water while adding CBA instead of natural sand in the concrete mixture. Also, it has been reported that the pH value degraded with the inclusion of more water into the concrete mixture and consequently, this increases the distance among concrete hydration products which further delay the hydration undertakings of cement particles and consequently, elongate the setting times of CBA concrete mixture. It has been reported that if higher doses of water reducing admixtures have been used in the bottom ash concrete then the setting time decreases for the higher concentration of cement otherwise for lower concentrations, it gets increased.

Ghafoori and Bucholc (1996) [82] explored the upshot of water cutting compounds on the setting times when mixed in a high CBA concrete. Authors have found that the average final and initial setting intervals for CBA concrete were 9.5% and 6% incremental to that of base mix, respectively. Authors have observed that the setting times was unaltered when for the bottom ash concrete when water reducing admixtures were used in the concrete having lower proportion of OPC. Although, with higher proportion of cement in the bottom ash concrete, the setting times were reduced slightly. Authors have reported that there is no any noteworthy influence on the setting intervals of concrete mixtures for either partial or complete replacement of sand with CBA.

Andrade et al. (2009) [85] viewed the upshot of CBA proportion used as a partial change of natural sand fraction of concrete, on the setting times. Authors identified that the setting times were found to higher for CBA concrete compared to natural concrete. It has been reported that for a corrected CBA as per moisture content in bottom ash concrete, the initial setting times increased with the proportion of CBA content. Authors have found that the initial setting times have been increased from 230 min to 350 min when 75% sand replaced with CBA and for 100% CBA it was 270 min. It has been reported that the final setting time improved with the inclusion of more and more CBA in the bottom ash concrete.

2.3.4 Plastic Shrinkage

Plastic shrinkage is a consequence of evaporation of water from the surface of the concrete and which is increased with high rate of evaporation. It has been reported that CBA has significant influence on the plastic shrinkage and CBA unveils large dimensional constancy equated to traditional concrete. It has been identified that the porous units of CBA behave as water pool in samples. As the time elapsed, it has been found that the water absorbed released by the porous particles into the concrete thus reduce the extent of plastic shrinkage. It has been found that higher bleeding rates and capacity of bottom ash concrete favours in tumbling plastic shrinkage.

Ghafoori and Bucholc (1996) [82] found that compared to control concrete, CBA samples exhibited improved dimensional permanency. Authors have found that plastic contraction strain of CBA was 0.309% compared to control concrete 0.467% and it has been concluded that equated to control mixture, bottom ash concrete mixtures possesses 35% fewer average plastic shrinkage.

Andrade et al. (2009) [85] has found that CBA concrete works significantly good and has shown lesser total deformations. It has also been found that with the inclusion of more proportion of CBA in bottom ash concrete where CBA quantity was corrected as per moisture content, the maximum deformation decreased to a certain level i.e. from 0.031 mm/m to 0.009 mm/m.

2.4 Properties of Hardened Coal Bottom Ash Concrete

2.4.1 Density

It has been reported that with the usage of CBA in place of natural sand in mixture, a significant amount of unit weight reduction has been noticed as the CBA structure is porous and unit weight is also low comparison to natural sand. Thus, such factors involve in the lowering the unit density of CBA and it lowers with the degree of replacement of natural sand with CBA.

Andrade et al (2007) [86] examined that with inclusion of CBA to be included as a change in concrete will reduce the density by 25%. Kim and Lee (2011) [50] investigated the influence of fine and coarse CBA on concrete density. Authors have found that with the rise in the replacement ratio of fine and coarse bottom ash, the hardened concrete density decreased linearly. It has been found that when fine and coarse fine bottom ash aggregates have been added as a part change for natural sand, the density of concrete decreased by 4.6% an 9.6% respectively.

Topcu and Bilir (2010) [49] examined impressions of CBA on density of the mortar and authors have done analysis on 7th and 28th day. Mixed proportions of mortar have been considered where 500 kg/m^3 cement, 3 kg/m^3 water tumbling admixtures and contrasting proportions of CBA having 1.39 g/cm^3 specific gravity. Authors have concluded that with the inclusion of CBA, the density of unit specimen decreased.

2.4.2 Compressive Strength

Porosity of hydrated paste can affect the strength of the concrete. Further, it has been found that porosity get affected with the variation in water/cement ratio and occurrence of cracks among bonds at the hydrated paste and aggregate interface. Strength of concrete may also get affected by the individual contribution of the ingredients present among the concrete. It has been reported that in order to maintain same workability, the w/c ratio of concrete mixture increases when CBA is used as a fractional change of natural sand. For greater W/c value, overall volume of pores enlarged. As CBA samples results in more bleeding, thus there are numerous chances of water trapping under the aggregates which generates enormous enlarged pores, bear to aggregate surfaces. Such gaps do not allow bonding among the aggregate-binder paste which consequently weaken and porous the changeover phase among aggregate binder paste, thus diminishing the concrete strength. This happened as the inclusion of CBA in the concrete results in weak microstructure thus reduces the compressive strength.

Cheriaf et al. (1999) [37] revealed the outcome and resultant of CBA which can be used in place of 100% of river sand the result of which was found in such an equation that the strength activity index (SAI) of CBA when used with OPC was 0.88 and 0.97 after 28 and 90 days of hydration. These values are quite greater than 0.75 for 28 days and 0.85 for 90 days, specified upper limits by European standard EN 450 which indicates that CBA is appropriate to be employed as construction material in concrete. Such higher values of SAI indicate the pozzolanic activity of CBA which starts at 14^{th} day and consume significant amount of calcium hydroxide after 90 days of hydration.

Kurama and Kaya [55] (2008) examined the influence of CBA used as part change of fine aggregate in concrete sample and noticed that on mixing of CBA up to 10%, the compressive strength of mixture increased and it has been concluded that for this concentration of CBA, the compressive strength of the bottom ash concrete mixture surpassed by 5% than that of control concrete. It has also been examined that inclusion of CBA more than 10% resulted in decrease in the compressive strength at lower age of 7^{th} and 28^{th} day of study. Although, the compressive strength of CBA concrete mixture was found to 15% higher at 56^{th} day of study than that of concrete mixture.

Kou and Poon (2009) [84] examined the influence of CBA on the concrete properties where CBA along with saturated surface dry sand have been used for the analysis. Authors have found that for a set W/c value, with the inclusion of more and more CBA content into concrete, the overall strength parameters of the CBA samples decreased for all ages. Although, authors have noticed that for a fixed slump range and all ages, the compressive strength is found to higher for bottom ash concrete equated to base sample and this improvement in strength can be understood with the decrease in the w/c ratio.

Topcu and Bilir (2010) [49] studied the influence of CBA incorporated as fine aggregate replacement on the compressive strength of cement mortar and authors have noticed that the cement mortar compressive strength decreased with the inclusion of more and more CBA content. Authors have concluded that the rate of decline in compressive strength on 7th day is analogous to 28th day. It has been reported that the mortar compressive strength after the inclusion of CBA was on a lower side when equalled to that of base mortar.

2.4.3 Flexural Strength

CBA when changed in concrete in place of natural sand has affected the flexural parameter of concrete and it has been reported that with the infusion of CBA, the flexural strength of concrete reduced considerably. It was drawn that the quality of paste in concrete mixture affects the flexural strength. As with the addition of CBA in concrete, the paste becomes porous and weak thus flexural strength reduced. It has been determined that on contribution of CBA in place of sand, overall bulk of pores increased in the concrete and thus microstructure becomes porous.

Yuksel and Genc (2007) [47] observed that with infusion of CBA, the flexural strength of the concrete mixture lowered than the control concrete. Authors have noticed that with 10% change of sand with CBA, almost 10% weakening of flexural strength has been detected equated to base sample.

Kurama and Kaya (2008) [55] searched and established that flexural parameters of CBA samples which were used in place of cementing material was found to similar to base concrete. The flexural strength of bottom ash concrete having CBA proportion other than 25% in concrete found to be higher than that of control concrete and this happened due to low commotion of bottom ash at initial curing ages.

Kim and Lee (2011) [50] studied that due to escalation in part change of fine and coarse CBA, decline in the flexural strength was linear. Authors have found that with 100% change of sand with CBA, modulus of rupture reduced by 19.5% and 24%, respectively.

2.4.4 Splitting Tensile Strength

The behaviour of splitting tensile strength (STS) of CBA assisted concrete may be considered to be in equation to that of base concrete specimens. It has been reported that CBA has more impact on STS compared to compressive strength of concrete. STS is found to be decrease when CBA added and changed with sand. High degree of porosity and much higher dispersion of pores in CBA samples resulted in decrease in STS. Water reducing admixtures reduces the water requirement, recover the microstructure of CBA assisted concrete and which further improve the STS.

Ghafoori and Bucholc (1997) [87] noticed that with rise in curing period, STS of CBA samples increased. For a concrete mixture having 356 kg/m^3 of cement or even higher, STS of the mixed concrete was established to be greater when equated with control concrete at all curing ages. For 50% CBA assisted concrete having 297 kg/m^3 cement resulted in 5% reduction in STS however, by using admixtures, 12% improvement above control concrete strength has been observed.

Yuksel and Genc (2007) [47] examined that STS has no effect up to 10% inclusion of CBA in place of sand however, beyond this proportion, STS is found to decrease significantly with the incremental hike in the CBA content. It was also drawn that the maximum reduction in the STS was found to 58% for CBA samples having 50% CBA as change of natural sand. The reduction in STS of CBA samples was found to be linear when CBA was used in place of sand.

Aggarwal et al. (2007) [39] noticed that for all curing ages, the STS of CBA samples was less than that of the base mix. The STS for CBA mixtures was found to be 121-126 percent of the 28-day curing age STS of control concrete after 90 days of curing.

2.4.5 Modulus of Elasticity

The modulus of elasticity of CBA was affected by increasing the amount of CBA change of sand was done. According to the literature, the modulus of elasticity decreases as CBA content increases. This is because CBA particles are less compressed and firm than sand particles, resulting in a weak and porous paste that reduces the modulus of elasticity. However, with the implementation of chemical substances, it tend to improve the modulus of elasticity due to decrease in W/c value.

Topcu and Bilir (2010) [49] noticed that on rise of CBA content increased from 0 to 60%, modulus of elasticity of the mortars decreased. Authors have concluded that the porous structure among the molecules was responsible behind this decline in the modulus of elasticity. Andrade et al. (2009) [85] stated that modulus of elasticity dipped from 25.8 GPa to 8.9 GPa on 28-days of curing period and with the complete change of river sand with CBA.

Kim and Lee (2011) [50] observed that with the rise in aggregate proportion in concrete which is used as a replacement of natural sand, the modulus of elasticity decreased. For 100% change of sand with CBA, modulus of elasticity reduced to 41 MPa to 34.9 MPa. When 100% coarse CBA aggregate was used in the CBA mixes, the modulus of elasticity is 77.5% (31.8 MPa) of the base specimen.

2.4.6 Drying Shrinkage

Very few studies have been testified in the literature where drying shrinkage of CBA have been evaluated. It has been reported that in order to control the drying shrinkage of concrete, porous structure of CBA particles is favourable. CBA porous particles behaves as reservoir and in line with the drying regime of CBA specimens, such CBA particles slowly releases the moisture which leads to reduction in shrinkage. Ghafoori and Bucholc (1997) [87] found that when equated with CBA mix, samples offered excellent dimensional stability. Authors concluded that higher bleeding rates ended up in sinking the drying shrinkage strain (DSS) index of CBA mixtures. It has been reported that for 50% CBA, the DSS values of CBA assisted concrete mixture were established to be lower than that of base mixture and for 100% CBA, DSS values of CBA specimens were upgraded when equated with controlled specimens. Bai et al. (2005) [38] investigated that the drying shrinkage index for all CBA assisted concrete was lesser than base sample when permanent W/c value of 0.45 and 0.55 was considered. However, for static workability parameter, drying shrinkage index was more when equated. It has been noticed that when CBA raised in mix, resultant led to the growth of overall porous material quantity which keeps the water absorbed within it and discharge the water on drying regime of specimen, which further drops the drying shrinkage.

2.5 Durability Properties of Bottom Ash Concrete

2.5.1 Permeability

Concrete permeability relies on the distribution, size and permanence of pores existing in the cement paste and permeability of aggregates. It has been reported that the permeability of CBA samples was superior when equalled with natural sand concrete. With the addition of CBA content, the bottom ash concrete permeability found to increase. Porous microstructure of CBA, elevated demands of mixing water and higher water loss due to bleeding are the essential features that can influence the permeability characteristics. The infusion of CBA in place of natural sand results in porous microstructure. Concretes having lower water-binder value along with longer curing's, displays slightly inferior permeability.

Aramraks (2006) [83] evaluated that when equated to control mix, chloride permeability of CBA is far better. It has been reported that for 100% CBA assisted concrete, the charge passed through it was found to 1975 Coulombs matched to 4178 Coulombs through base concrete. Kou and Poon (2009) examined that for a set W/c ratio, with rise in the CBA component in to CBA mixes, it has been found that there was a decrease in the opposition to chloride-ion penetration of mixtures. The presence of adequate freely available water content in CBA assisted concretes compared to control one results in looser microstructure.

2.5.2 Resistance to Sulphate Attack

Ghafoori and Bucholc (1996) [82] reported that natural sand and bottom ash concrete displayed similar resistance to the external sulphate attack. Authors have found that CBA assisted concrete (containing 356 kg/m^3) without any admixture showed 0.035% expansion strain when dipped in 5% sodium sulphate solution for 180-D.

Ghafoori and Cai (1998) [88] examined the influence of calcium rich (22.5%) CBA incorporated as a percentage change of naturally available sand in 'concrete consolidated by roller' on its durability parameters for a long curing period. Authors have claimed that excellent resistance to sulphate attacks can be achieved if dry CBA employed as fine aggregate in roller compacted concrete. A mean expansion of the order of 0.0017% has been noticed when CBA assisted roller compacted concrete articles have been immersed in the sodium sulphate solution for 28 days. When same specimens immersed for 365 days in the 5% sodium solution experienced an expansion strain of 0.00203 to 0.0388%. It has been reported that strength of the water cured (180 days) specimens was somewhat similar to that of corresponding sample cured with 5% sodium sulphate solution. Authors have noticed that with the use of coarse particles in CBA roller compacting concrete, resistance to external sulphate attack improved.

2.5.3 Abrasion Resistance

In order to have longer service life, the abrasion resistance properties of paved surfaces and concrete floors are imperative. Exterior surface must be competent to counter grinding which is commonly instigated due to sand confined underneath vehicle tyres. The prominent parameters that can affect the abrasion of concrete surface are its aggregate properties (such as properties of CBA), compressive strength and surface finish quality. Hardness of aggregate material and the nature of bonds among the aggregate material and paste decides the degree of abrasion resistance. Moreover, it has been found that the bonding among paste and aggregate material depends upon various factors like grading, texture, shape and soundness of aggregate. CBA particles are generally porous and less stiff when equalled to natural sand particles and thus inclusion of CBA, as a fractional change in lieu of sand, can affect the concrete's abrasion resistance and diminishes the abrasion quality of the concrete. It has been reported that as bottom ash concrete is more porous than natural sand concrete thus such concrete's are more prone to moisture. Moreover, it has been found that with the influence of water reducing admixtures within the mixtures, abrasion resistance quality can be modified.

Ghafoori and Bucholc (1996) [82] explained his conclusion that the high-calcium CBA concrete gave 40% lower abrasion resistance when equalled to base mix. Authors have found that with the inclusion of water reducing admixtures, the abrasion resistance of

CBA mixture was achievement of excellence when outcomes were compared to base mixture. Ghafoori and Cai (1998) [88] demonstrated that with the increase in the cement content in the concrete, the depth of wear of BA roller compacted concrete decreased. Authors have noticed that the resistance to abrasion of concrete having high calcium CBA for dry air conditions was superior to wet air conditions. The depth of wear under wet conditions was found to 7.25 times higher than that of dry conditions. It has been reported that when cement content raised from 9 to 12% and 15%, the ratio 7.25 dropped to 6.42 and 6.00. This implies higher cement content can create smoother surface and stronger paste.

2.6 Research Gap

After the intensive literature review, it is concluded that lot of experimentation have been carried out on the Coal Bottom Ash usage in concrete as a partial or full replacement of fine aggregates separately or in combination with the other manufactured by-products alike waste slag, fly ash, steel fibres and silica fumes. On the contrary, various studies have been carried out on replacement of cement with silica fumes, fly ash, Alccofine etc. in concrete. As none of the study encompasses on simultaneous evaluations of the strength and durability parameters of concrete with CBA and Alccofine in combination, an experimental program is scheduled to analyse the effect of CBA as a fractional change in lieu of fine aggregate and Alccofine as an alternative option to cement, together in different combinations on fresh and hardened concrete properties. Further, micro structural analysis and statistical studies will be carried out for this new combination.

2.7 Objective of the Study

The dissertation work has following objectives-

1. To study the effect of coal bottom ash as a partial replacement of fine aggregates on fresh and hardened properties of concrete.
2. To analyse the property of fresh concrete for the partial replacement of combination of coal bottom ash as fine aggregate and Alccofine as cement.

3. To assess the strength and durability characteristics of hardened concrete for the partial replacement of combination of coal bottom ash as fine aggregate and Alccofine as cement.

2.8 Scope of Work

The scope of this dissertation work includes the following-

- Characterization of the concrete's constituents
- Design of controlled concrete mix.
- Preparing concrete mixtures with CBA in different percentages.
- Studying the effect of varying percentage of CBA on the workability.
- Casting of the specimens for the controlled concrete and for the concrete containing CBA as a partial alternative to fine aggregates.
- Testing for the strength parameters based on experimental conclusions for controlled mixes and CBA mixtures.
- Selection of the percentage of FA replacement with CBA from the reasoning of the results for CBA mixtures for the further investigation.
- Preparation of the concrete mixtures by varying percentage of Alccofine as a fractional change in lieu of cement along with the chosen percentage of CBA as a fractional alternate to FA.
- Analysing properties of fresh concrete for Alccofine assisted bottom ash concrete samples.
- Casting of the specimens for the Alccofine assisted bottom ash concrete samples.
- Testing of the Alccofine assisted bottom ash samples for mechanical and durability properties of concrete.
- Analysis of results and evaluation of determination coefficient (R^2) for the developed empirical equations, for correlating the concrete properties

To accomplish the objectives of this dissertation, following tests have been performed:

a) Characterization of material

- Specific gravity
- Sieve analysis
- Chemical composition

b) Concrete tests

- Slump test
- Compressive strength test
- Split tensile strength test
- Flexural strength test
- Scanning Electron Microscopy (SEM)
- Rebound hammer test
- Ultrasonic pulse velocity test
- Initial Surface Absorption Test (ISAT)
- Rapid Chloride Penetration Test (RCPT)

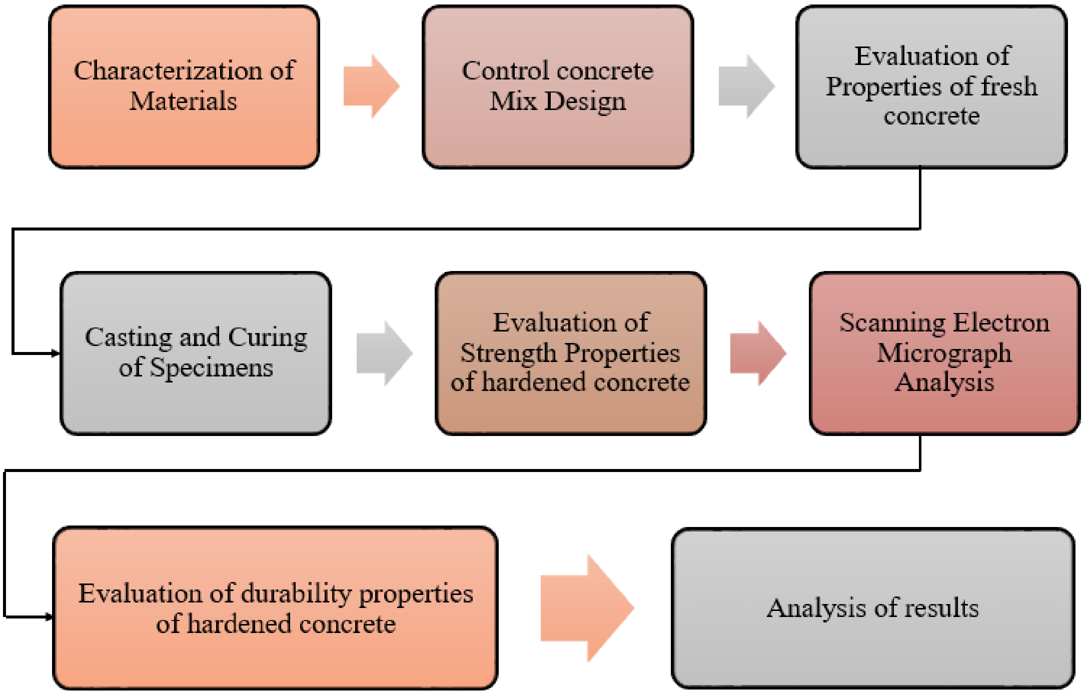
CHAPTER
3 EXPERIMENTAL METHODOLOGY

This chapter defines the methods applied in achieving the various research objectives of this dissertation work. The properties of coal bottom ash have been studied along with their effect on fresh and hardened properties of the concrete when coal bottom ash is used as partial replacement of fine aggregates. Further, methodology for partial replacement of combined coal bottom ash as fine aggregate and Alccofine as cement has been discussed in this chapter. In order to evaluate the performance parameters such as strength and durability of the concrete, various testing procedures have been discussed in this chapter.

Keywords: Concrete, fine aggregates, coal bottom ash, Alccofine, concrete properties.

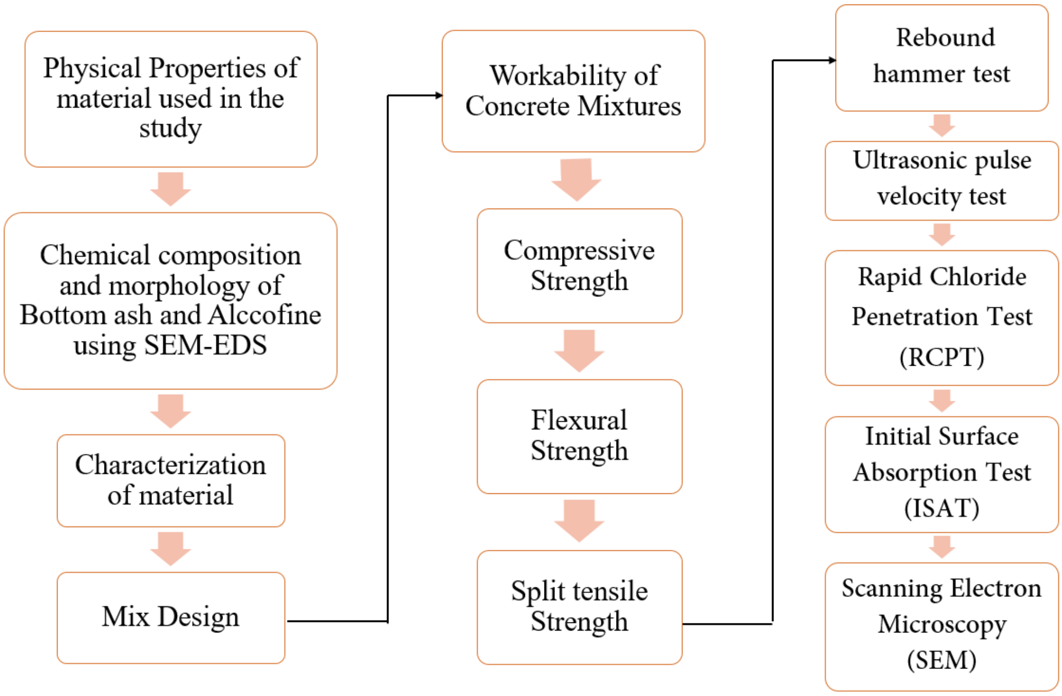
3.1 Introduction

An experimental strategy has been planned to examine the effect of CBA as replacement of sand on the concrete properties. In this regard, various tests need to be performed on fresh and hardened concrete. Following experimental strategy has been employed in this dissertation work:



3.2 Research Scheme

In order to accomplish the objectives of the dissertation, an experimental study has been demonstrated to identify the concrete properties at fresh hardened and stage consisting Alccofine as a partial replacement of cement and CBA as a partial replacement of fine aggregates. The research work includes the following investigations-



Experimental studies have been performed in the laboratory in order to evaluate the properties of concrete constituents. Research methodology employed for this dissertation work has been divided in two phases:

Phase-1:

In this phase, a controlled concrete mix has been prepared where up to 50% of fine aggregates were replaced with coal bottom ash where fine aggregate concentration has been increased by 10% for every study e.g. 10%, 20%, 30%, 40% and 50% [53]. The specimens were trouped for various concrete mixtures such that their properties have been evaluated at fresh and hardened state. Depending upon the strength and workability properties of bottom ash concrete mixtures, a replacement concentration has been chosen which was used in further investigation done in Phase-II.

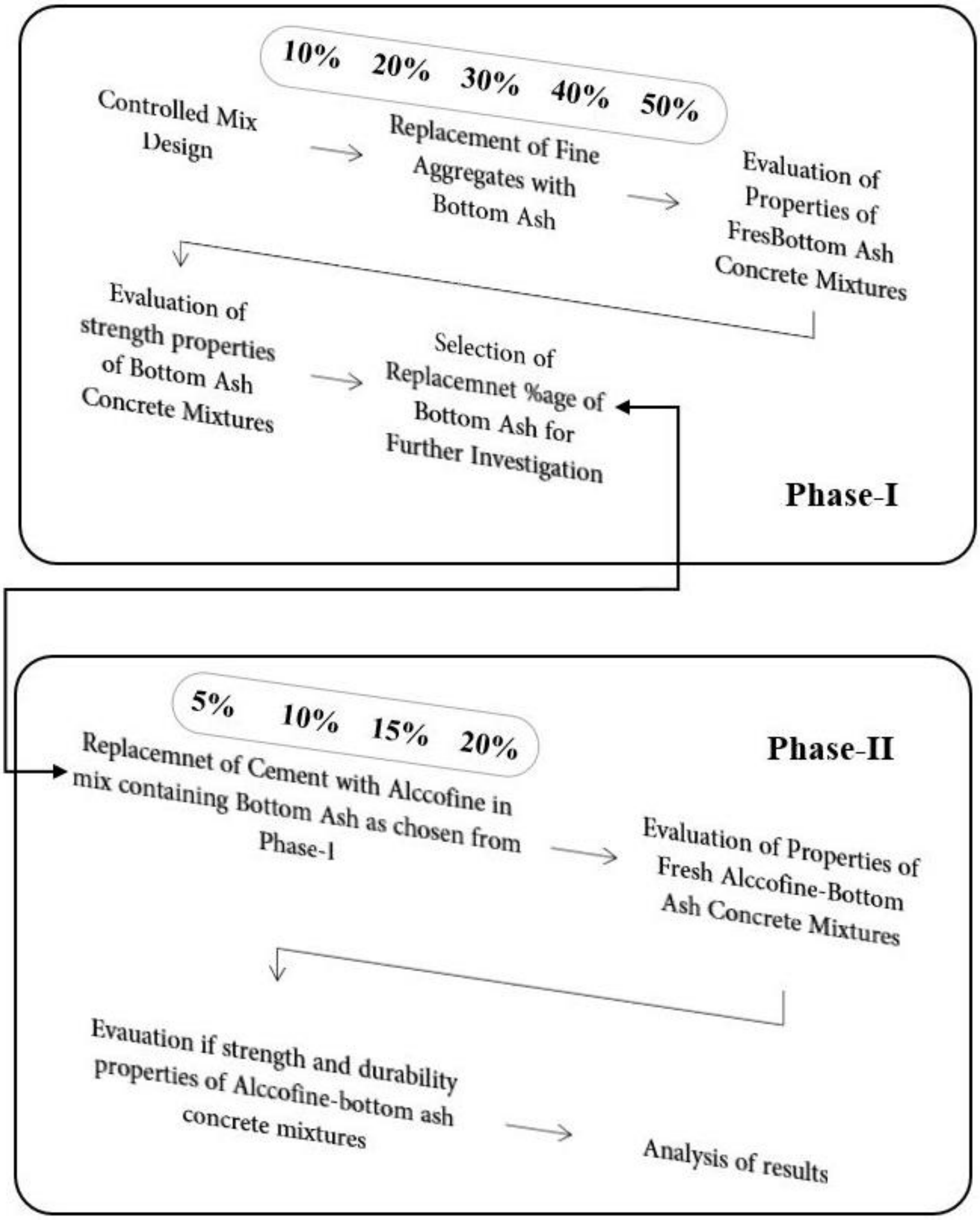


Figure 3-1 Research Methodology used

Phase-II:

In phase-II, the effect of Alccofine used as a partial replacement of cement has been investigated on the bottom ash concrete mix obtained from Phase-I. Alccofine has been used as a partial replacement up to 20% in a mix where coal bottom ash has already been employed as a partial replacement of fine aggregates and properties of this novel mix has been investigated. Further such properties have been compared among bottom ash concrete mix and controlled concrete.

3.3 Classification of Materials

Concrete is composed of various constituents which contain major two components; cement paste and aggregates. The strength of any structure is significantly depends on the quality of the concrete which further rely on the strength of its constituents, their mechanical properties and adhesion among the paste and aggregate surface. Thus, before evaluating the performance parameters, one should know the properties of such constituents.

Figure 3-2 Ordinary Portland Cement (OPC 43 grade)

3.3.1 Cement

The Ordinary Portland Cement (OPC) is one of the main constituent used in the production of concrete. Cement is a powder which holds adhesive and cohesive properties and when mixed with other ingredients along with water it provides a binding medium that generate strength. In this research work, ordinary Portland Cement grade 43 (Shree Ultra Cement) imitating to BIS: 8112-1989 [89] has been employed. Compressive strength, setting time and consistency of the cement has been evaluated as per BIS: 4031-1988.

3.3.1.1 Compressive Strength

Following BIS: 4031 (Part-6)-1988 [90] standards, cubes of size 69.5 mm * 69.5 mm * 69.5 mm have been made in order to perform compressive strength test of cement. In order to prepare cement-sand mix cubes of 1:3 ratios, BIS: 650-1966 sand standard has been incorporated. Cement-sand mixer quantities consist 200 g cement and 600 g standard sand and water quantity of (P/4+3.0) percent of combined mass of cement and sand, where P is the water %age needed to generate a paste of standard consistency.

A vibrating machine has been used for two minutes at a frequency 200 Hz in order to make cubes compact. After 24 hours, the cubes were demoulded using water followed by the tempering of cubes at 27 ±1^{o}C. During the tests, the cubes were loaded with a uniform load at 35 N/mm^{2}/min and in order to evaluate the compressive strength of cubes, the readings were noted at 7, 28, 56, 90 and 180 days of curing age.

3.3.1.2 Setting time

In order to determine setting time of cement, standard procedure defined by BIS: 4031-(Part-5)-1988 [91] has been used. Fresh cement paste has been prepared through appraising the cement with 85% of water used to produce a cement paste of standard consistency. Cement paste has been filled in Vicat mould and the upper layer was levelled using trowel. Vicat mould and non-porous plate was resided under rod-bearing needle of Vicat apparatus. The apparatus was placed above the cemented paste such that the needle touched the top of paste and immediately released permitting it to pierce in to the paste sample. This operation have to be repetitive in nature till when the needle failed to pierce the block. When calculated from the bottom of the mould, the block should be pierced beyond 5 ± 0.5 mm. The time period intervening between the instance when water was poured in to the cement and when the needle failed to pierce the test block to specified limit from the foot of the mould was the initial setting time.

Vicat apparatus needle was then swapped with the needle having an annular attachment. Subsequently, needle leaves an impression on the surface of the cement paste bed when needle was gently applied on the surface, the cement was supposed to settled while attachment failed to do so. This time period is called final setting time.

3.3.1.3 Consistency

When the Vicat plunger penetrate to a point 5 to 7 mm from the bottom of Vicat mould, this is called as consistency of a cement paste. Generally, BIS: 4031-(Part 4)-1988 [91] standards were used to determine the consistency of cement. A paste of 0.5 kg cement has been prepared in the Vicat mould and top surface of mould was levelled using trowel. In order to expel air from the mould it has been shaken gently. Vicat mould and non-porous plate was resided under rod-bearing plunger of Vicat apparatus. The plunger was allowed to touch down the paste surface gently and then suddenly released permitting to sink into the paste. In order to achieve standard consistency, various trials have been made using paste consisting contrast percentages of water until the optimum one was achieved.

3.3.2 Coarse Aggregate

From the local market a coarse aggregate of maximum size 20 mm has been obtained for this experimental study. As per IS 2386 (Part-3) – 1963 [92], the specific gravity assessment on Coarse aggregate was performed. As per IS 2386 (Part-1) – 1963 [92], the fineness modulus of coarse aggregate was examined. The physical properties of coarse aggregates are tabulated in Table 3-1. 3 kg. Sample of aggregate was placed in water for a day so that it is immersed thoroughly. Afterwards, the sample was taken from liquid and placed outside at room temperature until no free surface moisture was noticed. The samples of saturated surface dry aggregates were weighed (Weight W1). The coarse aggregate samples were weight (weight W2) when placed in bag occupied with water. The samples were weighed (Weight W3) after expelling out the coarse aggregates from the bag and oven dried at 110^{o}C for 24 hrs. Thus, Water absorption and specific gravity were evaluated as:

Sp. gravity of coarse aggregate = W3/ (W1-W2)

Water Absorption= [100(W1-W3)]/W3

Figure 3-3 Coarse aggregate

Table 3-1 Physical properties of coarse aggregate, fine aggregate and coal bottom ash

Property	**Coarse aggregate**	**Fine aggregate**	**Coal bottom ash**
Specific gravity	2.66	2.63	1.71
Fineness modulus	6.68	2.53	1.63
Water absorption by mass (%)	0.42	2.13	29.57

3.3.3 Fine aggregate and CBA

In this research work, Coarse aggregate of maximum size 20 mm is used and fine aggregate is confined to ZONE II (BIS: 383-1960). Coal bottom ash is collected from Guru Gobind Singh Super Thermal Power Plant, Ropar, Punjab. A sieve of mesh size 4.75 mm has been used while sieving the coal bottom ash and sand in order to obsolete the coarser particles than 4.75 mm before use in concrete. Parameters like particle size distribution, specific gravity and water absorption of coal bottom ash and fine aggregate has been determined using BIS: 2386 (Part I and II)-1963 [92] standards. The physical properties of fine aggregates and coal bottom ash is tabulated in Table 3-1.

Figure 3-4 Fine aggregate

3.3.3.1 Particle size distribution

Ordinary sand and CBA samples were kiln dried at 100^{o}C and then cooled at room temperature. Each sample of 500g has been mechanically sieved through various sieves including 4.75 mm sieve at the top followed by 2.36 mm, 1.18 mm, 600 µm, 300 µm, 150 µm, 90 µm and pan at the bottom to draw the particle size distribution curve as a standard procedure. For each sample, the retained material over individual sieve was recorded.

3.3.3.2 Specific gravity and water absorption

According the standard procedure described in BIS:2386 Part-III 1963 [92], Pycnometer is generally used to determine the specific gravity of CBA and natural sand. A mass of 500 g of both natural sand and CBA was located in a dish which was enclosed with water. In order remove the entangled air, a mild excitement with a solid rod is done. Then the samples were kept submerged in H_2O for 24 hr. Using decantation technique, the water was sapped from the models by means of filter paper. Then the samples were dried at room temperature. The surface dry and saturated samples of CBA and sand were weighed (Weight A). The surface dry aggregate and saturated samples were placed in Pycnometer that was filled with water. In order to remove trapped air, Pycnometer was rotated on its sides and then the Pycnometer was topped with water and weighed (Weight B). Further, the Pycnometer was washed off and re-filled with the water to the same level and then weighed (Weight C). Samples of CBA and natural sand obtained from the Pycnometer was dried at 110°C for 24 hr. and then cooled to room temperature and weighed (Weight D). Thus, Water absorption and specific gravity were evaluated as:

Figure 3-5 Bottom ash

Table 3-2 Chemical Composition of Bottom Ash

Compound	Percentage
SiO_2	35.13
Al_2O_3	25.63
MgO	0.54
CaO	0.46
Fe_2O_3	7.92
K_2O	0.58

EDS done at SAI LABS, Thapar University, Patiala, Punjab

$$\text{Specific Gravity} = D/[A-(B-C)]$$

$$\text{Water Absorption} = [100\times(A-D)]/D$$

where,

A = Weight of saturated surface dry sample, g.

B = Weight of pycnometer containing sample and filled with water, g.

C = Weight of pycnometer filled with water, g.

D = Weight of oven dried sample, g.

3.3.4 *Alccofine*

Alccofine is obtained from the store of Ambuja cement. The plant from which the Alccofine is manufactured is located at Pissurlem Industrial Estate, Goa (India). Super plasticizer used in this study is Glenium – 51 which is based on modified polycarboxylic ether. Glenium was purchased from BASF INDIA LIMITED, Chandigarh.

Alccofine bag was purchased from the local dealer store of Ambuja cement. Specific gravity test on Alccofine was conducted according to IS 8112-1989 [25].

Figure 3-6 Alccofine powder

Table 3-3 Chemical Composition of Alccofine

Compound	Percentage
SiO_2	35.05
Al_2O_3	24.34
MgO	9.66
CaO	28.86
Fe_2O_3	1.97

EDS done at SAI LABS, Thapar University, Patiala, Punjab

3.4 Mix Design

Concrete mix design is a process of choosing appropriate concrete ingredients and evaluating their relative quantities in such a way through which the objectives of fabricating concrete can be achieved as per required strength, durability and workability within economically viability.

3.4.1 Concrete Mix Design requirements

Following are the basic requirements which contain basic steps of selection and proportioning of mix ingredients:

a) The minimum compressive strength required from structural consideration	b) The adequate workability necessary for full compaction with the compacting equipment available.
c) Maximum water-cement ratio and/or maximum cement content to give adequate durability for the particular site conditions.	d) Maximum cement content to avoid shrinkage cracking due to temperature cycle in mass concrete.

3.4.2 Design Procedure

Concrete mix was designed as per IS 10262-2009 [93] and the design procedure was as follows:

1. By using 28th –day compressive strength (f_{ck}) and quality control level, the mean target strength (f_t) has been evaluated.
   $f_t = f_{ck} + 1.65\ S$
   where, S signifies the SD calculated form the Table of approximate contents given after the design mix.
2. Depending upon the desired mean target strength, the water-cement ratio has been evaluated using empirical correlations. The correlation among the water-cement ratio and compressive strength has been chosen in such a way that it should compare with the limiting water-cement ratio to match the durability requirements provided in the table and chose the lower among the two values.
3. For the nominal size (maximum) of the aggregate, there is a need to estimate the amount of entrapped air from the table.

4. From the table, the water content has been chosen to attain maximum size of aggregates in saturated surface dry condition and designed workability of the concrete.
5. Evaluate the fraction among fine aggregate % age in total and absolute volume of crushed coarse aggregate (from the table).
6. In order to tune the workability, grading of fine aggregate, water-cement ratio and for rounded aggregate, there is a need to adjust the % age of sand and water content as per the values given in table.
7. Using water-cement ratio to evaluate the cement content and the final water content can be achieved after alteration. To achieve the designed durability, the cement concentration has been checked against the minimum level and then the greater among two has been chosen.
8. To evaluate the fine and coarse aggregates content per unit volume of concrete, following expressions have been used:

$$V = \left[W + \frac{C}{S_c} + \frac{1}{p}\frac{f_a}{S_{fa}} \right] \times \frac{1}{1000}$$

$$V = \left[W + \frac{C}{S_C} + \frac{1}{1-p}\frac{C_a}{S_{ca}} \right] \times \frac{1}{1000}$$

Where, V=absolute volume of concrete

= gross volume (1 m^3) minus the volume of entrapped air

S_c = Specific gravity of cement

W = Mass of water per cubic metre of concrete, kg

C = Mass of cement per cubic metre of concrete, kg

p = Ratio of fine aggregate to total aggregate by absolute volume

f_a, C_a = total masses of fine and coarse aggregates, per cubic metre of concrete, respectively, kg, and

S_{fa}, S_{ca} = specific gravities of saturated surface dry fine and coarse aggregates, respectively.

9. For the 1st trial mix, then evaluate the concrete mix proportions.

3.4.3 Concrete Mix Design M40

Concrete Mix Design for M40 Grade of Concrete is done as per IS 10262:2009 [93] and IS 456:2000 [94].

Table 3-4 Components of concrete mix design

A1	**Design Stipulations**	
a)	Characteristic Compressive Strength of Concrete at 28 days	40 N/mm^2
b)	Maximum Size of aggregate	20 mm
c)	Target Slump Value	100 mm
d)	Degree of Quality Control	Good
e)	Type of Exposure	Mild
A2	**Test Data for Materials**	
a)	Cement Used	OPC 43 Grade
b)	Specific Gravity of Cement	3.13
c)	Specific Gravity	
	i) Coarse Aggregates	2.66
	ii) Fine Aggregates	2.63
d)	Zone of Fine Aggregates	II
e)	Chemical Admixture Type (Superplasticiser)	Glenium 51
f)	Specific Gravity of admixture	1.095
A3	**Target Mean Strength of Concrete, ft = fck +1.65S**	48.25 N/mm^2
	S = Standard Deviation (Table 8 in IS 456:2000)	5 N/mm^2
A4	**Selection of Water Cement Ratio**	
a)	From Table 5 of IS 456:2000, Maximum W/C Ratio	0.4
b)	Based on Experience, adopt water cement ratio as	0.38
A5	**Selection Water Content**	
a)	From Table 2 of IS 10262:2009, Maximum Water Content for 20mm aggregates (slump of 25-50 mm)	186 ltr.
	For desired workability, an increase of about 3 percent for every additional 25mm slump is required.	
b)	Estimated Water Content for 100 mm slump =	197.16 ltr.
	As any Superplasticizer is used, the water content can be reduced up to 20 percent and above.	
c)	Reduction of water content percent assumed	20 %
d)	Hence, the arrived water content	157.73 ltr.

A6	**Calculation of Cement Content**	
a)	Water - Cement Ratio	0.38
b)	Cement content	415 kg
	From Table 5 of IS 456, check for minimum cement content.	
	415>360, Hence O.K.	
A7	**Proportion of Volume of Coarse Aggregates and Fine Aggregates Content**	
	From Table 3 of IS 10262:2009, volume of coarse aggregate corresponding 20 mm aggregate and fine aggregate for water cement ratio	
a)	Volume of Coarse aggregate corresponding to 20 mm size aggregate and fine aggregate(Zone II) for w/c ratio of 0.50 is	0.62
b)	In present case, w/c ratio is	0.38
c)	Correction at the rate of -/+ 0.01 for every -/+ 0.05 change in water cement ratio	0.024
d)	Corrected Volume of Coarse Aggregate for the water cement ratio of 0.38	0.644
e)	For pumpable concrete, these values should be reduced by 10%, therefore volume of coarse aggregate	0.58
f)	Volume of Fine Aggregates Content = 1-Volume of C.A.	0.42
A8	**Mix Calculations**	
	The mix calculations per unit volume of concrete shall be as follows:	
a)	Volume of Concrete	1
b)	Volume of Cement = Mass of Cement / Specific Gravity of Cement	0.133
c)	Volume of Water = Mass of Water / Specific Gravity of Water	0.158
d)	Volume of Chemical Admixture @ 2 % by mass of cementitious material	0.0008
e)	Volume of all in aggregate = [a-(b+c+d)]	0.7082
f)	Mass of Coarse Aggregates = e x Volume of C.A. x S. Gravity of C.A. x 1000	1092.61 kg
g)	Mass of Fine Aggregates = e x Volume of F.A. x S. Gravity of F.A. x 1000	782.27 kg

A9	**Mix Proportion**		
		Ratio	**kg/m³**
a)	Cement Content	1	415
b)	Fine Aggregates Content	1.88	782.27
c)	Coarse Aggregates Content	2.63	1092.61
d)	Water	0.38	157.73

3.5 Experimental Test Procedure

In this section, various test procedures, which are used to evaluate the concrete properties, have been discussed.

3.5.1 *Workability*

Using BIS: 1199-1959 standards [95], the workability of the mixed concrete has been evaluated by conducting slump test. A brief description about these tests is discussed below:

3.5.1.1 *Slump Test*

The cleaned mould was filled with four layers of concrete. Using tamping rod (16 mm diameter with rounded end), the layers of the concrete were compacted through 25 strokes such that the concrete gets uniformly distributed among the mould. After the tamping of top surface, by using trowel the extra concrete mass was removed. The concrete was then extracted through the mould immediately by raising the mould in vertical direction. The slump was measured by evaluating the height difference among the mould and the peak point of the specimen after the subsidence of concrete (as shown in Figure 3-7).

Figure 3-7 Setup of slump test

3.5.2 Tests for Strength properties of concrete

3.5.2.1 Compression Test

Using BIS: 516:1959 standards [95], the compressive strength of the concrete was measured. After a specified curing age, the cubes were removed from the water, and the remained surface water and grit was wiped off. Then the cubic specimen is placed in the apparatus having 3 MN capacity (shown in Figure 3-8) in such a way that the load is applied on the opposite sides of the cubic specimen.

Figure 3-8 Compression test setup

A gradual load is applied on the test specimen at a rate of 4.5 kN/sec till the confrontation offered by the cube breaks. The maximum load that has been sustained by the specimen was recorded. For each test, three cubes were tested for compressive strength which has been evaluated by dividing the extreme weight applied during the test to the cube's cross-sectional area.

3.5.2.2 Splitting Tensile Strength

According to the method mentioned in BIS: 516-1959 [95], the splitting tensile strength of concrete specimen has been evaluated. In a Universal Testing Machine (UTM) of capacity 1000 kN, a cube specimen is place as indicated in Figure 3-9 such that the load is increased gradually without shock at a rate of 1.2 to 2.4 N/mm^2 until failure occur. Three specimens have been tested and maximum load in each case has been evaluated. Tests were performed at 7, 28, 56, 90 and 180 days of curing age. The ages were considered from the duration of casting of moulds. It has been ensured that the concrete cube is properly cleaned and no water and projecting fins are there. Lines were drawn on the centre of two opposite cube faces and it has been ensured that both lines lying on same axial plane. Splitting tensile strength has been evaluated after taking average of three tests which can be calculated as:

$$f_{ct} = \frac{2P}{\pi LD}$$

where, *'P'* is maximum load applied in kN and *'L'* is the length of specimen (mm) and '*D*' is cross-sectional dimension of specimen (mm).

Figure 3-9 Splitting tensile strength setup

3.5.2.3 Flexural strength

Using IS: 516 (1959) standards, the flexural strength of the concrete member has been evaluated (test setup is given in Figure 3-10). The beam mould size of (100 × 100 × 500) cm has been used for the analysis. A tamping bar of taping section (25 × 25) mm, 40 cm long and having a weight of 2 kg. Testing machine bed was supported with two 38 mm in diameter size steel rollers such that the centre to centre distance is 400 mm for 100 mm specimen. The load is applied from the third points of the supporting span which was placed 133 mm from centre to centre. The specimen is loaded among the two loading rollers (Figure 3-11) in such a way that there was only axial loading on the specimen and no torsional restraints were subjected to specimen.

Before the experimentation, the samples were positioned at a temperature of 24°C to 30°C in water bath and were tested immediately when taking them out of water i.e. in the wet condition. After the test, the final dimensions of the specimen were noted. The specimen is applied with shock load such that the load was increased continuously at a rate of 7 kg/cm^2/min which means the specimens were loaded at 180 kg/min. The flexural strength of specimen is a measure of modulus of rupture, f_b, such that if ‘a’ equals the distance between the line of fracture and the nearer support, then f_b can be evaluated as:

$$f_b = \frac{Pa}{bd^2} \, kg/cm^2$$

And when, ‘a’ is greater than 200 mm for 150 mm or greater than 133 mm for 100 mm specimen, then,

$$f_b = \frac{3Pa}{bd^2} \, kg/cm^2$$

Where ‘P’ is maximum load applied, ‘b’ is width, ‘d’ is measured depth at the point of failure and ‘L’ is span length on which specimen was supported.

Figure 3-10 Compression testing machine

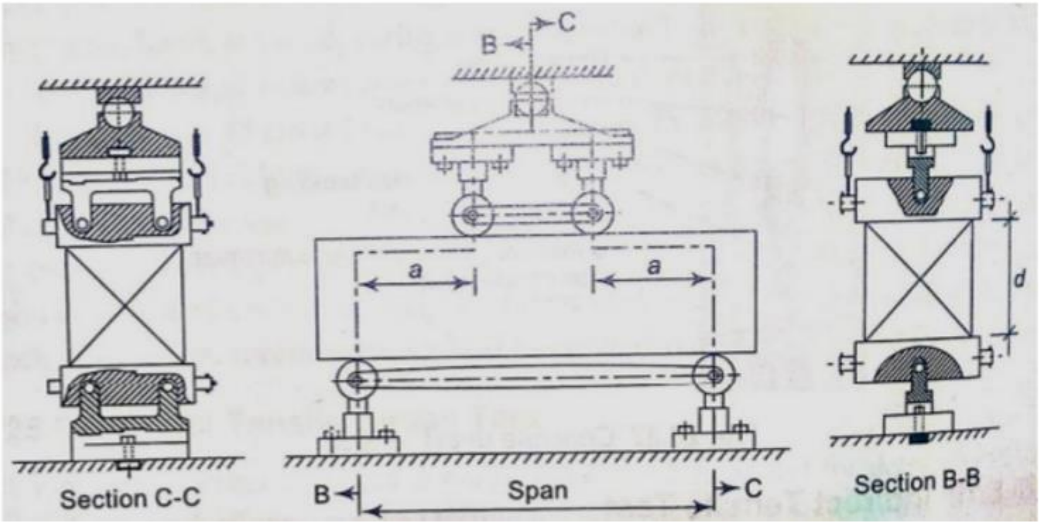


Figure 3-11 Loading arrangement for flexural test

3.5.3 Non-destructive testing of concrete mixtures

3.5.3.1 Ultrasonic Pulse Velocity Test

As per the method given in ASTM C 597-02 [96], the pulse velocity has been determined through the concrete using Portable Ultrasonic Non-destructive battery operated Digital Indicating Tester. An electro acoustical transducer generates longitudinal stress pulses where transducer is held in contact with one face and the signal is received at the other end which is in contact with the other end. Transit time is the time taken by the pulse to pass through the specimen of length (L). Thus, by taking ratio of length of the specimen and transit time, pulse velocity can be calculated. By taking average value of three experiments, the pulse velocity of the concrete mix can be evaluated. Figure 3-12 shows the apparatus of pulse velocity setup and Table 3-5 shows the pulse velocity values for concrete's grading as per BIS 13311-92 (Part-1) [97].

Table 3-4 Concrete Quality Grading

Pulse Velocity (m/s)	**Concrete Quality Grading**
< 3000	Doubtful
3000-3500	Medium
3500-4500	Good
>4500	Excellent

Figure 3-12 Experimental set up for measuring pulse velocity through concrete

3.5.3.2 Rebound Hammer Test

Rebound hammer test evaluates the elastic rebound of the concrete for compressive strength measurements. This test was performed on a cube specimen (150 mm) at 28-day, 90-day and 180-day curing age. A digital Schmidt rebound hammer was used for testing as shown in Figure 3-13. In this technique, the concrete is hit by round hammer with a definite energy 2.2 Nm and the digital meter displays compressive strength value directly. During experimentation, the device is held vertically at right angle and pressed strongly and steadily over the surface of concrete. The testing points are 20 mm apart from each other and total 12 readings were taken to evaluate the mean compressive strength of the concrete as per BIS: 13311 (part 2) guidelines [97]. Also, as per BIS:13311 guidelines, the compressive strength evaluated using rebound hammer method is not very accurate and there will be a ±25% accuracy can be imagined.

Figure 3-13 Rebound hammer testing device

3.5.4 Durability tests for concrete mixtures

3.5.4.1 Rapid Chloride Penetration Test

Durability of concrete is one of the important aspects and a concrete is said to be durable if it performs pleasingly under the harsh conditions as expected during its operations. Durability of concrete is very much affected due to chloride presence and its permeability to access the chloride ion is a serious concern. The presence of chloride ions in the concrete may lead to destructive footprints on concrete wall and reinforcement. Compared to water penetration, swelling in case of chloride ion penetration is about 2 to 2.5 times higher. Therefore, in this electrical conductance of the concrete block is evaluated experimentally which offer rapid clue against the chloride penetration resistance.

Using ASTM C 1202-97 standards, resistance to chloride ion penetration of concrete mixtures was evaluated. The specimens (cylindrical of size 102 mm diameter and 51 mm thickness) were placed in the assembly in such a way that one end of it was exposed to 0.3% sodium hydroxide solution and other end to sodium chloride solution. Thus, chloride penetration has been measured by evaluating the total charge passed through the concrete mix after duration of 6 hours.

Table 3-5 RCPT based on charge passed (ASTM 1202-97)

Charge passed (Coulomb)	Chloride Ion Penetrability
> 4000	High
2000 – 4000	Moderate
1000- 2000	Low
100 – 1000	Very Low
< 100	Negligible

Table 3-6 indicates the standard values which defines chloride penetrability on the basis of chloride ion passed. A voltage difference of 60 V has been maintained among the terminals of specimen out of which one terminal is immersed in NaOH solution and other is immersed in NaCl solution. The charged passed across the concrete is a measure of resistance offered to chloride ion penetration.

Specimens of size (100 mm × 200 mm) were cast and placed in a vacuum desiccator bowl as described in Figure 3-13 and Figure 3-14. A vacuum in bowl is preserved for 3 hours and deaerated water was permitted to flow through the desiccator such that it entirely covers the samples and no air is entered to the system. Further, vacuum is extended for another an hour and samples were left to soak for 18 hours. Then specimens were taken out to make them dry and placed in gasket. Solution of NaCl and NaOH were filled in two cells and a potential difference of 60 V is applied. The working temperature of the voltage cell, specimen, surrounding air and solution at the start of the power supply was maintained between 20^{o}C to 25^{o}C.

Figure 3-14 RCPT setup

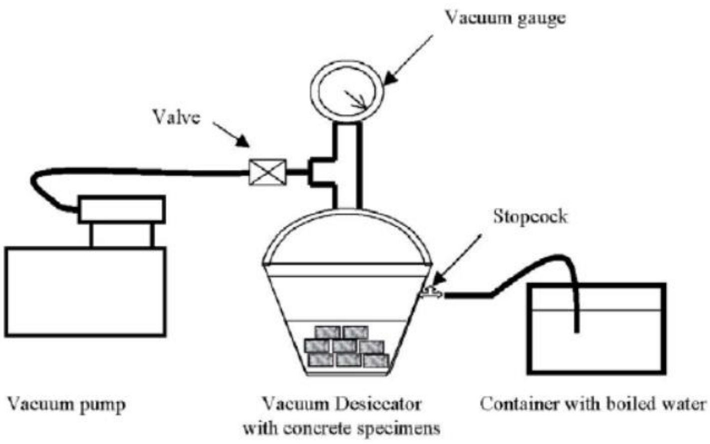


Figure 3-15 Schematic of RCPT setup

3.5.4.2 Initial Surface Absorption Test

For an oven dried concrete, the technique to evaluate the initial surface absorption has been recommended by BIS: 1881: Part 208:1996 [98]. These samples were then cooled at laboratory temperature. It is a measure of rate of flow of water into concrete per unit area it is generally evaluated by testing 150 mm sized cubes under water for 10 minutes, 20 minutes, 30 minutes, 60 minutes and 120 minutes at 28-day, 90-day and 180-day of curing age. Figure 3-16 represents the schematic of the ISAT setup.

During experimentation, a head of 180 mm to 220 mm of water was applied at the concrete surface. The water is allowed to fall on the concrete block surface and readings were recorded at 10 min, 20min, 30min, 60min and 120min. Due to flow of water the moisture level of the concrete block increased which fills the capillary pores adjacent to test area within the concrete block and thus, the rate of surface soaking get reduced with time. Close the water tap after each specified test intervals and allow water to flow back along the capillary tube. Stop watch is started once the meniscus is observed to reach the scale. After each 5 seconds, number of divisions are recorded which have been covered by the meniscus and then time elapsed is evaluated during this process.

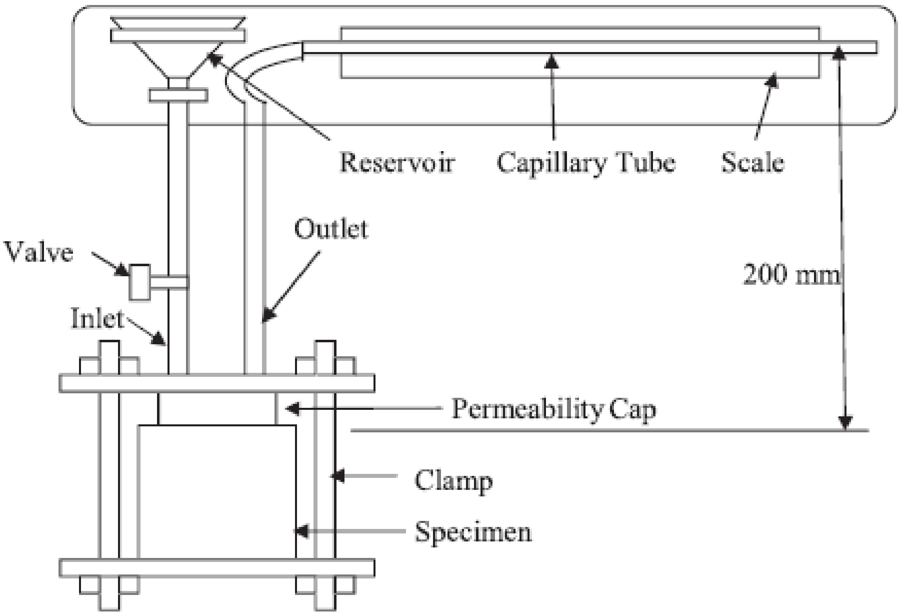


Figure 3-16 Schematic of ISAT setup

Table 3-7 Evaluation of period of movement

Number of scale divisions moved in 5 seconds	Period during which movement is measured
< 3	120 s
3 to 9	60 s
10 to 30	30 s
> 30	Record initial surface absorption as more than 3.60 ml/(m^2.s)
Note one division= 0.01 unit	

3.5.5 Scanning Electron Microscopy (SEM)

Hydrated cement adhesive, aggregate and interfacial interim zone are the main microstructural constituents of concrete. In order to understand the morphology of concrete, SEM plays an imperative role and offers both compositional and topographic analysis of materials. SEM helps in identifying the factors that can affect the durability and concrete's mechanical properties and enhances the capability to describe the microstructure of concrete. Concrete microstructure is cohesive system having calcium hydroxide, CSH gel, calcium sulfoaluminate hydrate (ettringite- needle like crystals with no branching and monosulphate- hexagonal platy crystals), coarse and fine aggregate and interfacial alteration zone among aggregate and cement hydration products. It has been noticed that CSH morphological structure differs from common fibrous to rough grains forming a reticular grid. It has been found that fibrous type of morphological structure is prominent during the early stages of cement hydration however, reticular network also arises intermittently. With the proceeding of cement hydration, equant particle morphology of CSH performs. The other variant of CSH morphology has dimpled appearance having ordered pores or closely packed equant grains.

In order to observe the morphology of the concrete through SEM, the fractured bottom ash concrete pieces were generated through compressive strength test. Then the fractured pieces were kept in SEM stub and using secondary electron (SE) image code, the required images were obtained. In order to enhance the electric conductivity, the fractured pieces of concrete specimens were coated with gold before placing them on SEM stem in secondary electron (SE) mode. SEs are generally low energy beam which comes into picture through inelastic collision of primary beam electron with an electron of a specimen atom. During the analysis, the secondary electron produced in the vicinity of the surface, escape and result in image of surface topography. In order to perform chemical studies of concrete specimen, energy dissipative spectroscopy is used. Figure 3-17 shows the experimental setup of SEM.

Figure 3-17 Experimental set up for Scanning Electron Micrograph

CHAPTER
4 RESULTS AND DISCUSSIONS

In this chapter, characterization of the constituents of concrete mix along with properties of the fresh and hardened controlled concrete mix, coal bottom ash (CBA) concrete mix and Alccofine assisted CBA concrete mix has been studied. Scanning electron microscopy analysis has been done to discover the morphology of CBA and Alccofine particles. The variation among the bottom ash concrete properties has been observed and a strategy of incorporating Alccofine as partial replacement of cement has been developed. A comparison among the properties of CBA concrete and Alccofine assisted CBA concrete has been performed. Further, statistical studies have been performed to develop empirical relationship among varied concrete mixtures and strength properties.

Keywords: *bottom ash concrete, strength properties, Alccofine 1203, pulse velocity, chloride penetration, initial surface absorption test.*

4.1 Introduction

In the present work, material characterization of cement, bottom ash and Alccofine has been executed. Surface morphology analysis for CBA and Alccofine was studied using scanning electron microscopy. To achieve the objectives, research is planned in two phases PHASE- I and PHASE- II. Phase-I inculcate the design of controlled concrete mix. Waste material of thermal power plants i.e. coal bottom ash has been incorporated replacing river sand to preserve the natural resources. The addition of CBA as a fractional change in place of fine aggregates (sand) is done at five different concentrations i.e. 10% (MB1), 20% (MB2), 30% (MB3), 40% (MB4) and 50% (MB5). A well-defined BIS standard codes have been used for the experimental study. Superplasticizers have been incorporated to maintain the water/cement ratio and to achieve 100 mm slump value. Concrete is designed for 100 mm slump value to attain medium to high degree of workability.

Further, the effect of the partial replacement of fine aggregates with bottom ash on workability and strength properties of all the concrete mixes for all the curing ages has been studied and compared with control mix. Moreover, the effect of inclusion of CBA in concrete mix on the superplasticizer dosage has been discussed. Finally, statistical equations have been developed to fit the data using regression curve.

In Phase-II, Alccofine has been added by replacing cement in order to improve the properties of CBA concrete. A detailed study has been performed where effect of Alccofine concentration on the concrete properties has been studied and results are compared with control concrete and CBA concrete mixtures. Further, percentage change in strength properties has been compared with 40% bottom ash concrete mixture. Finally, statistical analysis has been performed where various regression curve fits have been developed to correlate the concrete properties.

The study has been planned to produce high strength concrete with the utilization of waste material with a view point of which M40 grade of concrete mix was considered for the study. The idea behind the selection of the particular grade of concrete was to compensate the negative effect on strength properties of concrete by incorporating Alccofine in order to achieve high strength concrete using waste.

4.2 Materials Characterization

Material characterization has been done for cement, coal bottom ash, coarse aggregates, fine aggregates and Alccofine. The description is given below:

4.2.1 Cement

In this research work, as per BIS: 8112-1989, the ordinary Portland cement is used whose test results are tabulated in Table 4-1.

Table 4-1 Properties of cement

Chemical composition			**Physical properties**		
Composition	**Test result**	**BIS value**	**Property**	**Test result**	**BIS value**
Lime saturation factor (l_{sf})	0.877	$0.66 < l_{sf} < 1.02$	Fineness (m^2/kg)	278.6	>225
Ratio of Alumina and Iron oxide	1.51	> 0.66	Initial setting time (min)	125	>30
Loss on Ignition (%)	1.93	< 5.0	Final setting time (min)	175	<600
Total Sulphur content (SO_3) (%)	2.10	< 2.5	Compressive strength (N/mm^2)		
Magnesia (%)	0.97	< 6.0	3 days	32.0	>23
Insoluble residue (%)	1.85	< 2.0	7 days	40.3	>33
Alkalies (K_2O) (%)	0.4	< 0.6	28 days	51.5	>43
Na_2O (%)	0.10	< 0.6	Consistency (%)	28	
Total chloride content (%)	0.02	< 0.05			

4.2.2 Coal Bottom Ash

Coal bottom ash is collected from Guru Gobind Singh Super Thermal Power Plant, Ropar, Punjab. A sieve of mesh size 4.75 mm has been used while sieving the coal bottom ash and sand in order to obsolete the coarser particles than 4.75 mm before use in concrete. Table 4-2 representing the chemical composition of CBA. Energy Dispersive Spectrometer (EDS) has been used to perform the chemical analysis of CBA. Samples were tested and it has been found that CBA is majorly composed of silica, alumina and iron with minute concentrations of magnesium, calcium, sulphate etc. When measured with Pycnometer method, the specific gravity of CBA was 1.71.

Particle size distribution of natural sand and coal bottom ash is given in Figure 4-1. From the curve, it can be observed that CBA has finer particle size compared to natural sand for all sieve sizes.

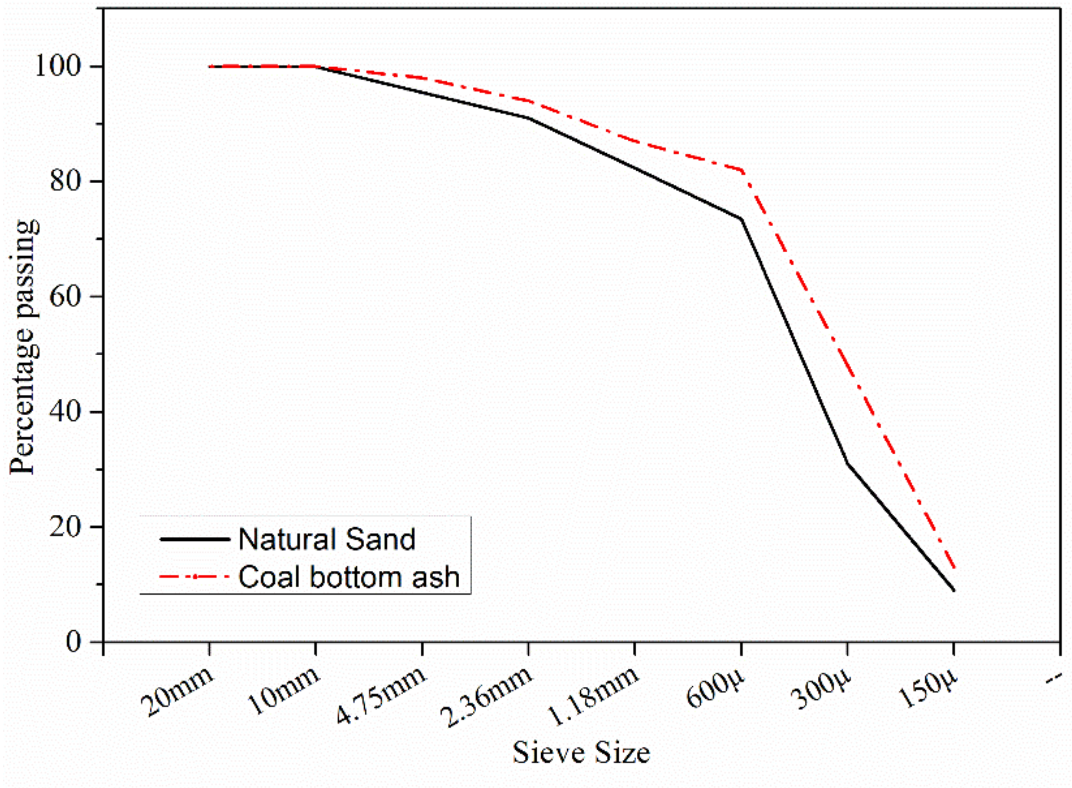


Figure 4-1 Particle size distribution of natural sand and coal bottom ash

4.2.3 Alccofine

Alccofine 1203 is a manufactured new generation cementitious material that can be used in order to partly replace cement. It is an ultra-fine slag material hence does not increase water demand thus has a capability to control superplasticizer usage. Also, it can be seen from Figure 4-2 that Alccofine has much finer particle size for all sieve sizes compared to OPC. Table 4-2 representing the chemical composition of Alccofine.

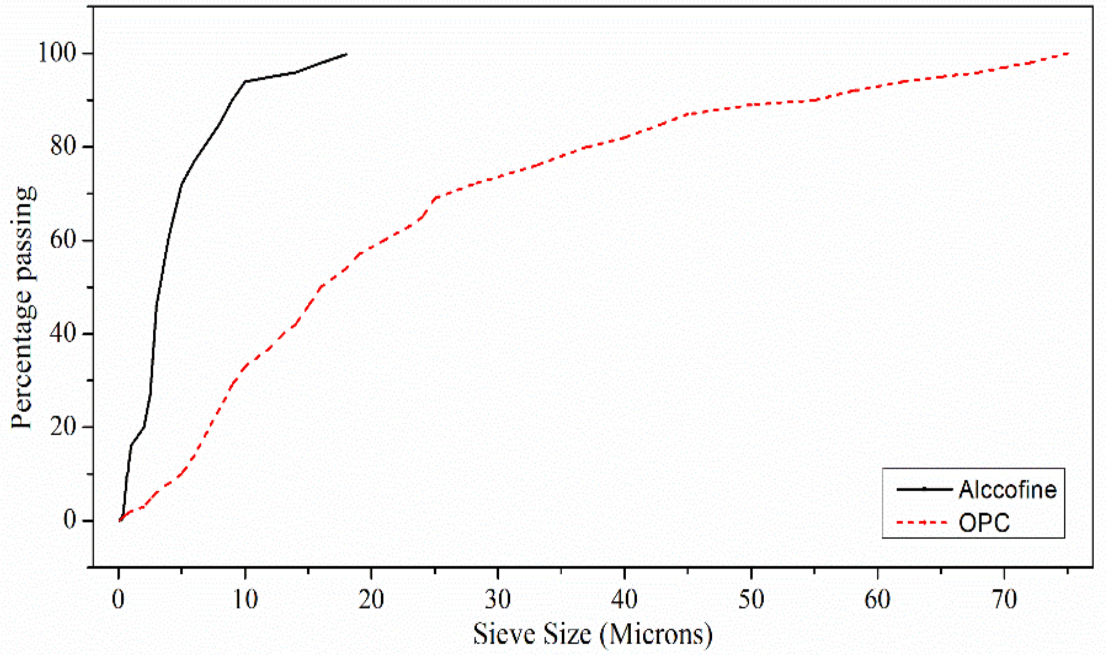


Figure 4-2 Particle size distribution of OPC and Alccofine 1203

Table 4-2 Properties of bottom ash and Alccofine

Chemical properties (%)			**Physical properties of Alccofine** [99]	
Composition	**Bottom Ash**	**Alccofine**	**Property**	**Value**
SiO_2	35.13	35.05	d10	1.8 µm
Al_2O_3	25.63	24.34	d50	4.4 µm
MgO	0.54	9.66	d90	8.9 µm
CaO	0.46	28.86	Bulk density	680 kg/m^3
Fe_2O_3	7.92	-	Specific gravity	2.70
K_2O	0.58	1.97	Sp. Surface area	1200 (m^2/kg)

4.2.4 Surface morphology

The morphology can be visualized from Figure 4-3 and it can be observed from Figure 4-3 (a) and (b) that CBA has irregular shaped and rough textured morphology whereas Alccofine is an ultra-fine slag material and has well round-shaped structure Figure 4-3 (c) and (d). This implies that coal bottom ash molecules have interlocking properties as it has angular shaped particles, hence workability is decreased. On the contrary, flow-ability improved on integration of Alccofine particles due to its rounded nature, leading to very minimal inter-particle friction. Due to its ultrafine nature, pozzolanic reactions are excellent leading to dense and compact formation.

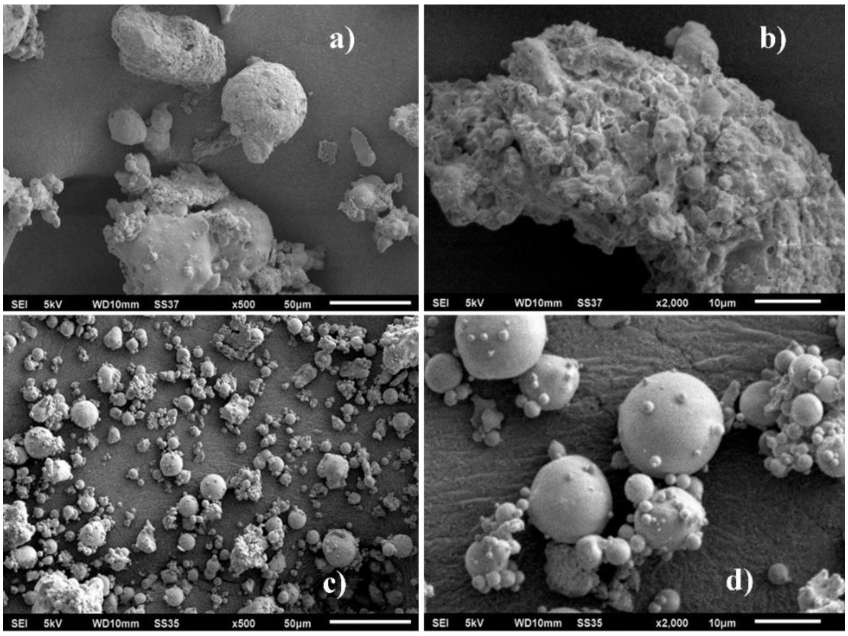


Figure 4-3 Morphology of CBA and Alccofine particles at 500 and 2000 magnification

4.3 Properties of fresh and hardened concrete (Phase-I)

In Phase-I, a controlled concrete mix was designed having the 28-days compressive strength of 47.92 N/mm^2. CBA has been used as a fractional change from 10%-50% in place of natural sand. The effect of CBA integration on the workability, strength and durability properties has been examined. Different mixtures were prepared containing 10%, 20%, 30%, 40% and 50% bottom ash as fractional change in place of fine aggregate. To maintain the water/cement ratio constant, superplasticizers have been incorporated in the concrete mixture as they have capabilities to reduce the water consumption.

4.3.1 Mix Proportions

In the Phase-I studies, the control mix has been prepared as per BIS: 10262-1982 standards [95]. River sand used in preparing the base mix (MBO) was restrained to grading of zone-II as directed in BIS: 383-1960 [100]. This control mix has been labelled as MB0 in the present work. CBA has been acquired from thermal power plant situated in Ropar, Punjab, India. Coal bottom ash is used as a partial replacement of river sand and a concentration of river sand 10% (MB1), 20% (MB2), 30% (MB3), 40% (MB4) and 50% (MB5) has been replaced by CBA. Both CBA and natural sand were dried in an oven at 100^{o}C for 24 ±1 hr, and then cooled to room temperature for a same time period to remove moisture before use in preparing concrete mix. As CBA has lesser water retention capacity, it has been collected in wet-state and then was dried in an oven to avoid outflow of water absorbed. Moreover, the water absorption affinity of CBA cannot be measured in actual practice during mixing process. In the present study, a fixed amount of water is used in all concrete mixtures. Table 4-3 represents the mix proportions for control and bottom ash concrete.

Table 4-3 Detail of Mix Containing Bottom Ash as a Partial Replacement of Fine Aggregates

Mix Designation	**Bottom Ash %**	**Cement (kg/m^3)**	**Coarse Aggregate (kg/m^3)**	**Fine Aggregates (kg/m^3)**	**Bottom Ash (kg/m^3)**	**Water (kg/m^3)**
MB0	0	415	1092.61	782.27	0	157.73
MB1	10	415	1092.61	704.043	78.227	157.73
MB2	20	415	1092.61	625.816	156.454	157.73
MB3	30	415	1092.61	547.589	234.681	157.73
MB4	40	415	1092.61	469.362	312.908	157.73
MB5	50	415	1092.61	391.135	391.135	157.73

Note: For all the mixtures during casting and testing, 100 mm slump value was achieved by adding required dosage of super plasticizer. Water/cement ratio is 0.38

4.3.2 Properties of fresh concrete

4.3.2.1 Workability of the different mixtures

Workability is a property of fresh concrete that measures the ease and homogeneity of the mix with which concrete can be assorted, positioned, trampled and finished. It is a measure of energy counts to astounded surface friction and source complete amalgamation. Ease defines the stability, mobility and compactability and is a measure of rheological aspects of concrete. The performance of fresh concrete can be evaluated using two critical parameters; consistency and homogeneity. Consistency can be measured through slump test and for homogeneity evaluation, there is no such standardized testing method available.

Slump Test

Slump values were recorded for each mix with fix amount of water content. The water content for all the mixes was kept 157.73 kg/m^3. Various trials were performed on each mix with different dosage of super plasticizer to achieve 100 mm slump value. Superplasticizer was added as percentage of weight of cement. The volume of concrete taken for the slump test was 0.010 m^3. Table 4-4 shows the variation of slump value with different superplasticizer dosage (in %age by weight of cement) for various coal bottom ash concrete mixes (Phase – I). It has been noticed that with the inclusion of CBA, the workability of the concrete mix is decreased. Chun et al. (2008) [101], Andrade et al. (2009) [85] and Siddique (2015) [102] also noticed the reduction in slump on addition of CBA as partial replacement of fine aggregates. However, Bai et al (2005) [38] found that there is an increase in slump when CBA added as partial replacement of river sand at fixed w/c ratio. Authors concluded that due to the presence of finer particles (40% of particles are < 150 µm), the overall slump values have been increased.

It can be observed that for controlled concrete mix (MB0), 1.2% dose of superplasticizer is required to achieve a slump value of 100 mm. Further, with the addition of CBA in concrete resulted in increase in the superplasticizer dosage as follows; for MB1 (10% CBA) the dose is 1.2%, 1.6% for MB2 (20% CBA), 2.2% for MB3 (30% CBA), around 2.5% for MB4 (40% CBA) and 3% for MB5 (50% CBA). It was discovered that for MB5 mix, the required dosage of superplasticizer increased to 3% to attain the desired slump value of 100 mm (Dosage range of 500 gm to 1500gm per 100kg of cementitious material is normally recommended. Because of variations in concrete materials, job site conditions, and/or applications, dosages outside of the recommended range may be required- see Appendix for more details). Aim of the investigation was to replace maximum percentage of fine aggregate in such a way that adverse impacts of inclusion of CBA, on fresh and hardened properties of bottom ash concrete mixtures, are compensated by inclusion of Alccofine as a partial replacement of cement and at the same time, required dosage of superplasticizer is also restricted to 2% which we will discuss in Phase-II studies. Table 4-4 represents the percentage superplasticizer used to achieve 100 mm slump for bottom ash concrete at fixed water/cement ratio (0.38). Figure 4-4 describes the dosage of superplasticizer required to achieve 100 mm slump for control and bottom ash concrete mixtures.

Table 4-4 Variation of Slump Value with the Different Dosage of Super Plasticizer in Different Concrete Mix

	SLUMP (mm)					
Mix → **Dosage of superplasticizer ↓**	**MB0**	**MB1**	**MB2**	**MB3**	**MB4**	**MB5**
0%	0	0	0	0	0	0
0.6%	30	25	15	0	0	0
0.8%	50	50	30	15	0	0
1%	80	70	55	25	10	0
1.2%	105	100	80	40	25	10
1.4%	-	-	90	50	30	25
1.6%	-	-	115	60	40	35
1.8%	-	-	-	65	45	40
2%	-	-	-	85	60	55
2.2%	-	-	-	100	70	65
2.4%	-	-	-	-	85	80
2.6%	-	-	-	-	110	85
2.8%	-	-	-	-	-	95
3%	-	-	-	-	-	105

Note: - Dosage of plasticizer in %age by weight of cement

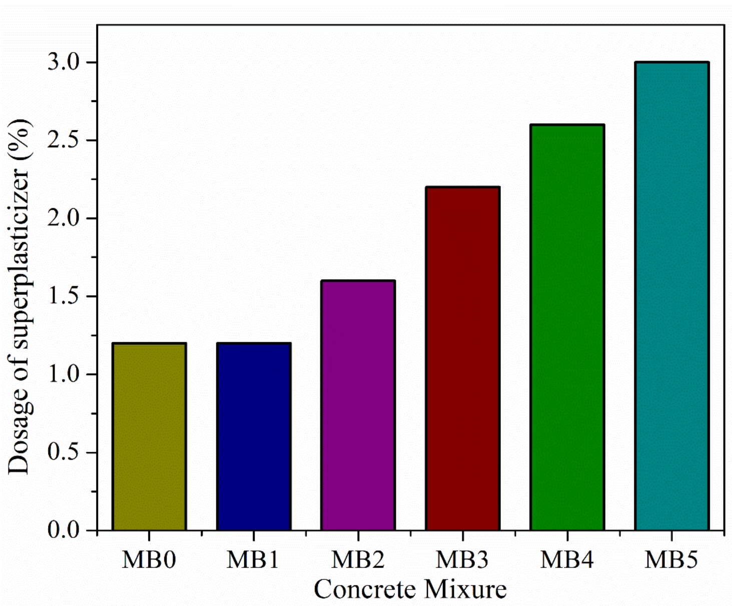


Figure 4-4 Required dosage of super plasticizer in percentage by weight of cement to achieve 100 mm slump value

4.3.3 *Strength properties of hardened concrete*

In Phase-I, the consequence of CBA addition as a fractional change of fine aggregates on the characteristics of concrete has been studied. The variation in compressive, splitting tensile, flexural strength, durability parameters and judgement of concrete's quality via Non- Destructive Testing techniques has been examined in this section.

4.3.3.1 *Compressive Strength*

Table 4-5 represents the test results for compressive strength of CBA concrete at various concentrations of ash percentages varying from 0% to 50%. Based upon the experimental work, it has been evaluated and concluded that a fall in compressive strength values were drawn with raise in the replacement level of fine aggregate with CBA at all ages. Strength dipped drastically after 30% fractional replacement and maximum drip was seen on 50% fractional change of CBA in place of natural sand. Figure 4-5 indicates the strength variations of concrete mixtures at different curing ages for all the concentrations of sand replacement. It was drawn that strength of MB0 specimen is highest at all ages and with the inclusion of CBA, the strength has decreased to a significant level and the lowest strength is found at 50% replacement of fine aggregates.

Table 4-5 Compressive strength of bottom ash concrete mixtures

Curing Age	**Compressive strength (N/mm^2)**					
	MB0	**MB1**	**MB2**	**MB3**	**MB4**	**MB5**
7 days	33.67	32.94	31.36	30.54	26.92	24.78
28 days	47.92	47.45	46.52	45.92	39.59	38.28
56 days	49.78	49.01	48.83	47.98	43.6	41.29
90 days	51.99	51.02	50.69	48.02	44.81	43.86
180 days	54.58	54.12	53.78	53.07	48.07	46.13

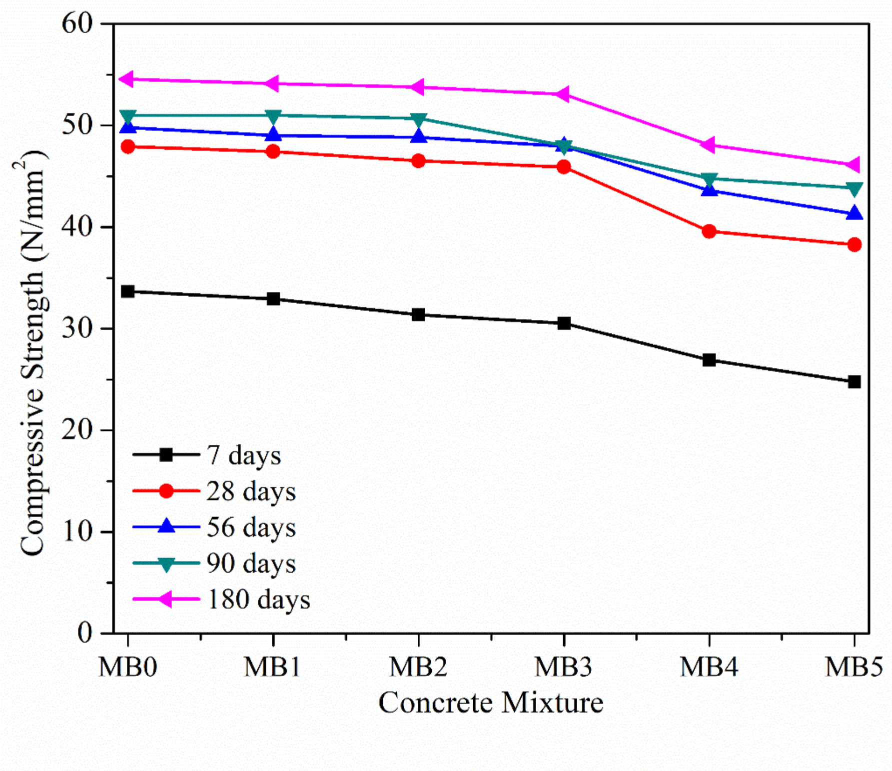


Figure 4-5 Compressive Strength test results for mixtures containing bottom ash as a partial replacement of fine aggregates

Figure 4-6 describes the variation of compressive strength w.r.t. curing age and it can clearly be noticed that with the addition of CBA, compressive strength has decreased for all the curing ages. However, the percentage change may vary w.r.t. both CBA content and curing ages.

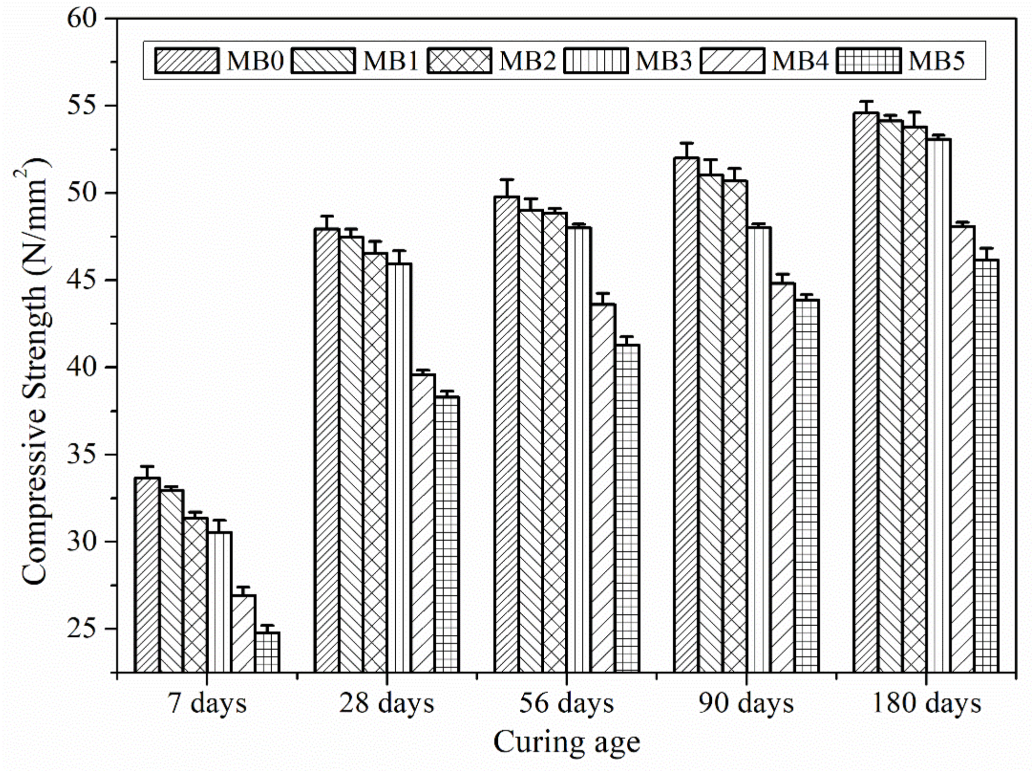


Figure 4-6 Effect of coal bottom ash on the compressive strength of concrete

With the addition of CBA in the concrete mix, the compressive strength of CBA drops gradually up to 30% on fractional change of fine aggregate with CBA for all the curing ages. There is sudden drop can be seen in compressive strength (Figure 4-6) between 30% and 40% change of fine aggregates with CBA for all curing ages. These test results for concrete mix design are comparable with the Siddique et al. [103], Kim and Lee, 2011 [50]; Chun et al. 2008 [101] as in both studies, authors have found decrease in compressive strength for mix design. This may be explained keeping in view the following reasons: 1) increased porosity of CBA mixtures, 2) lower strength of CBA (low specific gravity), 3) deficiency of pozzolanic motion by CBA.

4.3.3.2 Splitting tensile strength

Table 4-6 represents the test results for splitting tensile strength of control and CBA concrete at various concentrations of ash varying from 0% to 50%. On conduction of the analysis, it was effortlessly drawn that with the infusion of CBA, the splitting tensile strength of the concrete is decreased for all curing ages. The same variation can better be understood from Figure 4-7 and Figure 4-8. Due to the scarcity of pozzolanic activities among CBA concrete specimens, the quality of paste was not found to appropriate as a result of which splitting tensile strength found to decrease with CBA concentrations in concrete mix for all curing ages.

Table 4-6 Split Tensile Strength Test Results for Different Concrete Mixtures

Curing Age	Splitting tensile strength (N/mm^2)					
	MB0	**MB1**	**MB2**	**MB3**	**MB4**	**MB5**
7 days	3.28	3.17	3.08	2.99	2.87	2.79
28 days	3.95	3.83	3.67	3.44	3.25	3.22
56 days	4.51	4.36	4.26	3.81	3.53	3.44
90 days	4.74	4.63	4.28	4.09	3.67	3.6
180 days	4.92	4.81	4.68	4.31	3.98	3.86

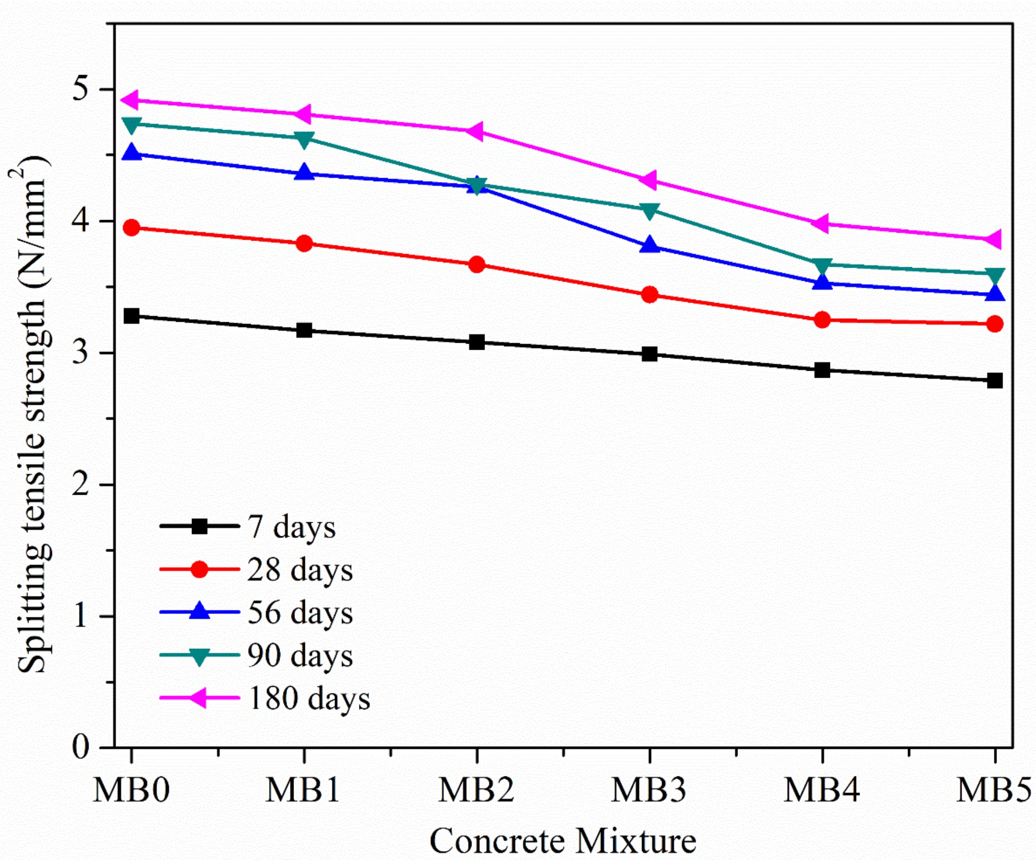


Figure 4-7 Split tensile Strength test results for mix containing bottom ash as a partial replacement of fine aggregates

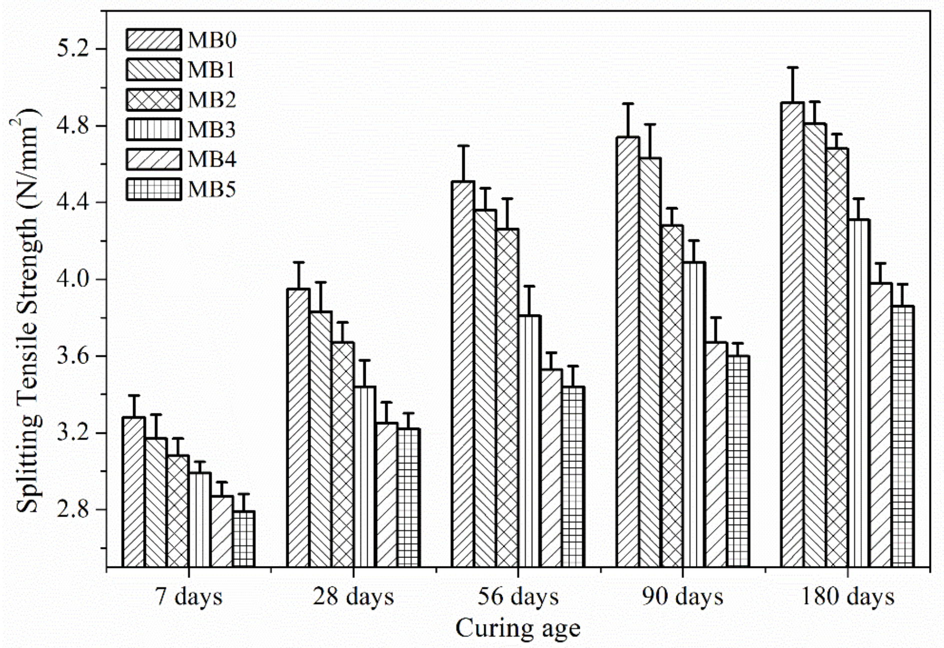


Figure 4-8 Effect of coal bottom ash on the splitting tensile strength of concrete

4.3.3.3 Flexural strength

Figure 4-9 represents the test results for flexural strength of the control and bottom ash concrete for all curing ages. On conduction of the analysis, it was smoothly drawn that with the addition of CBA, the flexural strength of the concrete is decreased for all curing ages (Table 4-7). Figure 4-9 and Figure 4-10 describes the variation in flexural strength w.r.t. bottom ash concentrations and curing age respectively. The variation in flexural strength is considered to be significant at all ages.

Table 4-7 Flexural Strength Test Results for Different Concrete Mixtures

Curing Age	**Flexural strength (N/mm^2)**					
	MB0	**MB1**	**MB2**	**MB3**	**MB4**	**MB5**
7 days	3.9	3.83	3.49	3.37	3.15	3.1
28 days	4.81	4.74	4.58	4.33	4.12	4.1
56 days	5.43	5.31	5.1	4.85	4.58	4.57
90 days	5.92	5.8	5.49	5.18	4.94	4.76
180 days	5.98	5.94	5.72	5.35	5.08	4.85

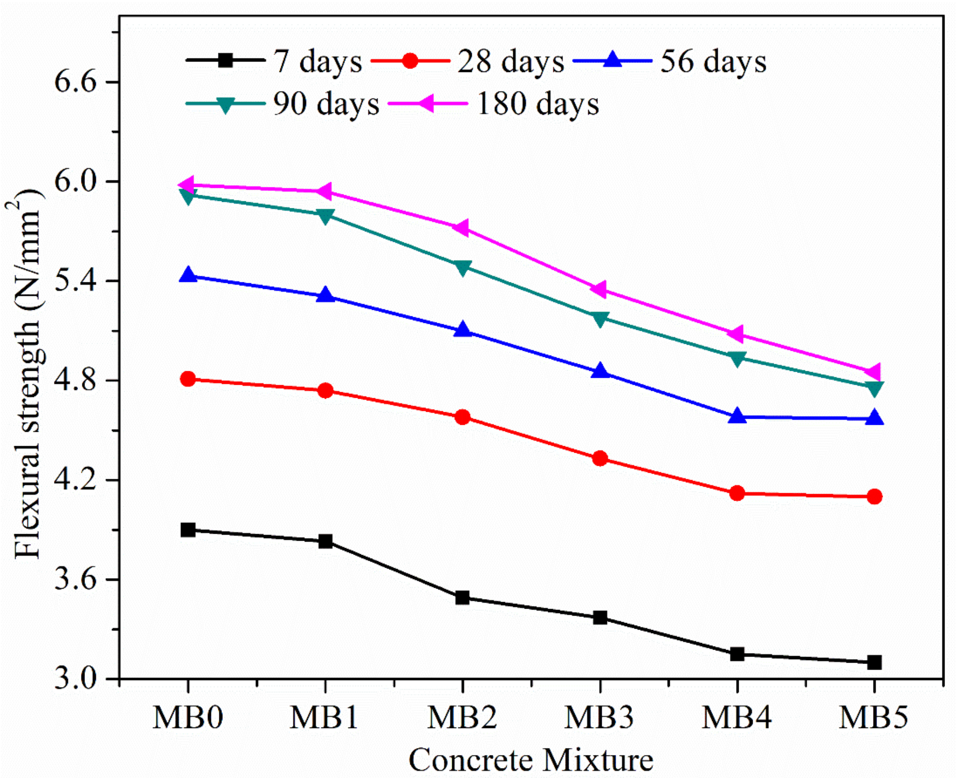


Figure 4-9 Flexural Strength test results for mixtures containing bottom ash as a partial replacement of fine aggregates

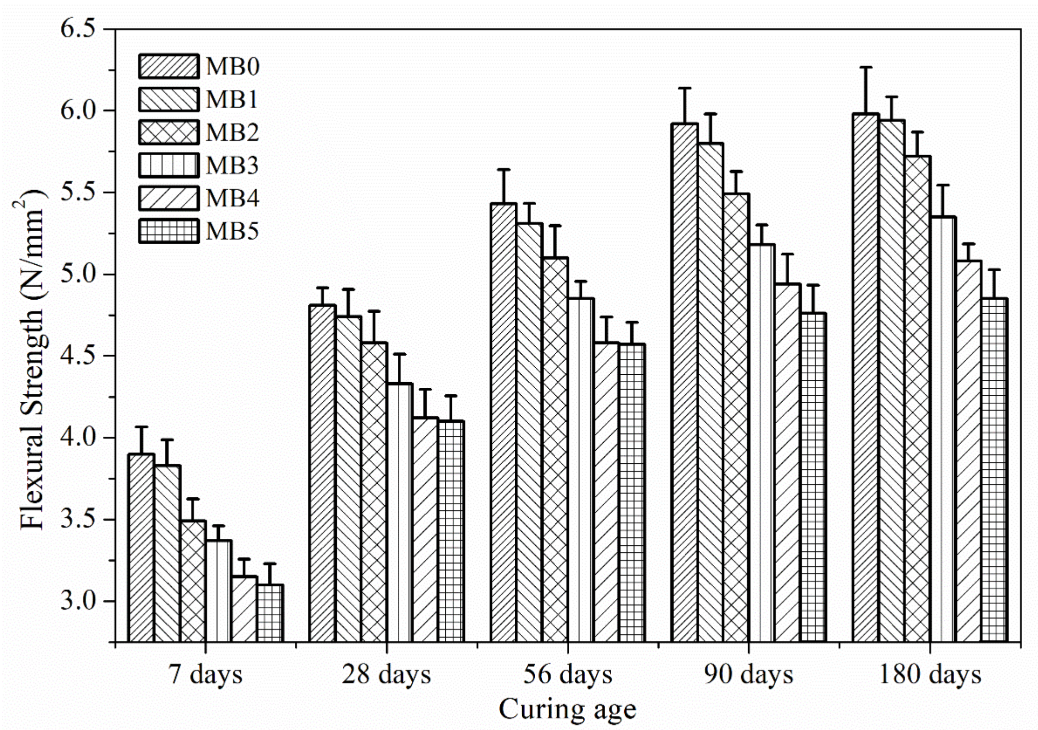


Figure 4-10 Effect of coal bottom ash on the flexural strength of the concrete

4.3.4 Change in hardened properties of bottom ash concrete

In this section, the percentage change in the strength properties of the concrete after the addition of CBA as a fractional change in place of fine aggregates has been evaluated. Percentage change in compressive strength of the CBA concrete in contrast to control concrete can be found Figure 4-11. It can clearly be observed that for all CBA concentrations, the compressive strength has decreased and the percentage change is significant at 7-day of curing age for MB1 (≈2.2%), MB2 (≈7%) and MB3 (≈9%) concrete mixtures. However, the percentage change is moderate at 28-day, 56-day, 90-day and 180-day of curing age. Moreover, it can be noticed that the change is very large for MB4 (maximum change of 20% at 7-day) and MB5 (maximum change of 27% at 7-day) concrete mixtures. Also, it can be seen from Figure 4-12 that the percentage drop in splitting tensile strength is significant for all the mixtures at all ages. The maximum decrease is experienced for MB5 (≈24% at 90-day curing age) where 50% of fine aggregates have been replaced with CBA. Figure 4-13 represents the percentage drop in flexural strength of the bottom ash mixtures w.r.t. MB0 i.e. control mix. It can be noticed that flexural strength of concrete mixtures has experienced a significant drop at all ages. The maximum drop can be observed for MB5 and minimum for MB1. Thus, it concluded that with the inclusion of more and more CBA, the percentage drop of flexural strength has increased abruptly. However, the trend is different for different concrete mixture at all ages.

Also, the objective of this study is to replace maximum possible fine aggregates with waste material, at the same time, required dosage of superplasticizer should have restricted to 2%.

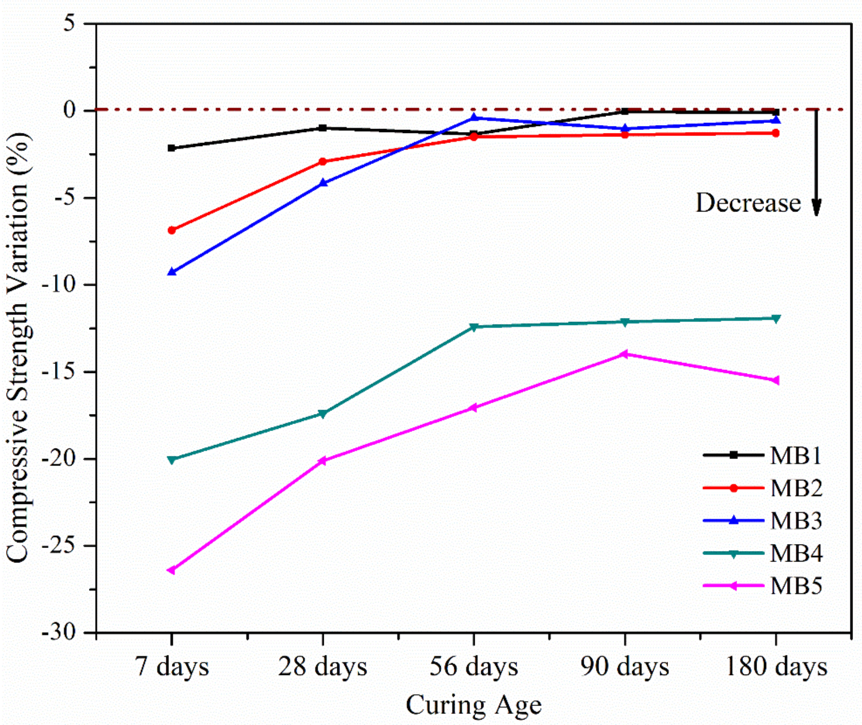


Figure 4-11 Percentage change in compressive strength of bottom ash concrete mixtures w.r.t. MB0

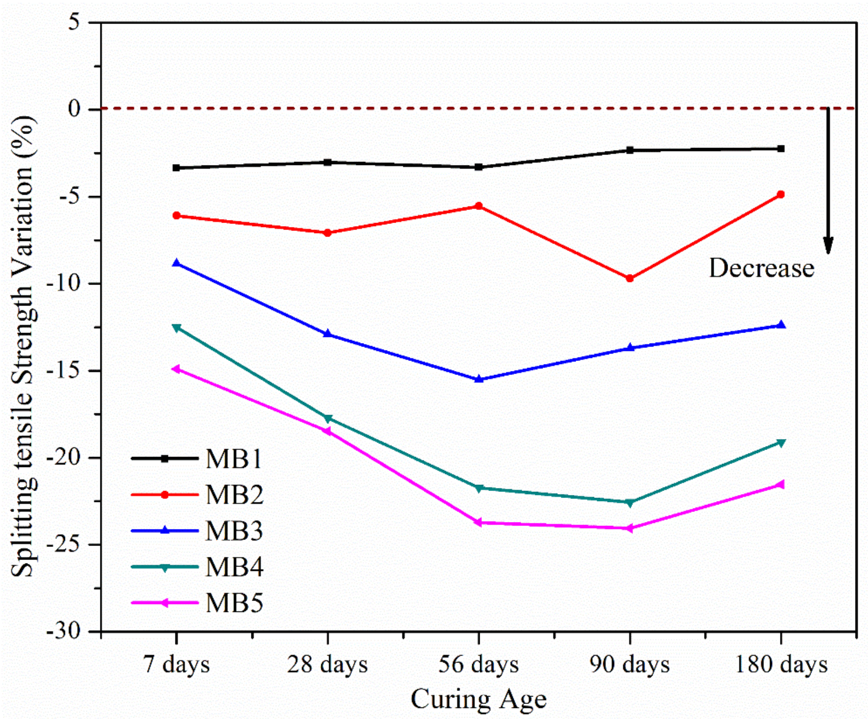


Figure 4-12 Percentage change in splitting tensile strength of bottom ash concrete mixtures w.r.t. MB0

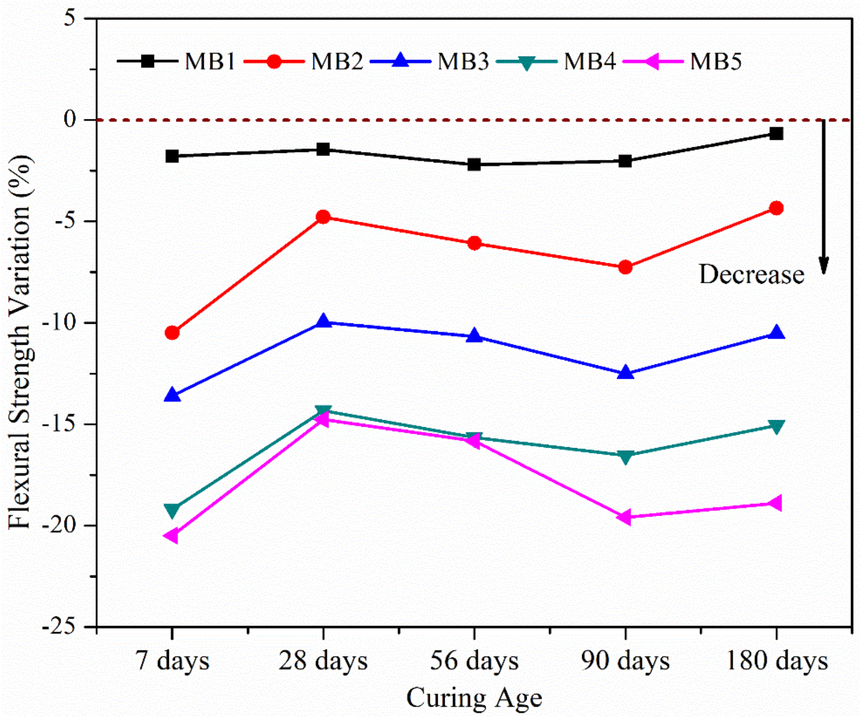


Figure 4-13 Percentage change in flexural strength of bottom ash concrete mixtures w.r.t. MB0

4.3.5 Selection of bottom ash concrete mix

In Phase-I studies, it has been determined that with the addition of CBA as fractional change in place of fine aggregates, the strength properties i.e. compressive, splitting tensile and flexural strength of the concrete drops significantly for all CBA mixtures. As the aim of the investigation was to replace maximum amount of fine aggregate in such a way that adverse impacts due to the addition of CBA, on fresh and hardened properties of bottom ash concrete mixtures, can be compensated by incorporating ultra-slag material i.e. Alccofine to be used as a fractional change in place of cement and at the same time, required dosage of superplasticizer should also restrict to 2%. To achieve the objective, Slump tests were carried out initially on combination of MB5 mix and partial replacement of 5%, 10%, 15% and 20% of cement with Alccofine. It was found that best result (maximum reduction in dosage of superplasticizer) was obtained at 15% replacement level having the Glenium dosage percentage of 2.4 % (for 100 mm slump value) and that too was on a higher side which is not acceptable. Hence, MB4 mix was selected for further investigation as for this mix superplasticizer dose restricted to 1.9%. A detailed discussion will be presented in Phase-II studies.

To examine the impact of coal bottom ash addition in the concrete mixture, further, non-destructive and durability tests have been performed where properties of MB4 mix is compared with MB0. It has been found that 40% replacement of fine aggregates with coal bottom ash has significantly affected the durability properties and non-destructive tests have revealed that the quality of the concrete has decreased for MB4 concrete mix.

4.3.6 Non-destructive testing

4.3.6.1 Pulse velocity

Table 4-8 describes the pulse velocity variation for control and MB4 concrete mix. It can be well noticed from the results that pulse velocity has decreased for MB4 mix when equated with control mix (MB0). It was well recognized that the pulse velocity grading has decreased from excellent (>4500) to good (<4500) after the addition of CBA in the control mix for 28-day and 90-day of curing age.

Table 4-8 Pulse velocity calculations for bottom ash concrete

Mix	**Ultrasonic pulse velocity (m/s)**			**Standard value as per IS: 13311-92 Part-I (m/s)**	**Concrete grading**
	28	**90**	**180**		
MB0	4564	4692	4810	<3000	Doubtful
MB4	4286	4419	4544	3000-3500	Medium
				3500-4500	Good
				>4500	Excellent

Ultimately, the investigation took a clear path in establishing that CBA inclusion in concrete, as a fractional change of fine aggregates, has affected the fresh and hardened concrete stages significantly. The strength of concrete mix has degraded at all levels of CBA addition. Therefore, to achieve maximum replacement of fine aggregates with industrial waste material, further an attempt has been made where ultra-fine slag material Alccofine has been incorporated to examine its effects on the properties and durability of the concrete.

4.3.6.2 Rebound hammer testing results

In Phase-I, the rebound hammer test is conducted to predict the compressive strength of control (MB0) and 40% bottom ash (MB40) concrete. As per BIS:13311 (part-2) standards, the error in predicting compressive strength in concrete structure is about ±25%. Table 4-9 describes the rebound hammer test results and it can be noticed that

11.5% error is found in control mix's (MB0) compressive strength (42.4 MPa) at 28-day curing age when compared with the destructive compressive strength test results (47.92 MPa). Similarly, an error of 9% and 7% is found for MB0, at 90-day and 180-day of curing age, among destructive and non-destructive compressive strength results. However, for MB4 bottom ash concrete, the error among destructive and non-destructive compressive strength results is approximately 9% at all ages.

Table 4-9 Rebound hammer test results (Phase-I)

Mix designation	**Compressive strength (N/mm^2)**		
	28-days	**90-days**	**180-days**
MB0	42.4	47.3	50.7
MB4	36.1	40.8	43.6

4.3.7 Durability properties of concrete

Durability of concrete is equally important as that of strength properties. Thus, in the present study, effect of CBA addition on the durability of concrete structure has been examined through chloride penetration test. While using any replacement of fine aggregates/cement, there is a need to verify the effect of such materials on the reinforced concrete structures. Resistance to chloride-ion penetration is one of such tests used to ensure the durability of the concrete structure. In the present study, an investigation has been carried out to check the ability of the bottom ash concrete in concluding the service life of steel reinforced concrete structures especially in marine engineering.

4.3.7.1 Chloride penetration

From the test results tabulated in Table 4-10, it has been observed that with the replacement of fine aggregates with CBA, the RCPT values are increased ($RCPT_{MB4}$>$RCPT_{MB0}$). This implies that the resistance to chloride-ion penetration has decreased that can affect the reinforced concrete structures.

Thus, we can conclude that addition of CBA has negative impacts on the concrete properties and durability.

Table 4-10 RCPT test results for bottom ash concrete

Concrete Mixture	Chloride penetration		
	28-days	**90-days**	**180-days**
MB0	1922	1633	1396
MB4	2292	1912	1483

4.3.7.2 Initial Surface Absorption

Table 4-11 describes the ISAT test results for MB0 and MB4 bottom ash concrete mixtures. It can be observed that the water absorption capacity has decreased with curing age and time for both MB0 and MB4 mix. Reason behind the same may be credited to the fact that the water length of capillaries has raised thus making the sample saturated. However, the water absorption capacity of MB4 bottom ash concrete mixture is more than MB0. This is may be due to the fact that with the addition of coarse CBA material to be used in place of fine aggregate, the overall voids among the structure has increased which has more capacity to soak the water. Figure 4-14 and Figure 4-15 shows the test results for MB0 and MB4 bottom ash concrete, respectively.

Table 4-11 ISAT test results (Phase-I)

ISAT [ml / (m^2 x sec)]				
Time	**Mix designation**	**28-days**	**90-days**	**180-days**
10 minutes	MB0	0.97	0.78	0.64
	MB4	1.43	1.35	1.26
20 minutes	MB0	0.82	0.66	0.57
	MB4	1.32	1.25	1.18
30 minutes	MB0	0.73	0.55	0.49
	MB4	1.28	1.16	1.07
60 minutes	MB0	0.69	0.48	0.4
	MB4	1.19	1.08	1
120 minutes	MB0	0.68	0.46	0.39
	MB4	1.14	1.07	0.99

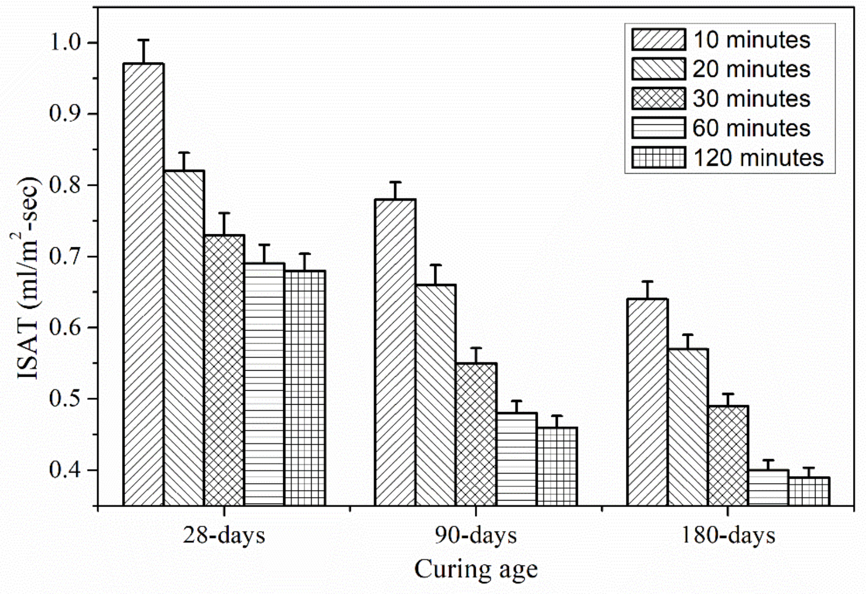


Figure 4-14 ISAT test results variation w.r.t. curing age for MB0 concrete mix

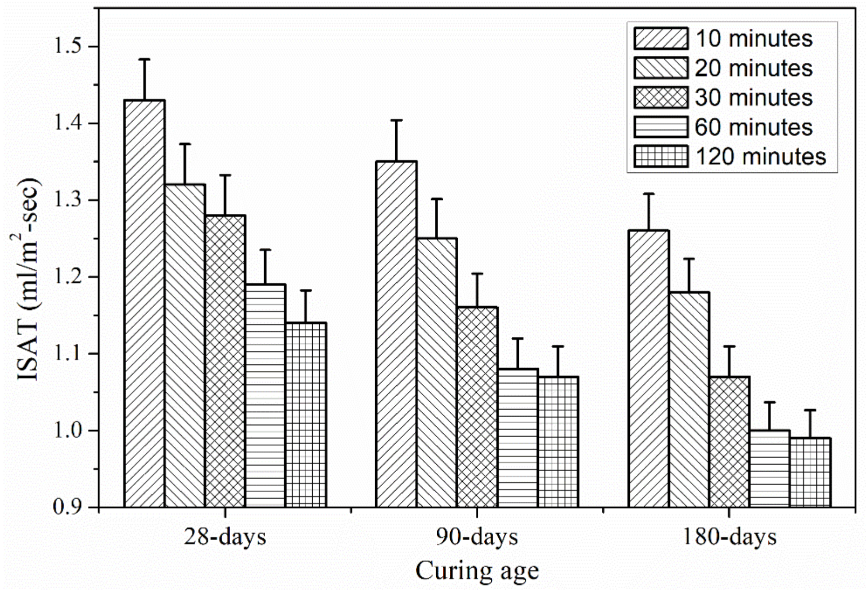


Figure 4-15 ISAT test results variation w.r.t. curing age for MB4 concrete mix

4.4 Properties of Alccofine assisted fresh and hardened bottom ash concrete (Phase-II)

In the Phase-II, Alccofine was mixed in MB4 concrete mix in varying percentage (5%, 10%, 15% and 20%) as a partial replacement of cement, to obtain the preeminent results leading to the improvement of workability and reduction in usage of superplasticizer along with improved mechanical properties and durability characteristics in comparison to CBA mix.

4.4.1 Mix proportions

In Phase-II studies, Alccofine has been added to the bottom ash concrete as a partial replacement of cement. The various mix proportions have been tabulated in Table 4-12. Water/cement ratio used in Phase-II studies is same as that of Phase-I.

4.4.2 Properties of fresh concrete

4.4.2.1 Workability of the different mixtures

Slump test has been performed after the addition of 5% to 20% Alccofine to the concrete mixture. To achieve 100 mm slump, it can be noticed that the amount of superplasticizer required has decreased with the inclusion of Alccofine. From Table 4-13, it can be seen that for control mix MB0, the superplasticizer dose limited to 1.2% to achieve 100 mm slump. However, for MB4 mix, this amount is approximately 2.6%. When Alccofine has been added to the bottom ash concrete, it can be noticed that 100 mm slump has been achieved at 2.4% for MB4A5, for MB4A10, the amount of superplasticizer required is 2.2% and for MB4A15 and MB4A20, the amount of dosage of superplasticizer restricted to 2%. Thus, MB4A15 and MB4A20, both have achieved the 100 mm slump at or below 2% dosage of superplasticizer. Due to the presence of high glass content, the requirement of water to achieve specific slump value decreases, thus resulting in reduction of dosage of superplasticizer.

4.4.3 Strength properties of hardened concrete

In Phase-II, an attempt has been made in order to recover the bottom ash concrete properties through partial replacement of cement with ultra-fine slag material i.e. Alccofine 1203. The properties of Alccofine assisted 40% bottom ash concrete (MB4) has been studied and examined for various concentrations of Alccofine varying from 5% to 20%.

Table 4-12 Mix proportions of various concrete mixes

Mix Designation	Alccofine %	Bottom Ash %	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregates (kg/m^3)	Alccofine (kg/m^3)	Bottom Ash (kg/m^3)	Water Content (Kg/m^3)	Water/ Cement ratio	Dosage of super plasticizer to achieve 100 mm slump value
MB0	0	0	415	1092.61	782.27	0	0	157.73	0.38	1.2
MB4	0	40	415	1092.61	469.362	0	312.908	157.73	0.38	2.5
MB4A5	5	40	394.25	1092.61	469.362	20.75	312.908	157.73	0.38	2.4
MB4A10	10	40	373.5	1092.61	469.362	41.5	312.908	157.73	0.38	2.1
MB4A15	15	40	352.75	1092.61	469.362	62.25	312.908	157.73	0.38	1.9
MB4A20	20	40	332	1092.61	469.362	83	312.908	157.73	0.38	2

Note: For all the mixtures during casting and testing, 100 mm slump value was achieved by adding required dosage of super plasticizer

Table 4-13 Variation of Slump Value with the Different Dosage of Super Plasticizer in Different Concrete Mix

Dosage of super plasticizer ↓	SLUMP VALUES					
	MB0	MB4	MB4A5	MB4A10	MB4A15	MB4A20
0%	0	0	0	0	0	0
0.6%	30	0	0	5	10	10
0.8%	50	0	5	15	25	20
1%	80	10	15	25	40	35
1.2%	105	25	25	35	45	40
1.8%	-	45	55	70	85	75
1.9%	-	50	65	75	100	95
2%	-	60	75	85	110	105
2.2%	-	70	85	115	-	-
2.4%	-	85	105	-	-	-
2.6%	-	110	-	-	-	-

4.4.3.1 Compressive Strength

Compressive, split tensile and flexural strength results have been plotted in Figure 4-16 to Figure 4-21. It is clearly marked from the detailed interpretation of results that with the inclusion of Alccofine 1203 into bottom ash concrete, all the properties have shown significant improvement at all curing ages. It has been found that when 40% fine aggregates replaced with coal bottom ash and 15% cement replaced with Alccofine 1203, the properties reach their maximum value.

Moreover, the dosage of superplasticizer is limited to 2%, which implies at MB4A15, the workability of bottom ash concrete gets improved due to its dense or finer structure which producing low void content. As for MB4A20 concrete mix, the strength properties have shown declination thus MB4A15 mix has been chosen as final designed concrete mix. Also, smaller particle size results in rendering more surface area for pozzolanic reactions which improves strength and workable concrete can be produced using less admixture content. Thus, this study concludes that with the maximum utilization of industrial waste i.e. CBA used as a fractional change in place of fine aggregates (natural sand) with 15% of Alccofine which is used as a fractional change in place of cement, we can achieve the properties of high strength concretes.

Table 4-14 Compressive strength of Alccofine assisted bottom ash concrete

Curing Age	**Compressive strength (N/mm^2)**					
	MB0	**MB4**	**MB4A5**	**MB4A10**	**MB4A15**	**MB4A20**
7 days	33.67	26.92	29.57	40.92	46.73	44.82
28 days	47.92	39.59	46.43	56.42	62.67	61.83
56 days	49.78	43.6	49.76	60.14	65.9	63.28
90 days	51.99	44.81	51.13	62.85	67.24	65.06
180 days	54.58	48.07	53.02	65.93	71.66	69.98

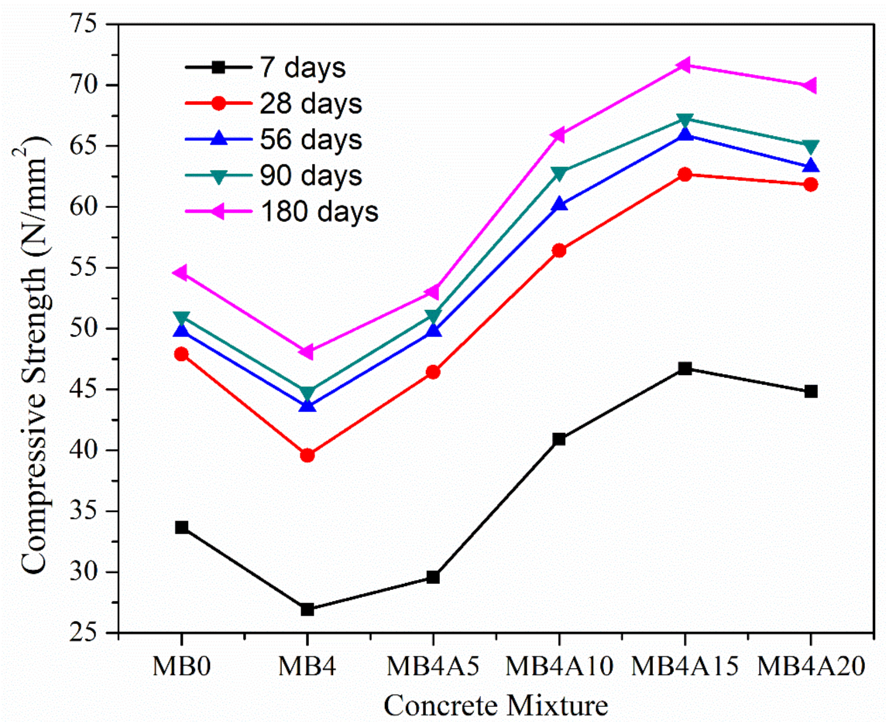


Figure 4-16 Effect of coal bottom ash and Alccofine on the compressive strength of concrete

It can be concluded that the workability and compressive strength at all ages of Alccofine 1203 assisted bottom ash concrete is improved due to the unique characteristics of Alccofine material which includes finer particle size distribution and inbuilt CaO which further form dense pore structure. Also, Alccofine 1203 inclusion in MB4 concrete mix has reduced the dosage of superplasticizer and improved the compressive, splitting tensile and flexural strength of the concrete compared to coal bottom ash.

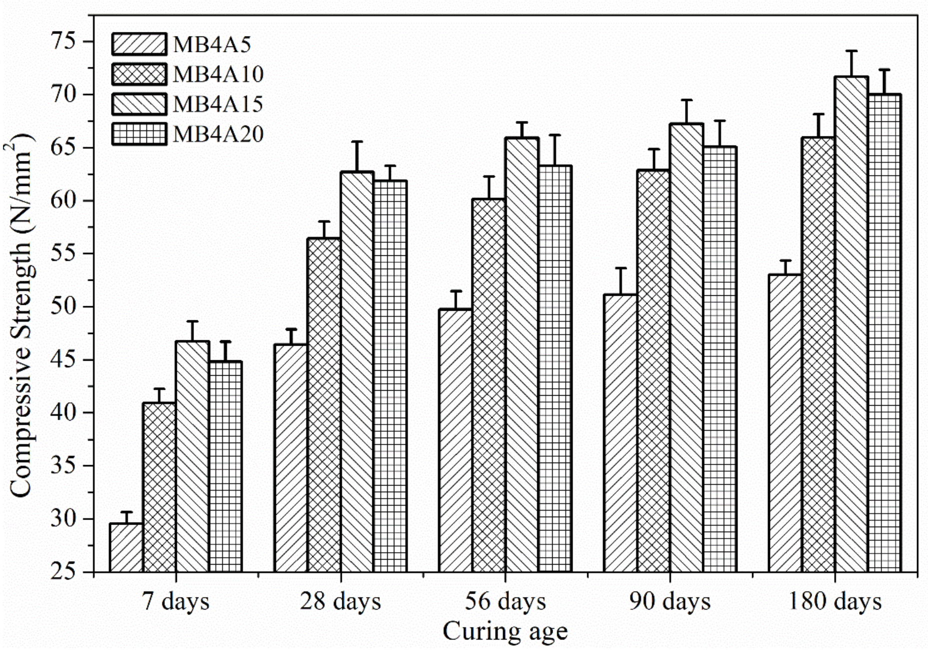


Figure 4-17 Effect of coal bottom ash and Alccofine on the compressive strength of concrete

4.4.3.2 Splitting tensile strength

Table 4-15 represents the test results of splitting tensile strength experiments for various concrete mixtures at various curing age. For more understanding, these test results are plotted in Figure 4-18 and Figure 4-19. It can be noticed from Figure 4-18 that the highest values for splitting tensile strength are achieved at MB4A15 and at 20% replacement of cement, the property values start decreasing.

Table 4-15 Splitting tensile strength of Alccofine assisted bottom ash concrete

Curing Age	**Splitting tensile strength (N/mm^2)**					
	MB0	**MB4**	**MB4A5**	**MB4A10**	**MB4A15**	**MB4A20**
7 days	3.28	2.87	2.95	3.33	3.37	3.41
28 days	3.95	3.25	3.5	4.27	4.5	4.38
56 days	4.51	3.53	3.79	4.4	4.84	4.81
90 days	4.74	3.67	4.02	4.86	5.12	4.93
180 days	4.92	3.98	4.17	5.63	6.01	5.87

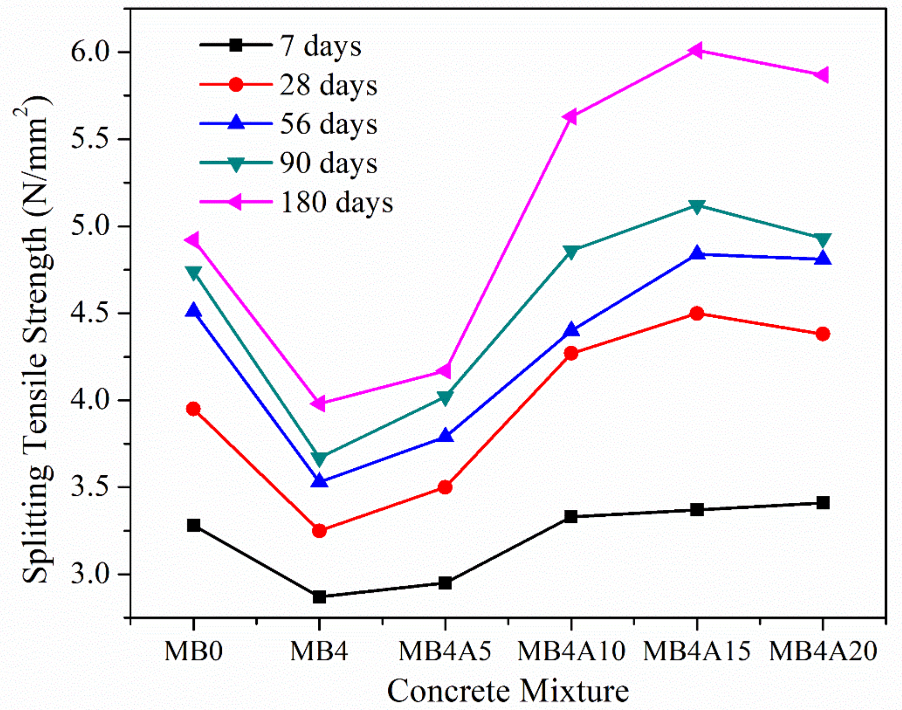


Figure 4-18 Effect of coal bottom ash and Alccofine on the compressive strength of concrete

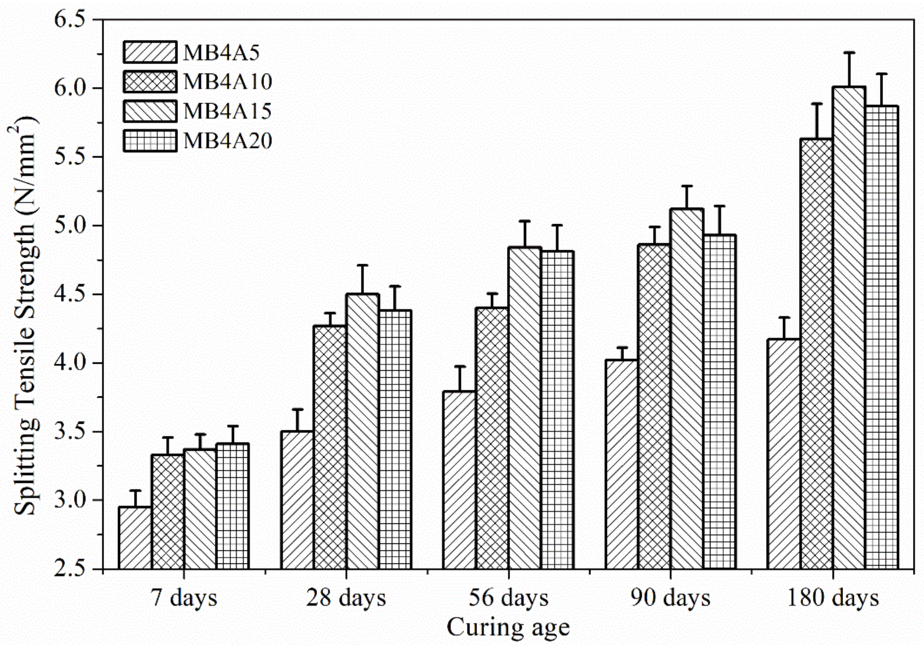


Figure 4-19 Effect of coal bottom ash and Alccofine on the splitting tensile strength of concrete

Figure 4-19 represents the variation of splitting tensile strength w.r.t. curing age and it be noticed that the splitting strength increased with curing age and for MB4A15 (left aligned hatching line), the strength has reached its maximum.

4.4.3.3 Flexural strength

Table 4-16 represents the test results for flexural strength of Alccofine assisted bottom ash concrete. Figure 4-20 and Figure 4-21 describes the variation in flexural strength w.r.t. concrete mixture concentration and curing age, respectively. From Figure 4-20 it can be observed that with the addition of Alccofine, the flexural strength of the concrete mixture starts increasing reach its maximum at MB4A15 and then drops.

Table 4-16 Flexural strength of Alccofine assisted bottom ash concrete

Curing Age	**Flexural strength (N/mm^2)**					
	MB0	**MB4**	**MB4A5**	**MB4A10**	**MB4A15**	**MB4A20**
7 days	3.9	3.15	3.24	3.8	4.45	4.21
28 days	4.81	4.12	4.15	4.72	5.29	5.17
56 days	5.43	4.58	4.6	5.41	5.78	5.7
90 days	5.92	4.94	5.06	5.7	6.08	5.94
180 days	5.98	5.08	5.57	6.13	7.03	6.52

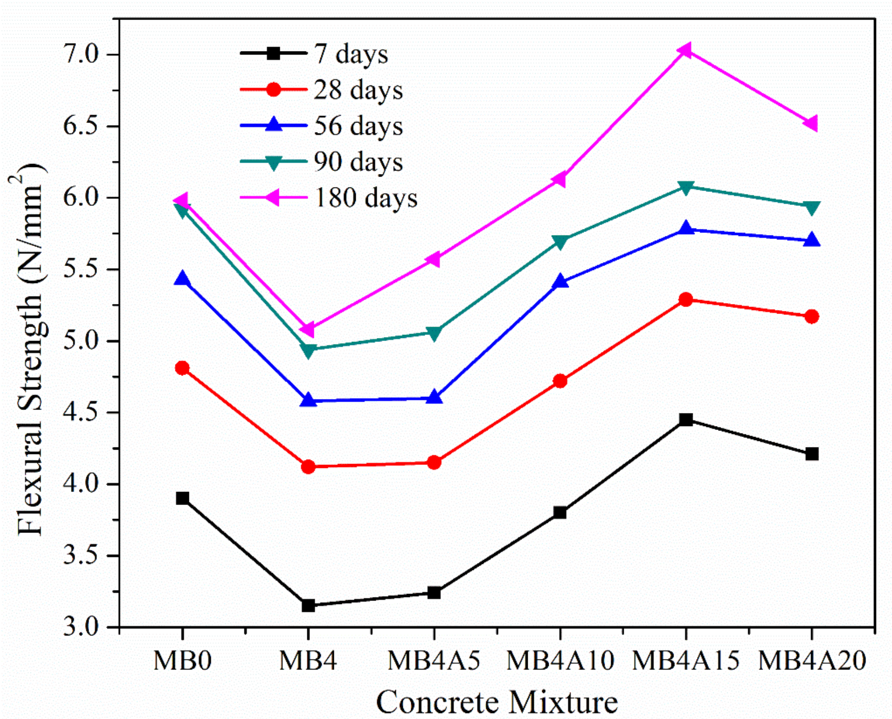


Figure 4-20 Effect of coal bottom ash and Alccofine on the compressive strength of concrete

From Figure 4-21, it can be noticed that the flexural strength increased with curing age and the maximum value is achieved for MB4A15.

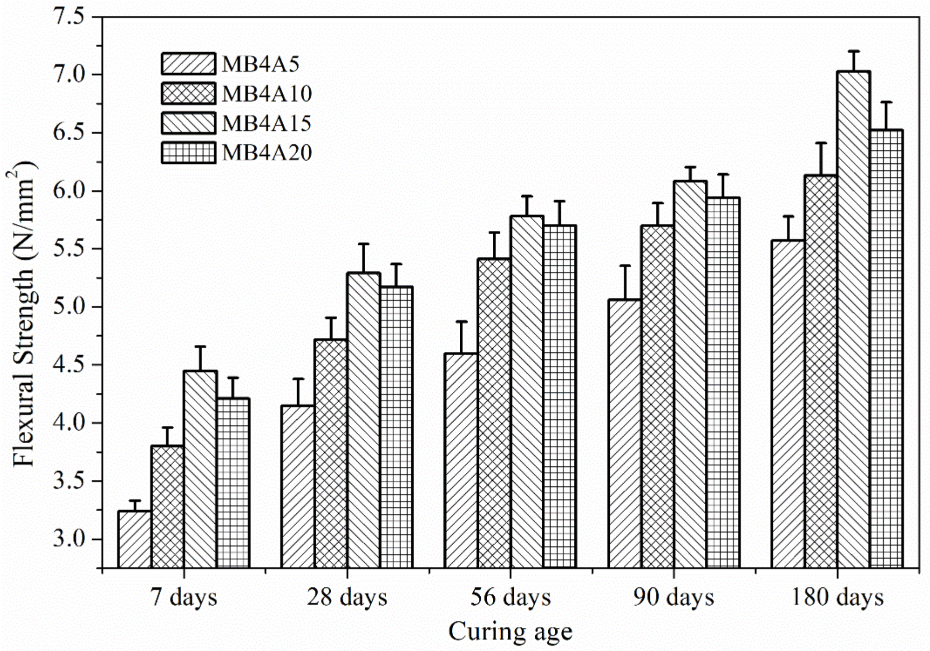


Figure 4-21 Effect of coal bottom ash and Alccofine on the flexural strength of concrete

4.4.4 Non-destructive testing

4.4.4.1 Pulse Velocity

Pulse velocity has been calculated to ensure the concrete grade. Table 4-17 represents can be observed that at higher in curing age, the pulse velocity is found to increase for all concrete mixes. At 28-day curing age, the pulse velocity of control concrete mix is 4564 m/s and at 180-day, it is 4810 m/s. For bottom ash concrete (MB4), the pulse velocity decreased by 6% at 28- day of curing age. Moreover, for Alccofine assisted bottom ash concrete (MB4A15), there is 1.3% increase in the pulse velocity of concrete mix at 28-day of curing age has been observed.

Similarly, for 90-day and 180-day of curing age, an increase of 1.7% and 2% has been found for MB4A15 mix compared to control mix and about 7.5% increase in pulse velocity when compared with MB4 mix, respectively. Figure 4-22 illustrates the pulse velocity variation w.r.t. concrete mixture concentration. The variation in pulse velocity is marginal with the infusion of CBA in the concrete, however, this negative influence can be overcome by using Alccofine as partial replacement of cement which is further beneficial as it can reduce overall CO_2 emissions. It has been concluded from pulse velocity test that the quality of the concrete degraded with the fractional change of fine aggregates with CBA. Thus, it has been found that due to consistent and continuous hydration process, the pulse velocity is increased with curing age which the signs of improved gel/space ratio.

Table 4-17 Pulse velocity for various concrete mix

Mix	Ultrasonic pulse velocity (m/s)			Standard value as per IS: 13311-92 Part-I (m/s)	Concrete grading
	28	90	180		
MB0	4564	4692	4810	<3000	Doubtful
MB4	4286	4419	4544	3000-3500	Medium
MB4A5	4310	4439	4572	3500-4500	Good
MB4A10	4517	4644	4792	>4500	Excellent
MB4A15	4623	4770	4903		
MB4A20	4638	4739	4859		

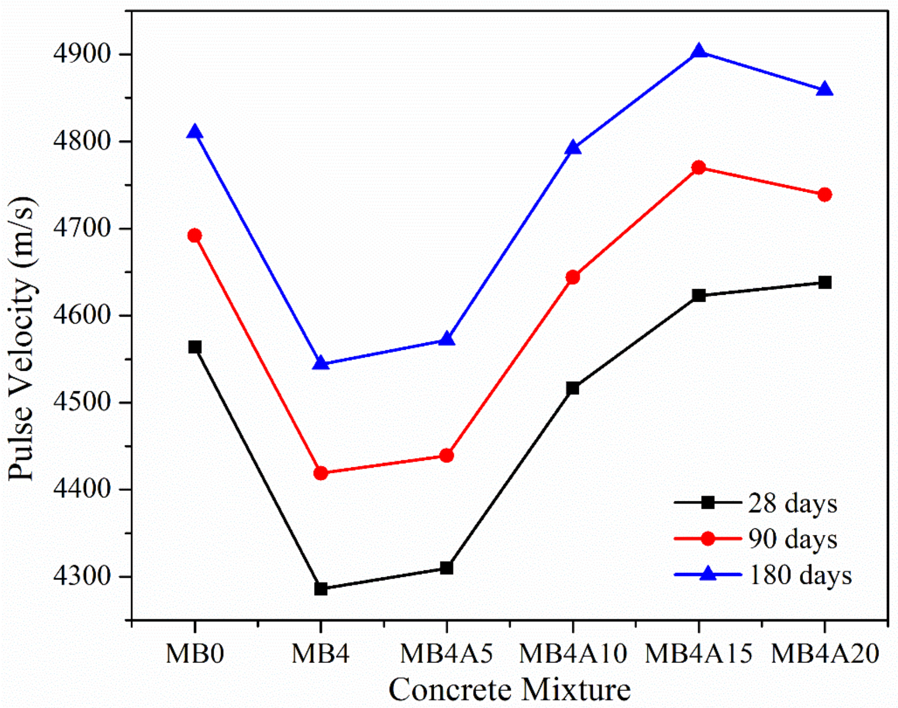


Figure 4-22 Pulse velocity variation w.r.t. concrete mixture content

4.4.4.2 Rebound hammer testing results

Rebound hammer test results for Alccofine assisted bottom ash concrete has been tabulated in Table 4-18. When compared with the destructive test results it has been found that at 28-day curing age, the errors in predicting compressive strength using rebound hammer test are 11% for MB4A5, 13% for MB4A10, 9% for MB4A15 and

MB4A20, at 90-day curing age, the errors are 11% for MB4A5, 11% for MB4A10, 8% for MB4A15 and 5% for MB4A20, at 180-day curing age, the errors are 7% for MB4A5 and MB4A10, 6% for MB4A15 and MB4A20.

Table 4-18 Rebound hammer test results (Phase-II)

Rebound Hammer Test Results			
Mix designation	**Compressive strength (N/mm^2)**		
	28-days	**90-days**	**180-days**
MB0	42.4	47.3	50.7
Error (%)	11.5	9	7
MB4	36.1	40.8	43.6
Error (%)	8.8	8.9	9.2
MB4A5	41.5	45.5	49.4
Error (%)	*11*	*11*	*7*
MB4A10	49.3	56.2	61.3
Error (%)	*13*	*11*	*7*
MB4A15	56.9	62.1	67.1
Error (%)	*9*	*8*	*6*
MB4A20	56.1	61.5	65.8
Error (%)	*9*	*5*	*6*

4.4.5 Durability properties of concrete

4.4.5.1 Chloride penetration

In Phase-II analysis, it has been observed from Table 4-19 that chloride penetration has decreased with the replacement of cement with Alccofine. It can be drawn that incorporation of Alccofine has enhanced the service life of RCC structures as RCPT values are at a lower side when equated to that of MB4 concrete mix for all curing periods. This implies it is safe to use Alccofine as partial replacement of cement in bottom ash concrete mixtures.

RCPT test values have been plotted in Figure 4-23 for controlled concrete mix, bottom ash concrete mix and Alccofine assisted bottom ash concrete mix. It can be observed form the plot that with the replacement of fine aggregates with CBA, the RCPT value is increased from 1922 Coulombs (MB0) to 2292 Coulombs (MB4) at 28-day of curing age. Further, it can be noticed that with the addition of Alccofine, the RCPT values decreased significantly which means concrete showed good resistance to permeability due to its finer pore structure and chemical stability. Moreover, the RCPT values decreased for large curing ages in all the concrete mixes. There are few studies where authors have found decline in RCPT values with escalation in curing age for normal and blend concrete[39][104]–[107]. In literature, authors have calculated very high RCPT values for normal concrete compared to the values obtained in the present study (Figure 4-23) i.e. 4251 coulombs [106], 2766 coulombs [108], 2869 coulombs [109], 7890 coulombs [110], 5250 coulombs [111] at 28 days of curing period and 3767 coulombs [106]at 180 days of curing age. The lower RCPT values may result due to the inclusion of non-cementitious material (Alccofine) and coal bottom ash addition into the concrete which has varied the water absorption capabilities and porosity of the concrete mix.

Table 4-19 RCPT test results for Alccofine assisted bottom ash concrete

Concrete Mixture	**Chloride penetration (in coulombs)**		
	28-days	**90-days**	**180-days**
MB0	1922	1633	1396
MB4	2292	1912	1483
MB4A5	1974	1610	1319
MB4A10	1438	1005	797
MB4A15	1101	856	478
MB4A20	1017	764	510

Due to finer particle size distribution and chemical stability of Alccofine results in formation of dense pore structure and inbuilt CaO triggers the secondary hydrated products which fill the pores which further reduces the hydrated product's permeability and shields the concrete from foreign chemical attack.

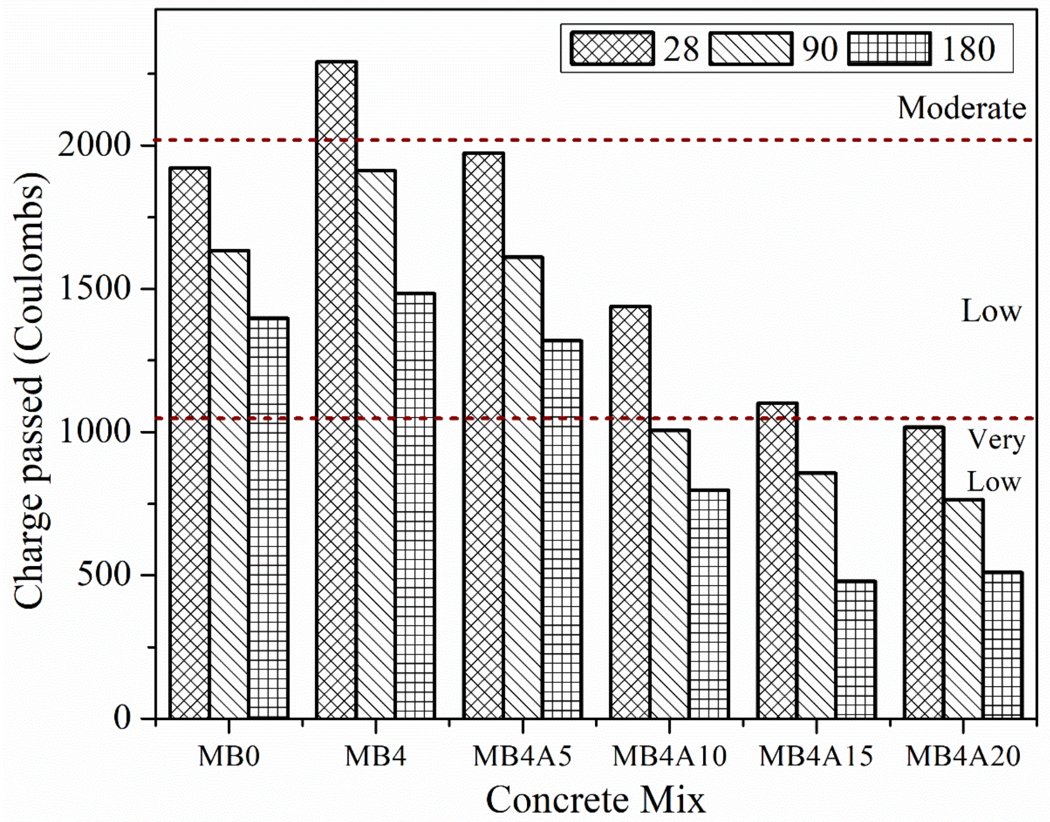


Figure 4-23 RCPT variations for different concrete mix

4.4.5.2 Initial Surface Absorption (Phase-II)

Table 4-20 illustrate the test results of ISAT which was performed on control (MB0), bottom ash concrete (MB4) and Alccofine assisted bottom ash concrete. The water absorption capability of the concrete has been studied for 10 minutes, 20 minutes, 30 minutes, 60 minutes and 120 minutes for each concrete mix at 28-day, 90-day and 180-day of curing age. It has been found from the Table 4-20 that water absorption capacity of MB0, MB4, MB4A5, MB4A10, MB4A15 and MB4A20 has been decreased with curing age and time. Further, ISAT value, at all times, increased as the coal bottom ash content increased in the mixture, and results improved i.e. ISAT value dipped after the incorporation of Alccofine in coal bottom ash concrete mixture upto 15%. When compared for 10 minute ISAT value at 28-days, the value was 0.97 ml/m^2-sec for MB0 mix but value surged up to 1.43 ml/m^2-sec. ISAT values for Alccofine assisted coal bottom ash concrete i.e. MB4A5, MB4A10, MB4A15 and MB4A20 were observed as 1.34, 1.11, 0.8 and 0.82 ml/m^2-sec respectively. From the results, good permeability characteristics can be seen for Alccofine assisted bottom ash concrete mixtures.

Infusion of Alccofine has greatly enhanced the weak pore structure of bottom ash concrete mixture leading to the extensive pore refinement. The water movement characteristics and transmission rate of harmful ions, within the concrete, were significantly modified. At higher curing ages, the void size among the concrete has decreased due to pozzolanic reactions and thus strength of the concrete is increased with time. The variation in ISAT values w.r.t. curing age for each Alccofine assisted bottom ash concrete has been plotted in Figure 4-24 to Figure 4-27. Similar results can be noticed from the plots that for each Alccofine assisted bottom ash concrete, a decrease in the water absorption capacity was noticed with respect to time and curing age. Further, Figure 4-28 to Figure 4-32 represents initial surface absorption variations for different concrete mixtures with respect to time. A common pattern was seen on analysis of the results at varied time intervals. Surface absorption increased for MB4 mix and is highest as equated to all other mixtures. With the inclusion of Alccofine in place of cement, ISAT value declined. For MB4A15 and MB4A20 mixtures, value dipped down when compared to MB0 mix thus justifying the durability concrete with good permeability characteristics.

Table 4-20 ISAT Test results (Phase-II)

Time	Curing Age	MB0	MB4	MB4A5	MB4A10	MB4A15	MB4A20
10 minutes	28-days	0.97	1.43	1.34	1.11	0.8	0.82
	90-days	0.78	1.35	1.13	0.85	0.73	0.77
	180-days	0.64	1.26	1.07	0.73	0.68	0.66
20 minutes	28-days	0.82	1.32	1.2	0.98	0.7	0.76
	90-days	0.66	1.25	1.06	0.74	0.62	0.68
	180-days	0.57	1.18	0.96	0.67	0.55	0.55
30 minutes	28-days	0.73	1.28	1.13	0.84	0.61	0.64
	90-days	0.55	1.16	0.99	0.66	0.54	0.58
	180-days	0.49	1.07	0.88	0.58	0.41	0.43
60 minutes	28-days	0.69	1.19	1.08	0.77	0.59	0.63
	90-days	0.48	1.08	0.92	0.59	0.47	0.52
	180-days	0.4	1	0.8	0.52	0.4	0.42
120 minutes	28-days	0.68	1.14	1.06	0.76	0.58	0.61
	90-days	0.46	1.07	0.88	0.57	0.46	0.5
	180-days	0.39	0.99	0.79	0.5	0.39	0.41

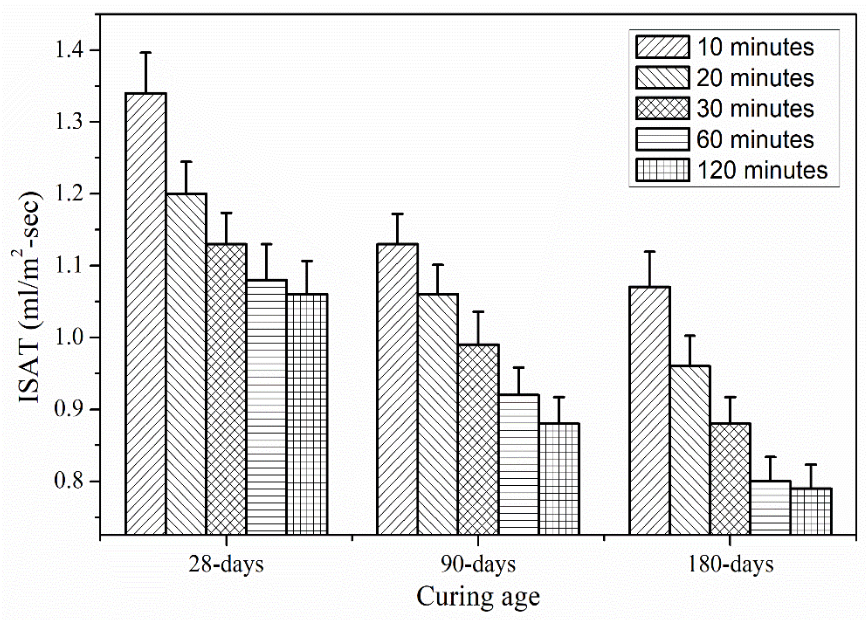


Figure 4-24 ISAT test results variation w.r.t. curing age for MB4A5 concrete mix

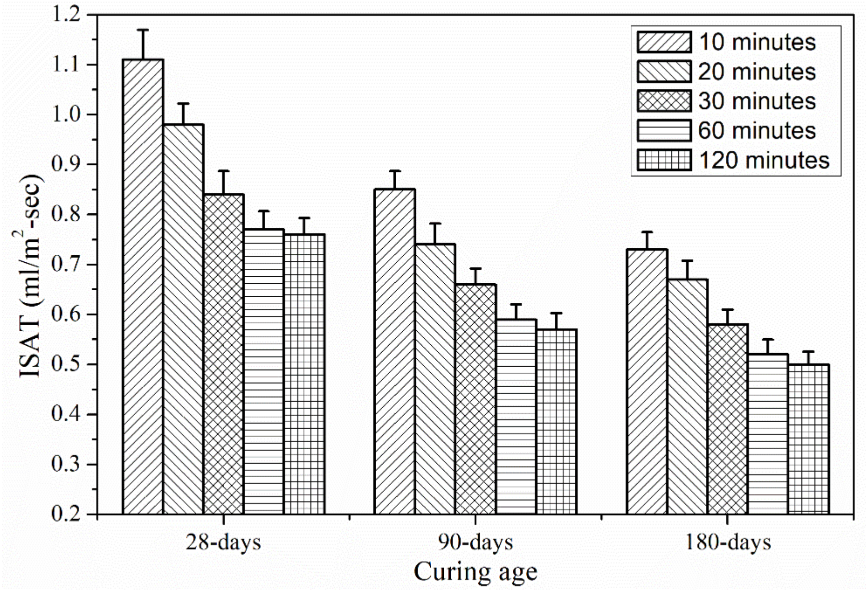


Figure 4-25 ISAT test results variation w.r.t. curing age for MB4A10 concrete mix

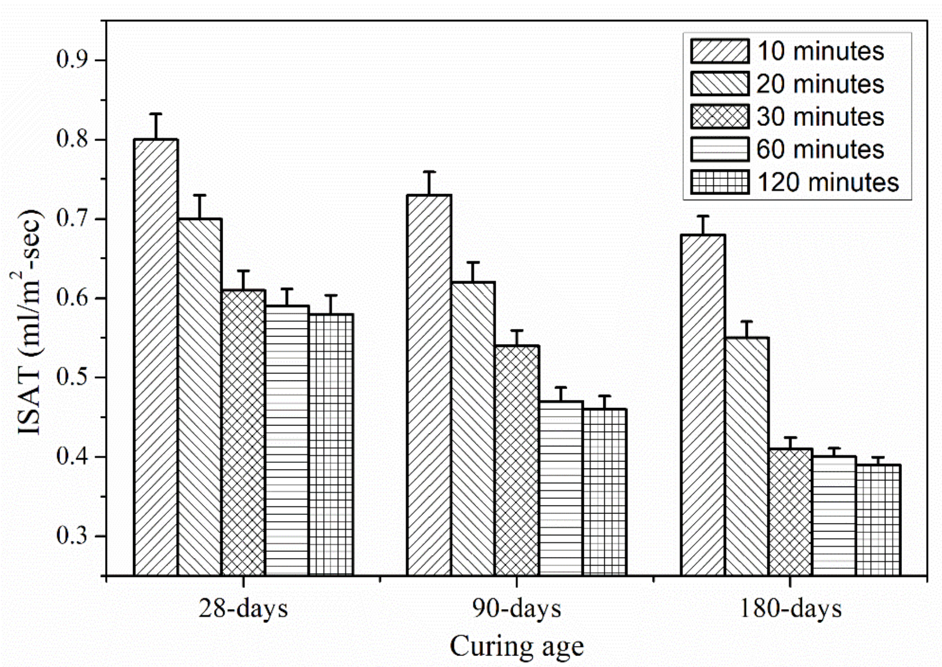


Figure 4-26 ISAT test results variation w.r.t. curing age for MB4A15 concrete mix

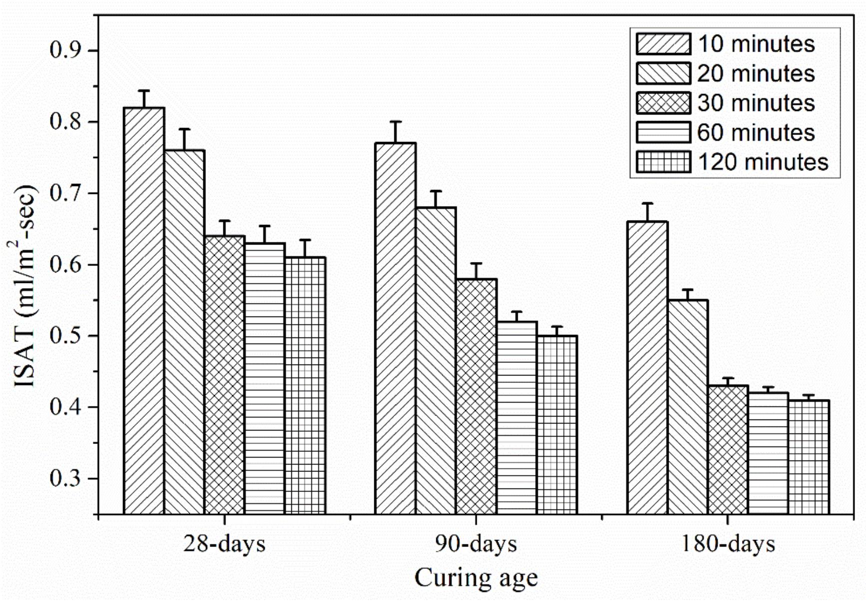


Figure 4-27 ISAT test results variation w.r.t. curing age for MB4A20 concrete mix

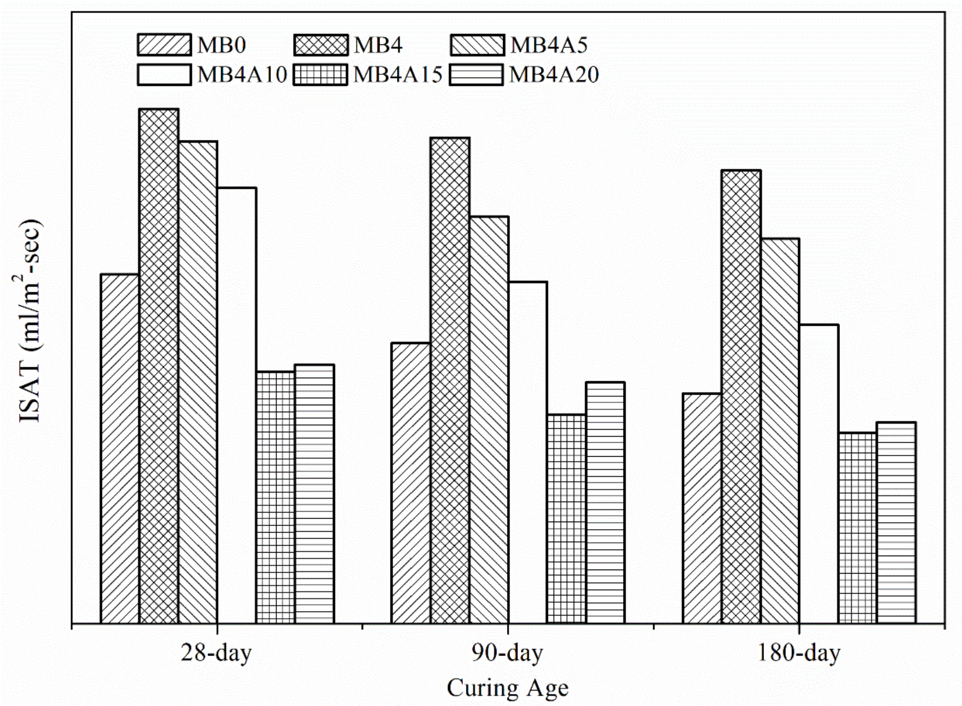


Figure 4-28 ISAT test results variation for various mixes at 10-minute duration

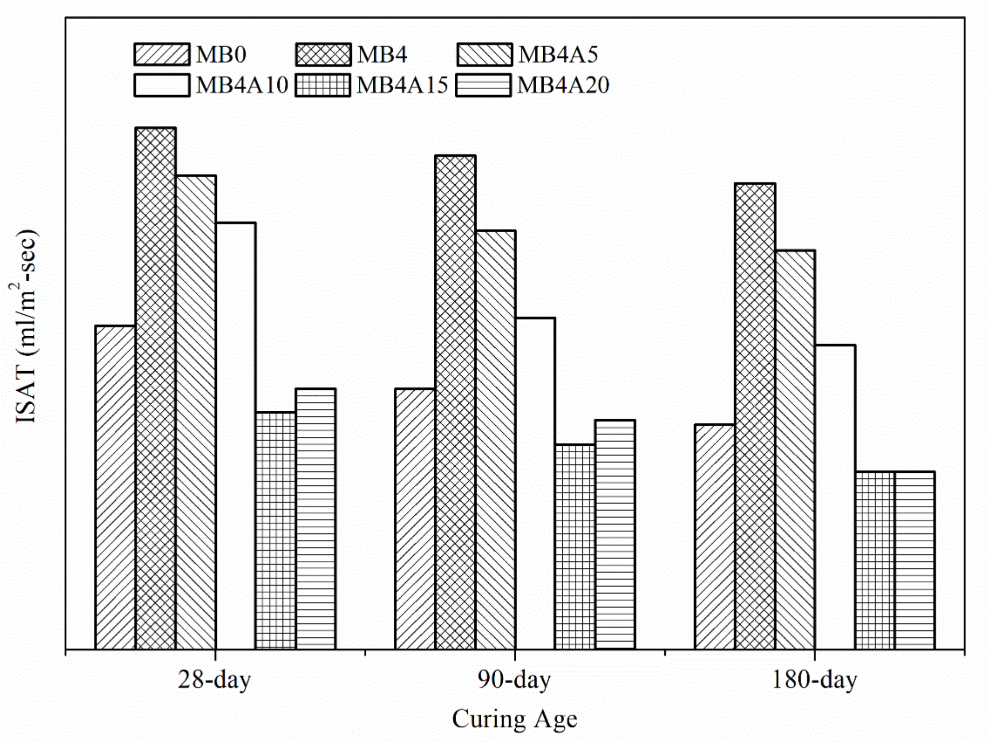


Figure 4-29 ISAT test results variation for various mixes at 20-minute duration

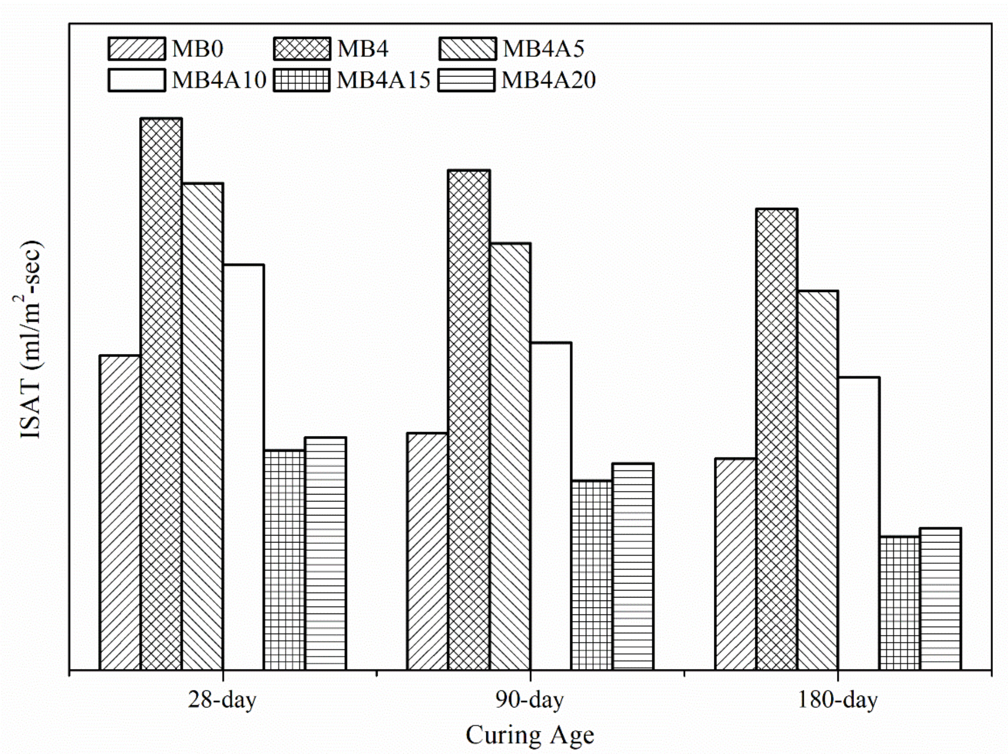


Figure 4-30 ISAT test results variation for various mixes at 30-minute duration

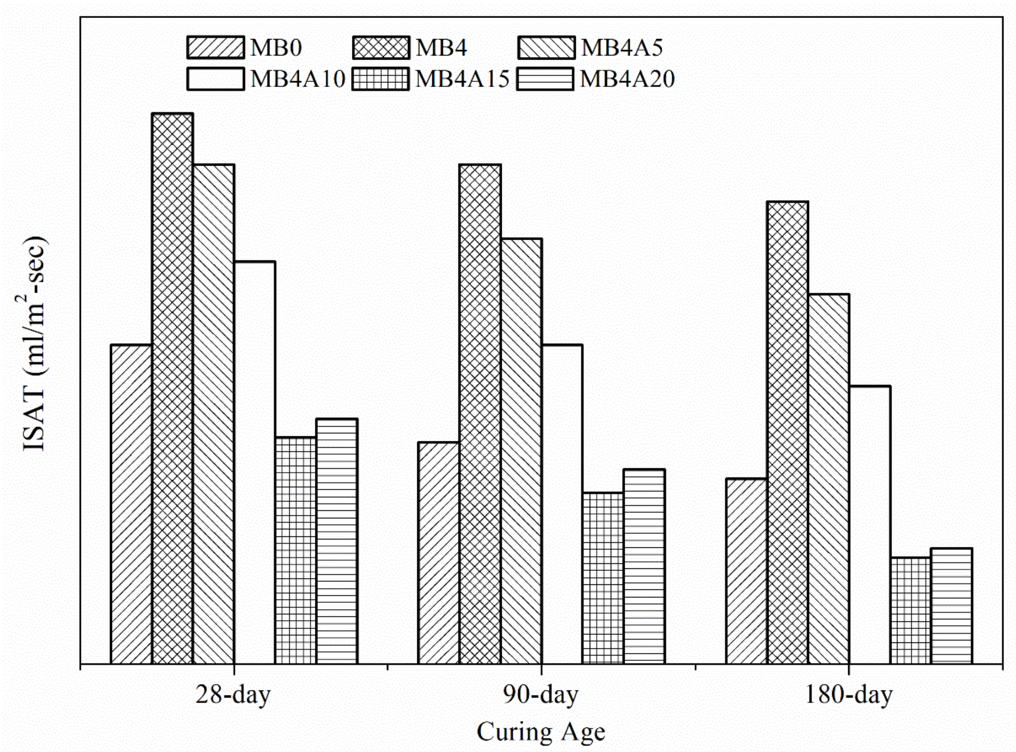


Figure 4-31 ISAT test results variation for various mixes at 60-minute duration

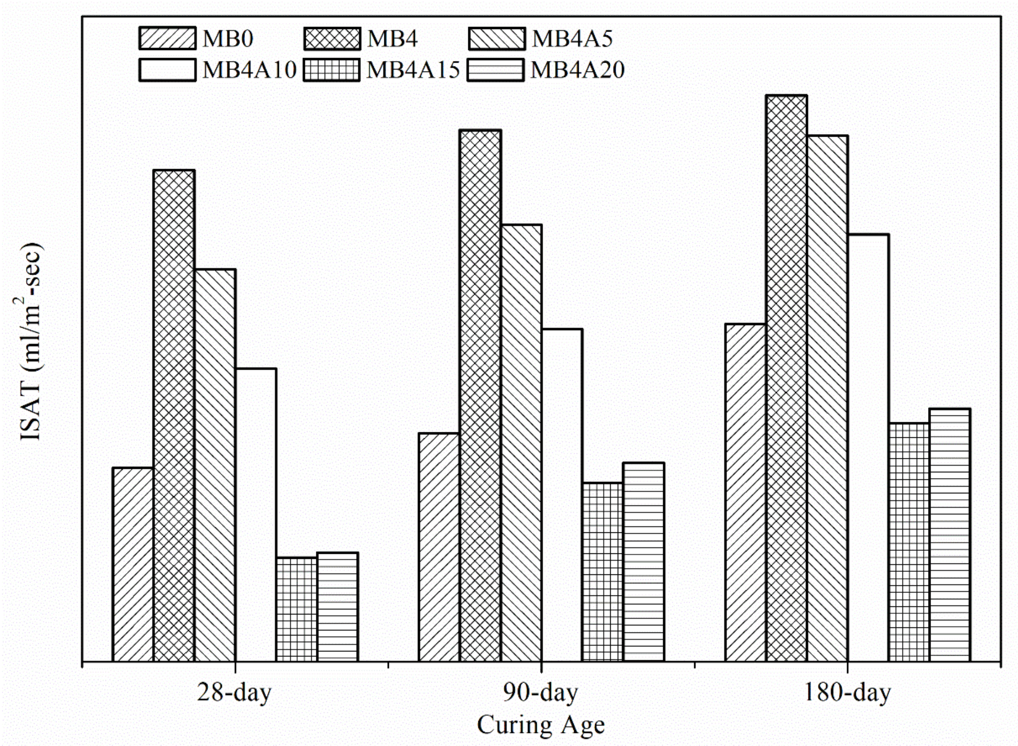


Figure 4-32 ISAT test results variation for various mixes at 120-minute duration

4.4.6 Change in hardened properties of Alccofine assisted bottom ash concrete

From Phase-I studies, it has been found that addition of CBA as a fractional change in place of fine aggregates in the concrete has affected the properties of the concrete significantly and the percentage change in compressive, flexural and splitting tensile strength has been discussed in section 4.3.5.

From Phase-II studies it has been concluded that when Alccofine used as a fractional change in place of cement, the strength properties have been improved significantly. Percentage increase (upper region from the reference dotted line) in properties w.r.t. MB4 mix has been plotted in Figure 4-33, Figure 4-34 and Figure 4-35. Table 4-21 represents the percentage variation among strength properties.

It has been found from Figure 4-33 that the percentage increase in compressive strength is quite significant of all the mixes (except MB4A5) for all the curing ages. It can be noticed that for MB4A15, the percentage increase in compressive strength is about 72% at 7-day, 59% at 28-day, 52% at 56-day, 49% at 90-day and 48% at 180-day. Figure 4-34 represents the percentage increase in splitting tensile strength of the concrete mix. It can be observed from the plot that the maximum increase in the property has been found for MB4A15 mix. Figure 4-35 shows that there is an increase in flexural strength of Alccofine assisted bottom ash concrete. It can be noticed form the plot that at 7-day curing age, the percentage increase in flexural strength of the all the concrete mixes is quite significant compared to 28-day and 56-day of curing age. Also, the percentage increase in flexural strength is maximum for MB4A15 mix.

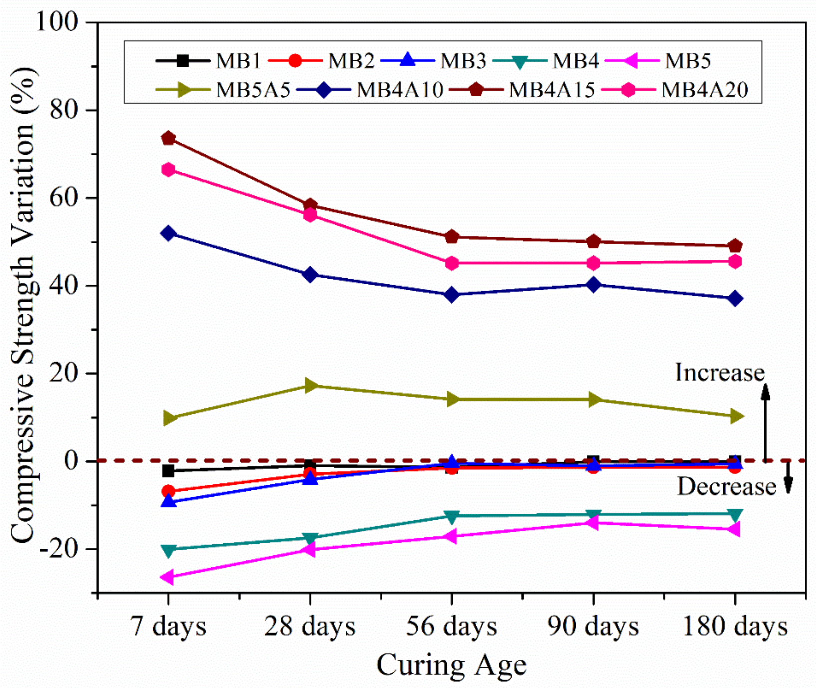


Figure 4-33 Percentage variation in compressive strength

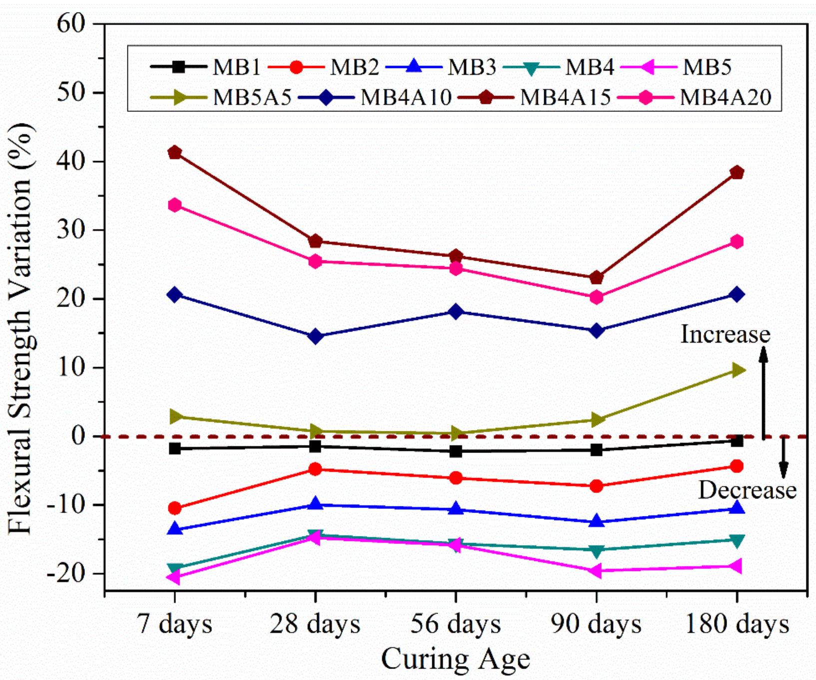


Figure 4-34 Percentage variation in flexural strength

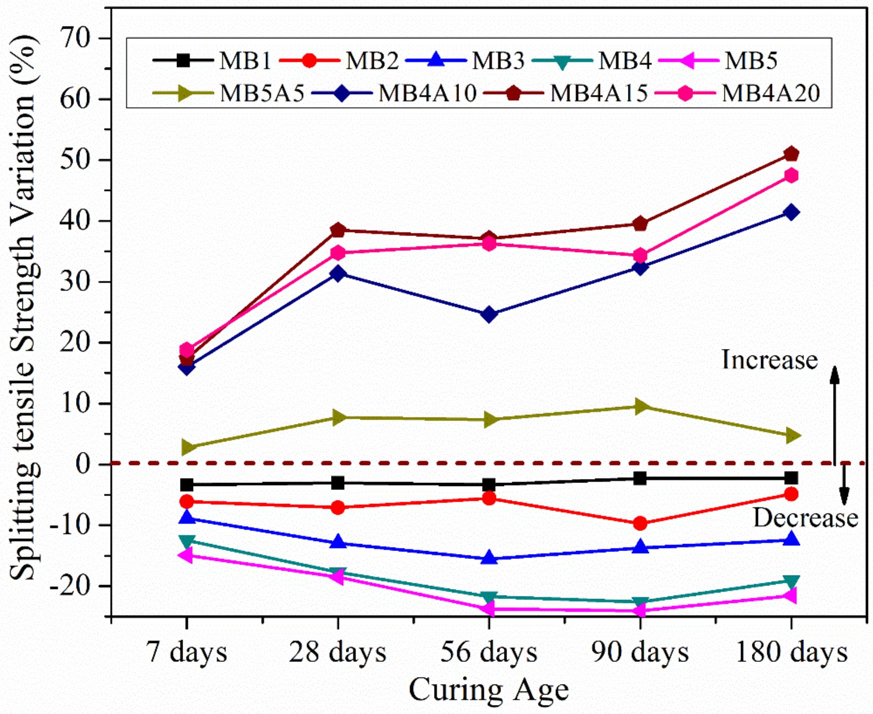


Figure 4-35 Percentage variation in splitting tensile strength

Table 4-21 Effect of CBA and Alccofine on strength properties at various ages

	Compressive Strength					**Flexural Strength**					**Splitting Tensile Strength**				
%age effect of coal bottom ash addition in concrete mix															
	7-day	**28-day**	**56-day**	**90-day**	**180-day**	**7-day**	**28-day**	**56-day**	**90-day**	**180-day**	**7-day**	**28-day**	**56-day**	**90-day**	**180-day**
MB1	-2.16	-0.98	-1.34	0.05	-0.10	-1.79	-1.45	-2.20	-2.02	-0.66	-3.35	-3.03	-3.32	-2.32	-2.23
MB2	-6.86	-2.92	-1.50	1.37	1.28	-10.5	-4.78	-6.07	-7.26	-4.34	-6.09	-7.08	-5.54	-9.70	-4.87
MB3	-9.29	-4.17	0.40	1.03	-0.56	-13.6	-9.97	-10.68	-12.5	-10.53	-8.84	-12.91	-15.52	-13.71	-12.39
MB4	20.04	-17.38	-12.41	-12.12	-11.92	-19.2	-14.34	-15.65	-16.55	-15.05	-12.5	-17.72	-21.72	-22.57	-19.10
MB5	-26.40	-20.11	-17.05	-13.98	-15.48	-20.5	-14.76	-15.83	-19.59	-18.89	-14.9	-18.48	-23.72	-24.05	-21.54
%age effect of Alccofine addition in 40% bottom ash concrete mix (%age change w.r.t. the properties of controlled mix)															
MB4A5	-12.18	-3.10	-0.04	0.27	-2.85	-16.9	-13.72	-15.29	-14.53	-6.85	-10.0	-11.39	-15.96	-15.19	-15.24
MB4A10	21.53	17.73	20.81	23.25	20.79	-2.56	-1.87	-0.36	-3.71	2.50	1.52	8.10	-2.43	2.53	14.43
MB4A15	38.78	30.78	32.38	31.86	31.29	14.10	9.97	6.44	2.70	17.55	2.74	13.92	7.31	8.01	22.15
MB4A20	33.11	29.02	27.11	27.59	28.21	7.94	7.48	4.97	0.33	9.03	3.96	10.88	6.65	4.00	19.30
%age effect of Alccofine addition in 40% bottom ash concrete mix (%age change w.r.t. the properties of MB4)															
MB5A5	9.84	17.27	14.12	14.10	10.29	2.85	0.72	0.436	2.42	9.64	2.78	7.69	7.36	9.53	4.77
MB4A10	52.00	42.51	37.93	40.25	37.15	20.63	14.56	18.12	15.38	20.66	16.02	31.38	24.64	32.4	41.45
MB4A15	73.58	58.29	51.14	50.05	49.07	41.27	28.39	26.20	23.07	38.38	17.42	38.46	37.11	39.51	51.00
MB4A20	66.49	56.17	45.13	45.19	45.57	33.65	25.48	24.45	20.24	28.34	18.81	34.76	36.26	34.33	47.48
Note: Positive sign indicates percentage increase and negative sign indicates percentage decrease															

4.5 Surface Morphology of Concrete

Microstructure of different concrete mixtures was studied using scanning electron microscopy to validate the results attained through the experimental program at 28 days of curing age. Scanning electron microscopy of concrete mixtures MB0 (controlled concrete), MB4 (concrete mix containing 40% bottom ash as a partial replacement of fine aggregates) and MB4A15 (concrete mix containing 15% Alccofine as a partial replacement of cement in a mix already containing 40% coal bottom ash as a partial replacement of fine aggregates) are shown Figure 4-36, Figure 4-37 and Figure 4-38 respectively. Analysis was conducted at different locations at varied magnifications, however, in this dissertation work, SEM studies at a magnification of ×5000 has been represented. Figure 4-36 illustrates the SEM image for control concrete mix where formation of C-S-H gel, micro cracks and dominant ettringite can clearly be observed. Similar microstructural details can be found in Figure 4-37 for MB4 mix. SEM images revealed multiple dominant pores in bottom ash concrete mixtures due to which a significant drop in strength and durability properties of concrete has been experienced for MB4 mix. Prominent phases of Calcium-Silicate-Hydrate (C-S-H), that is the fibrous loads and big chalky gel formations can be observed in Figure 4-38.

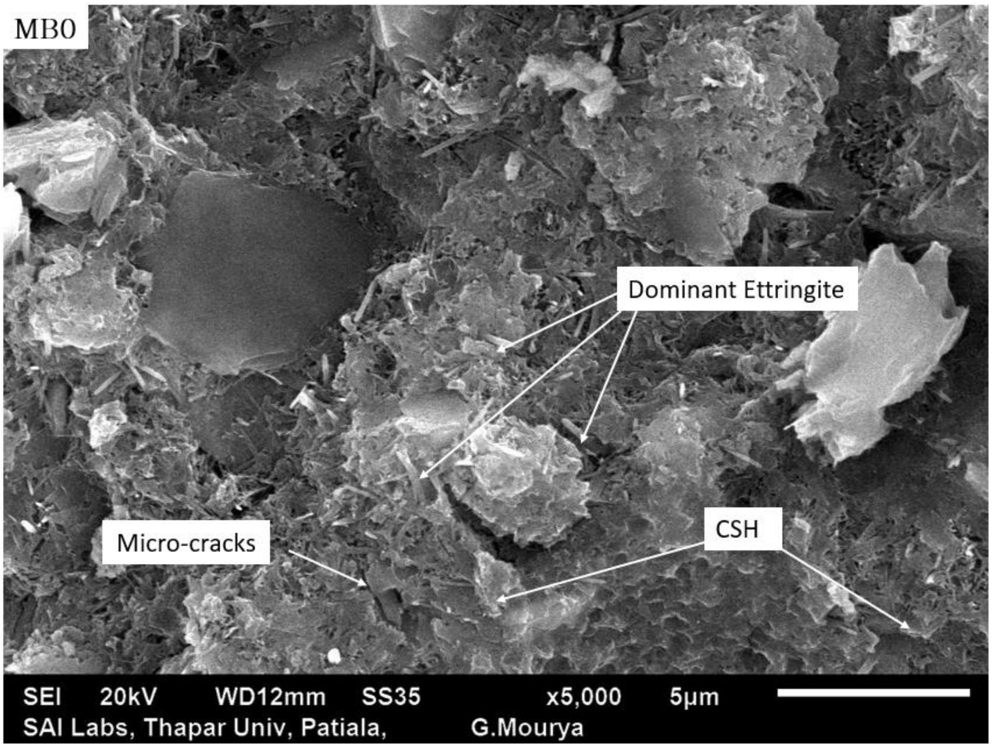


Figure 4-36 SEM micrograph of controlled concrete (MB0 mix)

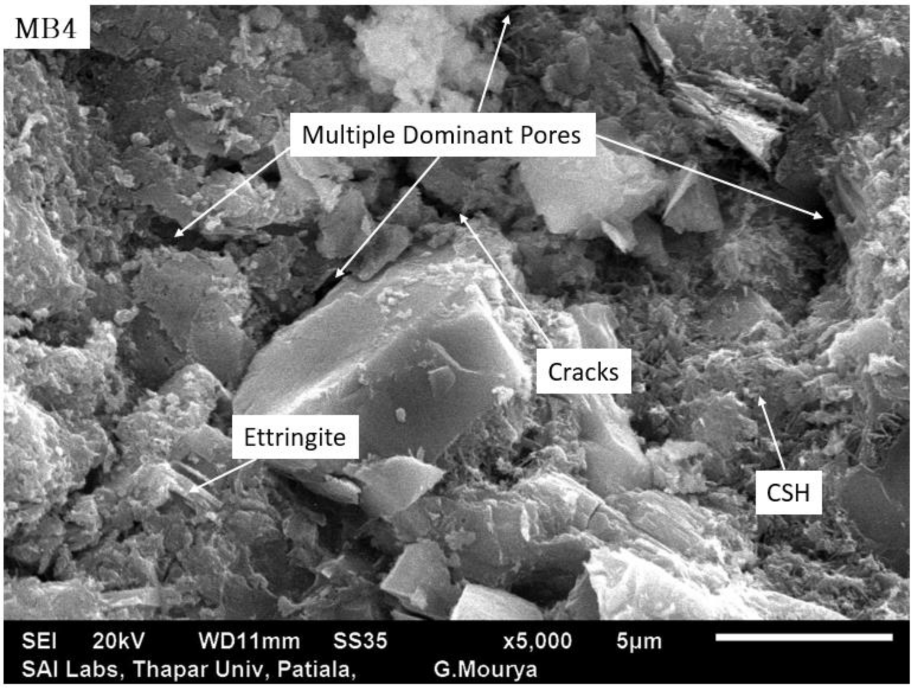


Figure 4-37 SEM micrograph of concrete mix containing 40% bottom ash as a partial replacement of fine aggregates (MB4 mix)

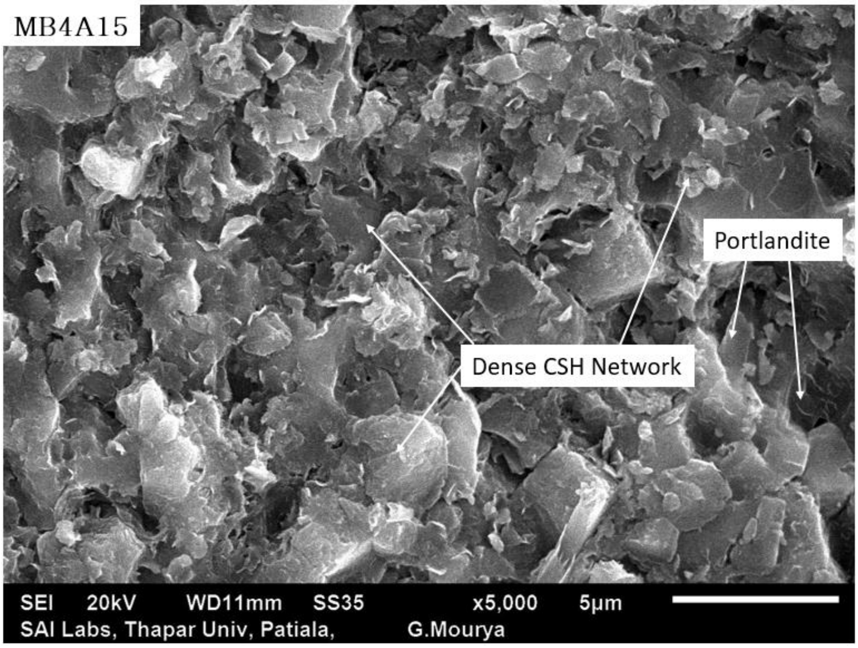


Figure 4-38 SEM micrograph of concrete mix containing 15% Alccofine as a partial replacement of cement in mix already containing 40% coal bottom ash as a partial replacement of fine aggregates (MB4A15)

Increase in the size and number of pores is evident for the mix containing 40% of CBA, thus resulting in reduction of strength for bottom ash concrete mixtures [37][102], as through these pores micro-cracks can propagate rapidly and bottom ash concrete mixes provide less resistance to external loading when equated to other mixtures. The development of needle shaped Ettringites were also observed in CBA mixtures as well as controlled concrete mixtures. SEM images revealed that MB4 mix possesses discontinuous/irregular C-S-H gel matrix network as compared to that of MB0 and MB4A15 mixtures. This may have been contributed to the fact behind the reduction in compressive strength and other mechanical properties for MB4 mixtures, when compared to that of MB0 and MB4A15 mixtures. Further, low Portlandite crystals have been observed for bottom ash concrete [112] and it is also evident that the inclusion of bottom ash in concrete mix can significantly reduce the Ca/Si ratio [113] and hence, compressive strength. The other reason behind the reduction of mechanical properties of bottom ash concrete can be correlated using XRD studies available in the literature, which revealed the weak diffraction peaks of discontinued and poorly crystalline calcium silicate hydrate phase of bottom ash concrete mix [51][114]. Also, the silica content in the coal bottom ash is found to be low as compared to that of natural sand used in this dissertation, which may responsible for the discontinuous network of CSH gel among all bottom ash concrete mixes.

Formation of calcium hydroxide in all the mixtures was observed as a result of hydrolysis of silicates and calcium present in the binder constituents after a few hours of hydration process. Generally, the presence of calcium hydroxide can be understood through Portlandite at early stages of hydration process. A continuous and dense CSH network can be observed for Alccofine assisted CBA mixtures (MB4A15). It is evident from the SEM images and previous studies [63] that hexagonal crystal shape Portlandite structure is more prominent in Alccofine assisted concretes. This happens due to the pozzolanic reactions of Alccofine among dicalcium and tricalcium silicates in cement. Such reactions create a honeycomb structure of C-S-H gel at the lateral stages due to maturation of hydrolysis process and pozzolanic reactions which provides maximum strength to the concrete mix at 28 days [115], [116]. This is the reason due to which almost all the Alccofine assisted concretes are having more strength than that of control concrete [63]. Formation of extra C-S-H due to the pozzolanic reactions projected dense pore structure and ultimately higher strength gain at all ages. Prolonged pozzolanic activities, due to the incorporation of Alccofine, can be assumed as a function of its particle size distribution and chemical composition. The fibrous C-S-H gel formation act as a membrane for the admittance of chloride ions into concrete, thus making it more durable to harsh environmental conditions as evident from RCPT values. Furthermore, it has been revealed through XRD studies available in the literature that calcium silicates such as Alite and Larnite are the minerals which are accountable for early and later stage strength growth in the concrete [63], [117], [118]. The increased intensity of $Ca(OH)_2$ for Alccofine assisted concrete mixes has been observed. Furthermore, a reduction in intensity of ettringite, due to the presence of Alccofine in concrete, has been concluded when compared to that of normal concrete [118]. Dense and continuous CSH gel network for MB4A15 mix may be due to the fact that the formation of CSH gel is more with Alccofine assisted concretes due to the conversion of $Ca(OH)_2$ to secondary CSH, thereby resulting in the enhanced strength as compared to the other mixtures. For MB4A20 concrete mix, a decrease in compressive strength was observed compared to MB4A15 concrete mix. This may be due to the fact that with the incorporation of 20% Alccofine in place of cement, concrete might be more prone towards excessive expansion and micro-cracks due to the unsoundness of binder caused by increase of free lime, alumina and magnesia [63]. These cracks among specimens can propagate on loading to generate large cracks and thus offer less resistance to the applied force, hence, decline in mechanical strength was noticed.

4.6 Cost analysis

Cost analysis becomes an essential part when percentage change of concrete constituent is done, as the replacement will only be feasible when the resulted concrete mix has lower or equivalent expenditure. In this dissertation, cost analysis has been performed to quantify the cost difference among Phase-I and Phase-II studies. Table 4-22 shows the cost comparison among Phase-I and Phase-II concrete mixes where ingredients have been procured form retailer and their cost has been tabulated. It can be observed from the Table 4-22 that the cost of control mix is about Rs. 5145 and it increased with the addition of coal bottom ash (10% to 50%).

Table 4-22 Cost comparison of Phase-I and Phase-II concrete mixes

Material	**Rate (INR) at source**	**Rate per Kg**	**PHASE - I MIXTURES**						**PHASE - II MIXTURES**			
			MB0	**MB1**	**MB2**	**MB3**	**MB4**	**MB5**	**MB4A5**	**MB4A10**	**MB4A15**	**MB4A20**
OPC-43 Grade	Rs. 400/- per 50 kg bag	8	3320	3320	3320	3320	3320	3320	3154	2988	2822	2656
Alccofine 1203	Rs. 177/- per 25 kg bag	7.08	0	0	0	0	0	0	146.91	293.82	440.73	587.64
Fine aggregate	Rs. 3400 per cu ft	0.45	352.02	316.81	281.91	246.41	211.21	176.01	211.21	211.21	211.21	211.21
Coal Bottom Ash	(available free of cost)	0	0	0	0	0	0	0	0	0	0	0
Coarse Aggregate	Rs. 2900 per cu ft	0.38	415.19	415.19	415.19	415.19	415.19	415.19	415.19	415.19	415.19	415.19
Super plasticizer	212.40 per kg	212.4	1057.75	1057.75	1322.19	1939.21	2203.65	2644.38	2115.5	1851.06	1674.77	1762.92
Total cost per cum			5144.96	5109.75	5339.29	5920.81	6150.05	6555.58	6042.81	5759.28	5563.9	5632.96
% change from control concrete (Cost difference)			-	-0.6844	3.77709	15.0798	19.5354	27.4175	17.4511	11.9402	8.14273	9.48501

It can also be noticed that for Phase-I analysis, the cost has increased up to 27.5% for MB5 mix due to the addition of superplasticizer dosage (Table 4-4) to maintain a 100 mm slump. Moreover, from Phase-II cost analysis, it can be observed that there is a significant cost reduction from MB4 (Rs. 6150) to MB4A20 (Rs. 5632), however, cost for all Phase-II concrete mixes is more than that of control mix.

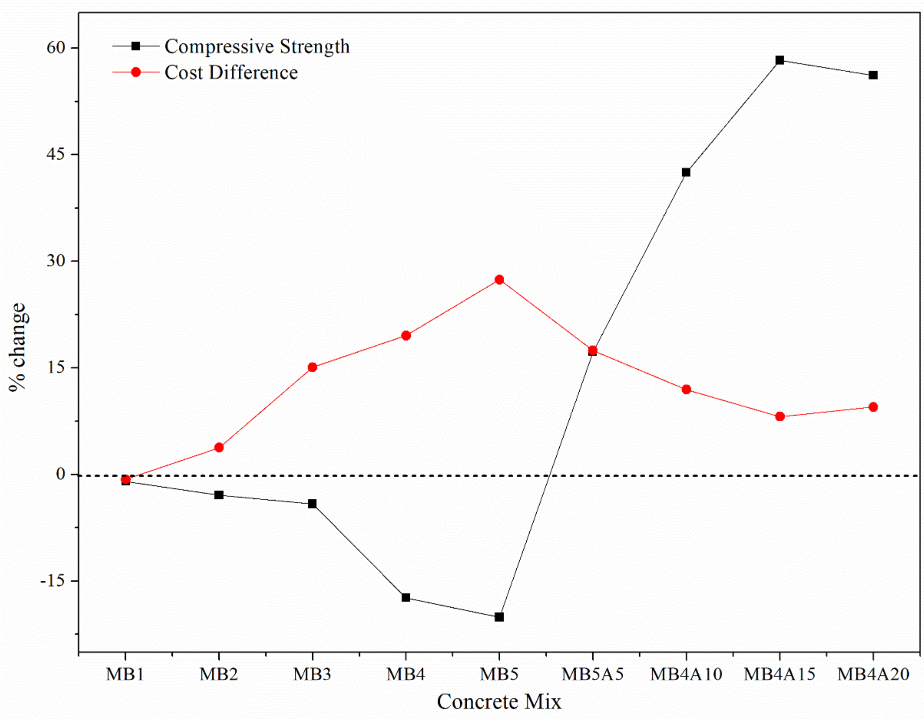


Figure 4-39 %age change in cost and compressive strength w.r.t. to control concrete

Figure 4-39 represents the percentage change in cost and compressive strength w.r.t. controlled concrete. It can be analysed that percentage change in cost has increased in Phase-I with simultaneous reduction in the compressive strength of the bottom ash concrete mixtures when equated with controlled concrete. However, with the addition of Alccofine in place of cement, the percentage difference in cost has decreased with simultaneous increase in the compressive strength of Alccofine assisted bottom ash concrete compared to control mix. Thus, in conclusion it can be noticed that for MB4A15 mix, the cost has increased to 8.14 % compared to control concrete, however, a significant increase of 58.3% in compressive strength can be observed which is very large compared to the cost involved. Thus, it has been concluded from this dissertation work, that 15% replacement of cement with ultra-fine material Alccofine in 40%

bottom ash concrete has achieved the properties of high strength concrete with 8.14% hike in cost comparison to control increase.

4.7 Statistical studies

4.7.1 Phase-I

Statistical significance of CBA on the properties of bottom ash concrete has been studied at all curing ages. The empirical equations have been established from the test results to determine the association among the compressive, flexural and splitting tensile strength of bottom ash concrete with the different concentrations of coal bottom ash used as partial replacement of fine aggregate in the concrete mix. Determination coefficient (R^2) has also been calculated for each empirical equation to know fitting characteristics. Higher value of R^2 is desirable as it indicates good agreement among data and regression curve.

4.7.1.1 Empirical relationships for properties of bottom ash concrete

The empirical equations (Equation 4-1 and 4-2) for the bottom ash concrete properties i.e. compressive strength, flexural strength and splitting tensile strength, are given below and its coefficient values are tabulated in Table 4-23.

Compressive strength

$$\textit{Compressive strength of CBA concrete mix} = a + \frac{b-a}{1+10^{(c-x)d}} \qquad (4\text{-}1)$$

Splitting tensile and flexural strength

$$\textit{Splitting tensile and flexural strength of CBA concrete} = a + bx + cx^2 + dx^3 \qquad (4\text{-}2)$$

where *a, b, c, d* are the correlation coefficients and '*x*' denotes the CBA concentration in the mix (10% to 50%). R^2 values calculated for bottom ash concrete properties are tabulated in Table 4-22 and it can be noticed that the relationship among the properties has been developed with high R^2 value which implies more accurately the data has been fitted thus can be used in future studies. Figure 4-40, Figure 4-41 and Figure 4-42 represents the fitting plots for compressive, flexural and splitting tensile strength at various curing ages, respectively.

Results obtained from this analysis has been compared with the existing empirical equations developed. Siddique et al. [103] has developed an empirical equation (Equation 4-3) for 7-days and 28-days of curing age to fit the effect of CBA on the compressive strength of bottom ash concrete mix. Similar empirical equation (Equation 4-4) were derived by M. a. a. abd elaty [119] for normal cement concrete to fit the compressive strength variation for 28-days of curing age (compressive strength=32 MPa and w/c=0.6).

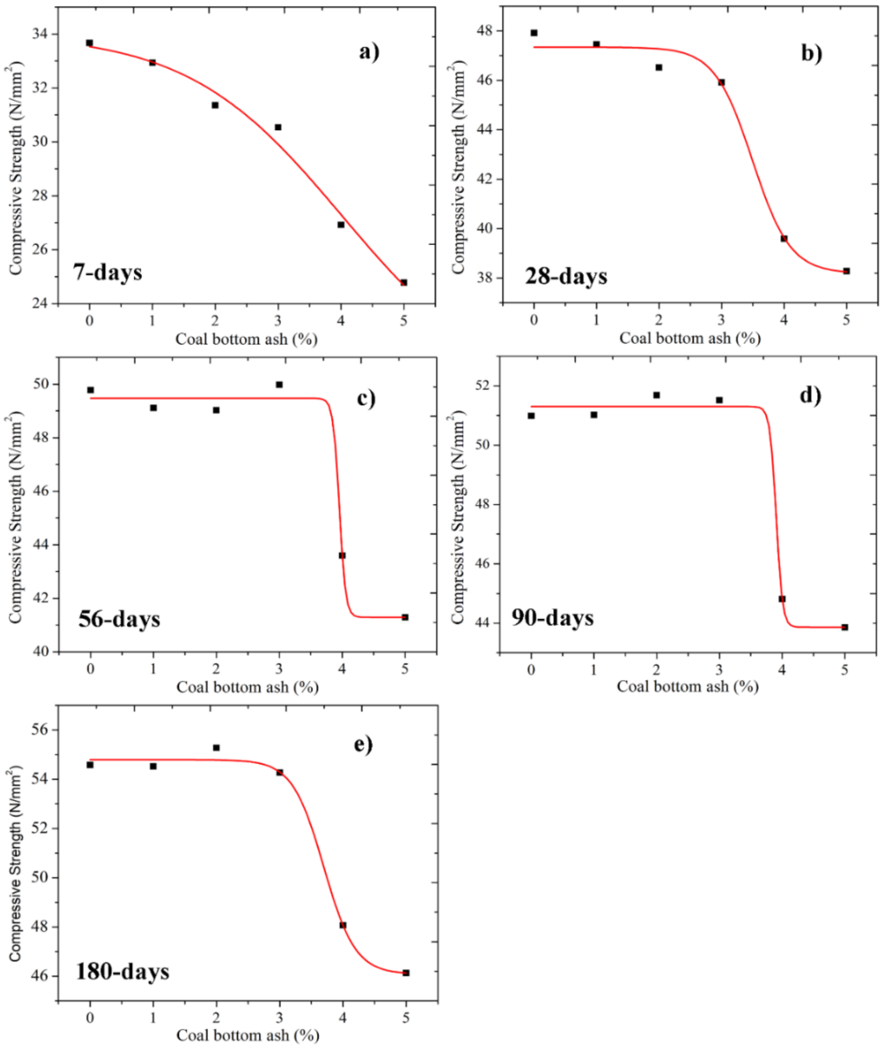


Figure 4-40 Regression curve for compressive strength of bottom ash concrete

$$f_t = C\ln(t) + D \quad (4\text{-}3)$$

$$C = 4.4077a^{0.1155} \quad D = 18.288e^{-0.019a} \quad R^2 = 0.9845$$

$$f_t = 6.2791\ \ln(t) + 9.2031 \qquad R^2 = 0.9907 \quad (4\text{-}4)$$

Where f_t is compressive strength of concrete, t is curing age in days and a is CBA content (%).

Table 4-23 Correlation coefficients for bottom ash concrete properties

Correlation Coefficient	**Bottom ash concrete**		
	Compressive Strength	**Flexural Strength**	**Splitting Tensile Strength**
	7 days		
A	20.49411	3.91341	3.27722
B	34.0307	-0.07049	-0.0997
C	4.01332	-0.07575	-1.5873E-4
D	-0.35364	0.01148	9.25926E-5
R^2	0.967	0.957	0.995
	28 days		
A	38.18893	4.80421	3.94413
B	47.34086	0.06089	-0.02132
C	3.49315	-0.12341	-0.08647
D	-1.43526	0.01657	0.01231
R^2	0.974	0.995	0.995
	56 days		
A	41.29	5.42294	4.48937
B	49.475	0.00935	0.08733
C	3.95374	-0.12016	-0.16444
D	-8.76299	0.01676	0.02093
R^2	0.975	0.992	0.965
	90 days		
A	43.86	5.9273	4.74056
B	51.305	-0.0613	-0.01763
C	3.90417	-0.10175	-0.12504
D	-8.71209	0.01352	0.01648
R^2	0.986	0.997	0.97
	180 days		
A	46.086	5.98111	4.90365
B	54.79033	0.09164	0.09519
C	3.69594	-0.14901	-0.15337
D	-1.74554	0.01713	0.01843
R^2	0.988	0.997	0.983

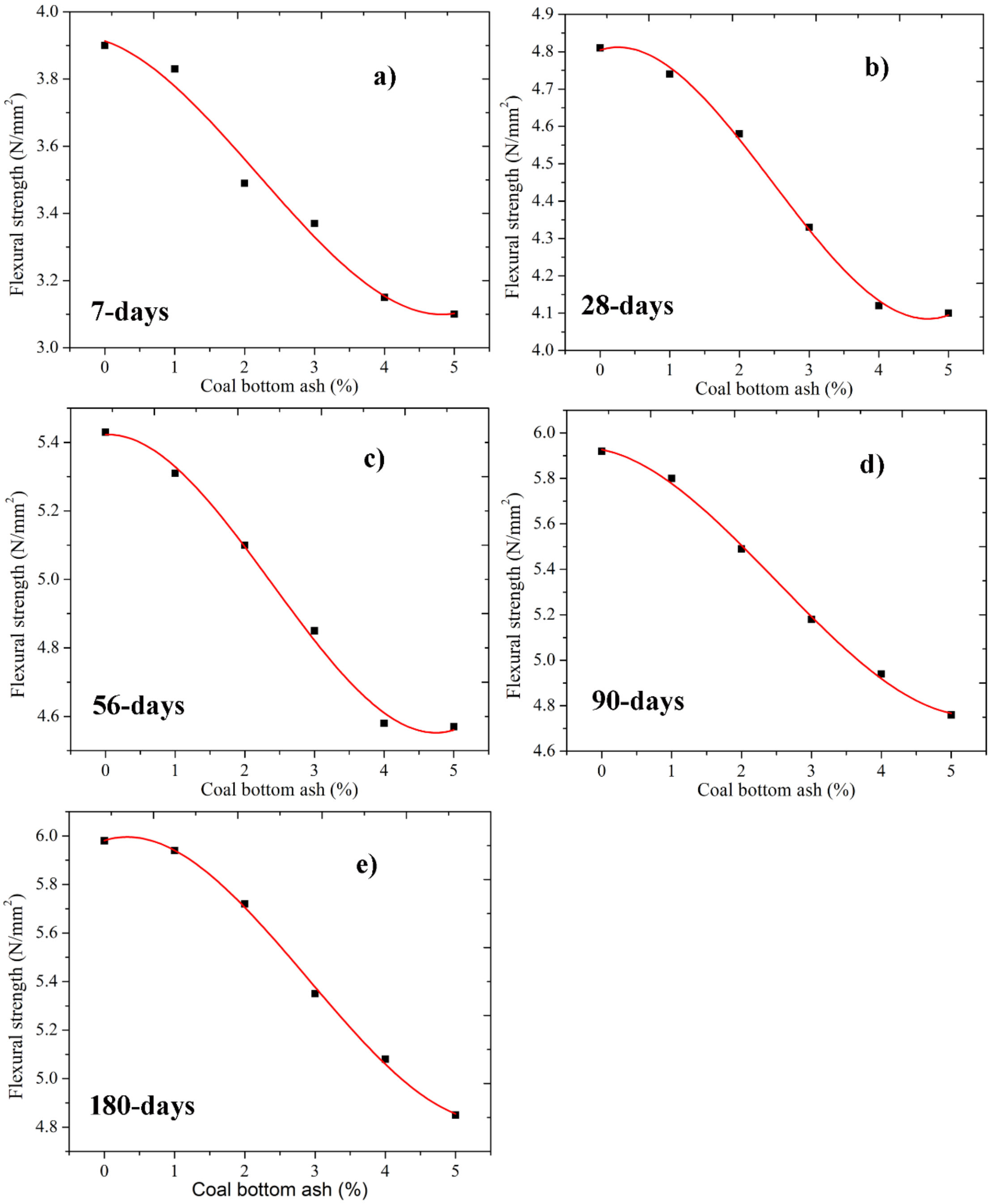


Figure 4-41 Regression curve for flexural strength of bottom ash concrete

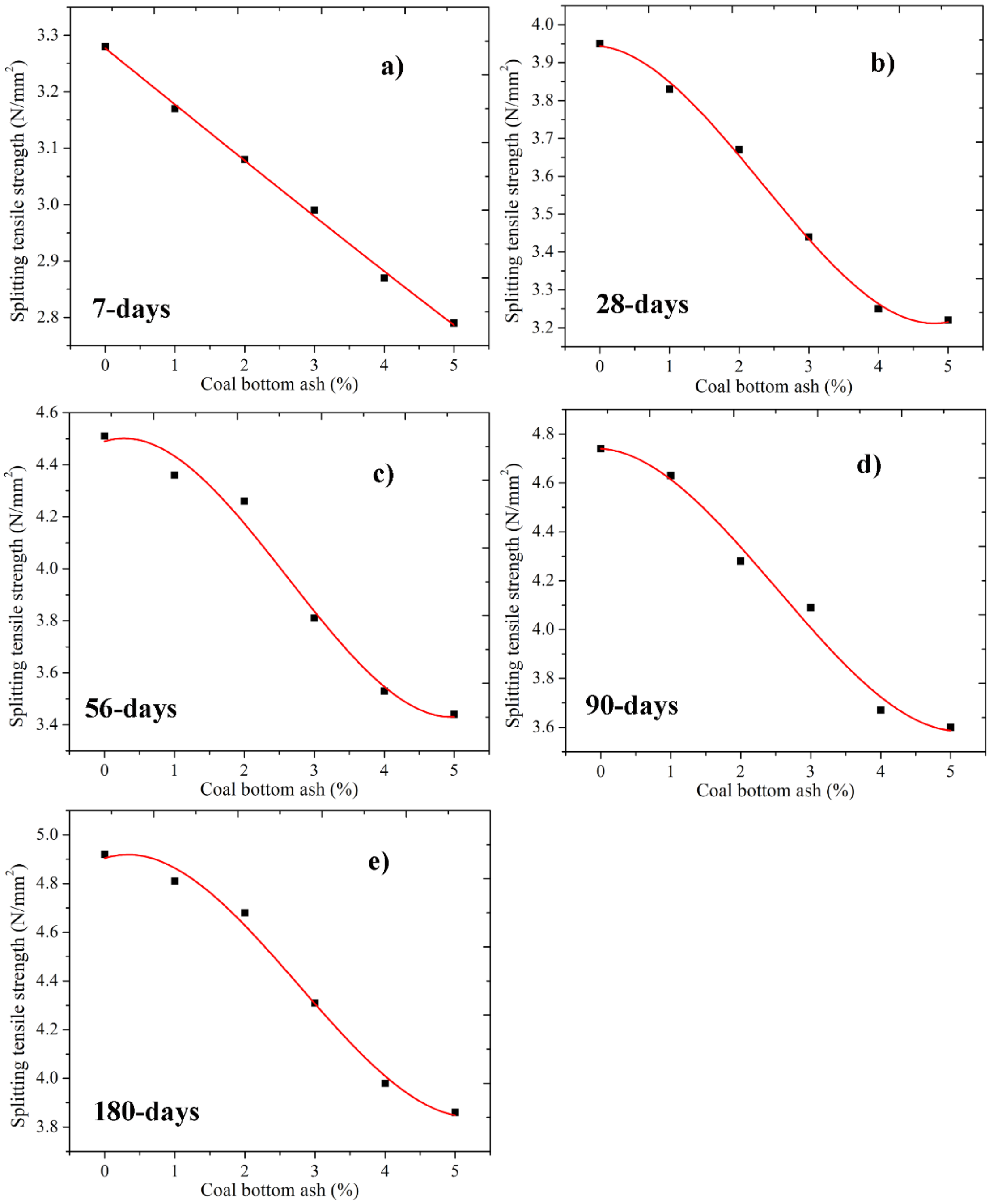


Figure 4-42 Regression curve for splitting tensile strength of bottom ash concrete

4.7.2 Phase-II

From Phase-II analysis, we have found that 15% inclusion of Alccofine in 40% bottom ash concrete can improve the properties of the concrete mixtures. A statistical analysis has been done to use these findings in future studies.

4.7.2.1 Empirical relationships for properties of Alccofine assisted bottom ash concrete

In this section, regression curve fitting has been performed to develop a relatioship among the various properties of Alccofine assisted bottom ash concrete.

Relation between compressive and split tensile strength (Phase-II)

Figure 4-43 represents the regression curve among compressive and splitting tensile strength and Equation 4-5 defines the relationship among compressive and splitting tensile strength. The R^2 value is 0.943 and the correlation coefficients are tabulated in Table 4-24.

$$Y = a + b * x^c \qquad (4\text{-}5)$$

Equation 4-5**,** 'Y' denotes the splitting tensile and flexural strength depending upon the coefficients values i.e. *a*, *b* and *c* (see Table 4-24). The term '*x*' denotes the compressive strength (along x-axis parameters).

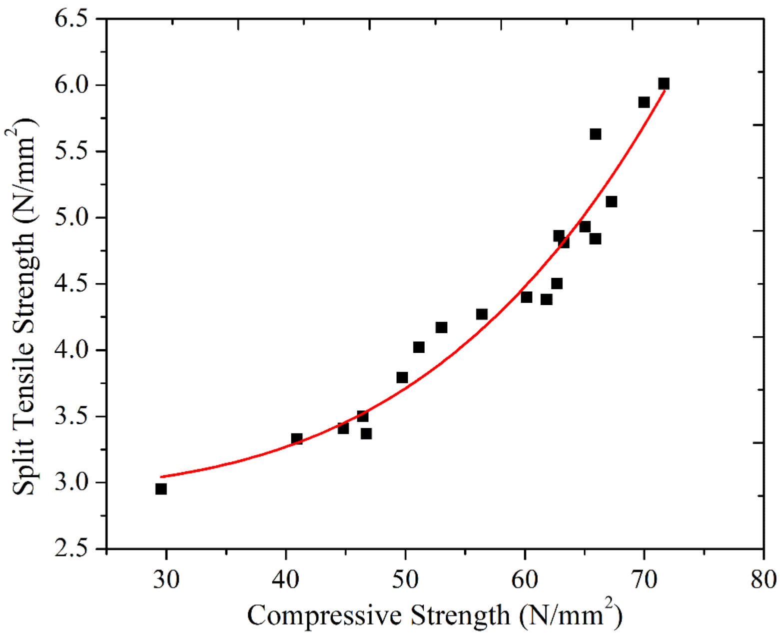


Figure 4-43 Regression curve between compressive and split tensile strength

Relation between compressive and flexural strength

Figure 4-44 describes the regression curve among flexural and compressive strength whose fitting curve is defined by Equation 4-5. Regression curve coefficients are tabulated in Table 4-24 and it can be observed that R^2 value is 0.941. These regression curves are modelled in such a way that if one calculates the compressive strength of any concrete at a specific curing age, then using Equation 4-5, the splitting tensile and flexural strengths can be evaluated for that perticular curing age.

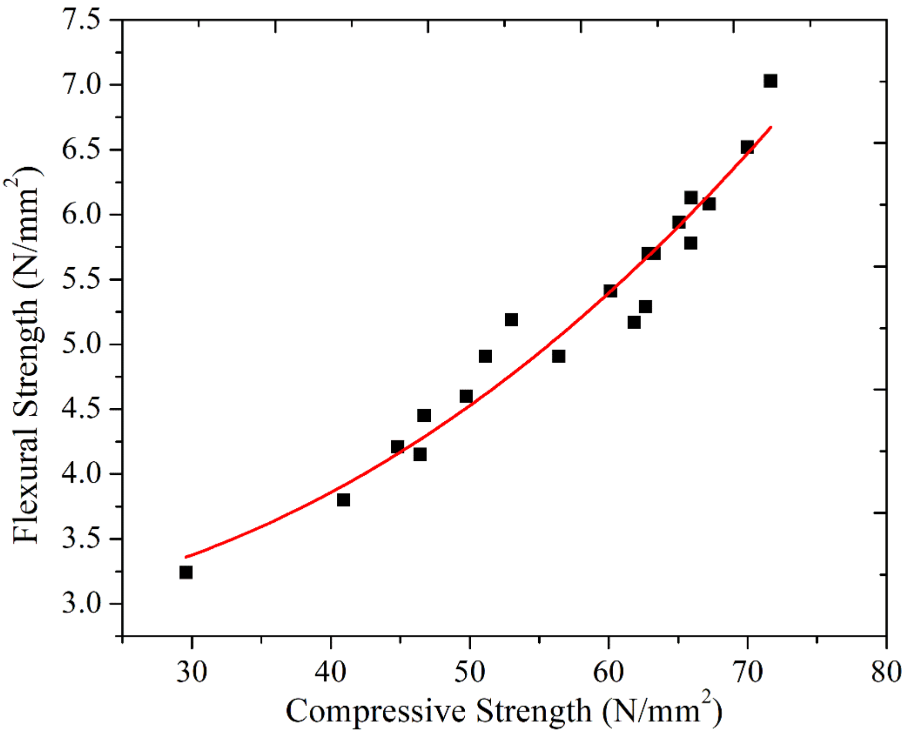


Figure 4-44 Regression curve between compressive and split tensile strength

Table 4-24 Correlation curve coefficients for concrete properties

Correlation Coefficient	Compressive strength and flexural	Compressive strength and splitting
a	2.85951	2.93665
b	2.0869E-4	2.96229E-7
c	2.2971	3.77727
R^2	0.943	0.941

Relation between strength properties and mixture content

Statistical analysis has been performed on compressive, flexural and splitting tensile strength and Alccofine assisted bottom ash concentrations to define an association among them such that if we know the concentrations of Alccofine in MB4 bottom ash concrete mix then one can calculate the compressive, flexural and splitting tensile strengths depending upon the values of correlation coefficients tabulated in Table 4-25. Equation 4-6 represents the regression fit where ‘Y’ describes the strength properties, ‘*x*’ denotes the Alccofine content and *a*, *b*, and *c* are the correlation coefficients. R^2 values are listed in Table 4-25 and it shows that the fit has excellently match the data.

$$Y = e^{(a+b*x+c*x^2)} \tag{4-6}$$

Figure 4-45, Figure 4-46 and Figure 4-47 describes the regression fits for compressive, flexural and splitting tensile strength properties at various curing ages.

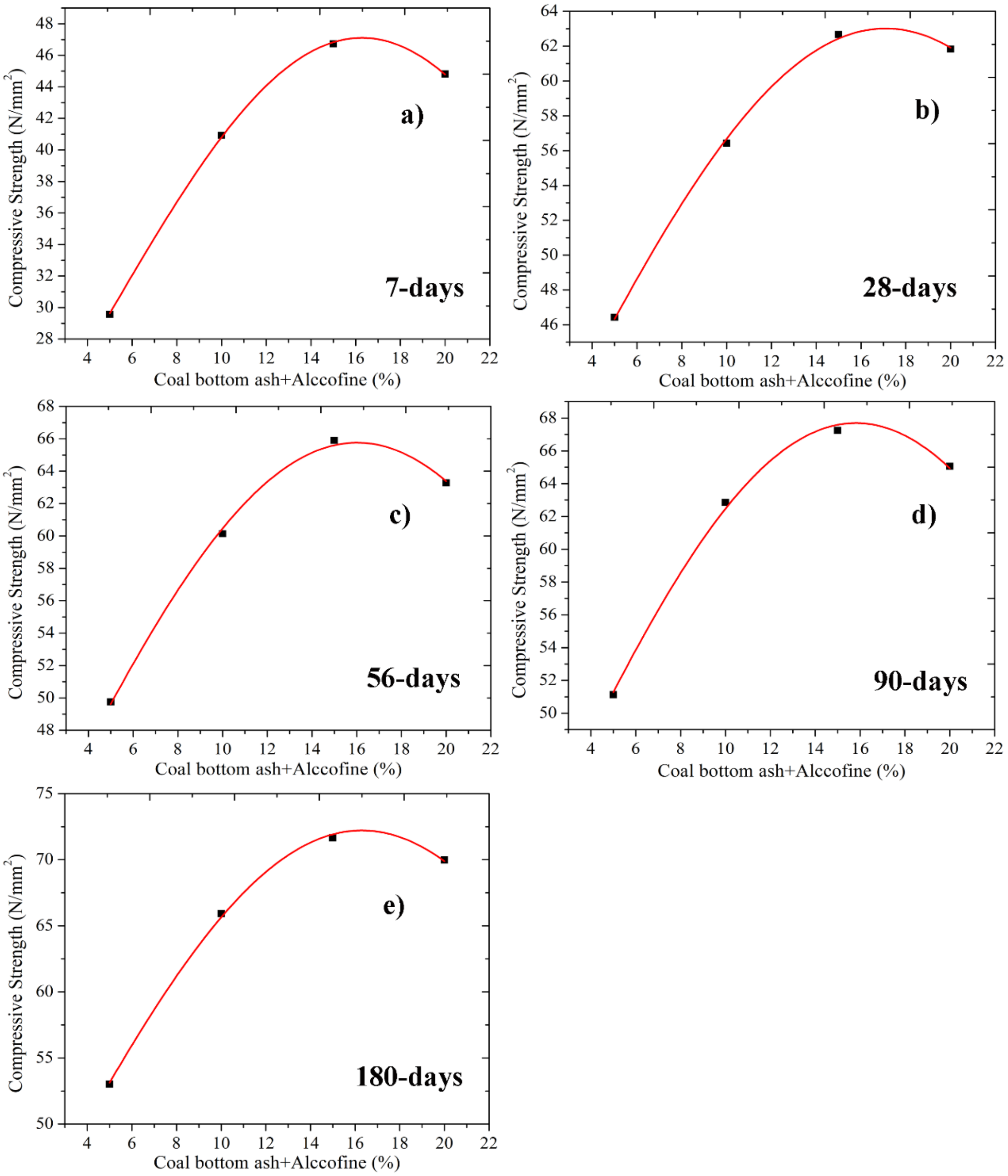


Figure 4-45 Regression curve among compressive strength and mixture content

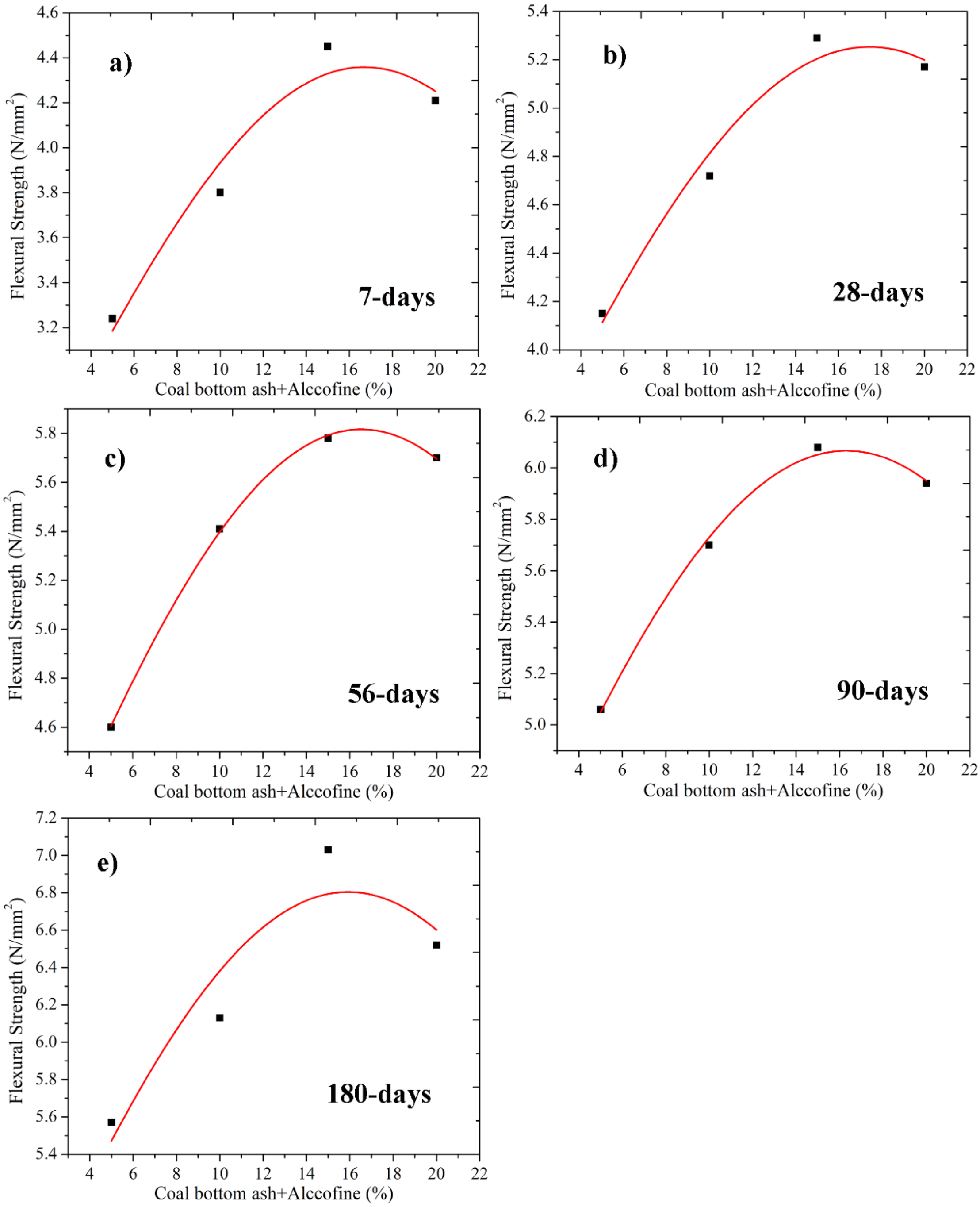


Figure 4-46 Regression curve among flexural strength and mixture content

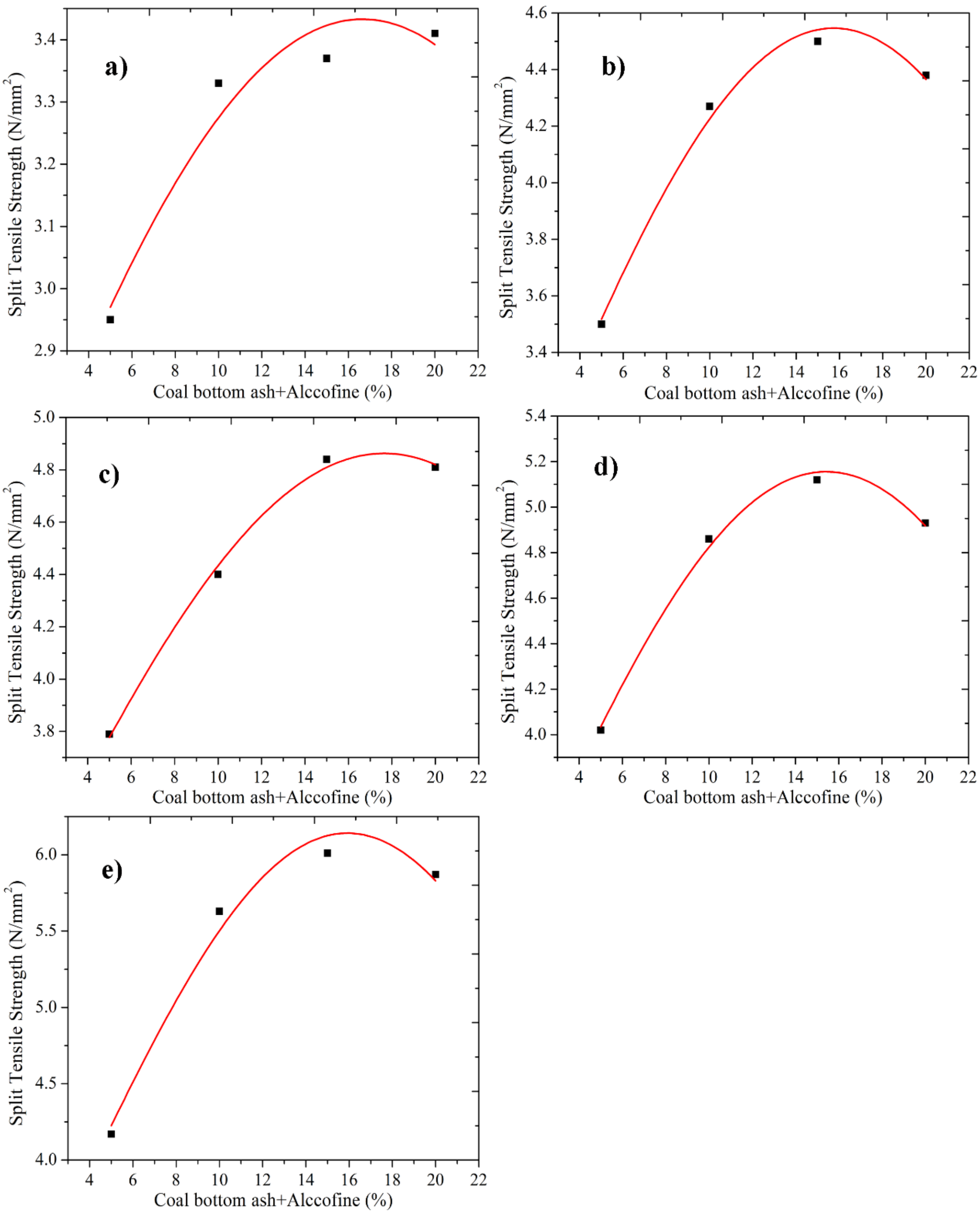


Figure 4-47 Regression curve among splitting tensile strength and mixture content

Table 4-25 Correlation coefficients for Strength properties of Alccofine assisted bottom ash concrete

Correlation Coefficient	**Compressive Strength**	**Flexural Strength**	**Splitting Tensile Strength**
		7 days	
a	2.88589	0.83337	0.93784
b	0.11878	0.0765	0.0355
c	-0.00365	-0.00229	-0.00107
R^2	0.999	0.87	0.855
		28 days	
a	3.52878	1.17826	0.96304
b	0.07189	0.05511	0.07009
c	-0.0021	-0.00158	-0.00223
R^2	0.997	0.932	0.98
		56 days	
a	3.59113	1.28096	1.08961
b	0.07428	0.05802	0.05576
c	-0.00232	-0.00175	-0.00158
R^2	0.995	0.999	0.99
		90 days	
a	3.6213	1.42085	1.10325
b	0.07508	0.04684	0.06959
c	-0.00237	-0.00144	-0.00226
R^2	0.994	0.991	0.988
		180 days	
a	3.64156	1.45464	1.02052
b	0.07827	0.05813	0.0998
c	-0.0024	-0.00183	-0.00313
R^2	0.998	0.65	0.95

Relation between pulse velocity and mixture content

In this study, an attempt has been made to correlate pulse velocity and mixture content such that if the concentration of Alccofine then pulse velocity can be reproduced for MB4 bottom ash concrete mixture for concrete design. Equation 4-7 represents the regression fit and the coefficient’s values are tabulated in Table 4-26. Figure 4-48 describes the regression curve fitting the data points at various curing ages. It can be noticed that curve has fitted the data very well and R^2 value is very close to 1.

$$Y = e^{(a+b*x+c*x^2)} \quad (4\text{-}7)$$

In the Equation 4-7, 'Y' represents the pulse velocity, '*x*' denotes the Alccofine mixture content in MB4 bottom ash concrete and *a*, *b* and *c* are correlation coefficients whose values are tabulated in Table 4-26.

Table 4-26 Coefficients for Pulse velocity and RCPT

Correlation Coefficient	**Pulse Velocity**	**RCPT**
	28 days	
a	8.30097	8.03608
b	0.01577	-0.10011
c	-4.36152E-4	0.0022
R^2	0.999	0.992
	90 days	
a	8.32315	8.00975
b	0.01743	-0.14547
c	-5.18754E-4	0.00389
R^2	0.989	0.98
	180 days	
a	8.35059	7.99035
b	0.01814	-0.18316
c	-5.61116E-4	0.00466
R^2	0.997	0.959

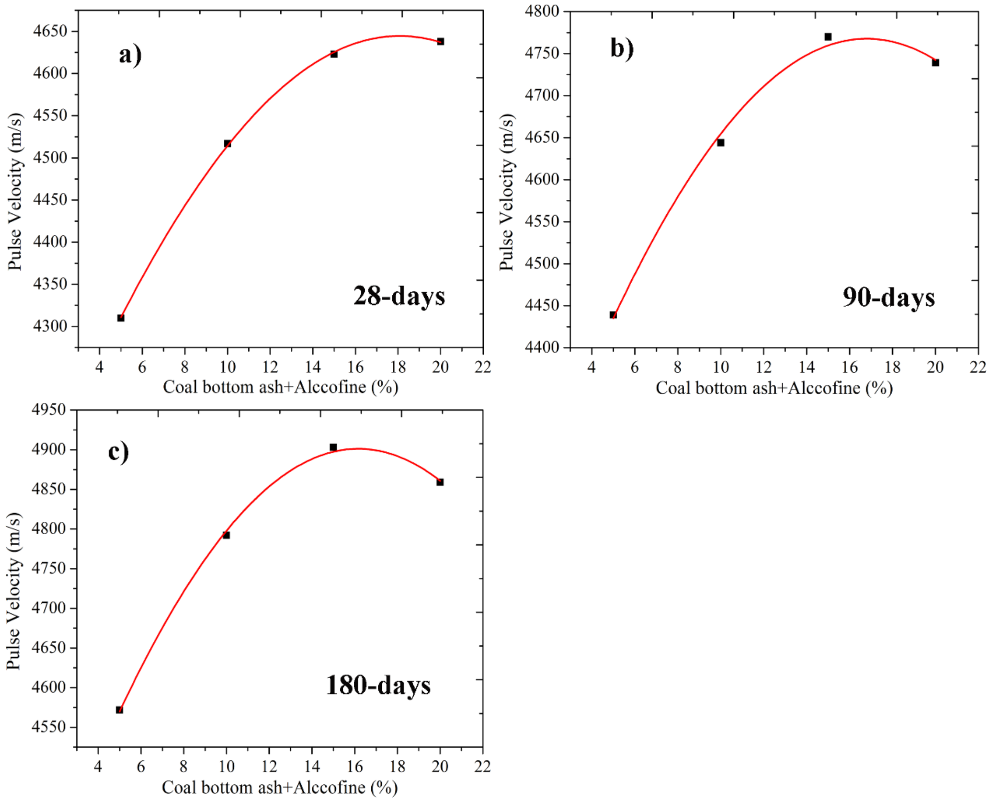


Figure 4-48 Regression curve among pulse velocity and mixture content

Relation between chloride penetration and mixture content

Similarly, chloride penetration has also been correlated with mixture content at various curing ages such that one can directly evaluate the chloride-ion penetration values using Equation 4-7. In Equation 4-7, ‘Y’ represents the charge passed in coulombs, ‘*x*’ denotes the Alccofine mixture content in MB4 bottom ash concrete and *a*, *b* and *c* are correlation coefficients whose values are tabulated in Table 4-26. Figure 4-49 describes the regression curve among pulse velocity and mixture content.

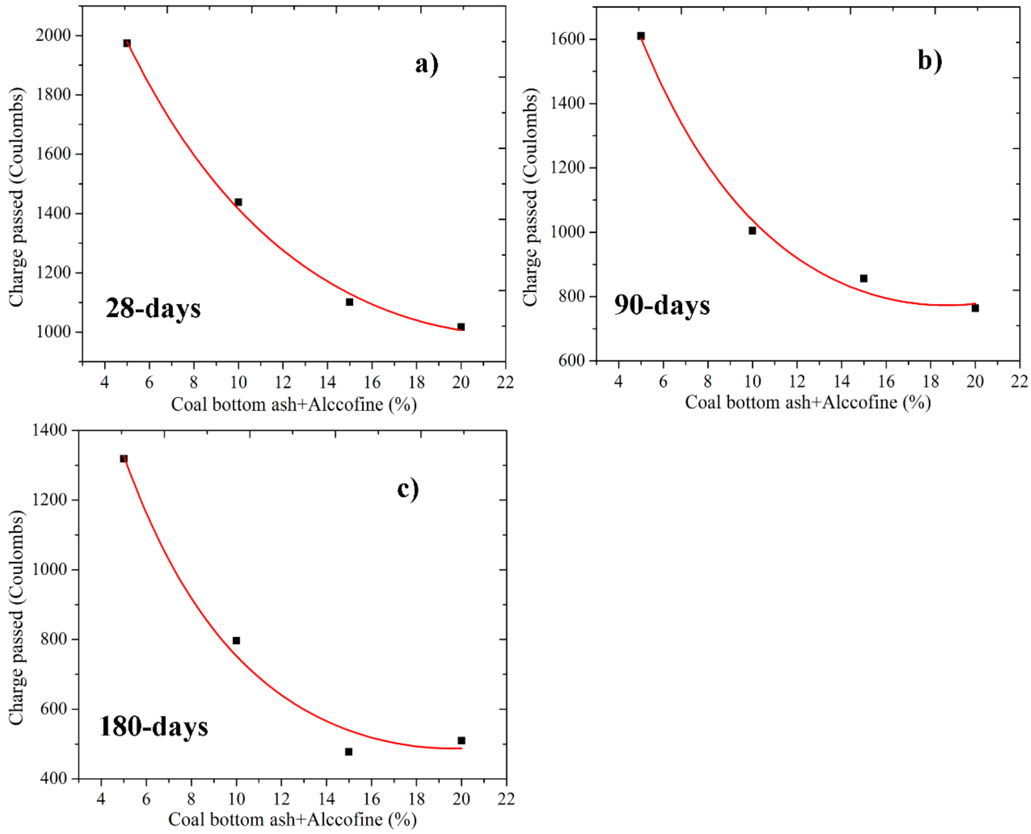


Figure 4-49 Regression curve among pulse velocity and mixture content

Relation between compressive strength and pulse velocity

Using regression analysis, association among compressive strength and pulse velocity has been developed and defiend by Equation 4-8 and plotted in Figure 4-50. In Equation 4-8, 'Y' represents the pulse velocity, '*x*' denotes the compressive strength of Alccofine assisted bottom ash concrete and *a*, *b* and *c* are correlation coefficients whose values are tabulated in Table 4-27.

$$Y = e^{(a+b*x+c*x^2)} \tag{4-8}$$

Relation between compressive strength and chloride penetration

Figure 4-51 represents the regression curve for the charge passed in Coulombs w.r.t. compressive strength of the Alccofine assisted bottom ash concrete. The correlation coefficients can be found in Table 4-27, where *a*, *b* and *c* are correlation coefficients. Equation 4-8 represents the fitted model and 'Y' is a measures of chloride penetration and '*x*' denotes compressive strength of Alccofine assisted bottom ash concrete.

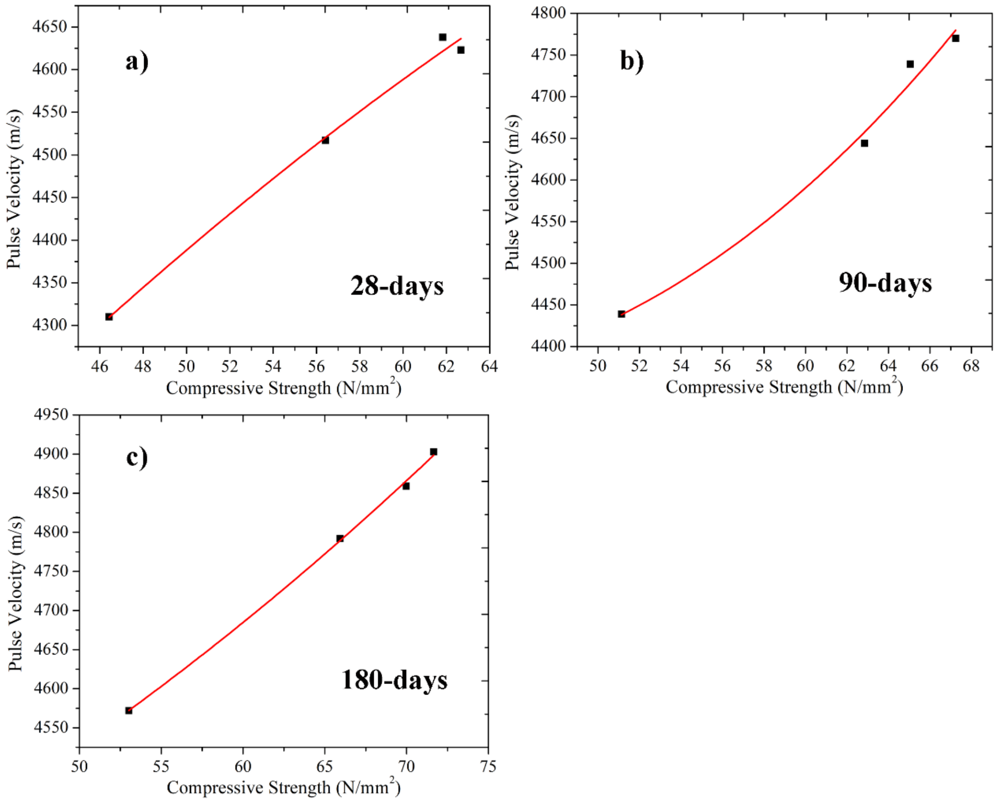


Figure 4-50 Regression curve among pulse velocity and mixture content

Table 4-27 Coefficients for compressive strength, pulse velocity and RCPT

Correlation Coefficient	**Compressive strength & Pulse Velocity**	**Compressive strength & RCPT**
	28 days	
a	8.02836	6.1642
b	0.00942	0.08272
c	-4.50826E-5	-0.00112
R^2	0.98	0.95
	90 days	
a	8.54356	11.41055
b	-0.00851	-0.10589
c	1.10737E-4	5.31059E-4
R^2	0.964	0.88
	180 days	
a	8.30186	-1.39636
b	0.00139	0.3241
c	1.85007E-5	-0.00306
R^2	0.997	0.988

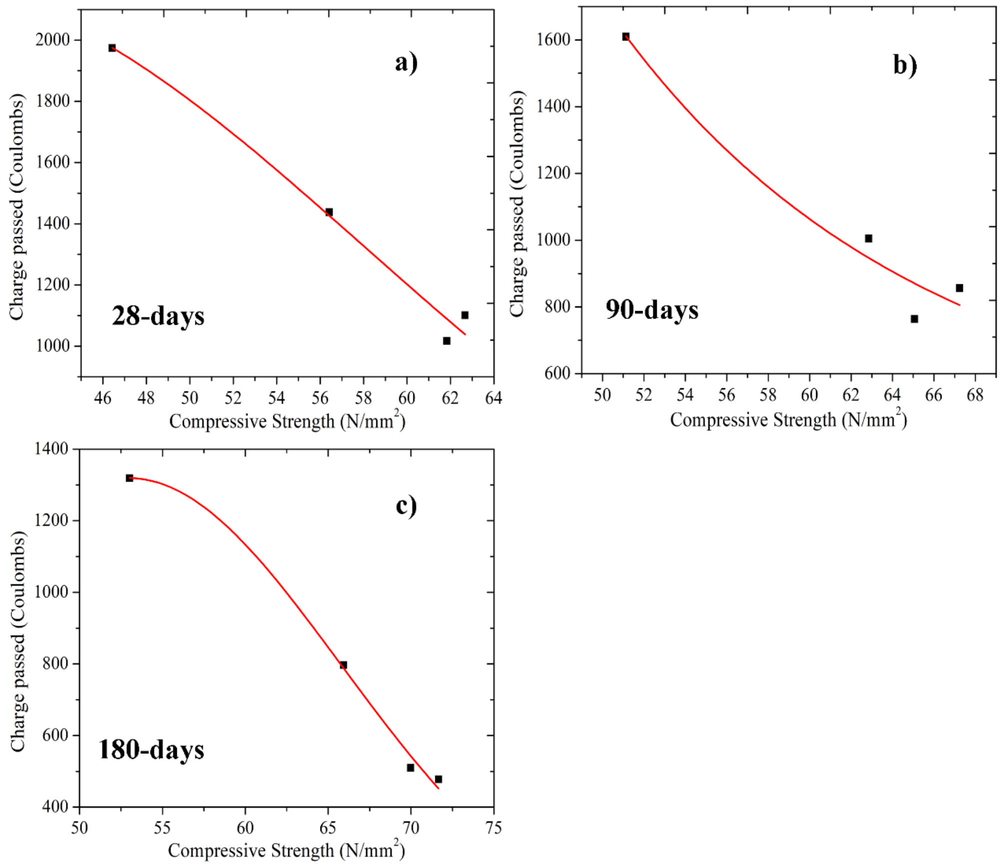


Figure 4-51 Regression curve among pulse velocity and mixture content

CHAPTER

5 CONCLUSIONS

In the present dissertation work, a challenge has been initiated to use industrial waste i.e. coal bottom ash (CBA) as an economical alternative to fine aggregate. Potential of CBA as a partial replacement of fine aggregates and Alccofine as a partial replacement of cement has been investigated. The microstructure of bottom ash concrete has also been examined. It has been found that 40% replacement of fine aggregates with coal bottom ash has potential to represent an alternative of natural sand. Based on the Phase-I and Phase-II studies, useful conclusions can be drawn.

5.1 Phase-I Outcomes

1. The workability of the bottom ash concrete mix has decreased as more superplasticizer has been added to maintain a slump of 100 mm and to keep the water/cement ratio constant. During analysis, it has been found that dosage of superplasticizer (DoS) increased with the addition of CBA in concrete i.e. DoS for control mix (MB0) is 1.1%, for MB1 is 1.2%, for MB2 is 1.5%, for MB3 is 2.2%, for MB4 is 2.5% and for MB5 is 2.9%. It has been concluded that the workability is decreased due to the porous behaviour of coal bottom ash particles (which have been observed from SEM analysis). Due to more water absorption of CBA particles, the reduction in availability of free water for lubrication can be concluded, which ultimately increase the superplasticizer dosage to maintain the water/cement ratio.
2. It has been observed from the test results that as compared to the controlled concrete mix, the compressive strength has decreased and the percentage change is significant at 7-day of curing age for MB1 (≈2.2%), MB2 (≈7%) and MB3 (≈9%) concrete mixtures. However, the percentage change is moderate at 28-day, 56-day, 90-day and 180-day of curing age. It has been observed that the percentage drop in splitting tensile strength is significant for all the mixtures at all ages. The maximum decrease is experienced for MB5 (≈24% at 90-day curing age) where 50% of fine aggregates have been replaced with CBA. It has

also been observed that the percentage drop in flexural strength of the bottom ash mixtures w.r.t. MB0 i.e. control mix. It can be noticed that flexural strength of concrete mixtures has experienced a significant drop at all ages.

Finally, it can be concluded that the decrease in properties may resulted due to following reasons: 1) increased porosity of CBA mixtures, 2) lower strength of CBA (low specific gravity), 3) deficiency of pozzolanic motion by CBA.

3. From Ultrasonic Pulse velocity testing, it has been found that the flowability and quality of bottom ash concrete is decreased.
4. RCPT has also indicated that the resistance to chloride-ion penetration is poor for bottom ash concrete compared to control mixture. This implies concrete mixture has poor performance to acid attacks.
5. It has been perceived that the surface water absorption capacity has decreased with curing age and time for both MB0 and MB4 mix. However, the water absorption capacity of MB4 bottom ash concrete mixture is more than MB0. This is may be because of the fact that with the addition of coarse CBA material as a fractional change in place of fine aggregates, the overall voids among the structure has increased which has more capacity to soak the water.
6. SEM images revealed multiple dominant pores in bottom ash concrete mixtures due to which a significant drop in strength and durability properties of concrete has been experienced for MB4 mix. Increase in the size and number of pores is evident for the mix containing 40% of CBA, thus resulting in reduction of strength for bottom ash concrete mixtures as through these pores micro-cracks can propagate rapidly and bottom ash concrete mixes provide less resistance to external loading when equated to other mixtures. SEM images revealed that MB4 mix possesses discontinuous/irregular C-S-H gel matrix network as compared to that of MB0 and MB4A15 mixtures. This may have been contributed to the fact behind the reduction in compressive strength and other mechanical properties for MB4 mixtures, when compared to that of MB0 and MB4A15 mixtures. The other reason behind the reduction of mechanical properties of bottom ash concrete can be correlated using XRD studies available in the literature, which revealed the weak diffraction peaks of discontinued and poorly crystalline calcium silicate hydrate phase of bottom ash concrete mix.

5.2 Phase-II Outcomes

1. It can be concluded that the workability and compressive strength at all ages of Alccofine 1203 assisted bottom ash concrete is improved due to the unique characteristics of Alccofine material which includes finer particle size distribution and inbuilt CaO which further form dense pore structure. Also, Alccofine 1203 inclusion in MB4 concrete mix has reduced the dosage of superplasticizer and improved the compressive, splitting tensile and flexural strength of the concrete compared to coal bottom ash.
2. At 28-day curing age, the pulse velocity of control concrete mix is 4564 m/s and at 180-day, it is 4810 m/s. For bottom ash concrete (MB4), the pulse velocity decreased by 6% at 28- day of curing age. Moreover, for Alccofine assisted bottom ash concrete (MB4A15), there is 1.3% increase in the pulse velocity of concrete mix at 28-day of curing age has been observed. It has been concluded from pulse velocity test that the quality of the concrete degraded with the replacement of fine aggregates with coal bottom ash. Thus, it has been found that due to continued hydration process, the pulse velocity is increased with curing age which shows there is significant increase in the gel/space ratio.
3. Also, RCPT test results empower the MB4A15 concrete mix as it showed very low chloride-ion penetration due to its dense pore structure and chemical stability. Due to finer particle size distribution and chemical stability of Alccofine results in formation of dense pore structure and inbuilt CaO triggers the secondary hydrated products which fill the pores which further reduces the hydrated product’s permeability and shields the concrete from foreign chemical attack.
4. Some good permeability characteristics can also be seen for Alccofine assisted bottom ash concrete mixtures. Infusion of Alccofine has greatly enhanced the weak pore structure of bottom ash concrete mixture leading to the extensive pore refinement. The water movement characteristics and transmission rate of harmful ions, within the concrete, were significantly modified. Ultrafine nature of Alccofine enhanced the packing density, thus improved pozzolanic reactions

to reduce pore size and porosity of concrete. Minimized voids resulted in low absorption and permeability.

5. Furthermore, empirical equations have been established for the strength properties at various curing ages for bottom ash and Alccofine assisted bottom ash concrete which show an excellent agreement in calculating determination coefficient when compared with previous studies. Thus, these empirical equations can be used in future studies to validate the results.
6. Formation of extra C-S-H due to the pozzolanic reactions projected dense pore structure and ultimately higher strength gain at all ages. Prolonged pozzolanic activities, due to the incorporation of Alccofine, can be assumed as a function of its particle size distribution and chemical composition. The fibrous C-S-H gel formation act as a membrane for the admittance of chloride ions into concrete, thus making it more durable to harsh environmental conditions as evident from RCPT values. Dense and continuous CSH gel network for MB4A15 mix may be due to the fact that the formation of CSH gel is more with Alccofine assisted concretes due to the conversion of $Ca(OH)_2$ to secondary CSH, thereby resulting in the enhanced strength as compared to the other mixtures. For MB4A20 concrete mix, a decrease in compressive strength was observed compared to MB4A15 concrete mix.
7. It can be observed that percentage change in cost has increased in Phase-I with simultaneous reduction in the compressive strength of the bottom ash concrete compared to control concrete. However, with the addition of Alccofine as partial replacement of cement, the percentage difference in cost has decreased with simultaneous increase in the compressive strength of Alccofine assisted bottom ash concrete compared to control mix. Thus, in conclusion it can be noticed that for MB4A15 mix, the cost has increased to 8.14 % compared to control concrete, however, a significant increase of 58.3% in compressive strength can be observed which is very large compared to the cost involved.

Therefore, it has been concluded that 40 % of the industrial waste i.e. coal bottom ash with combination of 15% Alccofine material, as a replacement of cement, is a desirable combination in order to achieve enhanced properties of concrete at fresh as well as hardened stage. Rounded shape of ultrafine material with optimized particle size and unique chemical composition can be analysed as major factors contributed to improved properties of Alccofine assisted CBA mixtures.

5.3 Future Scope

Concrete production and utilization is going to increase in coming decades due to population growth and rise in living standards. Thus, replacement of fine aggregates is an essential and critical research topic along with discovering novel alternatives for cement replacement which will ultimately reduce CO_2 production. This dissertation work will enlighten the new directions of concrete research where ultra-slag material can be used cement replacements and industrial waste i.e. coal bottom ash can be used as alternative for natural sand.

However, in future more rigorous analysis can be performed to achieve optimum results and a few of such points of research problem has been summarized as follows:

- On inclusion of CBA, the drop in properties has been experienced at all curing ages and mix proportions, however, in future, some other alternate materials can be used as individual or in a combination with CBA.
- Water/cement ratio is fixed for this current experimental work, however, for variable water/cement ratio, such analysis can be performed to understand the physical and chemical properties of the concrete mixture.
- In this work, a particular Zone-II sand has been used for the analysis, however, in future the same study can be performed for other Zone-I or Zone-III such that the nature of CBA can be understood with more accuracy.
- In this study, authors have tried Alccofine material for 40% bottom ash concrete mix, however, in future other possibilities can also be explored.

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