

**STRUCTURAL PERFORMANCE OF SELF  
COMPACTING CONCRETE MADE WITH WASTE  
PLASTIC**

Thesis Submitted for the Award of the Degree of

**DOCTOR OF PHILOSOPHY**

in

**Civil Engineering**

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**LOVELY PROFESSIONAL UNIVERSITY, PUNJAB**

**2024**

***This thesis is dedicated to my Mother Vutukuru. Jaya Kumari, Father Vutukuru. Sai Babaiah, Elder Sister: Y. Sai Kusuma Kumari; Brother-in law: Y. Pradeep; Daughter: Y. Jasvika, Y. Parnika, my Supervisor Dr. Vaibhav Sharma, School of Civil Engineering, Assistant Professor, Lovely Professional University, Phagwar, Punjab, India, who supported me a lot to enter into the research field and my close ones who created interest in me for understanding the different aspects of life.***

## **DECLARATION**

I, hereby declared that the presented work in the thesis entitled “Structural Performance of Self Compacting Concrete Made with Waste Plastic” in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision of Dr. Vaibhav Sharma, working as Assistant Professor, in the School of Civil Engineering, of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

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## **CERTIFICATE**

This is to certify that the work reported in the Ph. D. thesis entitled “Structural Performance of Self Compacting Concrete Made with Waste Plastic” submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the School of Civil Engineering, is a research work carried out by Ms. V Sai Neeraja , 41800109 , is bonafide record of her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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## **ABSTRACT**

Over the past two decades, there has been a rapid growth of self-compacting concrete (SCC) in the construction industry. SCC is an emerging class of smart composites that have drawn the attention of researchers. SCC is characterized by its exceptional fluidity and self-leveling nature, allowing it to flow and occupy the formwork effortlessly without requiring mechanical vibration. This extraordinary attribute leads to a substantial decrease in labor demands, reduces noise pollution, and improves the quality and aesthetics of concrete structures. SCC marks a revolutionary change in concrete technology, gaining recognition for its efficiency and potential for sustainability.

The phenomenal rise in both population and urbanisation has increased demand for building supplies, with concrete being one of the most widely used materials worldwide. Furthermore, it is undeniable that the alarming surge in the generation of plastic waste is a primary contributor to environmental harm. Plastics waste (PW) is a ubiquitous material in modern life, owing to their exceptional adaptability and ease of use. They are obtained from petrochemical sources. Yet, the widespread use of plastics waste which is a non-bio degradable material has come at a high cost, with plastic garbage overflowing landfills, contaminating rivers, damaging food chain and corrupting ecosystems. In order to address this dilemma, it is necessary to find creative ways to reuse and repurpose recycled plastic materials in addition to lowering plastic use, which will keep them out of the trash stream.

In response to these challenges, the integration of sustainability as a major key parameter has become imperative in the construction industry's quest for more eco-friendly materials and practices. Numerous research teams have been focusing on the reinforcement of waste plastic materials into SCC in an effort to mitigate two pressing issues: the management of plastic waste and the environmental effects of producing concrete using standard methods. Although waste plastics have been used in SCC in certain studies, there is limited research that explores their combination with other industrial by products including fly ash, copper slag, and construction demolition waste like recycled coarse

aggregate. Analysing these synergies presents a chance to develop a sustainable concrete matrix that is more sustainable and all-encompassing.

This dissertation reflects the structural features SCC mixes after reinforcing the waste plastic as a main additive. For optimizing the SCC mixes with the different industrial wastes Taguchi technique was adopted. The Taguchi Optimization technique enables the identification of optimal combinations and proportions of these materials to achieve the desired structural performance while minimizing resource consumption, environmental impact and aiming to optimize the incorporation of industrial plastic waste along with other industrial by products. This research was carried out by cement replacement with 25, 30, 35, 40, 45 percentages of Fly Ash (FA), and also 0, 3, 6, 9, 12 percentages of Copper Slag (CS), and 0, 5, 10, 15, 20 percentages of Plastic Waste (PW) replacement with fine aggregate and 0, 25, 50, 75, 100 percentages of Coarse Aggregate are replacement with construction waste like Recycled Coarse Aggregate (RCA). The Design of Experiments (DOE) was developed with the L25 Orthogonal array (25 mixes). SCC mix design was performed using Indian Standard: 10262:2019 code of practice. The incorporation of waste plastic granules and recycled coarse aggregates demonstrates a substantial impact on both the fresh and hardened properties of SCC mixes.

This dissertation aims to provide a novel, comprehensive and scientifically grounded investigation into the structural performance and sustainability implications of SCC modified with waste plastic. In this dissertation based on the Taguchi design 25 SCC mixes were casted and fresh, hardened properties and microstructural analysis were evaluated. The findings exhibited that the significance of input parameters related to filling ability, passing ability, and viscosity in fresh properties is illustrated through the response curves of the Signal-to-Noise (S/N) ratio. The evaluation of the S/N ratio response curves at 7, 28, 56 and 90-days are conducted. The Analysis of Variance (ANOVA) indicates a lower ranking for PW, signifying that its incorporation can enhance the sustainability of SCC without compromising workability, compressive strength and split tensile strengths at 7,28,56 and 90-days of curing period.

In this current dissertation, plastic waste embedded SCC flexural test findings of M1 and M14 mixes are considerably nearby in connection to standard concrete mix. Besides the crack propagation finding also justify M1 and M14 mixes also improved structural performance with absence of web shear cracks. Additionally, the results obtained from durability assessments, such as the acid attack test, at 28 and 56-days curing periods offer a comprehensive insight into the chemical interactions and impact on the strength characteristics of plastic waste within the SCC. Furthermore, the findings from Rapid Chloride Penetration Tests (RCPT) at 28-days curing period suggest a discernible correlation, indicating that SCC members exhibiting higher compressive strength tend to exhibit lower voltage of charge passing through the test samples.

In this dissertation the findings of X-ray diffraction (XRD) characterization conducted on the mixes Mix 0, Mix 1, Mix 14, Mix 20, Mix 21 and Mix 19 at 56-day curing period, reveals that the diffraction peak positions at 2 Theta, falling within the range of 26 to 27 degrees, displayed a consistent pattern, indicating a well-progressed hydration process. These peaks corresponded to the presence of Calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ), underscoring effective hydration and due to carbonization, the compositions primarily consisted of unhydrated clinker, with a minor presence of  $\text{CaCO}_3$  and  $\text{Ca}(\text{OH})_2$ . This suggests that carbonation had a significant impact on the casted SCC mixes. Three Dimensional (3-D) optical microscope findings reveals the concrete composite damage interactions at specific locations, providing a deeper understanding of the interaction mechanism between plastic waste granules and the matrix, C-S-H crystalline structure, Interfacial transition zones at 7, 28 and 56-days curing periods for Mix 0, Mix 1, Mix 14, Mix 20, Mix 21 and Mix 19. As the construction industry continues to seek innovative solutions to environmental challenges, the utilization of waste plastic in self-compacting concrete emerges as a promising avenue for achieving both structural efficacy and eco-friendly construction practices.

**Keywords:** Self-Compacting Concrete, Plastic Waste, Sustainability, Taguchi Optimization technique, Fresh Properties, Mechanical Properties, Durability, Microstructural Analysis.

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## LIST OF SYMBOLS

S.NO	SYMBOL	FULL FORM
1	°C	Degree Centigrade
2	%	Percentage
3	MPa	Mega Pascal
4	CO <sub>2</sub>	Carbon dioxide
5	C-S-H	Calcium Silicate Hydrate
6	S/N	Signal-To-Noise
7	NaOH	Sodium Hydroxide
8	NaCl	Sodium Chloride
9	HCl	Hydrochloric
10	Ca (OH) <sub>2</sub>	Calcium Hydroxide
11	CaCO <sub>3</sub>	Calcium Carbonate
12	C <sub>2</sub> S	Dicalcium Silicate
13	C <sub>3</sub> S	Tri Calcium Silicate
14	µm	Micron Meter
15	N/mm <sup>2</sup>	Newton per Millimetre Square
16	w/c	Water Cement Ratio
17	Al <sub>2</sub> O <sub>3</sub>	Aluminium Oxide
18	Fe <sub>2</sub> O <sub>3</sub>	Ferrous Oxide
19	m <sup>2</sup> /Kg	Meter Square per Kilogram
20	mm	Millimetre
21	g/cm <sup>3</sup>	Grams per Cubic Centimetre
22	KPa	Kilo Pascals
23	kg/m <sup>3</sup>	Kilogram per Cubic Metre

## LIST OF ABBREVIATIONS

S.NO	ABBREVIATION	FULL FORM
1	SCC	Self-Compacting Concrete
2	CS	Copper Slag
3	FA	Fly Ash
4	PW	Plastic Waste
5	RAC	Recycled Aggregate Concrete
6	SF	Silica Fume
7	SCMs	Supplementary Cementitious Materials
8	C-S-H	Calcium Silicate Hydrate
9	PVC	Polyvinyl Chloride
10	ANOVA	Analysis Of Variance
11	ITZ	Interfacial Transition Zone
12	OPC	Ordinary Portland Cement
13	TTPS	Thermal Power Plants
14	CPCB	Central Pollution Control Board
15	CDW	Construction And Demolition Waste
16	NA	Natural Aggregates
17	R&D	Research And Development
18	CTM	Compression Testing Machine
19	XRD	X Ray Diffraction Analysis
20	3D	Three-Dimensional
21	UTM	Universal Testing Machine
22	GCS	Ground Copper Slag
23	EMs	Effective Microorganisms
24	IS	Indian Standard
25	SP	Super Plasticizer
26	OA	Orthogonal Array

27	DOE	Design Of Experiments
28	EFNARC	European Federation of National Associations Representing for Concrete
29	ASTM	American Society for Testing and Materials
30	RCPT	Rapid Chloride Penetration Test
31	CC	Conventional Concrete
32	NVC	Normal Vibration Concrete
33	ASH	Aluminium Silicate Hydrate
34	RCC	Reinforced Cement Concrete
35	SDGs	Sustainable Development Goals

# CHAPTER 1

## INTRODUCTION

### **1.1 Basic Overview:**

Concrete stands out as the preferred building material for construction when compared to alternatives. Its usage is only surpassed by water in the current state of the construction industry. Concrete's incredible adaptability, ease of building, and specific durability features has made it a key component of construction for decades [1]. The contemporary construction industry confronts a fundamental challenge in meeting the growing demand for cost-effective and efficient construction materials, with a particular focus on the sustainability of concrete, which heavily relies on natural materials in the form of fine and coarse aggregates, constituting over 70% of its volume.

The accessibility of natural resources such as natural river sand and coarse aggregate may diminish over time. The construction industry has been challenged to look at alternatives to minimize its dependency on natural fine aggregate due to the significant issue with natural sand. However, waste generation has increased due to rapid urbanization and industrialization. Industries typically dispose of their waste by discharging it into the environment, frequently without any prior treatment [1]. It would seem reasonable at this point to dispose of this massive amount of industrial waste in concrete.

Utilizing resources conservatively is the key to sustainable growth, which makes it easier to meet future demands. Utilizing industrial waste in concrete can increase the sustainability of the material while also offering a cheap and plentiful source of fine aggregate [2]. This is because it reduces environmental contamination. Nevertheless, achieving this is feasible only when the alternative raw material enhances or, at the very least, preserves the characteristics of the concrete.

### **1.2 Present scenario of Self Compacting Concrete:**

The escalating demand for massive structural constructions worldwide, coupled with challenges such as reinforcement congestion, seismic risks, cyclonic vulnerability,

and the need for increased plant capacity, has driven the growing popularity of Self-Compacting Concrete (SCC) [3].

SCC's capacity to mitigate design complexities and reduce dependence on site-specific craftsmanship contributes significantly to enhancing construction durability and intrinsic concrete quality, underpinning the evolution of this innovative construction material [4]. It can be used for a variety of things, from small components to big, sturdy constructions. Over the years, SCC has been the most important technological advancement and creative growth in construction sector.

SCC, often referred to as Self Consolidating Concrete or Rheo dynamic Concrete, is a unique type of concrete that doesn't require vibration for compaction or placing [5]. Even when there is a lack of reinforcement, SCC can pass because of its self-weight, occupying different formworks by achieving total compaction [4].

Engineering properties and durability of the hardened concrete are equivalent to those of conventional vibrated concrete. It is also uniformly dense and durable. SCC's core principle is that aggregate settlement is inversely correlated with the viscosity of freshly laid concrete. The materials used to create normal concrete can also be used to create SCC.

Achieving precise control over workability attributes necessitates more rigorous tolerances in the case of SCC. SCC mix proportioning surpasses conventional concrete in terms of accuracy, requiring a specific combination of higher powder content, reduced coarse aggregate, an elevated dose of superplasticizer, and the incorporation of Viscosity Modifying Agent [4].

The equilibrium between fluidity, deformability, filling capacity, and resistance to segregation governs the workability of SCC, and maintaining this equilibrium for an adequate duration is vital for successful delivery, installation, and finishing. The evaluation of workability characteristics mandates the application of diverse testing methods.

SCC, which originated in Japan, became a ground-breaking invention in the late 1980s, following the prior use of low vibration or compaction concrete in Europe since the

early 1970s. Its notable application likely began during Sweden's mid-1990s civil infrastructure projects for transportation networks in Europe, catalyzing a worldwide industry-led initiative that received support from the European Commission between 1997 and 2000.

Subsequently, SCC has gained substantial global recognition, becoming increasingly popular in Europe and extending its influence on India. In India, notable projects such as the Nuclear Power Project located at Karnataka named Kaiga, the Kota Atomic Power Project located at Rajasthan saw the implementation approximately 5000 cubic meters of SCC. Furthermore, several other significant projects, including the Delhi Metro (10,000 cubic meters), Tarapore Atomic Power (6,000 cubic meters), Gosik Hurd (5,000 cubic meters), Purna Dam (500 cubic meters), and Lower Wardha (2,000 cubic meters), have effectively utilized SCC [4].

The use of SCC is increasing in India, as seen in its incorporation into major endeavors like the Bandra-Worli sea link project in Mumbai and "The Signature Bridge" on the Yamuna in New Delhi. SCC's advantages include expedited concrete placement, reduced project timelines, and improved flow through densely reinforced areas. Its natural fluidity and resistance to segregation guarantee a high degree of uniformity, few voids, and constant concrete strength, improving structural quality and longevity [4]. Utilizing a low w/c ratio, SCC is favored for attaining rapid initial strength, facilitating early demolding, and expediting the assembly of components and structures.

Enhancing the environment on and around construction sites where concrete is poured involves reducing worker noise and through the elimination of vibrating equipment. For precast concrete and on-site civil engineering projects, SCC is a preferred solution because of improved building procedures and benefits for health and safety.

### **1.2.1 Necessity to choose SCC:**

Due to its well-established qualities of flowability, passage capacity, and compatibility, SCC is suggested as a good substitute.

It is an efficient concrete encasement repair material that can go through tight spaces with ease [4]. The inclusion of shrinkage compensating admixtures is essential during repair work to mitigate concrete shrinkage and ensure the successful bonding of new concrete with the old.

### **1.2.2 Advantages of SCC:**

- Easy to fill the voids of congested reinforcement because of its self-weight.
- Avoids segregation of concrete mix due to its cohesion property.
- Decrease the entire construction time of a project.
- Its application in actual site is quick because of good workable properties.
- Its fluidity creates a proper structural finish.
- Its application minimizes the site noise which can enhance the good health of workers.
- Less number of labors are required
- Concrete can be pumped so easily.
- When compared to conventional concrete (CC), SCC is more resilient.
- Utilizing Self-Consolidating Concrete (SCC) results in the formation of an Interfacial Transition Zone (ITZ) that exhibits greater density and strength compared to traditional concrete (CC).
- SCC offers a favorable impact on the porosity and microcracking within the ITZ, leading to the production of concrete with enhanced durability.
- The presence of fly ash encourages a reduction in porosity within the ITZ area, leading to the management of microcracking and, consequently, the fortification of the transition zone's strength [4]
- The more compact microstructure of the Interfacial Transition Zone (ITZ) in SCC, in contrast to conventional concrete, holds some potential for several benefits, including decreased plastic settlement, enhanced bonding between steel and concrete, reduced oxygen permeability, and a lower chloride diffusion coefficient.

### 1.2.3 Limitations of SCC:

- **Quality Control and Skilled Personnel:** SCC requires stringent quality control and assurance procedures due to its relative novelty. Only qualified individuals should be entrusted with the production and placement of SCC.
- **Reduced Plastic Shrinkage, Increased Shrinkage Cracking Risk:** Unlike conventional vibrated concrete, SCC does not experience internal or external bleeding, which can reduce plastic shrinkage. However, this absence of bleeding increases the risk of shrinkage cracking. Therefore, prompt treatment after installation is essential to mitigate shrinkage-related issues with SCC.
- **Temperature Sensitivity during Hardening:** SCC exhibits heightened temperature sensitivity during the hardening phase, which sets it apart from conventional vibrated concrete. Special care and cooling measures are necessary to manage temperature-related concerns effectively.
- **Effective Temperature Control in Elevated Temperatures:** In situations with elevated temperatures, maintaining effective temperature control becomes crucial, primarily due to the substantial cementitious content in SCC.
- **Comprehensive Testing Required:** Thorough testing of SCC mixes is vital, involving the creation of numerous trial batches to replicate real-world production scenarios [4]. This testing should encompass both laboratory-scale and field-size trial batches to ensure the desired performance and consistency of SCC.

### 1.3 Current Fly Ash Scenario:

With the robust growth of the Indian subcontinent's economy, attracting substantial global investments, the region has become an attractive destination for investors. The International Energy Agency reports that thermal power plants (TPPs) account for over 70% of India's electricity generation [6].

Thermal power stations using coal produce fly ash, a byproduct that has been successfully used in a number of construction-related applications. These include making bricks, blocks, and tiles, building road embankments and developing low-lying areas [7].

The intricate composition of fly ash is influenced by various factors, including the type of fuel employed, boiler load, and separation methods.

Effective management of fly ash is crucial due to its space-intensive nature within power plants, requiring careful handling to ensure both environmental and human safety. Currently, only 63% of fly ash is being efficiently utilized. Indian coal contains a notably higher ash content compared to coal from other nations.

As a result, thermal power plants that burn fossil fuels generate significant quantities of fly ash, necessitating meticulous disposal to mitigate potential health concerns such as respiratory issues, skin disorders, and eye discomfort. Guidelines set by the Central Pollution Control Board (CPCB) aim to guarantee the appropriate disposal of fly ash, thereby mitigating potential hazards [7].

### **1.3.1 Fly Ash Management in India:**

Many of the operational Thermal Power Plants (TPPs) in India currently generate a slurry, which is transported through pipelines to designated disposal sites, often ending up in ponds and eventually being discharged into water bodies.

This practice has substantial adverse environmental consequences, including the loss of biodiversity and the discoloration of aquatic life, particularly fish, in these water bodies. In response to these concerns, the Central Pollution Control Board (CPCB) has introduced new guidelines aimed at promoting the responsible utilization of fly ash and improving the financial viability of TPPs as an incentive for safe disposal and compensation for biodiversity loss.

To address these issues, the CPCB has mandated that TPPs must utilize all generated fly ash within a three-to-five-year time frame. This approach aligns with the "polluter pays principle," which holds that those responsible for generating pollution should bear the costs associated with mitigating it to protect public health and the environment. In addition to these measures, the CPCB has imposed a fine of 1000 rupees per ton on non-compliant plants [7].

#### **1.4 Present scenario of plastic wastes:**

Due to rapid industrialization, many countries have witnessed a growing adoption of industrial symbiosis, which involves the utilization of waste generated by one industry as a valuable resource for another [8]. The plastic casting industry, however, poses significant environmental and ecological risks, as it relies on inorganic materials and waste generated by other manufacturing sectors.

Given plastic's non-biodegradable nature, its accumulation on the Earth's surface has increased. Improper disposal of plastic waste, including its entry into water bodies, can have detrimental effects on plant life, aquatic algae, and fungi. The primary remaining avenues for reducing global plastic waste involve recycling and its application across various essential industries. Recycled plastic waste has gained increasing popularity in recent decades.

Nonetheless, this waste could serve as a valuable resource for the construction industry. Recycled plastic waste has many potential uses, yet its utilization remains limited, largely due to uncertainties about its performance when incorporated into concrete. Particularly for the construction of robust and durable structures, comprehending the interaction of plastic waste within concrete becomes pivotal [8]. The relationships between strength, durability, and microscopic behaviors have been the focal point of numerous research endeavors involving concrete specimens [9]

#### **1.5 Present scenario of C&D wastes:**

Over the past few years, the construction industry has witnessed a significant increase in the depletion of natural resources. The traditional "construction-demolition" process produces large volumes of construction and demolition waste (CDW), which has a pronounced and detrimental impact on the environment [10].

This strain is particularly acute for natural aggregates (NA), which are facing significant demand. Considering the present economic and environmental challenges, the

building industry's pursuit of more sustainable development opens avenues for innovative approaches in concrete technology [11].

Notably, the investigation into integrating Recycled Concrete Aggregate (RCA) into SCC is positioned to close the divide between research and development (R&D) domains and the practical needs of both the construction industry and its end users. [12]. This alignment with client needs and the balance between performance, quality, and cost are central criteria for fostering healthy competition within the construction sector. A lot of studies have taken place using plastic waste and crumb rubber [13] even in bituminous concrete mixes to know its acceptance level [14]

### **1.6 Motive of the proposed Research work:**

The purpose of this study was to investigate the impact of incorporating plastic waste as a partial substitute for fine aggregate on the novel properties of SSC. Environmental concerns about excessive sand dredging, which directly affects the building industry's bottom line, sparked this study endeavour.

1. Using of dissimilar waste as concrete fillers helps improving the environmental situation due to utilization of waste;
2. Reducing the amount of cement used decreases CO<sub>2</sub> emissions produced during concrete manufacturing.
3. This activity is widespread. However, there is a problem which researchers need to solve each time: concrete is high stressed constructional material, and its physical properties are of high importance.
4. The most widespread waste used as fillers for concrete are fly ash and pvc /pet waste. Therefore, this research decided to consider such types of fillers.
5. Compressive and tensile strength represent two of the most crucial properties. This research was conducted to explore the impacts of varying material ratios on these attributes.
6. In addition, the properties of the concrete change in time. Thus, this regularity was investigated as well.

To investigate the feasibility of substituting FA, CS, PW and RCA for natural fine, coarse aggregate and cement, respectively, in SCC, a laboratory testing programme is being carried out.

### **1.7 Research Gap:**

1. To evaluate whether it is feasible to incorporate waste plastic into concrete, thorough research is being conducted.
2. Nevertheless, the feasibility of employing plastic-infused concrete in the construction industry remains uncertain at this stage.
3. In contrast, no study has reported the use of waste plastic should be done in solid or liquid stage in concrete mix.
4. Although there is no literature on the development of cracks and their propagation, concrete is made with plastic.
5. It is yet questionable whether to use plastic as a powder replacing fine aggregate, coarse aggregate or cement effectively is yet to be explored.
6. Furthermore, the distinct kinds of plastic waste developed could result in altered properties of concrete when adopting the latest Mix design using IS 10262-2019 is to be explored.
7. Few studies have been conducted for the same, requiring the research in waste plastic as a use in SCC.

### **1.8 Research Objectives:**

1. To investigate the qualities of self-compacting concrete formed from plastic waste, recycled aggregates, fly ash and copper slag in both fresh and hardened phases.
2. To examine the durability of self-compacting concrete created from plastic waste, recycled aggregates, fly ash and copper slag.
3. To explore the microstructural qualities of self-compacting concrete manufactured by using plastic waste, recycled aggregates, fly ash and copper slag.

4. To evaluate the crack propagation in structural elements (RC beams) made with copper slag, recycled aggregates, fly ash and plastic waste.

### 1.8.1 Planning of the Research work:

Proper planning is essential for successful research, as it helps to ensure that the project is well-organized, focused, and executed in a timely and effective manner. Table 1.1 represents the current research work plan for all objectives considered.

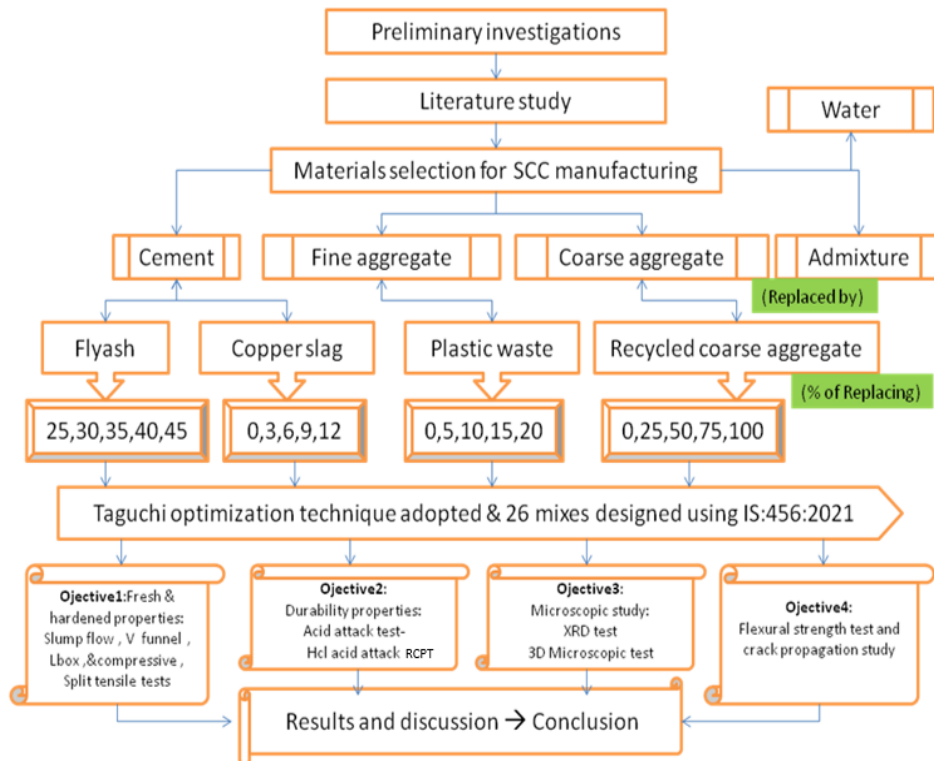
**Table 1.1: Current research work plan**

Objectives	Analysis to be undertaken	Instruments/ processes to be used
To investigate the fresh qualities of self-compacting concrete formed from plastic waste, recycled aggregates, fly ash and copper slag in both fresh and hardened phases.	Fresh properties- To evaluate workability/self-compact ability.	Slump cone L box V funnel
	Properties in the hardened state, including compressive and split tensile strength.	Compression testing machine (CTM)
To examine the durability of self-compacting concrete created from plastic waste, recycled aggregates, fly ash and copper slag.	Durability properties	Hcl Acid attack and RCPT test
To explore the microstructural qualities of concrete constructed from plastic waste, recycled materials, fly ash and copper slag.	Microstructural characteristics	X Ray diffraction Analysis (XRD) Three-Dimensional Microscope Analysis

To evaluate the crack propagation in structural elements (RC beams) made with copper slag, recycled aggregates, fly ash and plastic waste.	Flexural strength and types of Cracks propagation in RC beams	Universal Testing Machine (UTM)
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### 1.8.2 Workflow of current research:

The importance of a well-designed research workflow provides a clear roadmap for the research process, which helps to optimize the use of resources, identifies potential challenges and obstacles, and ensures that the research is rigorous and reliable. Fig.1.1 represents the current study workflow.



**Fig.1.1: Workflow of current research**

### **1.8.3 Uniqueness of Current Research:**

The current research on the structural performance of SCC made with waste plastic stands out due to several unique aspects. Firstly, it addresses the pressing environmental issue of plastic waste by exploring its potential utilization in concrete production, contributing to sustainable waste management practices. While previous studies have examined various waste materials in concrete, the focus on waste plastic in SCC offers a novel approach, considering both environmental and structural implications.

Moreover, the use SCC introduces another dimension of innovation. SCC is known for its high flowability and ability to fill intricate forms without the need for vibration, which can enhance construction efficiency and quality. By incorporating waste plastic into SCC, the research explores the synergy between these two innovative materials, potentially unlocking new possibilities for sustainable construction practices.

Furthermore, the research methodology adds to its uniqueness. The application of Taguchi optimization techniques in concrete research offers a systematic approach to identify optimal mix proportions and process parameters for SCC with waste plastic. This methodological rigor enhances the reliability and reproducibility of the study's findings, contributing to the advancement of concrete technology.

Additionally, the comprehensive investigation of fresh, hardened, and durability properties of SCC with waste plastic provides a holistic understanding of its structural performance. This multidimensional analysis sets the current research apart from previous studies that may have focused on specific properties or materials.

Overall, the unique combination of addressing plastic waste management, exploring innovative materials and technology, employing rigorous methodology, and conducting a comprehensive analysis distinguishes the current research on the structural performance of SCC made with waste plastic, making it a valuable contribution to the field of sustainable construction materials.

## **1.9 Organisation of Thesis:**

The dissertation titled "Structural Performance of Self Compacting Concrete using Plastic Waste" is structured into six chapters to comprehensively investigate the utilization of waste plastic in self-compacting concrete (SCC) and its impact on structural performance

### **CHAPTER 1: INTRODUCTION**

- Provides an overview of the research topic and its significance.
- Discusses the present scenario of SCC, fly ash, plastic waste, and construction & demolition (C&D) waste.
- Identifies the research gap and outlines the research objectives.
- Introduces the proposed research work and its motivation.

### **CHAPTER 2: LITERATURE REVIEW**

- Surveys existing literature on cementitious and aggregate replacing materials used in SCC.
- Reviews studies on Taguchi optimization techniques in concrete research.

### **CHAPTER 3: METHODOLOGY**

- Details the materials utilized in the study, including cementitious materials, fly ash, plastic waste, aggregates, and superplasticizer.
- Describes the methodology, including the Taguchi Method, design of experiments, and SCC mix design tool.
- Outlines the testing procedures for fresh properties, hardened properties, and durability properties.

### **CHAPTER 4: RESULTS AND DISCUSSION**

- Presents the results of the research objectives, including fresh properties, hardened properties, durability properties and microstructure properties of SCC made with plastic waste.
- Discusses the implications of the findings and compares them with existing literature.

- Provides contour plots and analyses the effect of process parameters on SCC properties.

#### CHAPTER 5: CONCLUSIONS

- Summarizes the key findings of the study.
- Draws conclusions regarding the structural performance of SCC made with waste plastic.
- Discusses the practical implications and potential applications of the research.

#### CHAPTER 6: LIMITATIONS AND SCOPE FOR FUTURE RESEARCH

- Identifies the limitations of the study and potential sources of error.
- Discusses avenues for future research and areas where further investigation is warranted.

This structured organization ensures a comprehensive exploration of the structural performance of SCC with waste plastic, offering insights into its potential as a sustainable construction material while acknowledging areas for improvement and future research directions.

## **CHAPTER 2**

### **LITERATURE REVIEW**

This chapter includes a thorough analysis of relevant academic publications, which was done to support ongoing research projects up to this period. The survey of literature serves as a foundational tool for establishing research objectives based on identified gaps within the existing body of knowledge.

#### **2.1 Research carried out on cementitious replacing materials:**

An investigation of incorporation of SCMs to lower carbon emissions during cement manufacture is covered in the article's conclusion published by Gupta and Chaudary [15]. The paper focuses on more than 20 different SCMs that were researched in India and offers details on their accessibility, traits, and influences on concrete's physical properties [15]. According to the review, to maximize the qualities of concrete, suitable SCMs should be chosen based on their physical, chemical, mineral, and morphological features. The essay also stresses how crucial it is to choose proper SCMs while taking sustainability and long-term environmental effect into account. To solve the unequal distribution of SCM availability across different regions of India, the paper suggests additional research to create new SCMs. Overall, the report offers helpful advice for construction industry stakeholders to choose the proper SCMs to achieve sustainable cement production.

Mohammad et.al. [16] examined the complex impacts of high temperatures on concrete, paying particular attention to nanostructure. Their investigation involved 300 samples, each subjected to varying curing durations, followed by exposure to temperatures spanning from 25 to 900°C for a two-hour duration. The study meticulously analysed alterations in sample weight, dimensions, compressive strength, and susceptibility to cracking. At 900°C, the disintegration of water resulted in a substantial decline in C-S-H nanostructure compressive strength, ranging from 79% to 100%. This research significantly contributes to our understanding of how concrete behaves under high-

temperature conditions and highlights the critical role of the nanostructure in augmenting stronger concrete [16].

A study looked at how cement suspensions and SCC mixtures characteristics were affected by rheological active additives carried out by Guvalov and Abbasova [17]. To improve the rheological matrix and give high fluidity in SCC, stone particles were utilized. To control the reotechnological characteristics of cement-based mixes, two distinct types of plasticizers polycarboxylate-based hyper plasticizer and sulfonaphthalen-formaldehyde oligomer were utilized. To assess the impact of the additives, the spread of cement-sand mortar, the slump, and flow are measured. The most effective stone powder, according to the test results, was limestone. Following the inclusion of 40% limestone powder into the blend, increase in compressive strength at ranging between 15% to 30% in comparison to both conventional samples and SCC samples are observed. This study also elucidated the optimal proportions of plasticizers and rheological active additives required for achieving these results.

An investigation of how steatite and fly ash affected the characteristics of SCC was carried out by Gnanaraj and Chokkalingam [18]. Researchers used different fly ash fractions and steatite percentages as fillers in place of regular Portland cement. The study investigated the qualities of the concrete both when it was still fresh and when it had hardened, adhering to European standards for SCC production. Within this range, there was some increase in strength attributed to fly ash, resulting in up to a 15% enhancement in compressive, tensile, and flexural strength when steatite was replaced [18]. Nevertheless, beyond the 15% replacement threshold, the strength attributes declined, although they still surpassed those of the control specimen.

Golewski and Szostak [19] explored the potential of enhancing both the mechanical properties of concrete and its environmental impact by incorporating siliceous FA. However, the substitution of FA for Portland cement was found to diminish the concrete's performance during the initial curing phase, thereby constraining its utility in specific

applications. To address this limitation and accelerate the minimum time period strength development of FA-containing concrete.

This NA was employed to expedite the concrete's strengthening process. The evaluations were based on macroscopic and microstructural examinations carried out over five time periods on modified concretes that had been added FA and NA. According to the findings, adding NA to concrete increases early strength and lessens the damaging effects of FA. These results imply that FA can be applied in a variety of management settings for environmentally friendly concrete prefabrication.

Manjunatha et.al. [20] study looked into the viability of using leftover PVC powder in place of some of the cement in M40 grade concrete. The research indicated that silica fume, as well as up to 15% of PVC waste powder, can be incorporated into the concrete mixture without adversely impacting its mechanical or fresh properties. Comparing concrete with 15% PWP to concrete with 20% PWP, the microstructure of the former revealed a better C-S-H gel. According to the research, managing plastic waste and the growing need for cement can both be overcome using PVC waste powder. Researchers and professionals in the building materials business may find the study useful. The outcomes also emphasize the significance of investigating substitute materials and waste disposal techniques to achieve sustainability in construction.

Reza Bani et.al. [21] study shows that four polymer admixtures were tested to see how they affected the characteristics of SCC made with both recycled and natural aggregates. Polymer additions increased concrete's capacity for filling by more than four times, resulting in a 100% passing rate as opposed to the control samples 80% passing rate. Materials lost around 50% of their compressive strength when recycled aggregates were used in place of natural aggregates then recycled aggregate-based concrete can be enhanced by incorporating 15% polymer content to enhance workability and preserve flexural strength. The outcomes suggest that SCC containing recycled aggregates can benefit from improved fresh properties through the introduction of polymer admixtures.

In 2020, Afshoon and Sharifi [22] investigated how substituting pulverized copper slag for cement affected the characteristics of SCC under different temperatures. They assessed SCC properties both before and after heating at varying replacement percentages, examining fresh and hardened states. The results showed that all replacement levels enhanced fresh characteristics, with mechanical qualities improving up to 15% replacement, with optimal results seen at 5% replacement. However, at higher replacement percentages (20%, 25%, and 30%), mechanical qualities at elevated temperatures deteriorated. The study suggests that incorporating Ground Copper Slag (GCS) as a cement substitute in SCC can enhance its characteristics and performance under elevated temperatures. Still, careful consideration of the replacement percentage is essential to avoid compromising the material's mechanical properties.

Gupta and Siddique [23] conducted an investigation into the effects of substituting natural sand using copper slag in SCC, examining both its fresh and hardened characteristics. The study maintained consistent parameters while varying the replacement of natural sand with copper slag, ranging from 0% to 60%, and also replaced 20% of cement with fly ash.

Fresh properties were assessed through tests evaluating the workability, flowability, and viscosity of SCC, while durability over a one-year period was evaluated through tests measuring compressive strength, water absorption, rapid chloride permeability, and sorptivity [23].

Sharma and Rahul [24] explored the incorporation of CS, FA, SF as SCMs acting for fine aggregates in SCC. Seven distinct concrete mix formulations were formulated and evaluated to assess the impact of CS substitution on SCC properties. The findings revealed that replacing a portion of fine aggregates with CS, up to 100%, led to an enhancement in the fresh characteristics of SCC. Moreover, the most substantial improvements observed in compressive and flexural tensile strength, compared to control mixture, were observed when CS replacement levels reached 20% and 60%. This research underscores the potential benefits of CS utilization as an SCM in SCC blends.

Fadaee et.al. [25] investigated the feasibility of replacing cement in SCC with slag from the Sarcheshmeh mining copper complex to reduce production costs and environmental harm on the slag and cement, physical and chemical testing was done, and SCC pasty phase tests were done on fresh SCC with various slag percentages. Discoveries state that compressive strength of SCC containing a substantial proportion of slag material showed no significant difference compared to SCC that did not include slag [25]. This study indicates that slag may be an appropriate replacement for some of the cementitious elements in SCC, however additional research on other SCC characteristics such as durability is necessary.

## **2.2 Research carried out on aggregate replacing materials:**

Yuanxun et.al. [26] conducted a study with the aim of enhancing the quality of RCA. This was achieved through the implementation of a specialized mortar removal tool and by immersing RCA in nano-silica solutions. The results revealed that after undergoing mechanical and physical reinforcement, RCA exhibited significant reductions in water-absorption rate (32.9%) and crushing value (23.9%). Additionally, by employing the ideal combination of physical reinforcement, immersing the material in a 2% nano-silica solution for two days, and applying vibration stirring, significant improvements were observed in the 28-day compressive strength (31.3%), splitting tensile strength (23%), and flexural strength (49%) of RAC. This suggested approach provides valuable technical knowledge for enhancing the mechanical properties and microstructure of RAC.

Nikita et.al. [27] was conducted a comprehensive analysis of the adding different wastes from industries as by-products in Self-Compacting SCC. These industrial by-products are incorporated into SCC primarily to address the management of industrial waste disposal and reduce the dependency on natural resources like river sand [27]. Following a thorough review of existing literature, the study draws the conclusion that the utilization of industrial wastes in SCC holds significant promise for fostering sustainable development [27]. However, further research is imperative to refine mix designs and

augment SCC's properties. In summary, the integration of industrial by-products in SCC offers the potential for a more eco-friendly and sustainable construction process.

Kim Hung et.al. [28] explored the feasibility of substituting RCA for natural aggregate (NA) in modified SCC. In their study, 5-10 mm crushed RCA was introduced into SCC mixtures at varying weight ratios (0%, 25%, 50%, 75%, and 100%). This study states the inclusion of RCA results in reduction of the mechanical strengths of SCC, an increase in water absorption, and the formation of permeability voids. However, these effects were less pronounced compared to what would typically occur in conventionally vibrated concrete [28]. The study concluded that the SCC matrix could adequately incorporate RCA, with the maximum recommended replacement level being 25%. It was also noted that while the RCA mortar interface exhibited lower micro-hardness compared to the NA mortar interface, the interfacial transition zone (ITZ) thickness remained comparable [28].

Mohammed and Najim [29] study explained the feasibility of employing RCA to create SCC was examined, and the mechanical qualities of the mixes were assessed in 2020. The study encompassed an evaluation of the mechanical characteristics of the resultant mixes. Despite the typical outcome of reduced hardened properties, decreased flexural stiffness, and toughness observed when RCA was introduced into the mix, the investigation revealed that it remained feasible to achieve the requisite compressive strength of 39 MPa by completely substituting all RCA components in the mixture. To further assess the impact, an image processing approach grounded in fractal theory was employed to analyse crack patterns, propagation, and tortuosity. The findings demonstrated a consistent reduction in strength, stiffness, and toughness in the tested beams that aligned with the conventional understanding of fracture energy. The outcomes show that RCA can be used in RASCC, but the reduction in mechanical properties needs to be carefully considered.

Sasanipour and Aslani [30] study primary focus was to assess the potential of using natural aggregates as alternatives to both fine and coarse RCAs in SCC. Their research

findings indicated that the removal of RCAs resulted in a reduction in compressive strength across all concrete mixtures, while the impact on tensile strength was minimal. Furthermore, as the proportion of RCA content increased, certain durability-related properties of SCC, like water absorption and the presence of voids, exhibited deterioration [30]. Nonetheless, further investigations are necessary to optimize mix designs and enhance the overall durability of SCC incorporating RCAs. Despite these findings, the study highlights the need for further investigations to optimize mix designs and enhance the overall durability of SCC incorporating RCAs. This implies that there is room for improvement in the use of natural aggregates as alternatives to RCAs in SCC, and more research is required to fine-tune the mix proportions and ensure that the resulting concrete maintains satisfactory mechanical strength and durability characteristics. The optimization of mix designs is crucial for promoting the sustainable use of recycled materials in concrete construction without compromising the performance and longevity of the structures.

Navdeep and Singh [31] conducted study to assess the impacts of substituting RFA, RCA for fine and coarse aggregates for formulation of the environmentally sustainable SCC. When these blends carbonation resistance was examined using an accelerated carbonation method, the results revealed that it decreased as the amount of recycled aggregates in the blend rose. Metakaolin was discovered to make up for this loss of carbonation resistance, though. Compressive strength testing and microstructural and crystallization investigations utilizing XRD and SEM methods were also included in the study. Overall, the utilisation of RA in SCC blends has the potential to promote sustainable building techniques, but additional study is required to completely comprehend the effects on the durability and physical properties [31].

Kumar [32] study examines the flexural behaviour of SCC that uses copper slag in place of sand. The study uses reinforced SCC beam specimens that have been cast and tested in the lab to look at the SCC's deflection, flexural strength, crack pattern, and strain pattern. According to the findings, substituting copper slag for sand in SCC increases the material's flexural behaviour and flexural strength. A further finding of the study is that the copper slag-containing SCC outperforms the reference SCC without copper slag.

Moreover, some crack and strain patterns on the SCC with copper slag are superior. According to the study, SCC using copper slag can be a more environmentally favourable option.

Job et.al. [33] conducted a study focusing on the assessment of the strength and durability of RCA as an eco-friendly substitute for natural crushed stone aggregates. Their experimental methodology encompassed nine distinct control mixtures, incorporating variations in cement content and water-cement ratios. The results of this study indicate that RCA can successfully substitute for up to 25% of natural aggregates in the concrete mix without causing a significant compromise in concrete strength [33]. Particularly in areas with moderate exposure conditions, RCA concrete was found to be suitable. To assist practical engineers in determining mix proportions for RCA concrete, mathematical models were developed to predict the material's strength properties. These models were subsequently utilized to propose a mix design approach. Such an assessment holds the potential to reduce the demand for virgin materials and minimize waste generation within the construction industry.

Carolyn et.al. [34] article talks about reusing C&D debris as aggregate has, however, become a more attractive choice for sustainability due to the dearth of land-filling sites, industrial expansion, and environmental regulations. To create concrete, concrete pavements, and new roads, recycled aggregates can be used. The study conducts a literature assessment on the creation and application of recycled aggregate, as well as the related standards and restrictions. The evaluation might satisfy consumer worries and encourage the usage of recycled aggregate on a greater scale.

Hama and Hilal [35] study explored into the unique characteristics of SCC and explored the relationship between the incorporation of plastic waste as a partial replacement for fine aggregate. The research involved the creation of various SCC mixtures, each incorporating plastic waste at varying volumes (ranging from 0% to 12.5%) and sizes (fine, coarse, or a combination), all while maintaining a consistent water-to-binder ratio and binder concentration.

Additionally, the researchers utilized Class F fly ash to partially substitute cement [35]. Moreover, the research examined the compressive strengths of the self-consolidating concretes (SCCs) after 28 days. Some findings of investigation revealed that plastic waste could effectively replace fine aggregate when specific sizes and compositions were employed, highlighting its potential as a sustainable alternative in concrete production [35].

### **2.3 Research carried out on Taguchi optimisation techniques:**

Ketabforoush and Abdul [36] study emphasizes the value of statistics in engineering and how using quality improvement methods may boost output and cut expenses. A new tool for businesses, building projects, and service centres to reduce variance and flaws in manufacturing and production processes is the Taguchi-based Six Sigma technique. This method combines the strengths of Taguchi with Six Sigma. The target is to assess how well this new quality improvement strategy worked in streamlining the manufacturing of green building material [36]. The outcomes demonstrated a considerable improvement in process performance of 50%, demonstrating the value of the Taguchi-based Six Sigma methodology for reducing variance and raising quality. The study shows how crucial it is to successfully apply statistics and quality improvement methods.

In the Suji et al [37] publication, the study's findings based on Taguchi-Grey relational analysis for optimizing SCC mixtures featuring FA and manufactured sand. The research employed an orthogonal array of test trials generated using the Taguchi method, and this array was subsequently assessed through grey relational analysis. Five key variables were chosen for experimentation: FA content, manufactured sand content, SP content, ordinary Portland cement content, and fine aggregate content

The study states most pronounced influence on the properties of the SCC blends [37]. The results demonstrated a significant correlation between the predicted and observed characteristics, which was instrumental in validating the optimal blend identified through the trials. These optimized mixtures also adhered to the constraints recommended by EFNARC, illustrating that SCC compositions incorporating FA and manufactured sand can

be tailored for various construction applications. The research places particular emphasis on Taguchi-Grey relational analysis as a valuable tool for enhancing the formulation of such mixtures and highlights the potential of optimization techniques in developing superior SCC combinations.

Nafeesa et.al. [38] investigated how self-compacting and traditional cementitious composites respond to the application of effective microorganisms (EMs) in 2021. To optimize formulations using three distinct types of types of cement and three diverse types of EMs, the Taguchi approach of experimental design was applied. The specimens were cured under various settings while the effects of variables. The ANOVA represented that the most important variables for influencing some of reactions of cement composites were w/c and EMs percentage replacement. The study discovered that nearly 4% EM (effective microorganisms) substitution was ideal. During forensic examinations, it was discovered that bio-precipitate had refined the microstructure of the material, increased its mechanical characteristics, and lowered its density. The paper suggests theoretical equations based on extensive regressions for Taguchi-based mix design prediction and optimization. According to the study, cementitious composites' durability and energy efficiency can be increased by utilizing EMs.

Sahibulla and Jaisingh [39] study was to minimize the cement content of the bio cement mortar, which was formed of eggshell waste powder, bio silica, and biochar in 2021. The pozzolanic components, bio silica, biochar, and calcite eggshell particles were the main targets. Taguchi L9 design pattern was examined. In comparison to bio silica and eggshell particles, the output represent that the weight percentage of biochar had a stronger responder on the overall performance of the cement mortar cubes. The experimental plan, with a grey relational grade of 0.705, was the most effective one These results suggest that a promising method for producing bio cement mortar with less cement while preserving good mechanical and functional qualities is to use bio-wastes such as bio silica, biochar, and eggshell waste powder.

Said et.al. [40] examined important quality of the usage of reinforced concrete in high-loading situations. The study investigated the influence of varying water-to-binder ratios and different concrete types on the adhesion between steel bars and concrete. This analysis was conducted using specimens of SSCC and normal vibration concrete (NVC), and the results from the pull-out test were compared. In contrast to the pull-out test, which provides a broader assessment, the study found that the interfacial indentation test more accurately represents the adhesion at the steel/concrete interface.

Ebrahim et.al. [41] research aimed to enhance Taguchi optimization for achieving the most suitable mix design for maximum strength SCC. To achieve this goal, they integrated various parameters into an orthogonal array using the Taguchi methodology. Subsequently, they employed the Best-Worst method to conduct pairwise comparisons of quality criteria, which enabled the calculation of overall weights for each experiment concerning quality characteristics.

The study utilized analysis of variance to assess the most advantageous mixture design and the components that had the most significant impact. The test results revealed a noteworthy enhancement in the overall quality of concrete compared to the mix design initially chosen by the decision maker [41]. Among the factors taken into account, the quantity of cement, the w/c ratio, and duration of mixing time were recognized as the three most pivotal elements that exerted influence on the design of concrete mixes [41].

Jithendra and Elavenil [42] adopted the Taguchi method to investigate the effects of different parameters and their respective levels on flowable geopolymer concrete. Various factors were considered, such as the molarity of the sodium silicate solution, the proportion of coarse aggregate, the solution-to-binder ratio, and the amount of superplasticizer. The study involved the formulation of nine distinct concrete mixtures employing the Taguchi methodology.

The findings of the study highlighted the significant influence of both the solution-to-binder ratio and the amount of superplasticizer on the properties of the mixtures. Among the combinations investigated, T10 emerged as distinctive, incorporating 1.75 M of sodium

silicate solution, 50% coarse aggregate, a solution-to-binder ratio of 0.55, and 1% superplasticizer. This specific composition exhibited the highest desirability, achieving a flowability of 575 mm and a compressive strength of 52.81 MPa [42]. Moreover, it still displayed a relatively high porosity, characterized by an 11.38% void content.

#### **2.4 Enhancing relevance through critical analysis:**

In hindsight, while reviewing the literature, a critical analysis was carried out as beneficial in highlighting the relevance of current research. Although the review provided a comprehensive overview of existing studies, a critical examination would have unearthed gaps within the literature. Such an analysis would have clarified how current research contributes to use plastic waste in SCC and to the existing body of knowledge by addressing limitations or providing novel insights. By critically evaluating prior research, current study's theoretical and practical implications could have been more effectively emphasized, bolstering its relevance and positioning within the sustainable SCC development.

Chapter 2's literature review explores cementitious materials, aggregate replacements, and optimization techniques. Studies emphasize the role of SCMs in reducing carbon emissions and improving concrete quality. Investigations into high-temperature effects on concrete nanostructure, rheological additives impact on SCC, and industrial by-products potential in concrete production are highlighted. Additionally, research on RCA and Taguchi optimization techniques for SCC mixtures are discussed. Findings emphasize the importance of sustainable materials selection, optimal mix designs, and statistical optimization for enhancing concrete performance and sustainability in construction practices.

## CHAPTER 3

### METHODOLOGY

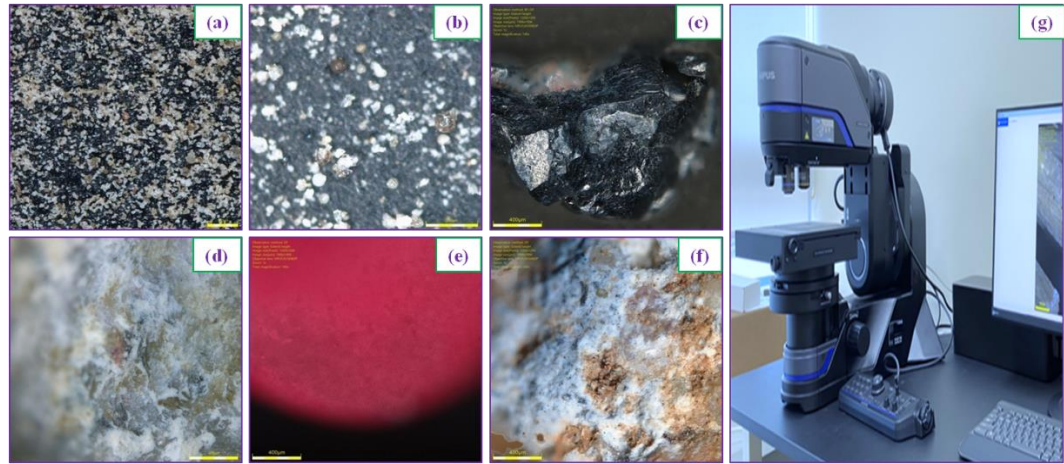
#### 3.1 Utilised Materials and its properties:

The sources of the materials employed in this study have been thoroughly explained. Detailed depictions of the materials used in this research can be found in digitalised three-dimensional (3D) microscope images in Fig. 3.1 and 3.2, respectively.



**Fig.3.1. Images of different types of materials used in this study**

In this current research, a 3-dimensional optical microscope (3D Microscope: DSX1000, Olympus Co., Japan) is used to check microscopic images and are represented in Fig.3.2 as Three-Dimensional microscope images of (a) Cement at 10  $\mu\text{m}$  (b) fly ash at 200  $\mu\text{m}$  (c) copper slag at 400  $\mu\text{m}$  (d) Coarse aggregate at 400  $\mu\text{m}$  (e) Plastic waste at 400  $\mu\text{m}$  (f) Recycled coarse aggregate at 400  $\mu\text{m}$  (g) 3D Microscope: DSX 1000 instrument. Moreover, Graph 3.1 illustrates the particle size distribution curves for the different additives used in this study.



**Fig.3.2 Three-Dimensional microscope images of (a) Cement at 10 μm (b) fly ash at 200 μm (c) copper slag at 400 μm (d) Coarse aggregate at 400 μm (e) Plastic waste at 400 μm (f) Recycled coarse aggregate at 400 μm (g) 3D Microscope: DSX 1000 instrument**

### 3.1.1 Cementitious material:

In this research, Grade 53 Ordinary Portland Cement (OPC) was employed, sourced from Shree Cement Limited and conforming to the Indian Standard (IS): 12269:1987. The compressive strength of OPC 53 grade cement after 28 days of curing was measured to be 58 N/mm<sup>2</sup>.

**Table 3.1: Details of Cement Chemical Composition**

S. No	Chemical Composition Particulars	Test results	Requirement as per IS 12269:1987
1	Factor for lime saturation	0.901	0.8-1.02
2	Al <sub>2</sub> O <sub>3</sub> /Fe <sub>2</sub> O <sub>3</sub>	1.23	0.66 (Minu)
3	Insoluble Residue (% By Mass)	1.20	4.0 (Max)
4	Magnesium (% By Mass)	1.20	6.0 (Max)
5	Anhydrite of sulphur (% By Mass)	2.23	3.5 (Max)
6	Total Ignition Loss (%)	2.83	4.0 (Max)
7	Chloride total (%)	0.007	0.1 (Max)

It possessed a minimum fineness of 225 m<sup>2</sup>/Kg. The chemical composition of the cement employed are illustrated in Table 3.1, as provided by the manufacturer. The fundamental physical characteristics of the cement, which encompass specific gravity, soundness, initial setting time, final setting time, and consistency, we carried out tests in accordance with the procedures outlined in the IS code [44]. The results of these tests, which met the required criteria, are presented in Table 3.2.

**Table 3.2: Details of Cement Physical properties**

S. No	Physical Property	Test value	Permitted range	Code
1	Specific gravity	3.1	-	IS 4031 (1998) part1
2	Fineness (m <sup>2</sup> /kg)	310	Min 225	IS 4031 (1998) part1
3	Soundness by Le-chatlier experiment (mm)	2	Less than 10	IS 4031 (1998) part3
4	Time of Initial setting (min)	55	Min 30	IS 4031 (1998) part5
5	Time of Final setting (min)	480	Max 600	IS 4031 (1998) part5
6	Normal consistency (%)	29	-	IS 4031 (1998) part4

### 3.1.2 Fly ash:

Fly ash is a byproduct produced by the combustion of pulverized coal in thermal power plants. It is generated through mechanical separation from exhaust gases [45]. Its composition is influenced due to various factors, including type of fuel burned, boiler load, and the separation process employed. In this study, fly ash was obtained from the Rayalaseema Thermal Power Plant (RTPP) situated near the Kadapa region in Andhra Pradesh, India.

The collection of fly ash adhered to IS: 3812-(2003) standards [46]. The fly ash is composed of spherical-glassy particles with diameters spanning from 1 to 150 microns, and it effectively traverses a 45-micron sieve. Experimental results demonstrate that the specific gravity of the gathered fly ash is 2.

### 3.1.3 Copper slag:

It is a residual material that results from the smelting and refining processes of copper matte [47]. In India, three major copper producers—Sterlite, Birla Copper, and Hindustan Copper each generate approximately 6.6 tons of copper slag [48]. For every ton of copper produced, there is a corresponding generation of 2.23 tons of copper slag. Utilizing copper slag has three benefits: it eliminates dumping costs, lowers concrete costs, and reduces air pollution issues [49]. These applications include Portland cement substitution (less work noticed), so it is proposed to use copper slag in current research. The copper slag was collected from National Enterprises near Faridabad, Haryana with maximum particle size of less than 10 microns. According to the experimental results, the copper slag has a specific gravity of 3.5, and its water absorption remains below 0.1% after a 24-hour period.

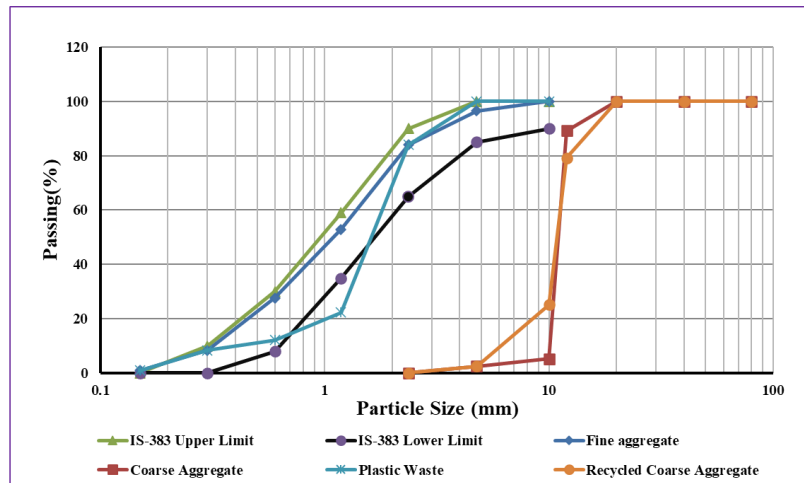
### 3.1.4 Fine aggregate:

Locally available river sand tested for its properties as per IS: 383-206 was used in research and it is in line with Zone II grading according to IS code standards [50]. Sands that are siliceous or calcareous are also used, in this study Table 3.3 represents the fine aggregate properties.

**Table 3.3: Properties of Fine Aggregates**

S. No	Properties	Results	Standard values	Codes
1	Specific gravity	2.5	2.4-3	IS 2386 (Part 3)-1963
2	Bulking of sand	3%	2%-4%	IS 2386 (Part 3)-1963
3	Fineness modulus	3.12	2-4	IS 2386 (Part I)
4	Grading zone	II	-	IS 2386 (Part I)
5	Bulk Density	1581 (kg/m <sup>3</sup> )	1500-1680	IS 2386 (Part 3)-1963

Due to a variety of weather-related factors, sandstones decompose to create it. Because fine particles have a substantially higher surface area per unit weight, their form and surface structure have a bigger impact on the water requirement of concrete [52]. Aggregate particles that exhibit a rounded, smooth, and fine texture tend to be more manageable than those with sharp and rough characteristics [53]. A graphical representation, denoted as Graph 3.1, has been constructed based on test results and in compliance with coding standards. This graph illustrates the particle size distribution curve.



**Graph 3.1: Particle size distribution curves of different additives used in this study**

### 3.1.5 Plastic waste:

Plastic waste especially recycled polyvinyl chloride (PVC) Granules of density 0.051-1.41 g/cm<sup>3</sup> are collected from Adhi Lakshmi plastic traders, Hyderabad with particle size of less than 2 mm and follows IS: 10151(1982), these granules were chosen as a replacement to natural fine aggregate, and it possess a specific gravity of 1.52 [54]. Table 3.4 offers a comprehensive overview of the properties associated with plastic waste, particularly focusing on PVC granules. The particle size distribution curve is depicted in Graph 3.1 based on the results of the conducted tests.

**Table 3.4: Properties of plastic waste (PVC granules)**

S. No	Property	Test value
1	Density (g/cm <sup>3</sup> )	0.051- 1.41
2	Water Absorption, 24 hrs.' (%)	0
3	Max Operating Temp (°F / °C)	140 / 60
4	Tensile Strength (Kpa)	51,675
5	Flexural Strength (Kpa)	88,192
6	Hardness	115 (Rockwell R)
7	Heat Deflection Temp (°F / °C) at 1818.96 Kpa	176 / 80
8	Melting Temp (°F / °C)	N A

### **3.1.6 Coarse aggregate:**

Fractured granite stones with a nominal size of 12 mm are employed as the coarse aggregate in this research. It's worth noting that, in SCC, the coarse aggregate typically differs from conventional concrete as it tends to be rounded, well-graded [51], and possesses a smaller maximum size.

### **3.1.7 Recycled coarse aggregate:**

The deteriorated building waste from which the recycled aggregate concrete for this study was made was collected and shown in Fig.3.1. The recycled aggregate was initially collected in enormous lumps, and then it was manually reduced in size by being pounded with a hammer so that it could be transported into a crusher. After crushing the small lumps of recycled coarse aggregate, the screen in the crusher is set up to obtain aggregate that is 20 mm downsize, and the material was sent from the crusher unit to the research laboratory. Table 3.5 provides a detailed comparison of the properties of coarse aggregate and recycled coarse aggregate with IS Code standards.

**Table 3.5: Properties of Coarse aggregate and recycled coarse aggregate**

S. No	Properties	CA Results	RCA Results	Standard values	Codes
1	Specific gravity	2.7	2.6	2.4-2.3	IS 2386 (Part 3)-1963
2	Water Absorption%	1.18%	2.45	0.1-2	IS 2386 (Part 3)-1963
3	Elongation Index %	20.20	23.4	20-35	IS 2386 (Part I)1963
4	Flakiness Index %	21.40	25.2	20-35	IS 2386 (Part I)1963
5	Fineness modulus	7.36	6.2	6.5-8.5	IS 2386 (Part I)1963
6	Bulk density kg/m <sup>3</sup>	1650	1721	1500-1680	IS 2386 (Part 3)-1963
7	Grading zone	Well graded	Well graded	-	IS 2386 (Part I)

**3.1.8 Super plasticizer (SP):**

Considerable research has been undertaken concerning the use of different superplasticizers in SCC, both with and without the inclusion of viscosity-modifying chemicals. The development and performance of SCC are notably influenced using superplasticizers. In contrast to the high dosages typically associated with SCC, which can lead to significant segregation issues, the primary role of SP is to enhance flowability and deformability [56]. For this study, a poly carboxylate ether-based concrete additive served as the SP, and its specific characteristics are represented in Table 3.6.

**Table 3.6: Properties of SP used in this study**

S. No	Colour	Phase	Density(g/ml)	P <sup>H</sup>	Specific gravity
1	Brown	Liquid	2	6-7	1.2

**3.1.9 Water:**

In this research, drinking water was utilized during the concrete mixing procedure, and the outcomes of water quality analysis are detailed in Table 3.7.

**Table 3.7: Properties of water used in this study**

<b>S. No</b>	<b>Parameters</b>	<b>Test results</b>	<b>Requirement as per IS 10500:2012</b>
1	Turbidity	4 NTU	Max 5
2	p <sup>H</sup>	6.9	6.5-8.5
3	Taste	Agreeable	Agreeable
4	Odour	Agreeable	Agreeable

### **3.1.10 Reinforcing steel:**

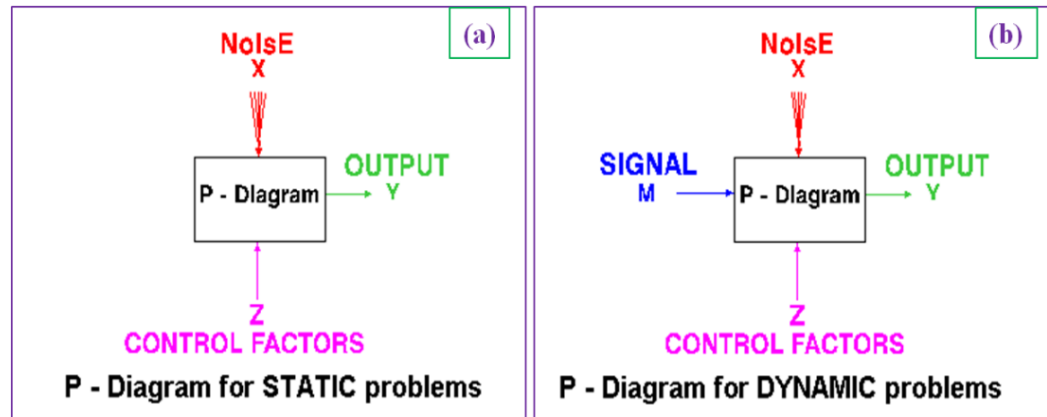
Fe 415 grade steel was used as reinforcement for RCC beams specimen manufacturing and followed IS 456:2000 for design of beams [57].

### **3.2 Methodology:**

Current study adopted optimisation technique in order to reduce the number of trails, so that the segregated laboratory waste pollution created by researchers can also be limited with a proper care.

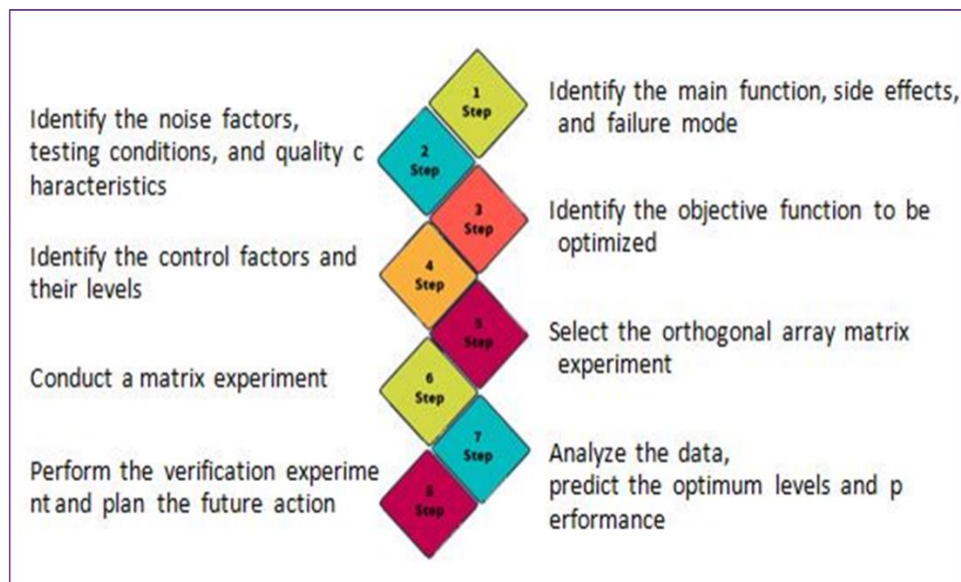
#### **3.2.1. Taguchi method:**

The Taguchi method, conceived by the Japanese engineer Genichi Taguchi, stands as a valuable tool for predicting and optimizing processing control parameters with the aim of improving quality [58]. This method finds applications across various domains, including industrial machining assessments, structural designs, and multi-parameter scenarios involving quantities [59]. Fig.3.3 represents the signal to noise ratio view in Taguchi optimization technique. The detailed steps of the Taguchi design are illustrated in Figure 3.4. For this study, the design of experiments (DOE) utilized the L25 orthogonal array (OA). Moreover, three specific types of functions were employed for data collection, determined by the quality aspect of interest: (a) Higher-the-better, (b) Medium-the-better, and (c) Lower-the-better [60].



**Fig.3.3: Taguchi's Signal-to-Noise ratios (S/N) (a) P is static (b) P is dynamic**

The research encompassed the choice of various factors, including FA, Coarse Aggregate CA, Plastic Waste PW, and Recycled Concrete Aggregate RCA as particulate enhancements within the concrete mixture [61].



**Fig.3.4: Steps followed in Taguchi methodology**

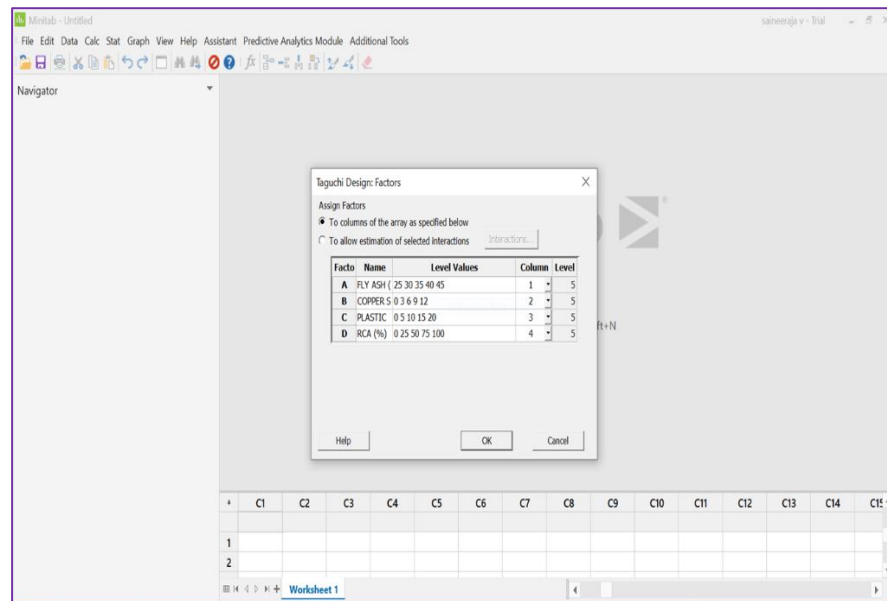
The goal was to pinpoint the ideal combination of these factors to attain the highest strength values for SCC. Consequently, Equation (1) is employed for scenarios where higher values are desired, whereas Equation (2) is used for situations where lower values are preferable [61].

$$\text{S/N ratio for higher-the-better} = -10 \log 1/n (\sum 1/y^2) \text{ ----- Equation (3.1)}$$

$$\text{S/N ratio for lower-the-better} = -10 \log 1/n \sum (y)^2 \text{ ----- Equation (3.2)}$$

Where n= Number of observations, y= Data from observations for each response

In the optimization procedure, the anticipated values are obtained in the form of S/N ratios. The S/N ratio is defined as the ratio of the mean to the standard deviation of the data. In this specific investigation, Minitab 17.0 software was employed to assess the quality attributes of SCC under various optimization parameters. Fig.3.5 provides a detailed view of the Taguchi design factors and their corresponding levels [37].

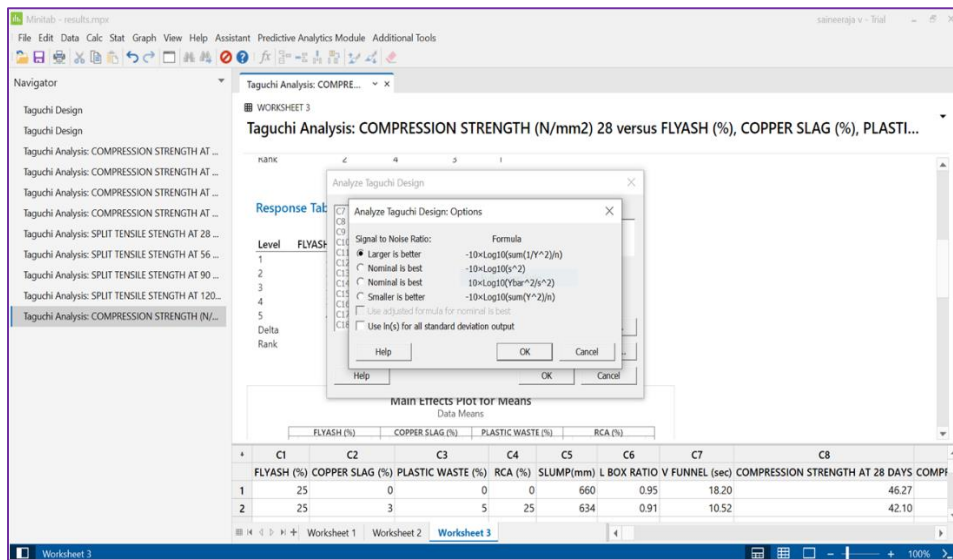


**Fig.3.5: Taguchi design factors in Minitab software**

A total of 25 different mix designs were formulated, each comprising five levels for every factor. The optimization was conducted with a focus on mechanical strength properties, specifically compression and tensile strength, within the SCC composites.

**3.2.2. Design of Experiments (DOE):** In current study, the Taguchi methodology was chosen over other Design of Experiments (DOE) techniques due to its distinctive advantages, which include its ease of application to real-world engineering problems and its flexibility. [62].

At the core of the Taguchi method, the foundation is built upon the utilization of OAs and the S/N ratio. Orthogonal arrays take the form of two-dimensional matrices featuring integer columns and rows, specifically designed to streamline the process of experiment design [59]. The unique characteristic of orthogonal arrays lies in their columns being orthogonal to one another, enabling the consideration of any possible combination of factor levels within each pair of columns. Genichi Taguchi introduced the S/N ratio as a performance metric to efficiently summarize response values for each data point within the internal array design [60]. Primary aim of Design of Experiments DOE is to pinpoint the optimal sets of control parameters that result in maximizing the response, as assessed through S/N ratios [58,63].



**Fig.3.6: Analyze Taguchi design option larger is better in Minitab software**

The S/N ratio essentially serves as an indicator of sensitivity to variability, and the objective is to enhance this ratio, consequently reducing the impact of random factors causing noise.

In this study, four variables are under examination: FA, CS, PW, and RCA, each variable has five distinct levels, as outlined in Table 3.8. Figure 3.6 illustrates the selection of the "larger is better" S/N ratio criteria within the Minitab software.

**Table 3.8: Plan for experiments and their respective levels**

Factor Notation	Factors	Level 1	Level 2	Level 3	Level 4	Level 5
A	Fly Ash	25	30	35	40	45
B	Copper Slag	0	3	6	9	12
C	Plastic waste	0	5	10	15	20
D	RCA	0	25	50	75	100

Factor A entails replacing cement with fly ash at different levels (25%, 30%, 35%, 40%, and 45%). Factor B involves substituting cement with industrial waste copper slag, ranging from 0% to 12%.

Factor C encompasses the replacement of fine aggregate with PVC granules, ranging from 0% to 20%. Factor D signifies the substitution of coarse aggregate with recycled coarse aggregate, with levels varying from 0% to 100%. [60], as outlined in Table 3.8.

This design is reminiscent of the "Lev Fac" model, where "Lev" represents the number of levels, and "Fac" stands for the number of factors [37]. Consequently, "L25 (5<sup>4</sup>)" indicates that 25 experiments are required to investigate four variables, each with five levels.

Table 3.9 presents an overview of the nominal (M0) and the 25 test mixtures (M1 to M25) investigated in this study. After finalizing the experimental design using the Taguchi method, the mix design proportions were calculated in accordance with IS: 10262: 2021[64].

**Table 3.9: Taguchi design with corresponding combinations, factors, and levels**

MIXES	Abbreviations	FA (%)	CS (%)	PW (%)	RCA (%)
M0	0%FA+0%CS+0%PW+0%RCA	0	0	0	0
M1	25%FA+0%CS+0%PW+0%RCA	25	0	0	0
M2	25%FA+3%CS+5%PW+25%RCA	25	3	5	25
M3	25%FA+6%CS+10%PW+50%RCA	25	6	10	50
M4	25%FA+9%CS+15%PW+75%RCA	25	9	15	75
M5	25%FA+12%CS+20%PW+100%RC	25	12	20	100
M6	30%FA+0%CS+5%PW+50%RCA	30	0	5	50
M7	30%FA+3%CS+10%PW+75%RCA	30	3	10	75
M8	30%FA+6%CS+15%PW+100%RCA	30	6	15	100
M9	30%FA+9%CS+20%PW+0%RCA	30	9	20	0
M1	30%FA+12%CS+0%PW+25%RCA	30	12	0	25
M11	35%FA+0%CS+10%PW+100%RCA	35	0	10	100
M12	35%FA+3%CS+15%PW+0%RCA	35	3	15	0
M13	35%FA+6%CS+20%PW+25%RCA	35	6	20	25
M14	35%FA+9%CS+0%PW+50%RCA	35	9	0	50
M15	35%FA+12%CS+5%PW+75%RCA	35	12	5	75
M16	40%FA+0%CS+15%PW+25%RCA	40	0	15	25
M17	40%FA+3%CS+20%PW+50%RCA	40	3	20	50
M18	40%FA+6%CS+0%PW+75%RCA	40	6	0	75
M19	40%FA+9%CS+5%PW+100%RCA	40	9	5	100
M20	40%FA+12%CS+10%PW+0%RCA	40	12	10	0
M21	45%FA+0%CS+20%PW+75%RCA	45	0	20	75
M22	45%FA+3%CS+0%PW+100%RCA	45	3	0	100
M23	45%FA+6%CS+5%PW+0%RCA	45	6	5	0
M24	45%FA+9%CS+10%PW+25%RCA	45	9	10	25
M25	45%FA+12%CS+15%PW+50%RCA	45	12	15	50

After finalizing the experimental design with the Taguchi method, the mix design proportions were determined following the guidelines outlined in IS: 10262: 2019. The five criteria selected for evaluation are presented in Table 3.10.

**Table 3.10: Selected quality characteristics and its target values**

S. No	Property characteristics	State of concrete	Target value
1	Filling ability	Fresh	Larger is better
2	Passing ability	Fresh	Larger is better
3	Viscosity	Fresh	Smaller is better
4	Compressive Strength at 7,28,56 and 90 days	Hardened	Larger is better
5	Split Tensile Strength at 7,28,56 and 90 days	Hardened	Larger is better

### **3.2.3 Importance of Mix Design of SCC:**

Creating an effective concrete mix design is essential for establishing a sturdy infrastructure. This process entails careful preparation, where a combination of ingredients [64]. Because each ingredient possesses distinct properties, devising an optimal concrete mix is a complex task. It is crucial that all components undergo testing to determine their physical characteristics and assess the suitability for the project's specific site conditions.

The values obtained from these physical property tests serve as the foundation for all considerations in the concrete mix design. This approach ensures the structural integrity of the project and guards against mix failure. It's important to acknowledge that the composition of mix ingredients may vary from one project location to another, necessitating that the physical properties be tested in accordance with the requirements specified for each unique location [65]. This meticulous approach guarantees that the concrete mix is tailored to meet the specific demands of the project and the environmental conditions at hand.

### **3.2.4 Detailed steps for SCC mix design tool**

In this research SCC mix design as performed using IS: 10262:2019 code of practice.

**Mix1- SCC Mix Design for M40 for w/c ratio of 0.4**

Grade designation	M40	
Type of cement (OPC)	53 Gade	
<b>Materials specific gravity</b>		
Cement	3.1	
Coarse Aggregate	2.7	
Fine Aggregate	2.5	
Fly Ash	2	
Copper Slag	3.5	
PVC	1.52	
Super Plasticizer	1.2	
Characteristic Compressive Strength	40	N/mm <sup>2</sup>
Standard Deviation, S	5	
<b>Step1: Target mean Strength</b>		
$F_{ck} = f_{ck} + 1.65 \times S$	48.25	N/mm <sup>2</sup>
<b>Step2: Approximate Air Content</b>		
For 12 mm	1%	
<b>Step3: Selection of water content ratio</b>		
max w/c	0.4	
water content	170	kg/m <sup>3</sup>
Slump flow	750-850	mm
Super plasticizer	0.60%	
For M1 mix design		
Fly ash	25	%
Copper slag	0	%
Plastic waste	0	%
RCA	50	%
Total Cementitious	425.000	kg/m <sup>3</sup>
Fly ash content	106.250	kg/m <sup>3</sup>
copper slag	0.000	kg/m <sup>3</sup>
Cement content	318.750	kg/m <sup>3</sup>
Admixture	2.550	kg/m <sup>3</sup>

**Step4: Selection of powder content and fine aggregate**

Powder Content	505	kg/m <sup>3</sup>
Fines required to be contributed by fine aggregate	80.000	kg/m <sup>3</sup>
Fine aggregate has 8 percent material < 0.125 mm		
Therefore, the fine aggregate quantity	1000.000	kg/m <sup>3</sup>
PVC content (plastic waste)	0.000	kg/m <sup>3</sup>
Fine aggregate content	1000.000	kg/m <sup>3</sup>

**Step 5: Selection of coarse aggregate content**

Volume of coarse aggregate	0.262	m <sup>3</sup>
Mass of total coarse aggregate	707.204	kg/m <sup>3</sup>
Mass of RCA	0.000	kg/m <sup>3</sup>
Mass of Coarse aggregate	707.204	kg/m <sup>3</sup>

**Step 6: calculation of volume of powder content**

Volume of powder content = vol. of OPC+ vol. of fly ash+ vol. of fine aggregate portion =	0.188
--	-------

**MIX PROPORTIONS FOR M1 MIX**

	<b>Weights (kg/m<sup>3</sup>)</b>
Cement	318.750
Fly ash	106.250
Copper slag	0.000
Fine Aggregate	1000.000
PVC	0.000
Coarse Aggregate	707.204
RCA	0.000
Chemical Admixture (SP)	2.550
Free water content ratio	0.4
Powder content	505

<b>M1 MIX RATIO</b>	<b>CEMENT</b>	<b>Fine Aggregate</b>	<b>Coarse Aggregate</b>
	1	2.353	1.664

All the rest of mixes are calculated in the same way and its mix ratios are represented in Table 3.11.

**Table 3.11: Design Mix ratios for different mixes obtained from mix as per IS 10262:2019**

MIXES	Cement: Fine Aggregate: Coarse Aggregate
M0	1: 2.794: 1.330
M1	1: 2.353: 1.664

### 3.2.5 Output Constituent Materials for SCC:

Based on the IS 10262:2019 the mix design of SCC incorporating plastic waste was carried out and the respective calculated weights of each individual ingredient are represented in Table 3.12.

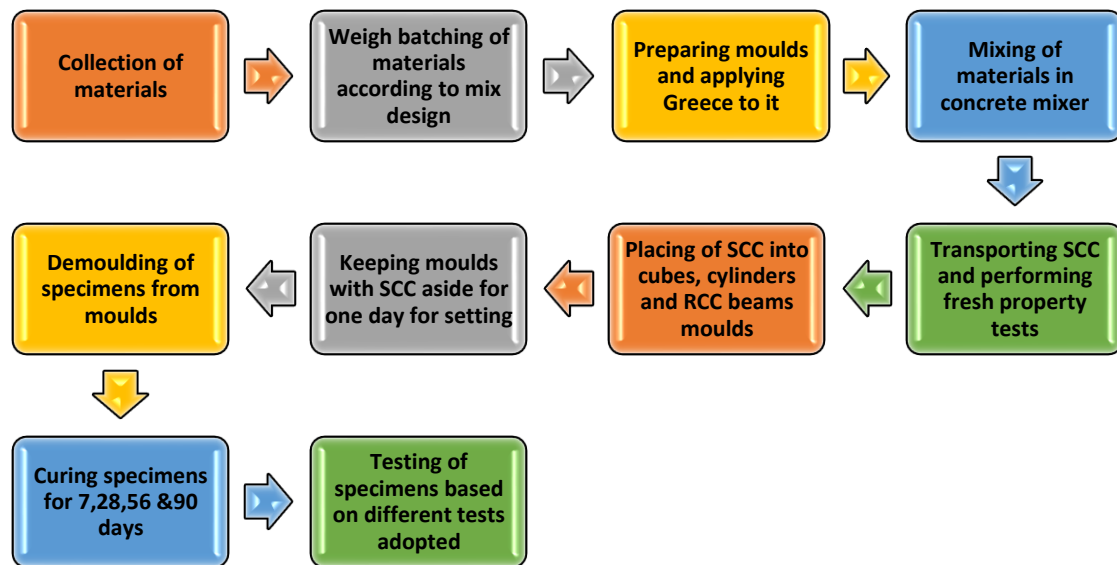
**Table 3.12: Materials Weights for SCC**

S.NO	MIX	CEMENT (kg/m <sup>3</sup> )	FLY ASH (kg/m <sup>3</sup> )	C S (kg/m <sup>3</sup> )	F A (kg/m <sup>3</sup> )	P W (kg/m <sup>3</sup> )	C A (kg/m <sup>3</sup> )	RCA (kg/m <sup>3</sup> )
1	M0	422	-	-	1188	-	494	-
2	M1	317	105	0	1000	0	707	0
3	M2	304	105	13	950	50	530	177
4	M3	292	105	25	900	100	354	354
5	M4	279	105	38	850	150	177	530
6	M5	267	105	50	800	200	0	707
7	M6	295	127	0	950	50	354	354
8	M7	282	127	13	900	100	177	530
9	M8	270	127	25	850	150	0	707
10	M9	257	127	38	800	200	707	0
11	M10	245	127	50	950	50	530	177
12	M11	274	148	0	900	100	0	707
13	M12	261	148	13	850	150	707	0
14	M13	249	148	25	800	200	530	177
15	M14	236	148	38	950	50	354	354
16	M15	214	148	60	900	100	177	530

17	M16	253	169	0	850	150	530	177
18	M17	241	169	13	800	200	354	354
19	M18	228	169	25	950	50	177	530
20	M19	232	169	21	900	100	0	707
21	M20	203	169	51	850	150	707	0
22	M21	232	190	0	800	200	177	530
23	M22	219	190	13	950	50	0	707
24	M23	207	190	25	900	100	707	0
25	M24	194	190	38	850	150	530	177
26	M25	181	190	51	800	200	354	354

### 3.2.6 Steps for manufacturing of SCC:

A detailed step wise steps of entire manufacturing process of SCC was represented in flowchart manner in Fig.3.7 and the respective images are also incorporated in Fig.3.8 for detailed outlook.



**Fig.3.7: Mixing procedure for preparation of SCC**



**Fig.3.8: SCC Specimen preparation in detail**

**Table 3.13: Total number of specimens casted in current research**

MIXES	Compressive Strength Tests (Cubes)				Split Tensile Strength Tests (Cylinders)				Acid attack test (cubes & cylinders)		Flexural test RCC beams
	7 days	28 days	56 days	90 days	7 days	28 days	56 days	90 days	28 days	56 days	
M0	3	3	3	3	3	3	3	3	6	6	3
M1	3	3	3	3	3	3	3	3	6	6	3
M2	3	3	3	3	3	3	3	3	6	6	3
M3	3	3	3	3	3	3	3	3	6	6	3
M4	3	3	3	3	3	3	3	3	6	6	3
M5	3	3	3	3	3	3	3	3	6	6	3
M6	3	3	3	3	3	3	3	3	6	6	3
M7	3	3	3	3	3	3	3	3	6	6	3
M8	3	3	3	3	3	3	3	3	6	6	3
M9	3	3	3	3	3	3	3	3	6	6	3
M10	3	3	3	3	3	3	3	3	6	6	3
M11	3	3	3	3	3	3	3	3	6	6	3
M12	3	3	3	3	3	3	3	3	6	6	3
M13	3	3	3	3	3	3	3	3	6	6	3
M14	3	3	3	3	3	3	3	3	6	6	3
M15	3	3	3	3	3	3	3	3	6	6	3
M16	3	3	3	3	3	3	3	3	6	6	3
M17	3	3	3	3	3	3	3	3	6	6	3
M18	3	3	3	3	3	3	3	3	6	6	3
M19	3	3	3	3	3	3	3	3	6	6	3
M20	3	3	3	3	3	3	3	3	6	6	3
M21	3	3	3	3	3	3	3	3	6	6	3
M22	3	3	3	3	3	3	3	3	6	6	3
M23	3	3	3	3	3	3	3	3	6	6	3
M24	3	3	3	3	3	3	3	3	6	6	3
M25	3	3	3	3	3	3	3	3	6	6	3
	78	78	78	78	78	78	78	78	156	156	78
	Total number of cubes casted			468	Total number of cylinders casted			468	Total number of RCC beams casted		78

### **3.3. INVESTIGATIONS ON FRESH PROPERTIES:**

Assessing the workability of SCC poses unique challenges compared to conventional concrete mixes. Workability tests typically applied to Normal Conventional Concrete may fall short in accurately characterizing SCC because they lack the sensitivity required to identify all its distinctive properties [66]. SCC is classified as such when it demonstrates distinct characteristics, which encompass exceptional filling capacity, effective passing ability, and resistance to segregation.

To thoroughly assess fresh properties of SCC, multiple guidelines and testing methods have been developed and put into practice. Nevertheless, it's crucial to emphasize that no single technique has been universally acknowledged as fully characterizing all the relevant workability aspects of SCC. This underscores the complexity and multifaceted nature of SCC, which demands a combination of assessments and tests to ensure it meets the necessary criteria for workability and performance [55].

This means that every mix is put through a variety of tests rather than being limited to just one method of evaluation. To evaluate each mix for various workability criteria, various testing methods must be used. The comprehensive analysis of the SCC's basic and hardened properties is essential for the application of the SCC to be successful. According to IS: 456-2019 guidelines, the total number of samples used in the current study for each of the 26 mixtures are described in Table 3.13.

#### **3.3.1. SLUMP FLOW TEST AND T500 mm TEST**

Guidelines from EFNARC (2005) [67] were followed for conducting this test. A slump cone, base plate, trowel, scoop, ruler, and stopwatch make up the testing equipment [67]. The droop cone is a geometric shape resembling a truncated cone, with a base diameter of 200 mm and a top diameter of 100 mm [67], the cone is positioned over a metal plate that is 1000 mm x 1000 mm in size and has markings to help you position it in the centre. In the same manner, the 500 mm diameter circle is marked to record how

long it takes SCC to spread to that size. Two side handles on the cone's rim allow users to lift and set anything on the plate.

For the test, about six litres of SCC were made. The cone's interior and base plate must remain moist. The cone was centred on the base plate and positioned over it at the appropriate marking. Using the scoop, concrete was now added to the interior of the cone from the top. A trowel was used to remove extra concrete from the cone's top and level the concrete once it had been filled. At this point, lifting the cone and starting a stopwatch must be done simultaneously. After lifting the cone, the concrete will flow circularly. T500 mm is the amount of time needed for the concrete to travel to the circle with a 500 mm diameter that is marked on the foundation plate [67].



**Fig.3.9: Fresh property tests (a) Slump flow (b) V Funnel (c) L –Box**

Measure the spread of concrete over the base plate in two directions that are parallel to one another. Concrete may segregate if the flow diameter is greater than 800 mm, and if it is less than 650 mm, it may not have enough flow to pass through heavily crowded reinforcing [5]. The experimental arrangement for evaluating the concrete's spreading flow and conducting the slump flow test is depicted in Fig.3.9(a).

### **3.3.2. V- FUNNEL TEST**

It is used in this test contains two rectangular pieces at the top and bottom, measuring 490 mm by 75 mm each. It is connected by a stem extending 150 mm from the top to the bottom, with a 425 mm-long connection section that resembles a hopper. The V-

funnel can stand up to a height of 575 mm from its base [43]. For the test, about 12 liters of concrete were prepared. The V-funnel, with oil applied inside, was positioned on its base.

Concrete was poured into the funnel using a scoop. A twelve-litre bucket was positioned at the bottom to collect the flowing concrete. Upon opening the trap door at the base, enabling the concrete to flow from the funnel into the bucket, a stopwatch was concurrently initiated [43]. The duration required for the concrete to entirely empty from the funnel was noted. For visual clarification, Fig.3.9 (b) offers the equipment dimensions and depicts the arrangement for the V-Funnel test.

### **3.3.3. L-BOX TEST**

The free-flowing and obstructed flow into the reinforced bars is two elements of SCC that are examined by this test. A movable gate divides the vertical and horizontal parts. The reinforcement bars with a specific size and spacing are installed at the transition point from the vertical to the horizontal portion. Depending on the test's requirements, the spacing and bar diameter can be changed. The horizontal part is 150 mm x 200 mm in size and has a length of 800 mm. The vertical section is 600 mm long with a size of 100 mm x 200 mm [43].

Concrete once poured into the vertical part, and the gate was then lifted so that it could flow into the horizontal section [43]. The slope of the concrete when it's at rest is indicated by the ratio of H2 to H1. This measurement serves as an indicator of passing ability. Fig.3.9. (c) displays the measurements of the testing-related equipment.

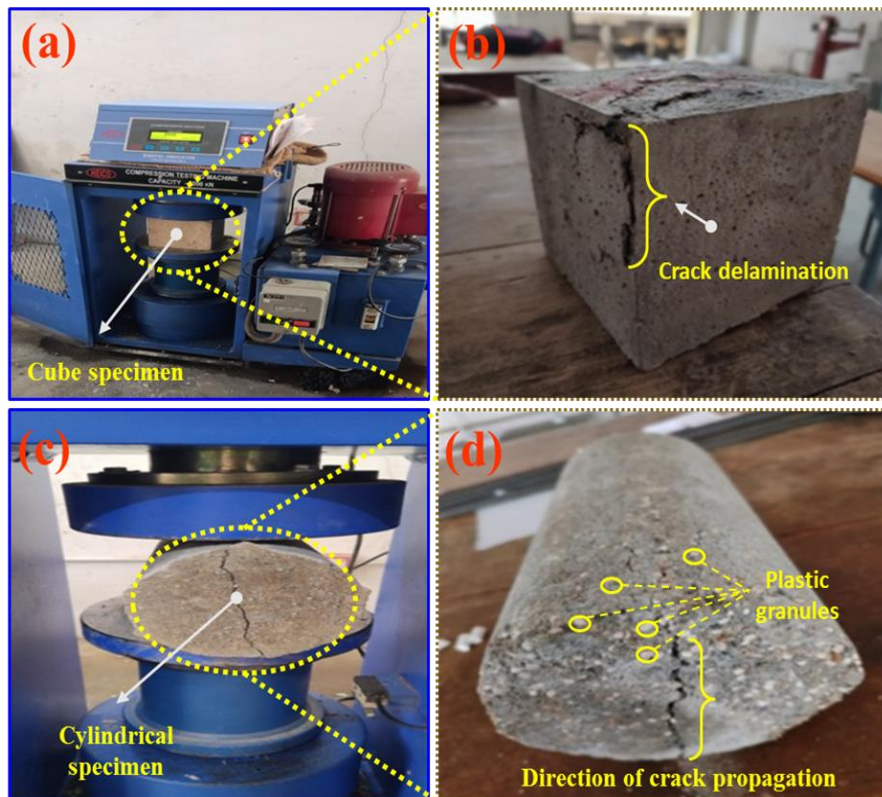
### **3.4. INVESTIGATIONS ON HARDERENED PROPERTIES**

Tests were performed on SCC specimens of standard dimensions in adherence to IS (Indian Standards) criteria to examine various strength-related properties of different mix compositions. These characteristics comprised compressive strength, splitting tensile strength, and flexural strength. Following the specified standards, the samples underwent

a comprehensive assessment, and the average values for each test conducted were calculated for every mix combination.

### 3.4.1. COMPRESSIVE STRENGTH TEST:

The procedures adhered to the guidelines outlined in IS: 516-1959. For the testing, 150x150x150 mm cubes were utilized, and these cubes remained submerged in water throughout the testing period [68]. The strength characteristics of these cubes were evaluated at three different time intervals: 28 days, 56 days, and 90 days. To initiate the test, the bearing surface of the compression testing machine was meticulously cleaned, and the specimen's axis was precisely aligned with the center of thrust of the testing machine's platen [68].



**Fig.3.10 (a) Illustration of a cube specimen subjected to compression load (b) Visual representation of the cube specimen failure (c) Depiction of a cylinder specimen undergoing tensile load (d) Visual representation of the failure of the cylindrical specimen.**

No supplementary packing material was inserted between the surface of the test specimen and the platen of the testing machine. This arrangement is illustrated in Figures 3.10 (a) and (b). The specimen was then subjected to a constant load until it reached the point of crushing, at which moment the crushing load was recorded. Subsequently, the calculation of compressive strength involved dividing the crushing load by the surface area of the cubes.

### **3.4.2. SPLIT TENSILE STRENGTH TEST:**

In accordance with the specifications outlined in IS 516-1959, this test is carried out utilizing cylindrical specimens with a diameter of 150 mm and a height of 300 mm [68]. The testing procedure requires placing the cylindrical specimen horizontally between the loading faces on the platform of the compression testing apparatus. To ensure proper separation, narrow packing strips are inserted between the specimen and the loading faces. Additionally, reference lines are marked at both ends of the specimen's diameter for precise measurements. In the test, a diametric compressive load is applied to the cylindrical specimen along its length [68]. This loading causes tensile strains on the surface where the load is applied. The experimental arrangement for this test is depicted in Figures 3.10 (c) and (d). The load is incrementally applied steadily until the specimen reaches the point of failure. The value of the load at which the specimen fails is recorded, and this recorded data is utilized in the computation of the split tensile strength. This strength measurement assesses the material's capacity to withstand tensile forces when subjected to this specific testing method, all in accordance with the IS 516-1959 standard.

### **3.4.3. Flexural strength test:**

In accordance with IS: 516-1959 standards, the flexural strength of plain concrete is assessed using a concrete beam with dimensions measuring 150x150x600 mm [68]. The test employs a two-point loading configuration. To ensure consistency, the specimens undergo a curing period of 28 days before testing. In the test, a moulded specimen placed in a mould is exposed to a gradual increment in load at a rate of 180 kg/cm<sup>2</sup>/min. The load

applied to the specimen is incrementally increased until it fractures, at which moment the corresponding failure load is recorded [68].

### **3.5. STUDIES ON DURABILITY PROPERTIES**

Concrete structure designers place a higher value on concrete's strength than its endurance. The instances of concrete structures degrading prematurely offer useful information for addressing the causes of their lack of durability. Water is implicated in all forms of degradation because solids have pores that allow them to enter easily [69]. Concrete durability is adversely affected by both physical and chemical factors. Due to chemical effects, acidic solutions will drain cement paste, and sulfate attacks will result in expansive reactions.

According to a few rough estimates, a developed nation spends 40% of its budget on maintaining and repairing old buildings, and the remaining 60% is allocated to brand-new projects [70]. Making construction materials more durable promotes resource-saving, a positive ecological step. Because of all these factors, architects and structural engineers are aware that durability is a key factor.

The issue of the lifespan of concrete constructions has drawn significant attention in Japan for many years, starting in 1983. Proper compaction by qualified professionals is necessary for the construction of enduring concrete buildings [71]. Because of this, considerable research is necessary to determine whether its strength and durability attributes are the same for identical grades of concrete.

The speed at which chemical deterioration occurs is influenced by several factors, including the concentration of ions, their presence in the water, and the chemical composition of the solid material. Alkaline substances, such as calcium, have a substantial influence on the hydration process of Portland cement [72]. However, concrete is highly vulnerable when exposed to acidic water. The primary objective of this project is to develop SCC using waste plastic as a building material component. In pursuit of this objective, the material's durability is a crucial consideration. This study focuses on investigating and

presenting information regarding the behavior of SCC when it encounters acidic environments and undergoes degradation.

### **3.5.1 Acid attack:**

It mostly occurs when calcium hydroxide, produced by Portland cement hydration, reacts with acid substances. The chemical reaction produces soluble calcium compounds, which the aqueous solution leaches away. Acid quantity and concentration, concrete permeability, and cement content all affect how quickly an acid attack occurs. Sulfuric acid attacks cause the wastewater treatment facilities and sewer pipelines to deteriorate, causing economic loss. Sulfate-reducing bacteria, a type of microorganism found in sewer pipes, starts the process by which sulfuric acid breaks down concrete [73]. In addition to foundations, other structural components are also vulnerable to acid attack because of sulfuric acid-containing groundwater. Supplementary cementitious material's function in a chemical attack in SCC.

### **3.5.2 Resistance to HCL acid attack:**

For each of the 25 different mixtures, both cubes and cylinders were cast to investigate the influence of plastic waste on acid attack in SCC. The cubes were submerged to a curing period of 28 days. After being removed from the water, they were subjected to a two-hour period of sun curing, followed by weighing. After the initial 28-day curing period, the specimens were submerged in a 5% sulfuric acid solution, with the pH level consistently maintained at 2 during the entire immersion process, as illustrated in Figures 3.11(a) and (b). Assessments were carried out at two time points: 28 days and 56 days after the commencement of immersion. Once the samples are removed from the sulphuric acid solution, their surfaces were carefully cleaned using a soft nylon wire brush and running water to eliminate any loose or weakened materials. Subsequently, the weight of the specimens, which had been exposed to the sulphuric acid for a duration of 28 and 56 days, was measured after allowing them to dry on the surface [74]. Specimens underwent both compression testing and split tensile strength testing at both the 28-day and 56-day intervals to assess their properties and how they responded to acid exposure.

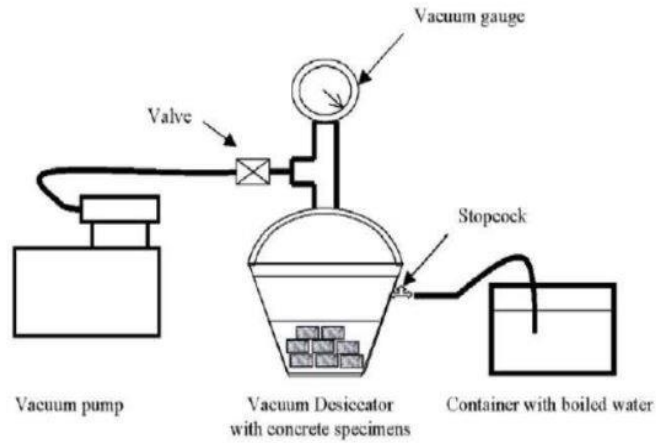


**Fig: 3.11 (a) Cubes immersed in water. (b) Cubes immersed in HCL solution.**

### **3.5.2 Rapid Chloride Penetration Test:**

Concrete's durability one of the notable traits, marked by its ability to function effectively even in unfavorable circumstances. A critical factor influencing this durability is the presence of chloride, which can significantly impact concrete's integrity [75]. The challenge lies in managing the access of chloride ions, as they have the potential to cause harm to both the concrete structure and its reinforcement. Unlike water penetration, chloride ion infiltration triggers more substantial swelling, about two to five times greater. To address this concern, the study focuses on assessing the electrical conductance of concrete blocks. This approach offers a rapid and informative way to gauge the material's resistance against chloride intrusion, aiding in the preservation of concrete's longevity and performance.

Following the guidelines specified in ASTM C 1202-97 standards, an assessment of the resistance of concrete mixtures to chloride ion penetration was carried out. Cylindrical samples, with dimensions of 102 mm in diameter and 51 mm in thickness, were prepared, exposing one end while immersing the other end in a solution containing sodium chloride and 0.3% sodium hydroxide [75].



**Fig.3.12 Schematic of RCPT setup**

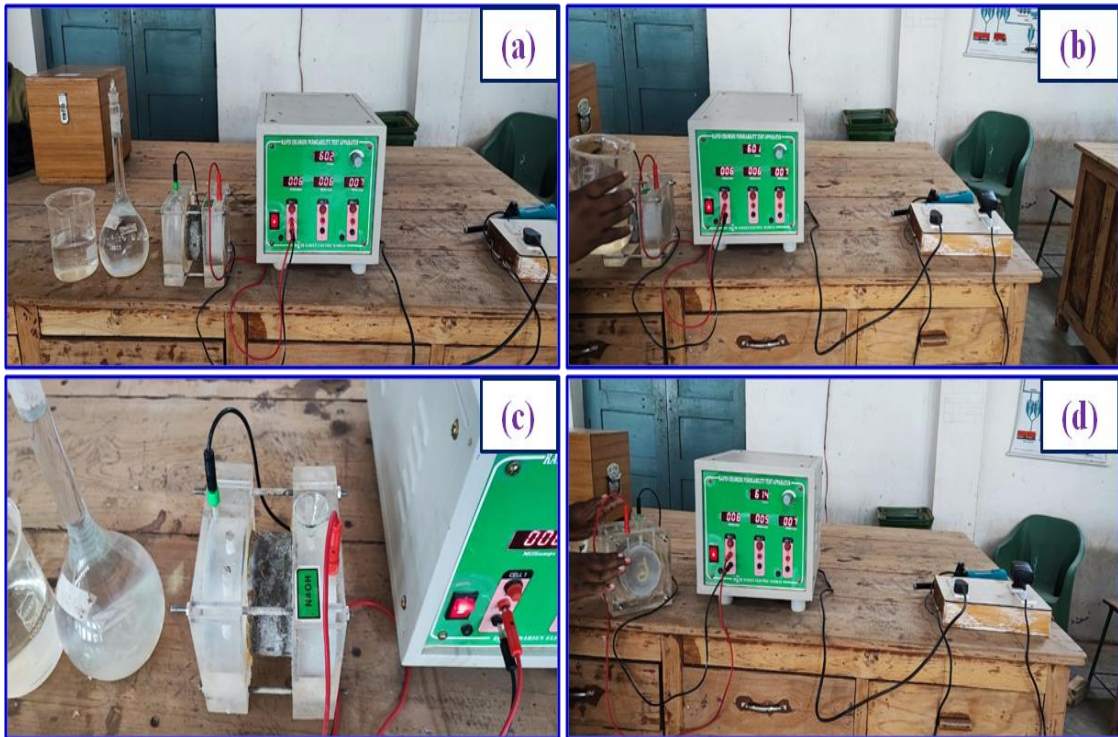
The extent of chloride infiltration was gauged by measuring the overall electric potential of six hours. Table 3.14 presents the established benchmarks for assessing chloride penetrability by quantifying the passed chloride ions. Fig.3.12 illustrate the procedures for constructing specimens that were housed within a vacuum desiccator bowl and had dimensions of 100 mm by 200 mm.

Deaerated water flowed through the desiccator, completely covering the samples, while preventing air ingress, thus sustaining a vacuum within for three hours. The vacuum persisted for an additional hour during a soaking period of 18 hours [76]. Fig.3.13 (a) illustrates RCPT Test Setup. Subsequently, specimens were extracted, dried, and enclosed in a gasket.

**Table3.14: 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

Two cells containing NaCl and NaOH solution were filled as shown in Fig.3.13 (b), followed by an application of 60 V potential difference, the initial operating temperature ranged from 20°C to 25°C [75] as represented in Fig.3.13(c) and the result of charge passed will be displayed in Fig.3.13 (d).



**Fig.3.13: (a) RCPT Test arrangement (b) Filling with NaOH and NaCl Solution (c) Applying charge to the specimen (d) RCPN display**

## CHAPTER 4

### RESULTS AND DISCUSSIONS

The findings of the study goals and experimental investigations are presented in this chapter after they have been thoroughly and clearly explored. The chapter includes an integration of the outcomes of all four research objectives, along with the experimental findings, and a detailed analysis and interpretation of the results.

**4.1 RESEARCH OBJECTIVE 1:** To investigate the fresh qualities of self-compacting concrete formed from plastic waste, recycled aggregates, fly ash and copper slag in both their fresh and hardened states.

#### 4.1.1 Fresh Properties of SCC:

The present study investigated the fresh properties of SCC in accordance with EFNARC standards [67]. Furthermore, following the procedures outlined in IS 1199-1959, the slump cone test was carried out on freshly mixed concrete. The resulting experimental data, which includes information on Filling ability, passing ability, and viscosity utilized in the study, is consolidated in Table 4.1. Visual inspections during the slump flow test confirmed that none of the mixtures exhibited any evidence of segregation or bleeding.

**Table.4.1: Experimental results of fresh properties in the present study**

MIXES	Filling ability (mm)	Passing ability	Viscosity (sec)
M0	835	0.98	7
M1	825	0.95	9
M2	816	0.93	10
M3	759	0.9	15
M4	633	0.84	19
M5	575	0.81	22
M6	821	0.94	12

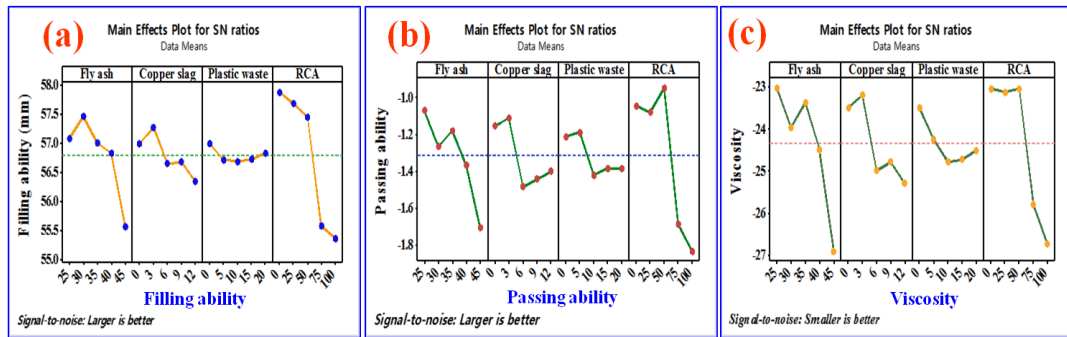
M7	663	0.82	18
M8	648	0.81	20
M9	815	0.86	15
M10	811	0.9	15
M11	586	0.82	19
M12	819	0.92	12
M13	767	0.87	14
M14	812	0.9	12
M15	598	0.86	18
M16	809	0.88	15
M17	815	0.93	12
M18	566	0.8	19
M19	552	0.8	24
M20	785	0.87	16
M21	552	0.8	24
M22	577	0.81	22
M23	683	0.84	17
M24	642	0.84	19
M25	559	0.82	22

#### **4.1.2 Effect of optimum process parameters on filling ability, passing ability and viscosity characteristics**

The significance of input parameters associated with fresh properties is demonstrated through the response curves of the S/N ratio at the 28-day evaluation point, as illustrated in Fig.4.1.

The control factors taken into account for optimizing the filling, passing, and viscosity properties of SCC comprised FA, CS, PW, and RCA. The results show that RCA exerted the most substantial influence on filling ability, passing ability, and viscosity, ranking first, followed by FA, CS, and PW, respectively.

Filling ability showed improvement initially as FA content increased from 25% to 30% in the casted mixes before gradually decreasing.



**Fig. 4.1 Main effect plots for the S/N ratio of (a) filling ability (b) passing ability and (c) viscosity**

As illustrated in Figure 4.1(a), the maximum mean S/N ratio is noticed in filling ability when FA is at 30%, CS at 3%, and both PW and RCA at 0%. Likewise, Fig. 4.1(b) illustrates that the superior mean S/N ratio is attained for passing ability when FA is at 25%, CS at 3%, PW at 5%, and RCA at 50%. To achieve the most favourable process parameters for lower viscosities, the mean Signal-to-Noise (S/N) ratio is 25% for FA, 3% for CS, 0% for PW, and 0% for RCA. In Fig. 4.1(c), the parameter factors can be ranked in the following order, as detailed in Table 4.2: RCA, FA, CS, and PW. These results signify that the composition of RCA significantly impacts the performance of SCC.

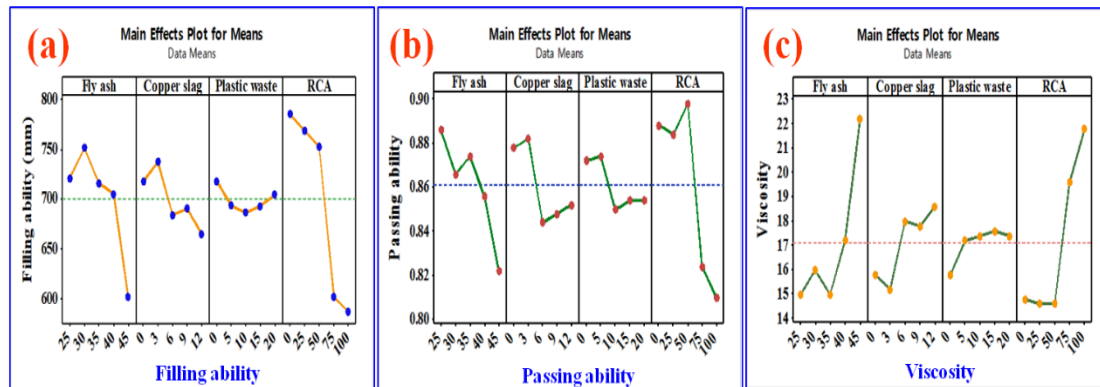
The systematic study was conducted on the selected raw materials used in this study at macro (Digital images) and micro level through 3-D microscopic images presented in the fig(s). 3.1, 3.2 respectively. The microscopic analysis of the cement, fly ash exhibits a bulk amount of an oblate spheroid in shape whereas the copper slag shows glaze surface pertaining irregular cross section. The coarse aggregates show rough and irregular in shape. Besides, the recycled coarse aggregates show rough surface containing radicle debris on it.

**Table.4.2: Mean S/N ratio response table for filling ability, passing ability and viscosity**

S. No	Factors	Level1	Level2	Level3	Level4	Level5	Delta	Rank
1	Filling ability							
	FA	57.08	57.47	57.01	56.83	55.57	1.90	2
	CS	56.99	57.28	56.66	56.69	56.35	0.92	3
	PW	57.00	56.72	56.69	56.73	56.83	0.31	4
	RCA	57.88	57.68	57.45	55.58	55.37	2.51	1
2	Passing ability							
	FA	-1.0671	-1.2633	-1.1766	-1.3653	-1.7042	0.6371	2
	CS	-1.1510	-1.1078	-1.4811	-1.4384	-1.3978	0.3737	3
	PW	-1.2089	-1.1861	-1.4173	-1.3806	-1.3837	0.2312	4
	RCA	-1.0408	-1.0760	-0.9444	-1.6849	-1.8306	0.8862	1
3	Viscosity							
	FA	-23.01	-23.95	-23.35	-24.47	-26.30	3.29	2
	CS	-23.47	-23.02	-24.53	-24.77	-25.28	2.226	3
	PW	-23.32	-23.78	-24.77	-24.71	-24.50	1.45	4
	RCA	-22.58	-23.11	-23.02	-25.79	-26.58	4.00	1

#### 4.1.3. Effect of process parameters on fresh characteristics

Each fresh property of SCC mix had experienced certain effects due to process parameters and its detailed studies are represented below.



**Fig. 4.2 Main effect plots for means of (a) filling ability (b) passing ability and (c) viscosity**

#### **4.1.4. Effect of process parameters on filling ability**

The impact of process parameters on the filling ability of SCC mixtures is visually represented in Fig. 4.2(a). According to the experimental findings, it's noteworthy that the addition of 25% to 30% FA leads to an enhancement in filling ability. However, as the FA content surpasses 30%, filling ability decreases. This decline in filling ability beyond 30% can be attributed to its significant influence on the rate of hydration and the efficacy of the superplasticizer. Moreover, an increase in CS from 0% to 3% positively influences filling ability. This is attributed to the fine particle size of CS, effectively acting as a filler and occupying voids within the SCC mixtures.

Nonetheless, a diminishing trend is observed when more than 3% of CS is added to the mixtures. This decrease in filling ability is linked to the increased density resulting from CS addition. Predictive outcomes also underscore that a rise in CS content percentage results in a reduction in filling ability.

Nonetheless, a moderate enhancement in filling ability is noted upon incorporating 6% CS. This enhancement is primarily attributed to the reduced water absorption capacity and the glassy characteristics of copper slag, allowing it to efficiently occupy densely packed reinforcements more rapidly. PW is a vital additive in this study to evaluate its influence on SCC mixtures. The filling ability exhibits a distinct decreasing trend from 0%

to 20% PW content. However, after reaching a 10% PW content, there is an increase in filling ability, which continues up to 20%. This favourable trend can be ascribed to the non-absorbent characteristics of PVC granules, along with their shape and substantial specific surface area.

Finally, the impact of RCA on filling ability was examined. Increasing the percentage of RCA in the mixtures from 0% to 50% has a relatively minor effect on filling ability. The results suggest that incorporating RCA up to 50% is optimal for achieving improved filling ability.

#### **4.1.5. Effect of process parameters on Passing ability**

Test results clearly show that a higher FA concentration (ranging from 25% to 45%) causes a passing ability decline. However, a slight enhancement in passing ability is noticed when the FA content is raised from 30% to 35%. Figure 4.2(b) shows the effect of FA, CS, PW, and RCA on the capacity of SCC combinations to pass. FA's spherical shape, smooth glassy texture, and small particle size are responsible for this enhancement. It's interesting to note that at a certain water content, FA appears to improve concrete workability when used as a partial replacement for cement.

On the other hand, CS and PW have a synergistic effect on passing ability. According to Fig. 4.2(b), passing ability is trending upward as both materials' percentages increase; for CS, this ranges from 0% to 3%, and for PW, it is between 0% and 6%. However, beyond these percentages, passing ability experiences a decline.

Additionally, the influence of RCA has a significant impact on the passing ability of SCC mixtures. It's observed that a 50% RCA content results in a significant enhancement in passing ability. However, when RCA content is increased from 0% to 25% and subsequently from 50% to 100%, passing ability is reduced.

Particle friction is primarily responsible for the decline in passing ability since it reduces workability at higher replacement levels.

#### **4.1.6. Effect of process parameters on Viscosity**

The primary effect charts in Fig. 4.2(c) depict the viscosity of casted SCC mixes. The graph makes it evident that greater viscosity results from raising the FA level from 25% to 45%. Moreover, there is a decrease in viscosity observed at 35% FA content. The influence of CS content is observed initially, where viscosity decreases as CS content increases from 0% to 3%. Subsequently, there is an improvement in viscosity with an increased CS content, reaching up to 12%.

PW content significantly affects the viscosity of SCC mixtures, with lower percentages of PW resulting in lower viscosity. Conversely, higher PW percentages contribute to higher viscosity. The rise in viscosity with a higher percentage of plastic waste can be explained by the presence of free water in SCC. This free water isn't absorbed by the plastic particles but stays within the concrete mix. Because plastic particles are non-absorbent, concrete compositions containing them have more free water, which promotes SCC flow more quickly.

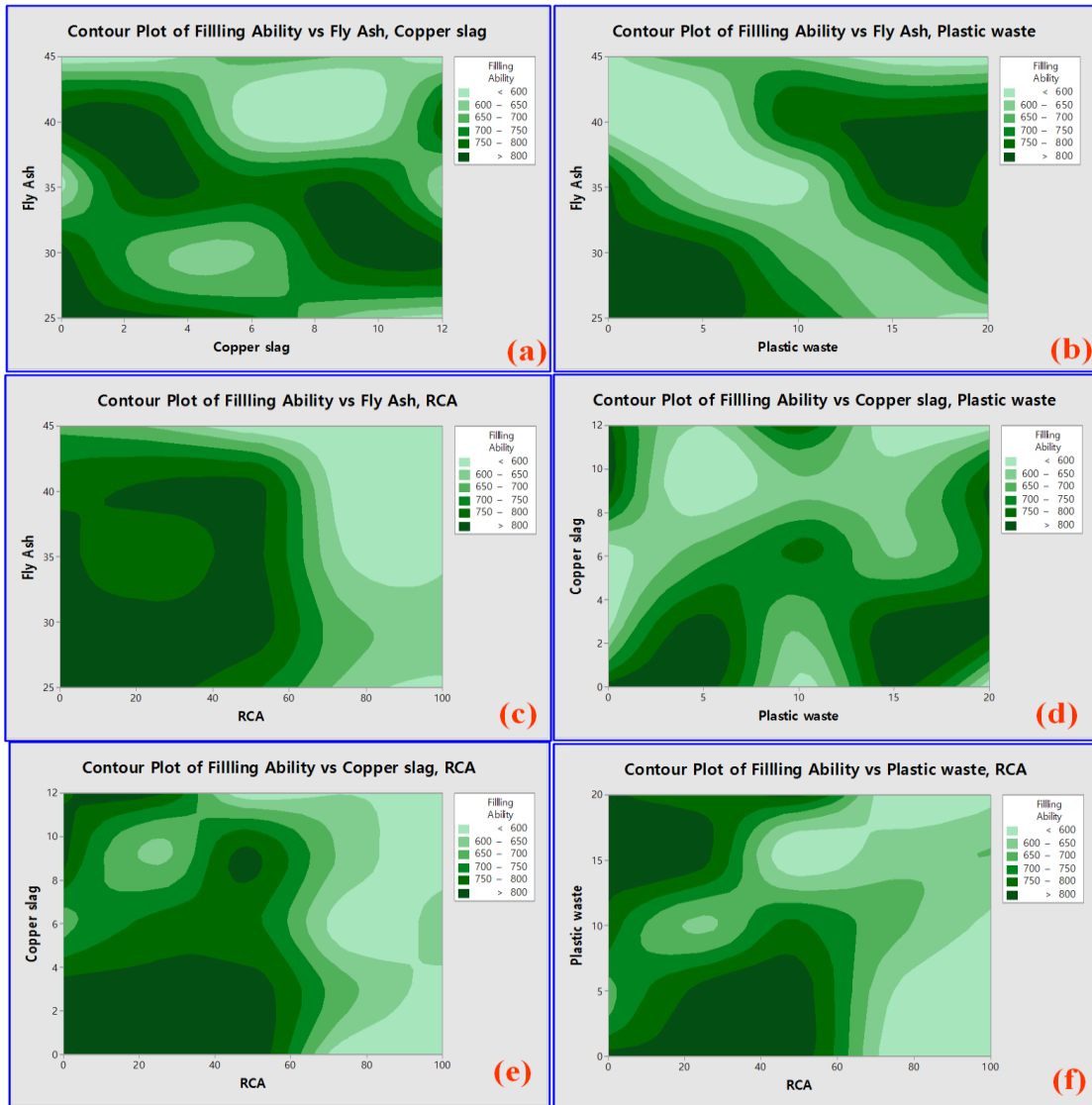
In the case of RCA, lower percentages (ranging from 0% to 50%) are more favourable for achieving lower viscosity in the mixtures. Superplasticizer use appears to have a negative impact when mixed with RCA, as indicated by an increasing trend in viscosity characteristics with a higher RCA percentage. However, to shorten the flow time, this impact can be somewhat controlled.

#### **4.1.7 Contour plots**

Contour plots were utilized to identify the process parameters with the most significant impact on performance.

#### **4.1.8 Contour plots: Filling ability**

It was determined that filling ability is significantly influenced by FA, CS, PW, and RCA. From Fig. 4.3(a), it is evident that a high level of FA and CS leads to an increase in filling ability.



**Fig. 4.3 Contour plots for filling ability (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.**

In Fig.4.3(b), it is demonstrated that high filling ability can be achieved with an optimum level of FA and a low level of PW. Fig.4.3(c) highlights that the optimal combination of FA and RCA leads to high filling ability. Fig.4.3(d) illustrates that a high level of CS and a low level of PW contribute to increased filling ability in concrete.

Fig.4.3(e) indicates that high CS content and a low RCA level result in enhanced filling ability.

Lastly, Fig.4.3(f) shows that high filling ability can be attained with a high level of PW and an optimum level of RCA.

Based on these plots, it can be concluded that to achieve the high filling ability the low level of copper slag, plastic waste and optimum level of fly ash, and RCA were preferable for SCC.

#### **4.1.9. Contour plots: Passing ability**

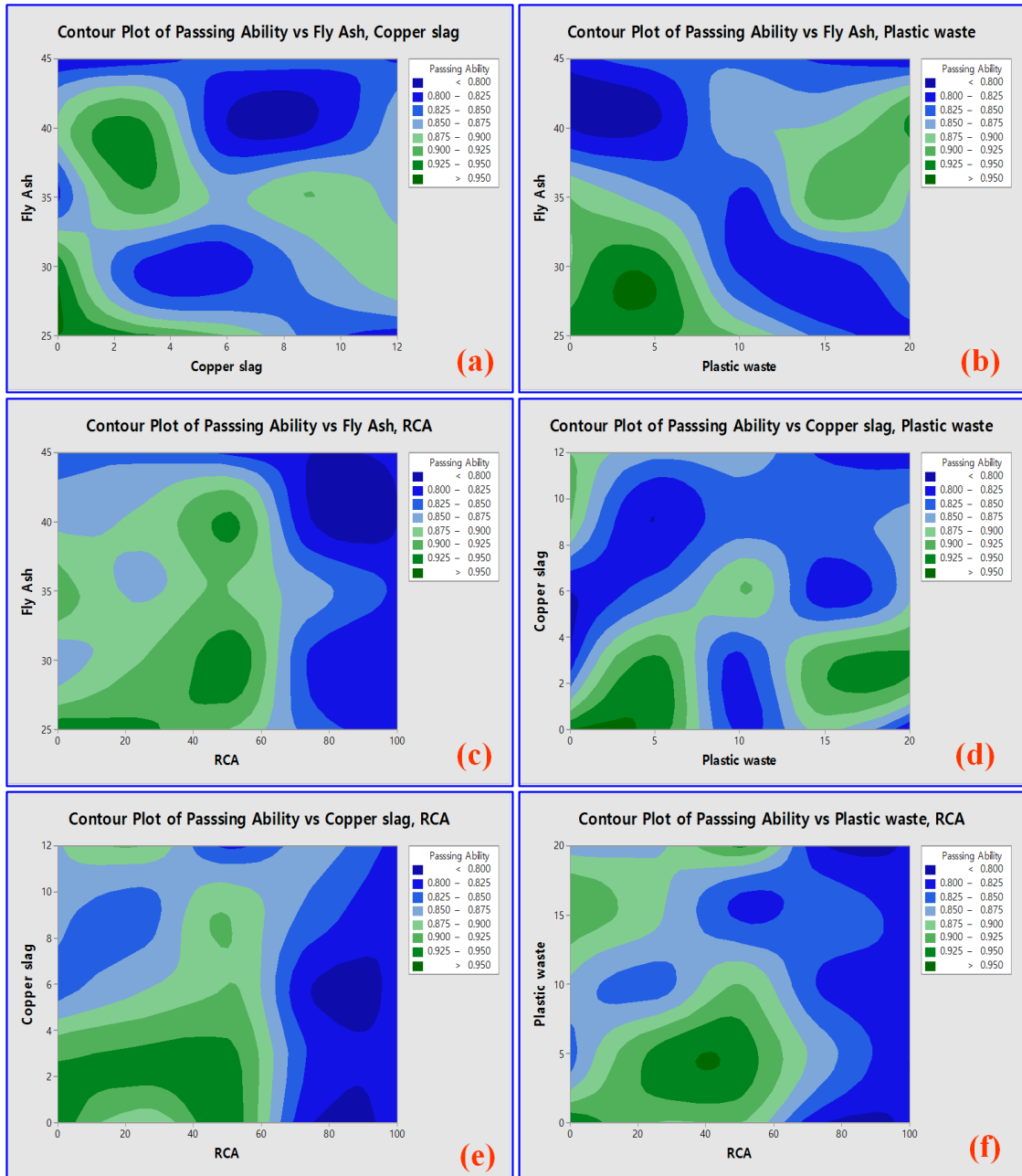
Passage ability, which validates the concrete's flowing capacity over the form by passing through the structural concrete without segregation or outflow obstruction.

Contour plots were drawn to know the combined effect on passing ability with adopted four parameters. From Fig.4.4(a) it is noticed that the higher passing ability is achieved with high level of fly ash content and medium level of coppers slag.

Fig.4.4(b-c) shows that the high level of fly ash and high level of plastic waste cause to attain the higher passing ability. Fig.4.4(d) illustrations the prominent levelled copper slag with medium to prominent level of plastic waste leads to achieve the higher passing ability of the SCC.

However, from Fig.4.4 (e-f) the passing ability is greatly influenced by the prominent level of parameter quantities. It as observed from Fig.4.4 (a-f) that the medium level of plastic waste and medium level of copper slag leads to get the higher passing ability.

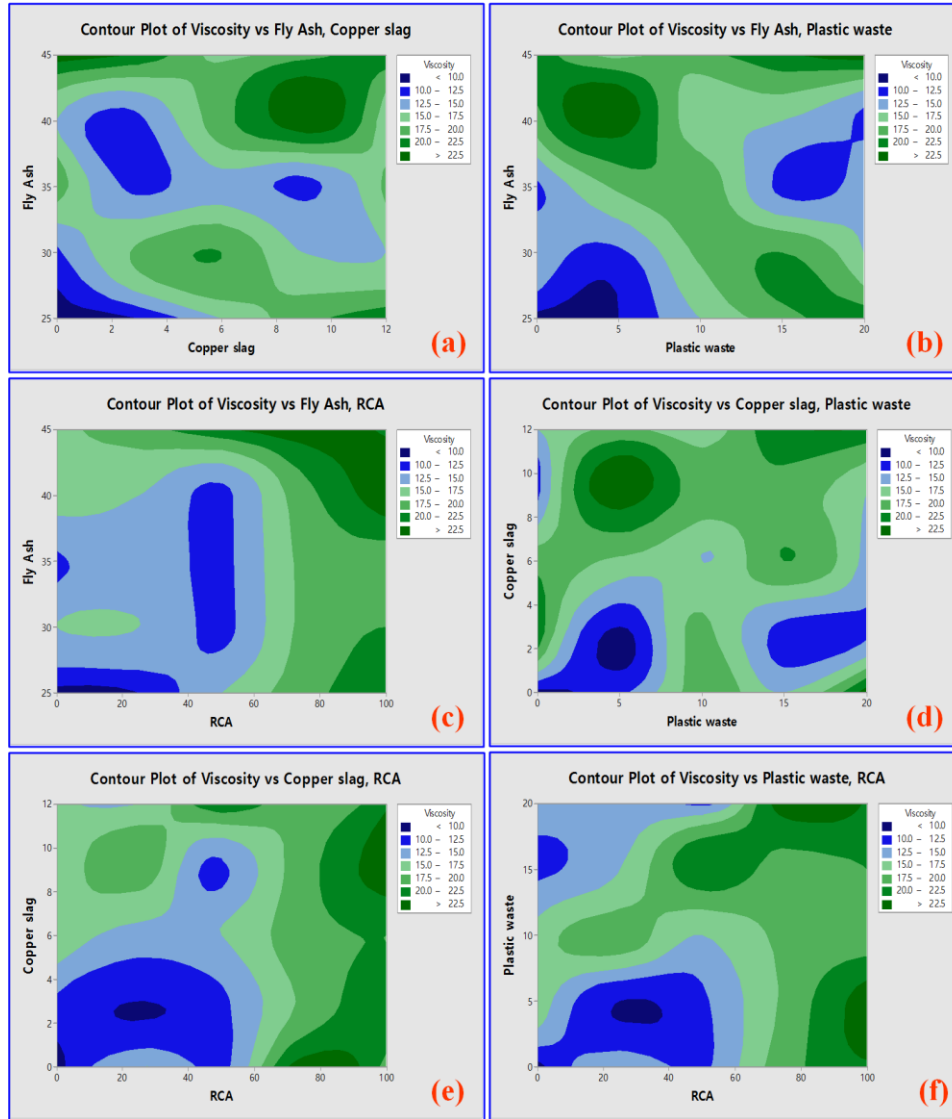
From the ANOVA plots for passing ability. In conclusion, it can be firmly established that a lower percentage of copper slag and a higher percentage of Recycled Coarse Aggregate (RCA) significantly influence the passing ability of the concrete.



**Fig.4.4: Contour plots for passing ability (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.**

**4.1.10. Contour plots: Viscosity** Water-soluble polymers known as viscosity-enhancing admixtures are used to improve the viscosity and cohesiveness of cement-based products.

This increase in viscosity property in liquid phase is essential in flowable systems as it helps diminish the tendency for material constituents to separate, ultimately enhancing the uniformity and performance of the resulting mechanical product.



**Fig.4.5: Contour plots for viscosity (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.**

From Fig.4.5 (a-f) it is noticed that the number of constituents used in this study are more responsible to get less viscosity at lower level of quantities. The results significantly

elucidate that each combination of factors which are more reactive at minimum percentages to get better SCC mixtures.

#### 4.1.11. Hardened Properties of SCC:

The hardened properties study incorporates various experimental results as follows

#### 4.1.12. Compressive strength

The compressive strength of cast cube specimens is evaluated after 7, 28, 56, and 90 days of curing following the standardized test procedure outlined in IS: 516-1989. This testing involves applying continuous loading at a rate of 2 kilonewtons per square millimeter per millimeter (2 KN/(mm<sup>2</sup>/mm)) using a 2000-kilonewton compression testing machine. Table 4.3 displays the compressive strength experimental data for the different factor and level combinations used in the current study. However, the objective is not to reach M40 grade concrete strength but to check what will happen when standard concrete is replaced with industrial waste.

**Table.4.3: Experimental results of compressive strength for a combination of factors and levels in the present study**

MIXES	Compressive strength at 7 days (N/mm <sup>2</sup> )	Compressive strength at 28 days (N/mm <sup>2</sup> )	Compressive strength at 56 days (N/mm <sup>2</sup> )	Compressive strength at 90 days (N/mm <sup>2</sup> )	% of compressive strength increased from 7 to 28 days	% of compressive strength increased from 28 to 56 days	% of compressive strength increased from 56 to 90 days
M0	23.51	44.76	45.66	47.45	47.48	1.96	3.77
M1	22.38	42.88	43.31	45.02	47.81	0.99	3.81
M2	17.65	36.14	36.86	38.31	51.16	1.96	3.77

M3	14.74	29.56	29.86	31.04	50.14	0.99	3.81
M4	13.65	21.35	21.56	22.42	36.07	0.99	3.81
M5	10.71	19.16	19.47	20.12	44.10	1.59	3.22
M6	21.07	38.42	39.19	40.73	45.16	1.96	3.77
M7	15.13	24.74	24.99	25.98	38.84	0.99	3.81
M8	11.93	22.76	22.99	23.90	47.58	0.99	3.81
M9	16.45	34.71	35.11	36.45	52.61	1.14	3.66
M10	17.01	35.14	35.84	37.25	51.59	1.96	3.77
M11	10.71	20.15	20.35	21.16	46.85	0.99	3.81
M12	17.19	36.81	37.18	38.65	53.30	0.99	3.81
M13	14.62	32.19	32.87	33.80	54.58	2.07	2.75
M14	21.14	41.24	42.06	43.71	48.74	1.96	3.77
M15	12.23	20.19	20.59	21.40	39.43	1.96	3.77
M16	15.19	33.54	33.91	35.22	54.71	1.09	3.71
M17	17.19	37.34	38.13	39.21	53.96	2.07	2.75
M18	9.76	18.72	19.09	19.84	47.86	1.96	3.77
M19	5.96	15.94	16.26	16.90	62.61	1.96	3.77
M20	12.05	29.42	30.43	31.19	59.04	3.32	2.42
M21	5.61	16.29	16.81	17.27	65.56	3.09	2.65
M22	7.16	18.69	19.06	19.81	61.69	1.96	3.77
M23	8.14	26.13	26.65	27.70	68.85	1.96	3.77
M24	13.42	32.1	32.42	33.71	58.19	0.99	3.81
M25	5.61	17.62	17.80	18.50	68.16	0.99	3.81

Based on the test results obtained by performing compression test after curing of 7, 28, 56 and 90 days, two plots can be drawn as represented in Fig.4.6 (a-b) for results of compressive and split tensile, representing that incorporation of different wastes like PW will also make SCC to withstand its fresh and hardened properties and so leads to a sustainable concrete.

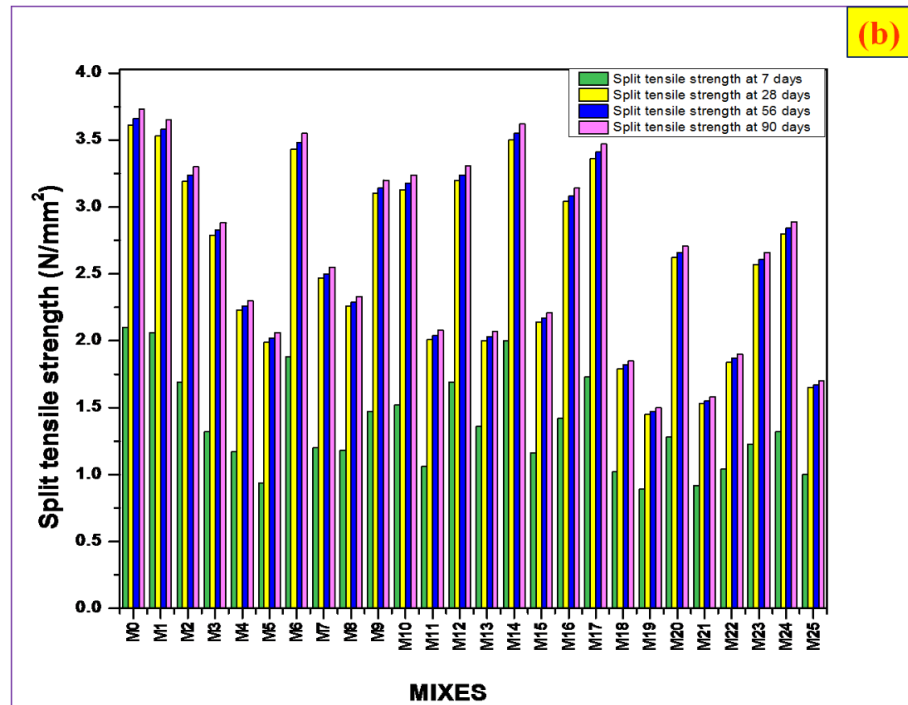
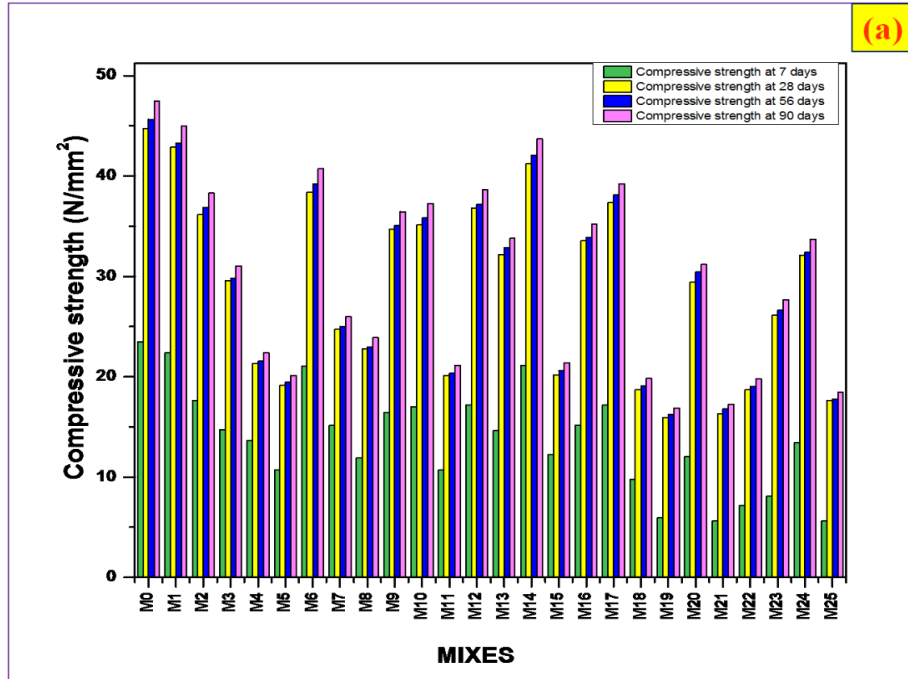


Fig.4.6: Experimental results of present study (a) Compressive and (b) split tensile strength after 7, 28, 56 and 90 days of curing age

#### 4.1.13. Effect of optimum process parameters on compressive strength

The importance of input parameters that impact compressive strength, as indicated by Signal-to-Noise (S/N) ratio curves at 7 and 28 days of curing age, is depicted in Fig. 4.7(a-b). In the quest for attaining the highest compressive strength in SCC mixtures, FA, CS, PW, and RCA play pivotal roles as primary control factors.

In the pursuit of achieving the highest compressive strength, RCA and FA are identified as crucial contributors, with RCA ranking first and FA second in importance. They are followed by CS and PW.

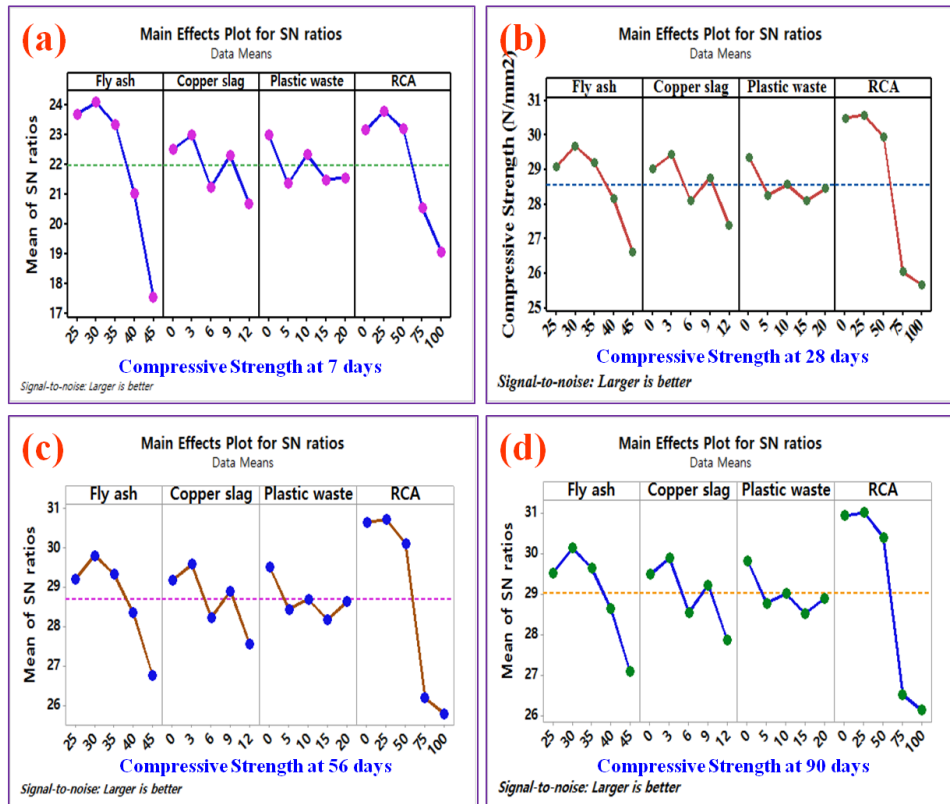


Fig. 4.7 Main effect plots for S/N ratio of compressive strength at (a) 7 days, (b) 28 days, (c) 56 days and (d) 90 days

The highest compressive strength was attained with the following mix proportions: FA content of 30%, CS at 3%, PW at 0%, and RCA at 25%. This combination led to the optimal SCC mixture for the specified control factors

The compressive strength values for 28 days are provided in Table 4.3. The observed variations in mix proportions underscore the significant influence of each control parameter on compressive strength.

It's worth noting that, within the specified range, the effect of each control parameter on compressive strength after a 28-day curing period can be discerned [60].

The significance of responses developed for 56 and 90 days of curing age, as illustrated by Signal-to-Noise (S/N) ratio curves with input parameters related to compressive strength, is shown in Fig. 4.7(c-d).

The corresponding compressive strength values for 56 and 90 days of curing age are provided in Table 4.3.

Once again, RCA and FA take the lead in contributing significantly to achieving the highest compressive strength, ranking first and second, followed by CS and PW, as demonstrated in Table 4.4 for both 56 and 90 days of curing age, respectively.

It's worth mentioning that previous studies have also observed similar ranking trends for the same input parameters concerning 28-day compressive strength results.

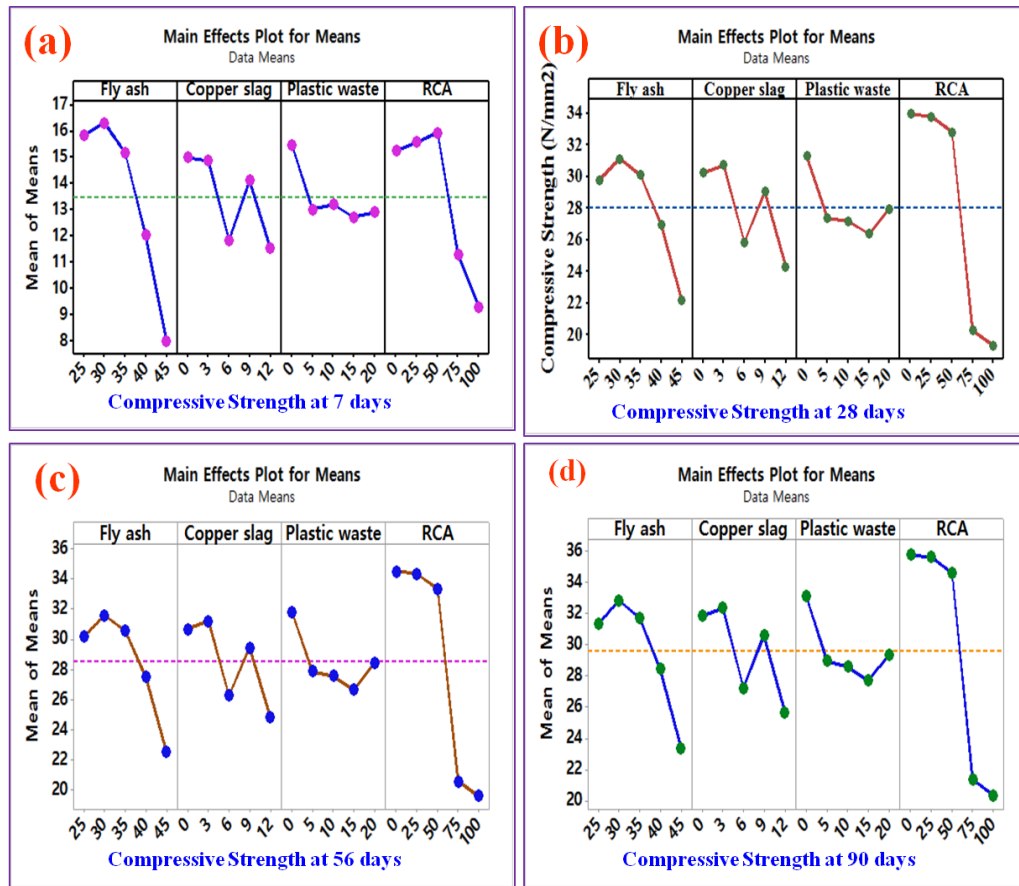
Similarly, the optimal mix proportions of 30% FA content, 3% CS content, 0% PW content, and 25% RCA content consistently yield the highest compressive strength in Fig.4.7(a-b), at both 56 and 90-day curing ages, emphasizing their importance in formulating the most effective SCC mixture for specified control parameters over extended curing periods.

**Table.4.4: Mean S/N ratio response table for compressive strength at 7,28,56 and 90 days**

S. No	Factors	Level1	Level2	Level3	Level4	Level5	Delta	Rank
1	Compressive Strength at 7 days							
	FA	23.72	24.1	23.37	21.05	17.56	6.54	1
	CS	22.54	23.011	21.24	22.32	20.71	2.30	3
	PW	23.00	21.32	22.35	2.51	21.58	1.63	4
	RCA	23.17	23.81	23.21	20.56	19.07	4.74	2
2	Compressive Strength at 28 days							
	FA	29.09	29.69	29.19	28.17	26.61	3.07	2
	CS	29.04	29.44	28.10	28.78	27.39	2.05	3
	PW	29.35	28.27	28.57	28.10	28.46	1.25	4
	RCA	30.50	30.57	29.95	26.05	25.67	4.90	1
3	Compressive Strength at 56 days							
	FA	29.21	29.81	29.33	28.35	26.77	3.04	2
	CS	29.18	29.58	28.24	28.90	27.56	2.02	3
	PW	29.50	28.44	28.70	28.18	28.63	1.32	4
	RCA	30.65	30.72	30.09	26.21	25.80	4.91	1
4	Compressive Strength at 90 days							
	FA	29.53	30.14	29.65	28.64	27.09	3.06	2
	CS	29.49	29.90	28.56	29.23	27.87	2.04	3
	PW	29.84	28.78	29.01	28.52	28.90	1.32	4
	RCA	30.95	31.03	30.41	26.52	26.13	4.90	1

#### 4.1.14 Effect of process parameters on Compressive strength

The influence of various process parameters on the compressive strength of SCC mixtures was extensively investigated. The compressive strength of these composite mixtures was evaluated at both 7 and 28 days of the curing period, as shown in Fig. 4.8(a-b).



**Fig. 4.8 Main effect plots for means of compressive strength at (a) 7 days, (b) 28 days, (c) 56 days and (d) 90 days**

The results clearly show that increasing the FA content from 25% to 30% substantially improves the strength of the SCC mixes. However, beyond 30% FA content, the strength begins to decrease. The high strength achieved at 30% FA content is primarily due to FA's properties, which reduce the heat of hydration in cement over an extended curing period. Numerous studies have indicated that FA tends to reduce the early age compressive strength of concrete and can delay the hardening process [30].

The findings demonstrate that the highest compressive strength was attained with RCA content ranging from 0% to 50% in the SCC mixes. Nevertheless, a significant drop in strength was observed when the RCA content exceeded 50%. Prior research has also shown that increasing the volume of RCA replacement results in a reduction in the

compressive strength of SCC [77]. This phenomenon can be attributed to the high porosity of RCA and its limited adhesion to the mortar matrix. The interfacial transition zone (ITZ) in concrete, which is known to be the weakest area, displays the lowest indentation modulus [78]. Consequently, higher RCA content in concrete results in more weak layers, leading to decreased compressive strength.

The impact of process parameters on the compressive strength of Self-Compacting Concrete (SCC) mixes was further explored for curing durations of 56 and 90 days, as illustrated in Figure 4.8(c-d). The findings reveal that elevating the Fly Ash (FA) content from 25% to 30% notably improves the strength of SCC mixes. However, subsequent increases in FA content gradually result in a decline in compressive strength.

The characteristics of FA, which mitigate the heat of hydration in cement over extended curing periods, primarily contribute to the elevated strength observed at 30% FA content. Numerous studies have incorporated up to 60% FA as a substitute for cement and evaluated various fresh and hardened properties of SCC mixes, including microstructure assessment [79]

Each study provides unique reasons for the decrease in compressive strength as the curing age increases, such as the effects of heat of hydration [19] water-cement ratio, water absorption, thermal variations during concrete curing, early shrinkage development, and extended setting times leading to difficulties in formwork removal [80] .

The analysis of variance results revealed that the addition of extra calcium (in the form of OPC, replacing fly ash) was identified as the most influential factor in regulating both compressive strength and water absorption [81].

It is noteworthy that 3% CS incorporation in SCC mixes is suitable for achieving maximum compressive strength, and a significant improvement in results was observed with 9% CS addition as shown in Figure 4.8(c-d). In Figure 4.7(a), the 15% PW addition exhibited a decrease in compressive strength compared to 5%, 10%, and 20%. This result

suggests that PW, despite its poor bonding with the matrix, plays a role in bearing load and contributes to the development of compressive strength.

This underscores the importance of this study in developing eco-friendly SCC[55]. Some studies have adopted a similar approach to replacing fine aggregate with PW[35]. One study noted that coarse PW as a replacement for fine aggregate reduces SCC compressive strength more than fine PW, resulting in eco-friendly SCC [35]

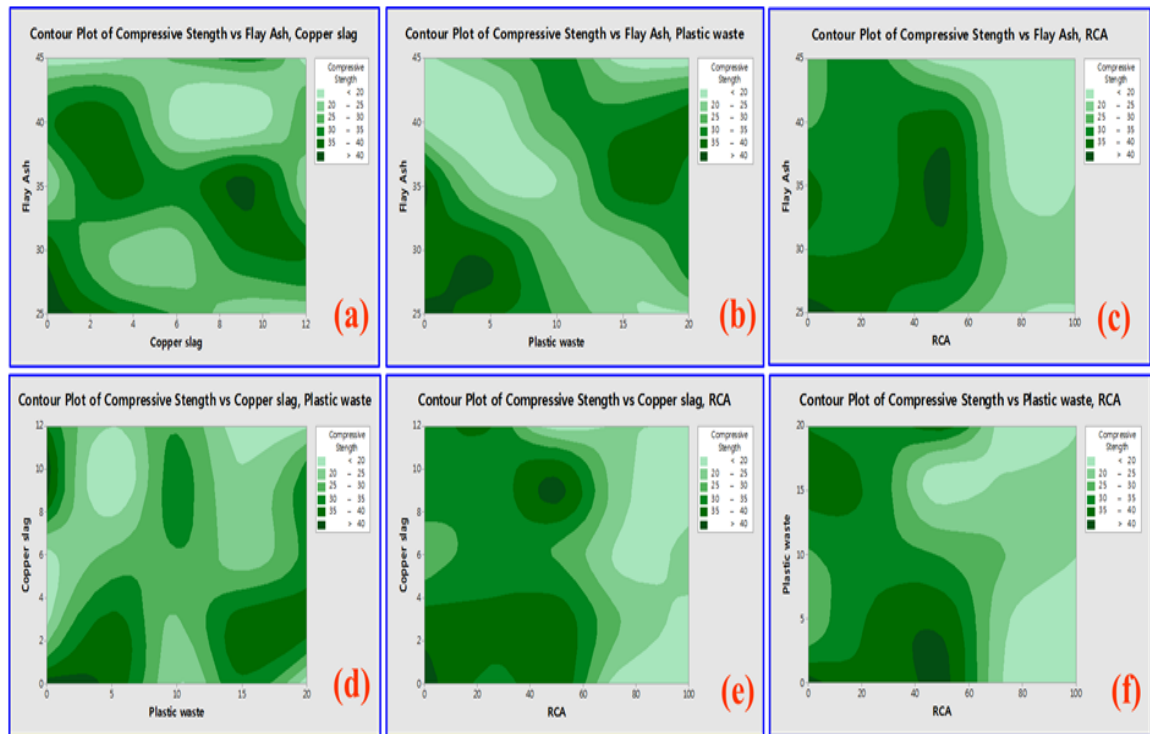
In a recent study, it was observed that manufactured plastic aggregates have the potential to substitute natural aggregates up to 25%, retaining the essential strength and ductility required for non-structural applications [82]

Additionally, this research delved into the impact of RCA on the compressive strength of SCC mixtures. The findings indicated that SCC mixes containing 25% and 50% RCA content exhibited higher compressive strength compared to those with 75% and 100% RCA content at both 56 and 90 days of curing.

A significant reduction in compressive strength was noted, attributed to insufficient bonding between Recycled Concrete Aggregate (RCA) and the matrix, leading to the development of a weak Interfacial Transition Zone (ITZ). This observation aligns with previous findings reported by other researchers [34]. Thus, increasing RCA content in SCC results in reduced compressive strengths.

#### **4.1.15. Contour plots for compressive strength at 28,56 and 90 days**

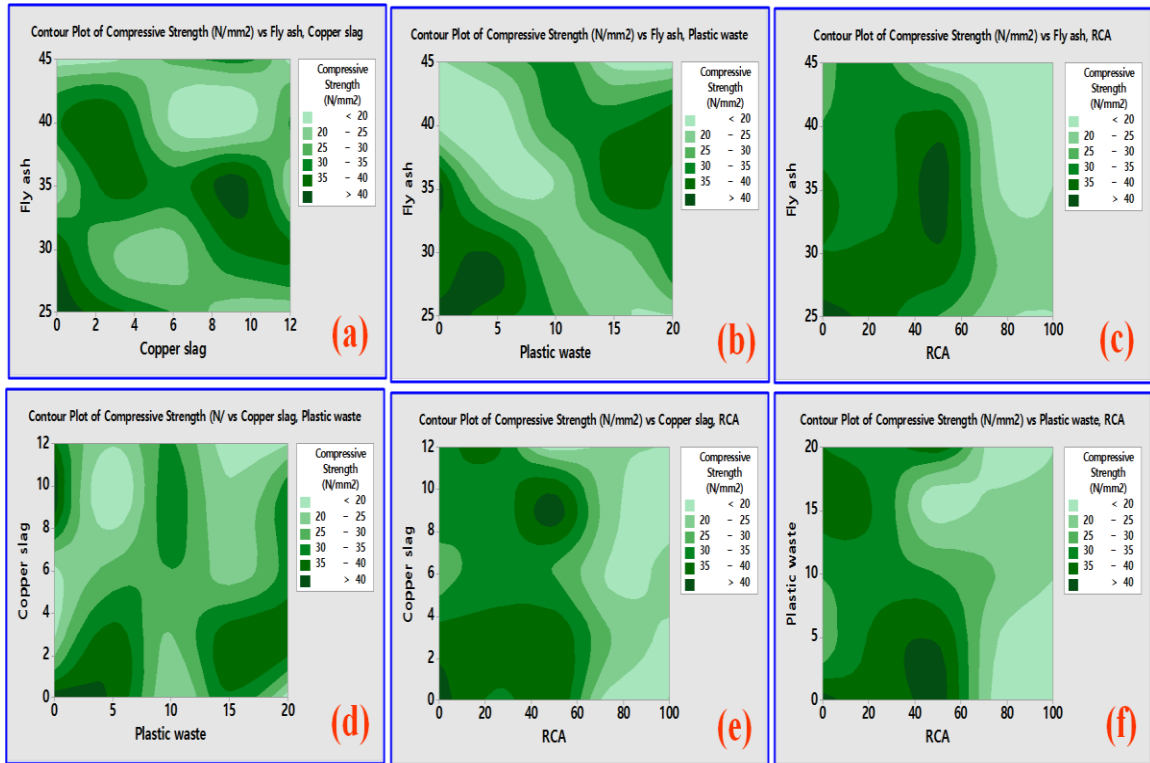
Contour plots are instrumental in categorizing the process parameters that exert the most significant influence on composite performance.



**Fig. 4.9 Contour plots for compressive strength at 28 days (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.**

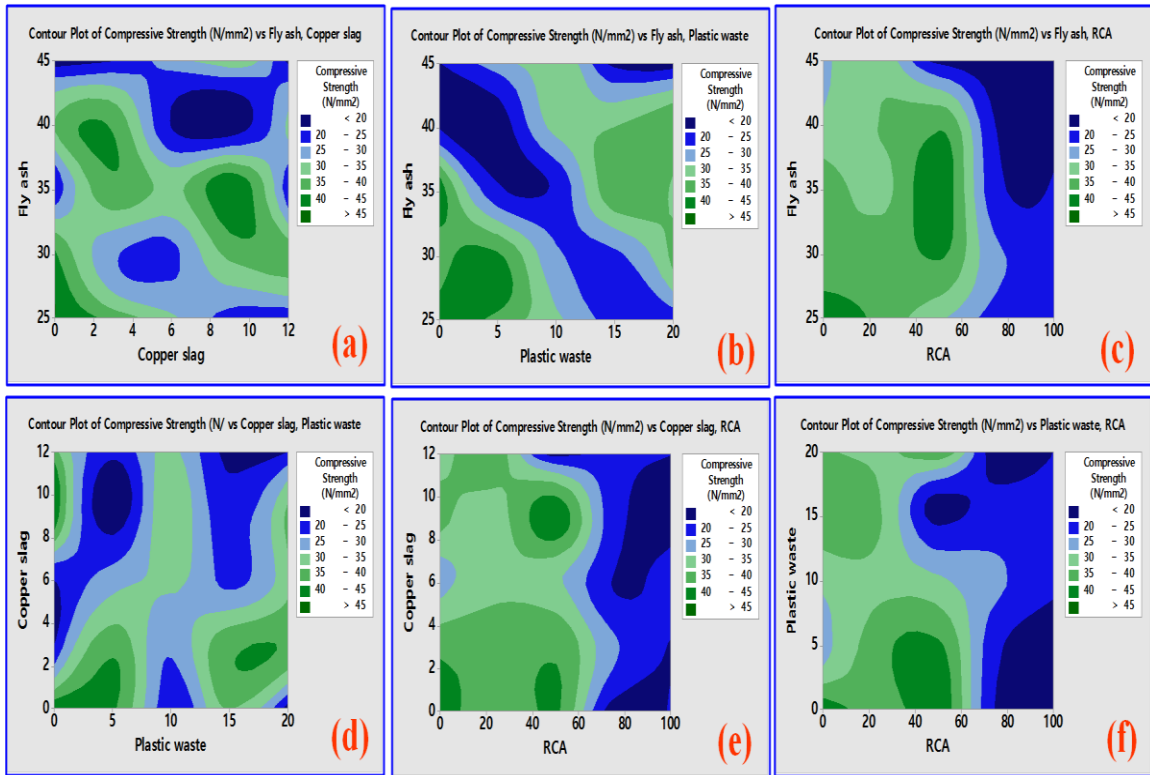
Analysing Fig.4.9(a), it becomes evident that the combination of CS and FA at a medium level has a more pronounced effect on improving compressive strength. Fig.4.9(b) highlights that a combination of plastic waste and fly ash at a lower level is preferable for achieving the maximum compressive strength.

Moving on to Fig.4.9(c), it is apparent that the combination of fly ash and RCA at medium levels is more effective in achieving maximum strength. Fig.4.9(d) demonstrates that a higher level of copper slag and a lower level of plastic waste are suitable for attaining the maximum compressive strength.



**Fig. 4.10** Contour plots for compressive strength at 56 days (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.

Finally, both Fig.4.9(e) and Fig.4.9(f) show that having both plastic waste and RCA at medium levels is better for achieving higher compressive strength. In conclusion, the optimal approach to enhancing the compressive strength of the prepared SCC mixtures involves using medium levels of fly ash and RCA in combination with low levels of copper slag and plastic waste.



**Fig.4.11 Contour plots for compressive strength at 90 days (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.**

#### 4.1.16. Split tensile strength

Cylindrical specimens measuring 150mm x 300mm were subjected to split tensile strength testing in accordance with IS: 5816-1999 [68].

The tests were conducted at curing periods of 7, 28, 56, and 90 days, utilizing a continuous loading rate of 2 KN/(mm<sup>2</sup>/mm) with the aid of a 2000 KN compression testing machine.

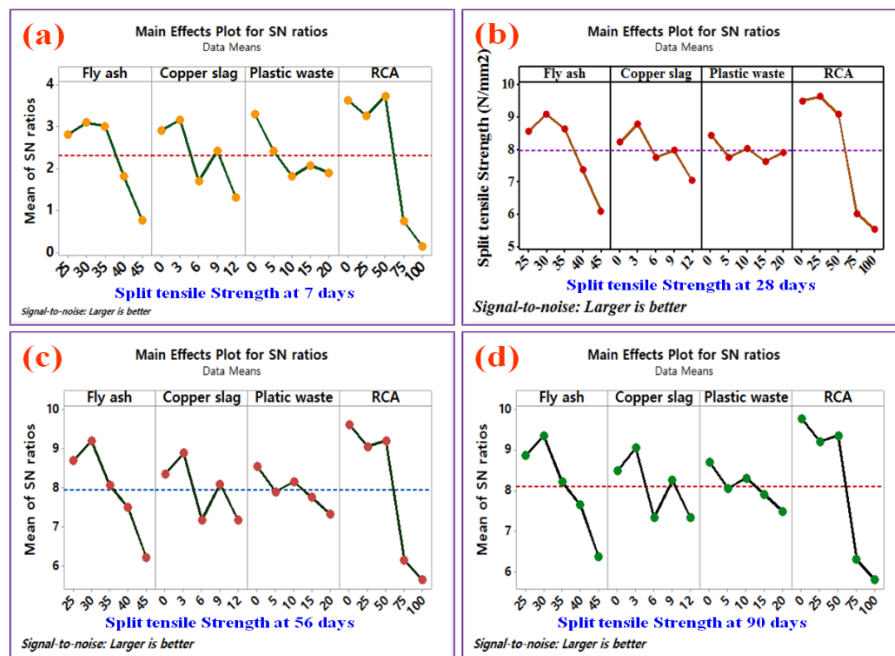
**Table.4.5: Experimental results of split tensile strength for a combination of factors and levels in the present study**

<b>MIXE S</b>	<b>Split tensile strength at 7 days (N/mm<sup>2</sup>)</b>	<b>Split tensile strength at 28 days (N/mm<sup>2</sup>)</b>	<b>Split tensile strength at 56 days (N/mm<sup>2</sup>)</b>	<b>Split tensile strength at 90 days (N/mm<sup>2</sup>)</b>	<b>% of tensile strength increased from 7 to 28 days</b>	<b>% of tensile strength increase d from 28 to 56 days</b>	<b>% of tensile strength increase d from 56 to 90 days</b>
M0	2.1	3.61	3.66	3.73	41.83	1.28	1.94
M1	2.06	3.53	3.58	3.65	41.64	1.48	1.74
M2	1.69	3.19	3.24	3.30	47.02	1.48	1.84
M3	1.32	2.79	2.83	2.88	52.69	1.38	1.84
M4	1.17	2.23	2.26	2.30	47.53	1.38	1.84
M5	0.94	1.99	2.02	2.06	52.76	1.38	1.84
M6	1.88	3.43	3.48	3.55	45.19	1.48	1.84
M7	1.2	2.47	2.50	2.55	51.42	1.38	1.84
M8	1.18	2.26	2.29	2.33	47.79	1.38	1.84
M9	1.47	3.1	3.14	3.20	52.58	1.38	1.84
M10	1.52	3.13	3.18	3.24	51.44	1.48	1.84
M11	1.06	2.01	2.04	2.08	47.26	1.38	1.84
M12	1.69	3.2	3.24	3.31	47.19	1.38	1.84
M13	1.36	2	2.03	2.07	32.00	1.38	1.84
M14	2	3.5	3.55	3.62	42.86	1.48	1.84
M15	1.16	2.14	2.17	2.21	45.79	1.48	1.84
M16	1.42	3.04	3.08	3.14	53.29	1.38	1.84
M17	1.73	3.36	3.41	3.47	48.51	1.38	1.93

M18	1.02	1.79	1.82	1.85	43.02	1.48	1.74
M19	0.89	1.45	1.47	1.50	38.62	1.48	1.84
M20	1.28	2.62	2.66	2.71	51.15	1.48	1.84
M21	0.92	1.53	1.55	1.58	39.87	1.48	1.84
M22	1.04	1.84	1.87	1.90	43.48	1.48	1.84
M23	1.23	2.57	2.61	2.66	52.14	1.48	1.84
M24	1.32	2.8	2.84	2.89	52.86	1.38	1.84
M25	1.00	1.65	1.67	1.70	39.39	1.38	1.84

#### 4.1.17. Effect of optimum process parameters on mechanical properties

The importance of split tensile strength responses concerning input parameters is demonstrated through S/N ratio curves at 7 and 28 days, as shown in Fig. 4.12(a-b).



**Fig. 4.12** Main effect plots for S/N ratio of split tensile strength at (a) 7 days, (b) 28 days, (c) 56 days and (d) 90 days

Among the primary control factors affecting split tensile strength, RCA and FA take the top two positions, followed by CS and PW [61]. As shown in Fig. 4.12(b), the maximum split tensile strength was attained with a combination of 30% FA content, 3% CS content, 0% PW content, and 25% RCA content.

In Fig. 4.12(b), it is evident that split tensile strength initially increased significantly with the addition of the specified additives to the cement but then decreased. The results for split tensile strength in SCC mixtures at 7 and 28 days of curing can be found in Table 4.5. The ranking of parameters based on their individual contributions to the mean S/N ratios for split tensile strength is reported in Table 4.6. These rankings were determined using samples from the 28-day curing period [60]. Cement, in conjunction with RCA and FA, makes substantial contributions to attaining the desired level of split tensile strength. The results for split tensile strength in all SCC mixtures can be found in Table 4.5.

The significance of the responses of input parameters, illustrated through Signal-to-Noise (S/N) ratio curves at 56 and 90 days of curing for split tensile strength, is presented in Figure 4.12(c-d). The predominant impact of adjusting the input parameters on split tensile strength emphasizes the crucial roles played by RCA and FA.

Therefore, they are ranked first and second, respectively, as shown in Table 4.6, followed by CS and PW. A previous study also reported a similar ranking system for these input parameters in terms of 28-day split tensile strength results.

High it is observed in mixes developed with 30% FA content, 3% CS content, 0% PW content, and 0% RCA content, are illustrated in Fig. 4.12 (c-d). Furthermore, it is noted that the incorporation of 10% PW content has some impact on increasing split tensile strength before losing its effectiveness, as shown in Fig. 4.12 (c-d). Similarly, at 50% incorporation of RCA content, a step increase in split tensile strength is observed before losing its overall effectiveness, as shown in Fig. 4.12 (c-d) for 56 and 90 days of curing age test.

The influence of each individual parameter on the mean S/N ratio of split tensile strength is ranked according to its specific contribution to the output results, and these rankings are detailed in Table 4.6. To determine the final rank parameters, the testing samples from 56 and 90 days of curing age are considered. Interestingly, it is observed that both FA and CS significantly contribute to achieving the required level of split tensile strength.

#### 4.1.18 Effect of process parameters on split tensile strength

The impact of process parameters on split tensile strength was investigated to identify the optimal conditions for achieving maximum strength in SCC composite mixes at 7 and 28 days of curing, as depicted in Fig. 4.13(a-b).

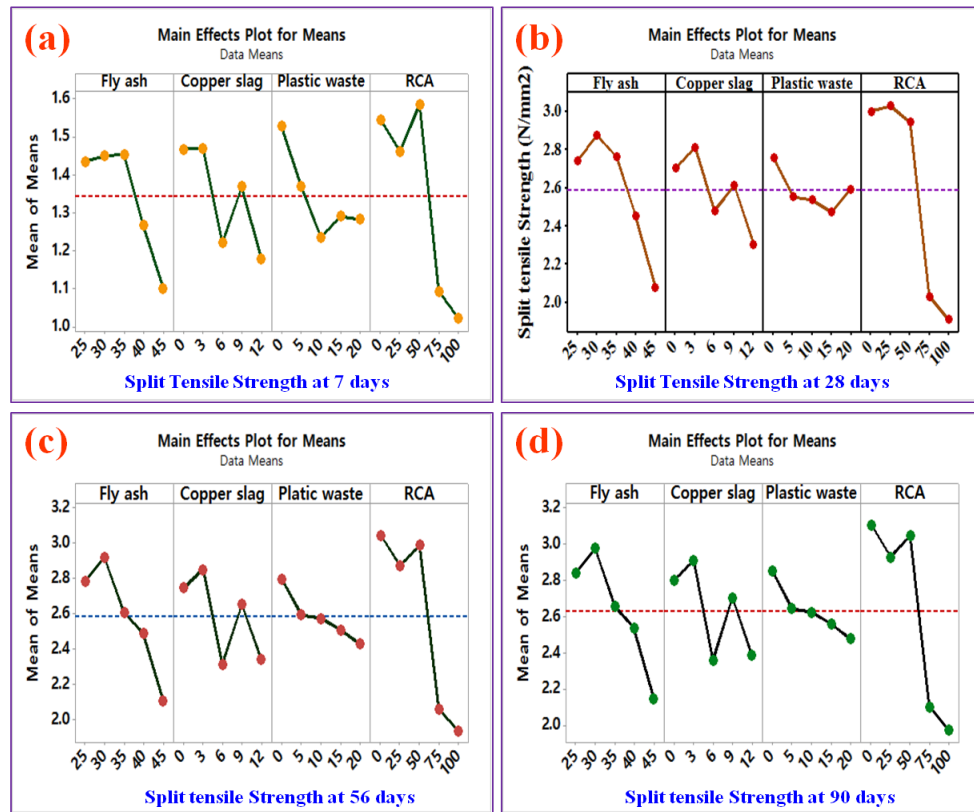


Fig. 4.13 Main effect plots for means of split tensile strength at (a) 7 days, (b) 28 days, (c) 56 days and (d) 90 days

The findings show that the highest tensile strength was achieved at 30% FA content, followed by a decreasing trend in strength with further increases in FA content. A 3% content of CS shows a higher tensile strength, but this strength decreases as the CS percentage increases. Interestingly, SCC mixes without plastic waste display higher strength compared to mixtures with higher plastic waste percentages. When examining the fractured surface of the concrete cylinder, it's evident that most of the plastic particles were displaced rather than breaking apart.

The concrete specimens containing plastic aggregates did not fail in the typical brittle manner observed in traditional concrete under compression loads. The observed failure was likely more gradual, and it depended on the content of plastic aggregates. As the plastic aggregate content increased, the type of failure became more ductile [83]. Samples containing plastic aggregates could withstand the load for a few minutes after failure before disintegrating completely.

The impact of process parameters on the split tensile strength of SCC mixes was investigated for 56 and 90 days of curing in this study, as shown in Fig. 4.13(c-d). It's worth noting that an increase in FA content from 25% to 30%.

significantly increased the split tensile strength of SCC mixes, but further increases in FA content up to 40% resulted in a gradual decrease in split tensile strength. This study also reveals that using 3% and 9% of CS leads to better split tensile strength compared to 6% and 12%, as shown in Fig. 4.13(c-d).

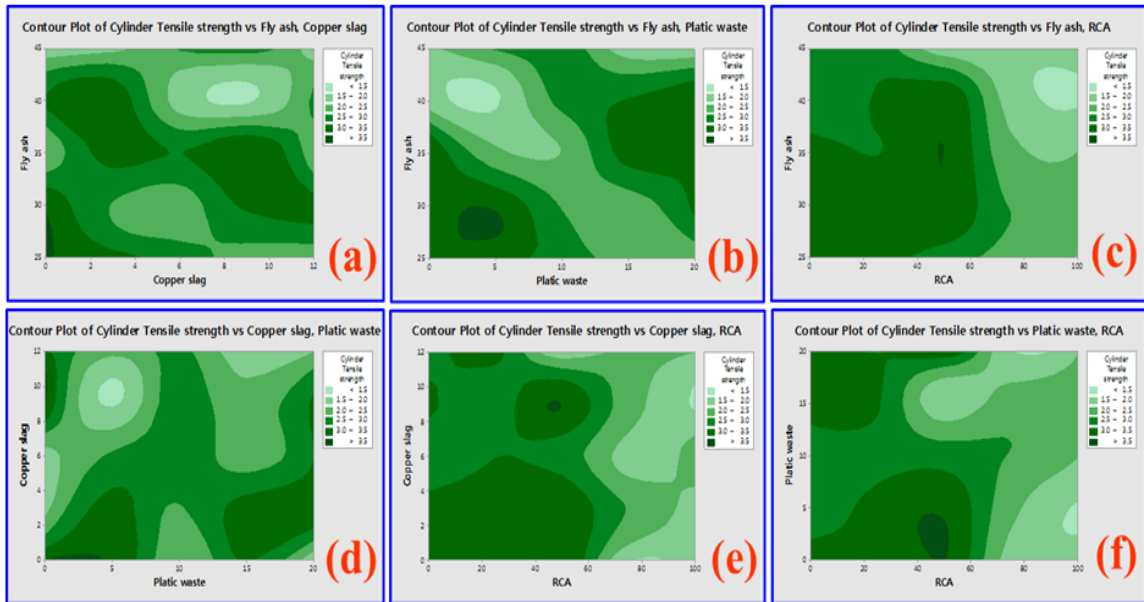
Mixes without plastic waste exhibit higher split tensile strength compared to those with any plastic waste content. Additionally, another study suggests that as the plastic aggregate content increases, the failure type tends to become more ductile. Furthermore, this study investigates the impact of RCA on the split tensile strength of SCC mixes. It is observed that at 56 and 90 days of curing, 25% and 50% RCA content results in higher split tensile strength compared to 75% and 100% RCA content, as depicted in Fig. 4.17(c-d). Notably, a significant decline in split tensile strength is observed beyond 50% RCA content.

**Table.4.6 Mean S/N ratio response table for split tensile strength at 7,28,56 and 90 days**

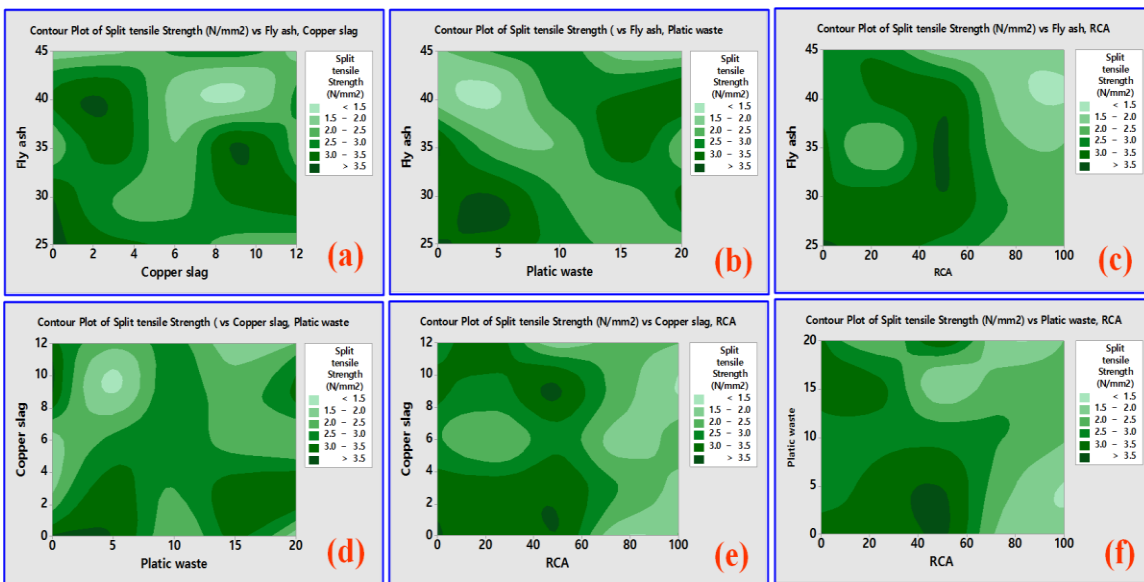
S. No	Factors	Level1	Level2	Level3	Level4	Level5	Delta	Rank
1	At 7 days							
	FA	2.8146	3.0975	3.0089	1.8221	0.7652	2.3323	2
	CS	2.9176	3.1601	1.6980	2.4260	1.3066	1.8536	3
	PW	3.2895	2.4232	1.8114	2.0810	1.9033	1.4781	4
	RCA	3.6247	3.2645	3.7352	0.7369	0.1470	3.5883	1
2	At 28 days							
	FA	8.577	9.076	8.634	7.367	6.096	2.980	2
	CS	8.215	8.771	7.753	7.969	7.042	1.729	3
	PW	8.420	7.763	8.028	7.632	7.908	0.789	4
	RCA	9.490	9.620	9.075	6.036	5.529	4.091	1
3	At 56 days							
	FA	8.700	9.200	8.060	7.493	6.222	2.978	2
	CS	8.340	8.895	7.178	8.093	7.168	1.727	3
	PW	8.548	7.893	8.150	7.752	7.332	1.216	4
	RCA	9.614	9.046	9.199	6.162	5.654	3.961	1
4	At 90 days							
	FA	8.861	9.361	8.221	7.654	6.383	2.978	2
	CS	8.501	9.058	7.338	8.254	7.329	1.729	3
	PW	8.707	8.054	8.321	7.914	7.494	1.213	4
	RCA	9.775	9.207	9.362	6.321	5.815	3.961	1

#### 4.1.19. Contour plots: Split tensile strength at 28,56 and 90 days

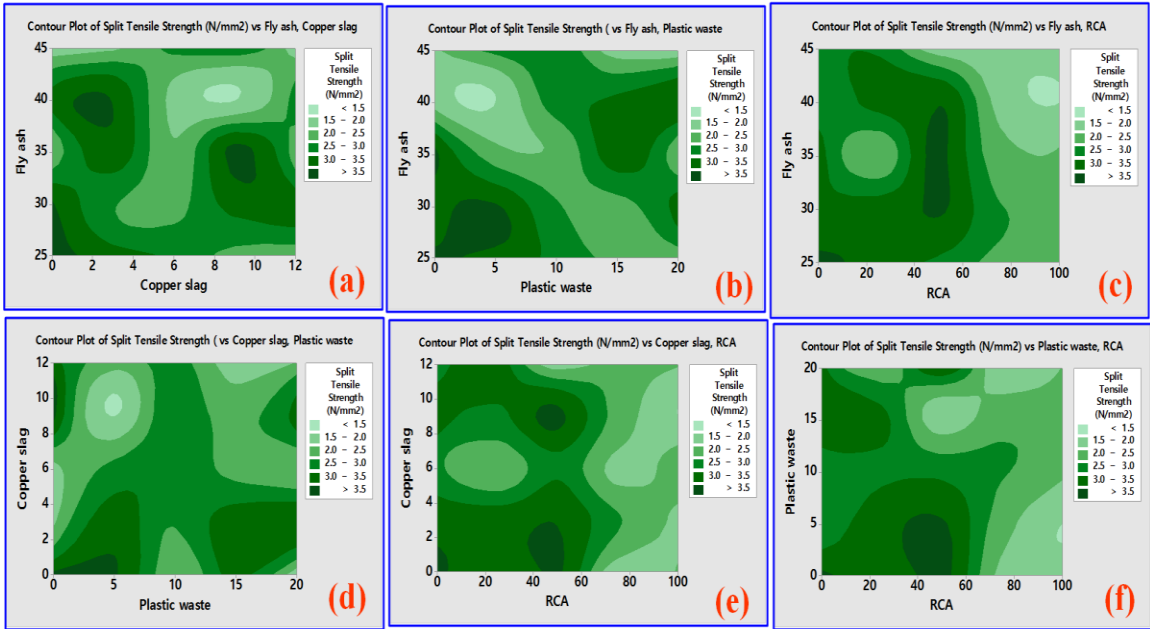
Analysing Fig. 4.14(a-f), it becomes evident that using a low level of fly ash in conjunction with both copper slag and plastic waste results in an improved tensile strength. Fig. 4.14(c) highlights that the combination of fly ash and RCA at medium levels is more suitable for achieving maximum tensile strength. Fig. 4.14(d-e) suggests that the combination of copper slag with the other three parameters at lower levels is more favourable for enhancing tensile strength. Nevertheless, Fig. 4.14(f) indicates that the compatibility of plastic waste with RCA at lower levels is the best approach to attain the maximum tensile strength.



**Fig.4.14 Contour plots for split tensile strength at 28 days (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.**



**Fig.4.15 Contour plots for split tensile strength at 56 days (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.**



**Fig.4.16 Contour plots for split tensile strength at 90 days (a) Fly ash Vs copper slag (b) Fly ash Vs plastic waste (c) Fly ash Vs RCA (d) Copper slag Vs plastic waste (e) Copper slag Vs RCA (f) Plastic waste Vs RCA.**

Based on these findings, it can be concluded that utilizing medium levels of fly ash and RCA in combination with low levels of copper slag and plastic waste yields the highest tensile strength in SCC mixtures.

**4.2 RESEARCH OBJECTIVE 2:** To examine the durability of self-compacting concrete created from plastic waste, recycled aggregates, fly ash and copper slag.

#### 4.2.1 Durability properties:

Concrete's resistance to degradation and damage over time when subjected to various external and environmental conditions is referred to as one of its durability qualities. Abrasion, chemical attack, freeze-thaw cycles, exposure to moisture, and other forms of wear and tear are some of these variables [3]. In this study using acid attack the durability properties of SCC mix are studied and its results are represented in Table 4.7. This study consists of Acid attack resistance that can be determined by how much weight

the specimen loses when exposed to hydrochloric acid (Hcl), higher acid resistance is indicated by a lesser weight loss [33]

#### **4.2.2 HCL Acid Attack test:**

Technically this test was performed to assess the degradation of concrete specimen immersed in acidic solution and resistance offered by the concrete specimen to chemical attack, cubical specimens of 150mm\*150mm\*150mm are cured in water for 28 days [3] as shown in Fig 3.11(b) and weighed before immersing them into Hydrochloric (HCl) solution of 0.5N concentration and a P<sup>H</sup> of 2 to 5% weight of liquid water are added to the immersed water for a specific duration of 28, 56 days in which concrete specimens[84] are stored as shown in Fig 3.11(a).

Moreover, proper monitoring and maintenance of solution at room temperature results in a proper assessment of weight loss of the specimen by comparing its initial and final weights[3]. The percentage of reduction in compressive strength, weight represents the specimen degradation level and the extent of degradation are represented in Fig.4.17(a-b) respectively.

Moreover, for conventional SCC mix M0 after 28 and 56 days of Hcl treatment a percentage of weight loss was observed as 4.3 and 8.4 as shown in Table 4.7 and their percentage reduction in compressive strength was 4.54 and 9.74 respectively shown in Table 4.7. During an acid attack, the hydrated cement paste decalcifies.

High volume reaction products are produced as a result [33].Additionally, the highest compressive strength mixes M1, M14 has a percentage reduction in weight of 7.12, 10 and 6.4 ,10.38 after 28 and 56 days of Hcl treatment which results in understanding that these mixes still exhibit the top less reduction in weight when compared to all other mixes and after 28 and 56 days of Hcl treatment their percentage decrease in was measured as 4.34, 7.59 and 4.17, 12.21 for M1 and M4 SCC mixes respectively[85]. This phenomenon is attributed to an enhancement in the quality of the hydrated paste, resulting in an increase in acid resistance with higher cement content for mixes maintaining the same water-to-

cement ratio. Besides that, for average strengthened mix M19 has a percentage reduction in weight of 11.99, 16.09 and percentage reduction in compressive strength of 9.00, 7.15 was observed after 28 and 56 days of Hcl treatment as shown in Table 4.7. Some studies state that as the water cement ratio is increased for RCA mixes with the same cement amount and aggregate replacement ratio, the paste's porosity increases and its acid resistance decreases [33] .

Furthermore, the least compressive strength mixes M20, M21 has a percentage reduction in weight of 6.28,11.49 and 11.71,15.56 after 28 and 56 days of Hcl treatment which results in understanding that these mixes exhibit the top more reduction in weight when compared to all other mixes and after 28 and 56 days of Hcl treatment their percentage decrease in compressive was measured as 8.46, 13.08 and 9.39, 16.95 for M20 and M21 SCC mixes respectively as shown in Table 4.7.

**Table.4.7: Percentage reduction in Compressive strength of test specimens after treating with HCl solution**

<b>MIXES</b>	<b>% Reduction of weight after 28 days immersed in HCL</b>	<b>% Reduction of weight after 56 days immersed in HCL</b>	<b>% Reduction in Compressive strength after 28 days HCL treatment</b>	<b>% Reduction in Compressive strength after 56 days HCL treatment</b>
M0	4.30	8.14	4.54	9.74
M1	7.12	10.00	4.34	7.59
M2	5.35	9.63	6.25	13.71
M3	9.87	10.82	5.65	13.45
M4	7.31	12.40	7.87	15.83
M5	8.04	13.02	8.35	15.67
M6	6.96	7.57	8.33	11.30
M7	6.22	10.89	8.89	8.51

M8	8.05	10.63	8.66	10.21
M9	5.72	9.06	6.37	9.46
M10	5.55	9.86	6.83	13.79
M11	11.27	14.33	8.93	14.75
M12	6.08	8.58	8.42	11.00
M13	6.11	9.40	8.57	11.07
M14	6.41	10.38	4.17	12.21
M15	7.33	11.54	8.92	13.47
M16	8.92	9.86	7.16	9.58
M17	6.74	8.93	6.43	11.96
M18	9.86	13.41	6.41	15.37
M19	11.99	16.09	9.00	17.15
M20	6.28	11.49	8.46	13.08
M21	11.71	15.56	9.39	16.95
M22	11.11	14.31	4.82	11.77
M23	6.47	11.71	8.80	13.18
M24	9.94	11.51	8.69	11.51
M25	12.98	14.06	6.81	14.70

When compared with conventional SCC mix M0, the least strengthened M21 SCC mix contains 75% of RCA in it, which makes the mix more reactive with acid treatment due to its poor bonding with the matrix; the structural load transfer mechanism will be affected more. In addition, high porosity of RCA develops a water transfer phenomenon from aggregate to paste that has caused a rise in water cement ratio at surroundings of RCA with less dense, wet cement paste as a result, calcium from C-S-H and  $\text{Ca}(\text{OH})_2$  can leak out more rapidly[86].

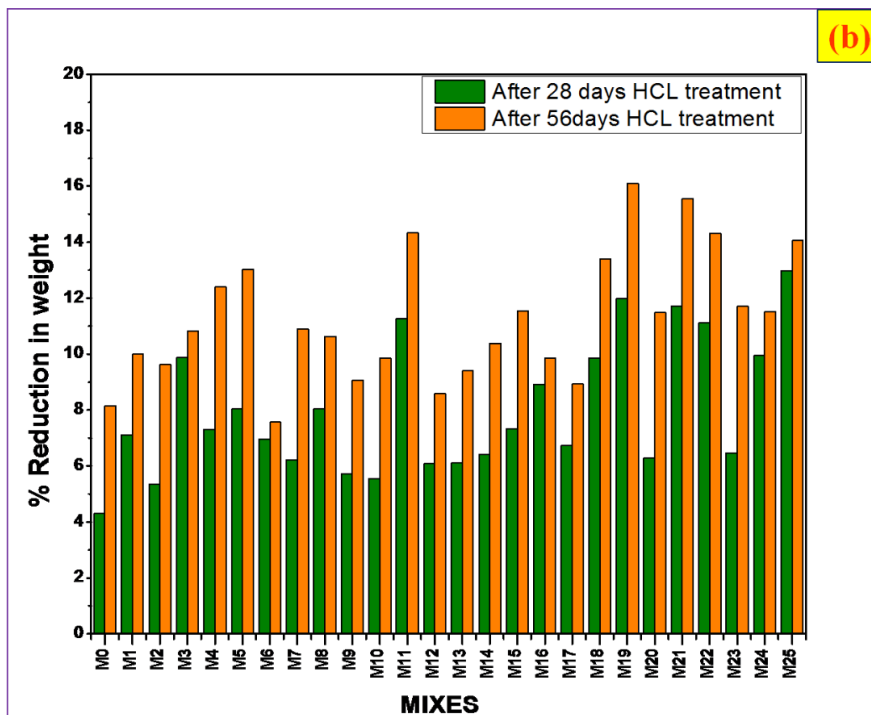
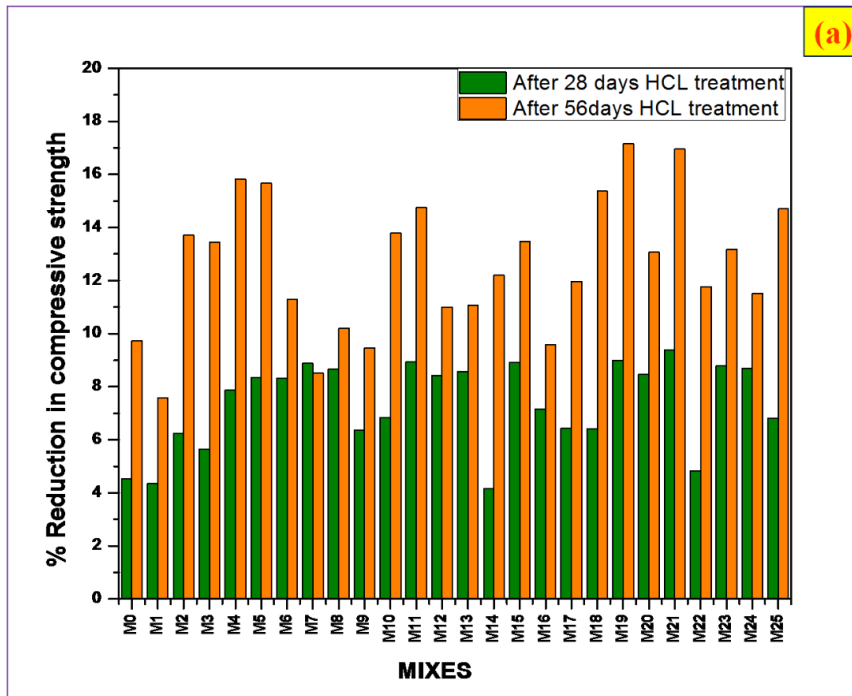


Fig.4.17: Percentage reduction in (a) Compressive strength (b) weight of test specimens after treating with HCL solution

#### 4.2.3. Rapid Chloride Penetration Test:

Based on the test results it seems to be well understandable that the SCC members which have maximum compressive strength seems to have less voltage of charge get passed through the test sample and the test results are noted down in Table 4.8.

**Table 4.8: RCPT based on charge passed (ASTM 1202-97)**

<b>MIXES</b>	<b>Charge observed in coulombs</b>	<b>MIXES</b>	<b>Charge passed in coulombs</b>
M0	448	M13	1931
M1	643	M14	825
M2	1446	M15	2019
M3	2069	M16	1845
M4	2028	M17	1120
M5	2108	M18	2153
M6	961	M19	2152
M7	2103	M20	2207
M8	2048	M21	2118
M9	1736	M22	2243
M10	1581	M23	2090
M11	2116	M24	2087
M12	1288	M25	2203

#### 4.3 RESEARCH OBJECTIVE 3:

To explore the microstructural qualities of concrete constructed from plastic waste, recycled materials, fly ash and copper slag.

#### **4.3.1. Micromorphology study:**

This study helps to get a clear idea about the key aspects of microstructure of concrete manufactured after its curing age. Most of this kind of study includes to analyse pore structure, gain knowledge about aggregate interface and cracks propagation along with mineralogical compositions some times.

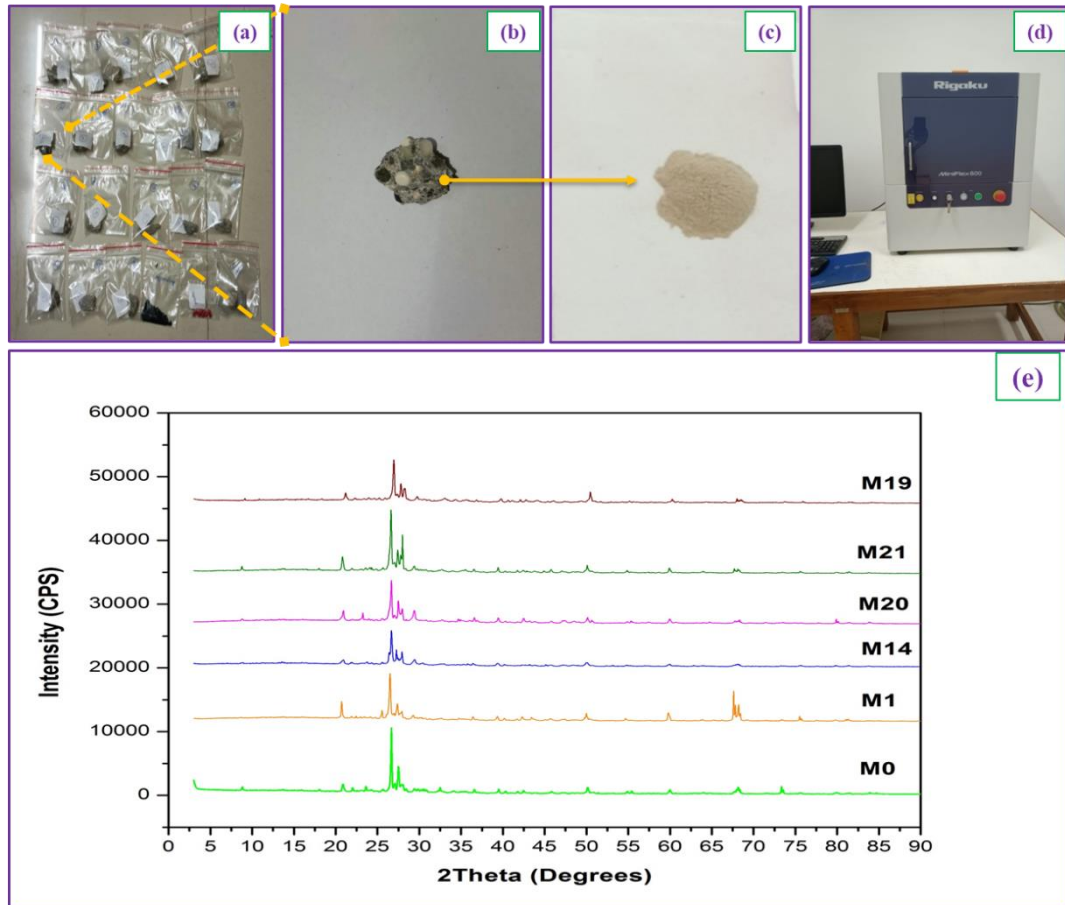
#### **4.3.2. X ray diffraction test (XRD):**

These studies were carried out for specimens after 56 days curing time. The specimens, which had cracked during compression testing are collected as shown in Fig.4.18(a) and each specimen as shown in Fig.4.18(b), were ground into a powder and passed through IS sieve no 9 as shown in Fig.4.18(c) so that XRD could be used to identify and measure any crystalline phases that might be responsible for the observed strength variation [87].

To identify the qualitative and quantitative analysis of powdered SCC samples RIGAKU Mini Flex 600 XRD instrument was used under 40mV voltage with 15mA Current. It uses K-Beta(x1) filter and K-alpha X Ray character, with a scan range from 3 to 90°, 0.02 step size and 0.12 speed setup was arranged for experimentation.

This instrument utilizes a highly intensified source of X-ray which are helpful in phase quantification and identification, crystallinity size and percentage calculation, determination of molecular structure, lattice parameter, Rietveld refinement and other features due to its three core requirements of flexibility, reliability, and durability[88].

The nominal mix M0 along with mixes M1, M14, M20, M21 and M19 are analyzed using RIGAKU Mini Flex 600 XRD instrument. Fig.4.18(e) represents XRD patterns developed by different mixes. The presented intensity patterns almost have similar patterns. Peaks show the presence of the material's crystalline structure, and their intensities show how much of this crystalline structure is there in the cement [89].



**Fig: 4.18 (a)Concrete specimens for all 26 mixes (b) Digital image of concrete specimen (c) Powdered sample of particle size  $\leq 90 \mu\text{m}$ (d) RIGAKU Mini Flex 600 XRD instrument (e) XRD pattern of M0, M1, M14, M20, M21 and M19.**

An XRD study states that incorporating different mineral admixtures did not change systematic hydration products at early stage of 28 days of curing, but obviously it changed number of hydration products[90]. So, the current study focused on 56 days XRD test results to make sure of exact patterns developed due to different wastes incorporating in SCC mixes.

From Fig.4.18(e) all mixes show similar diffraction peak positions at 2 Theta ranging in between 26 and 27 degrees have a good hydration process and produced Calcium hydroxide (Ca (OH)<sub>2</sub>) peaks. This shows that due to carbonization the

constitutions mainly Un hydrated clinker, and a small amount of  $\text{CaCO}_3$ ,  $\text{Ca}(\text{OH})_2$  generated of all the mixes with different mineral admixtures were basically the same[91]. As depicted in Fig. 4.18(e), it is evident that the  $\text{Ca}(\text{OH})_2$  diffraction peaks were noticeable at 56 days. This indicates that the cement had fully hydrated and exhibited good crystallinity despite the incorporation of various waste materials into the SCC mixes.

From Fig.4.19(a) it is observed that for nominal mix M0, the 2-Theta peaks are observed at 26 and 27 degrees justifying the formation of  $\text{CaCO}_3$ ,  $\text{Ca}(\text{OH})_2$  along with some other smaller peaks represent the formation of  $\text{C}_2\text{S}$  and  $\text{C}_3\text{S}$ . For mix M1 it is observed that some intensities are higher (for example for 2 Theta around 20.72, 26.48, 59.8 and 68.2) than nominal mix M0.

It has also been noted that a few new peaks with low intensities appeared for mix M1 as shown in Fig.4.19(b). It is consistent with XRD test results that showed a rise in some crystalline structures, including  $\text{Ca}(\text{OH})_2$ , at the beginning stages of hydration that is well known as Portlandite[92] which helps in higher strength development, and it could be related to the three-dimensional (3D) optical microscope results shown in Fig.4.20.

For mix M19 it is observed that some intensities are higher (for example for 2-Theta around 21.8, 26.96, 27.8, 28.18 and 50.46) than nominal mix M0.

For mix M19 it is observed that some new peaks are formed which might be due to formation of ITZ with apparent pores leading to a lowest strengthen SCC mix due to 40%FA, 9%CS, 5%PW and 100%RCA presence in it which are major key parameters that effect the water cement ratio of mix and it could be related to the three-dimensional (3D) optical microscope results shown in Fig.4.19(e) with unbonded PW, cavities formation along with some un hydrated FA and CS as more water absorption was carried out by RCA[16].

A few research studies show that copper slag incorporation in SCC develop a phase of aluminum silicate hydrate (ASH) that resulted in the heat being released and the development of cracks, which reduced strength and degraded characteristics, during the

mixing procedure, extra heat was seen to be released, this behavior might be the primary reason for crack initiation and be connected to Mix's microstructure [69]

According to the study's findings on XRD analysis of the trimixed composition, it was observed that the diffraction peaks of dicalcium silicate ( $C_2S$ ) and tricalcium silicate ( $C_3S$ ) were lower at 90 days compared to those at 28 days.

This observation suggests that  $C_2S$  and  $C_3S$  continued to hydrate over time, indicating that the cement had not fully hydrated at the 90-day mark [90].

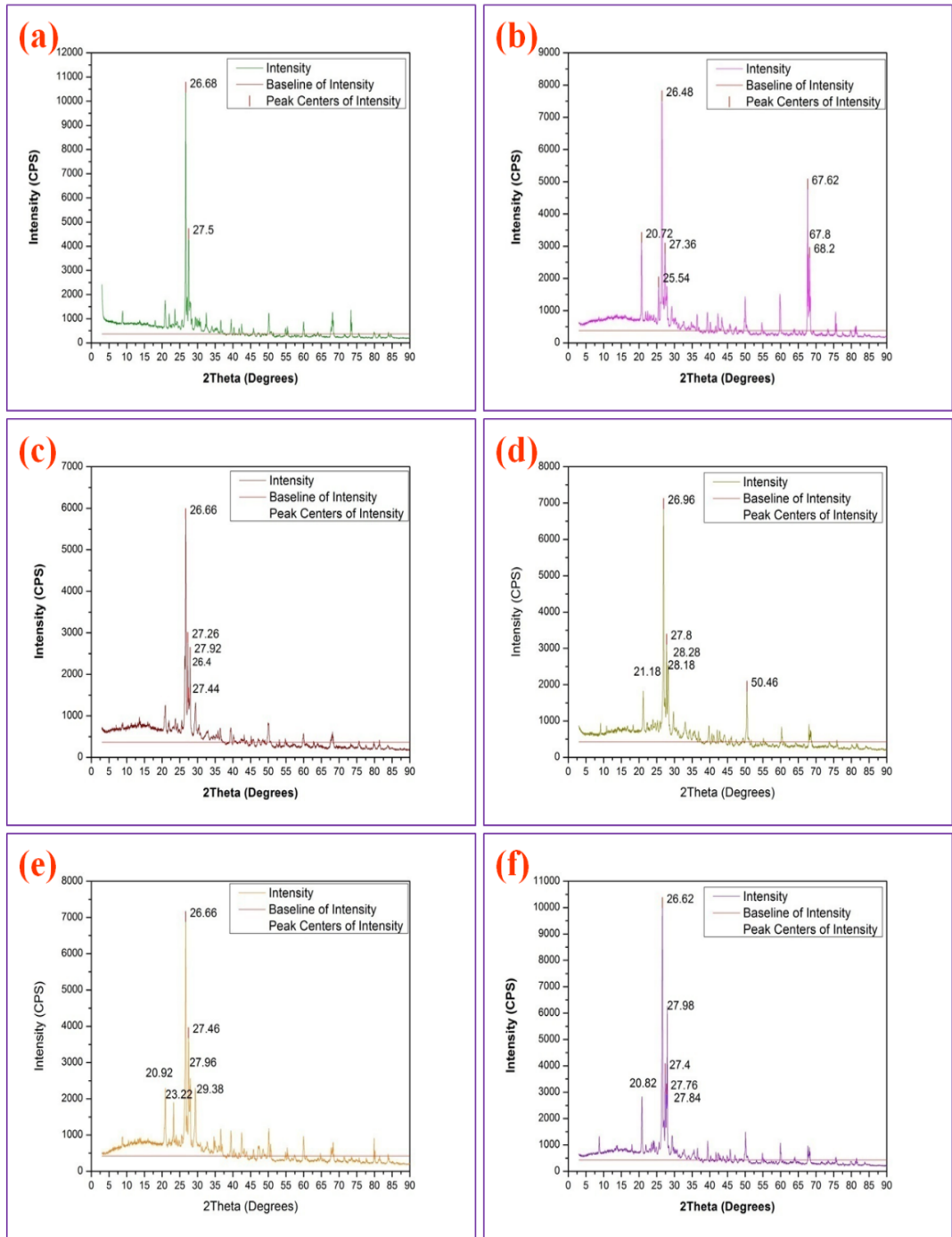
The XRD study supported the existence of calcium aluminosilicate formation in the Portland cement system, which produced a denser structure by occupying the matrix's voids [93].

Later ages were found to produce calcium aluminosilicate phases that were better [94].

It was observed that the lower diffraction peaks formed in all mixes represent the formation of  $C_2S$  and  $C_3S$  which are most significantly formed during the hydration process and results to strength enhancement with proper bonding between different wastes incorporated and matrix. Significantly XRD peak patterns obtained for mixes M0, M1, M14, M20, M21 and M19 are represented by considering median as baseline of intensities and are summarized in Fig.4.19(a-f) at 56 days of test specimen's age.

Each peak represents the existence of crystalline structure of the material and the intensities of peaks reflect the amount of this structure in cement justifying that a new compound was formed that will affect the hardened properties of SCC [95].

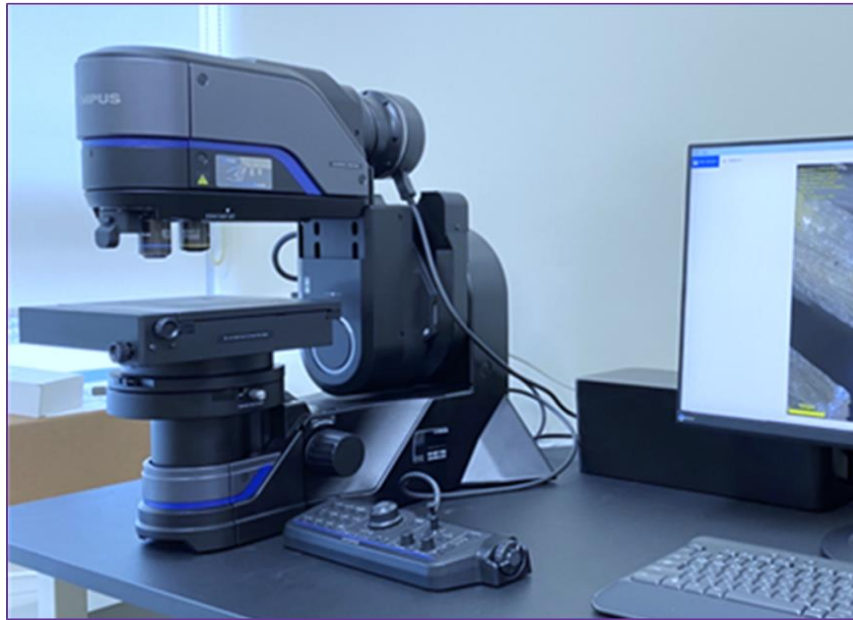
This indicated an increase in some crystalline structure such as  $Ca(OH)_2$  result of XRD [96].



**Fig:4.19 XRD peak images of (a) M0 at 56 days (b) M1 at 56 days (c) M14 at 56 days (d) M20 at 56 days (e) M21 at 56days (f) M19 after 56 days of curing**

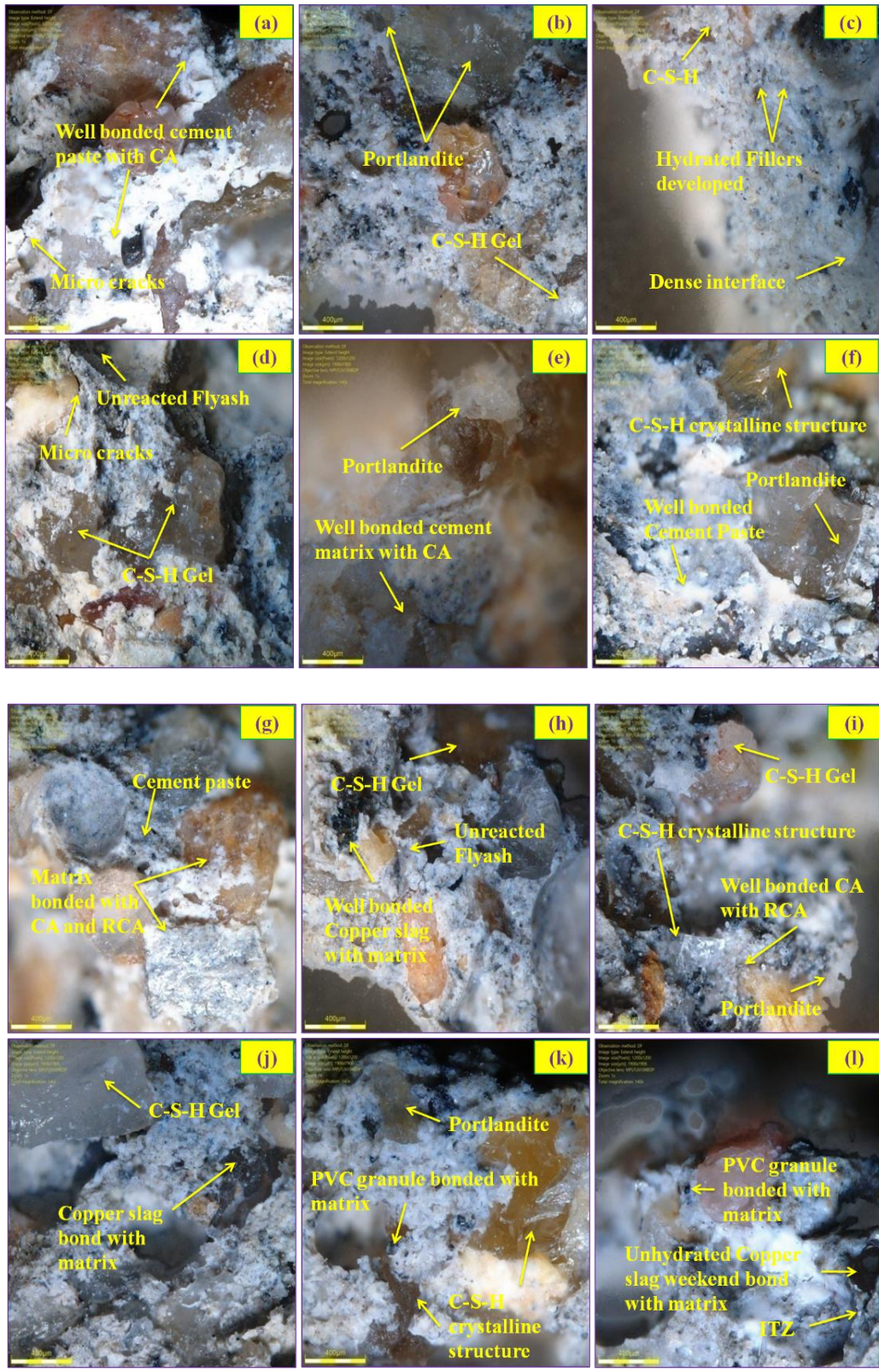
### 4.3.3 Three-Dimensional Optical Microscope study:

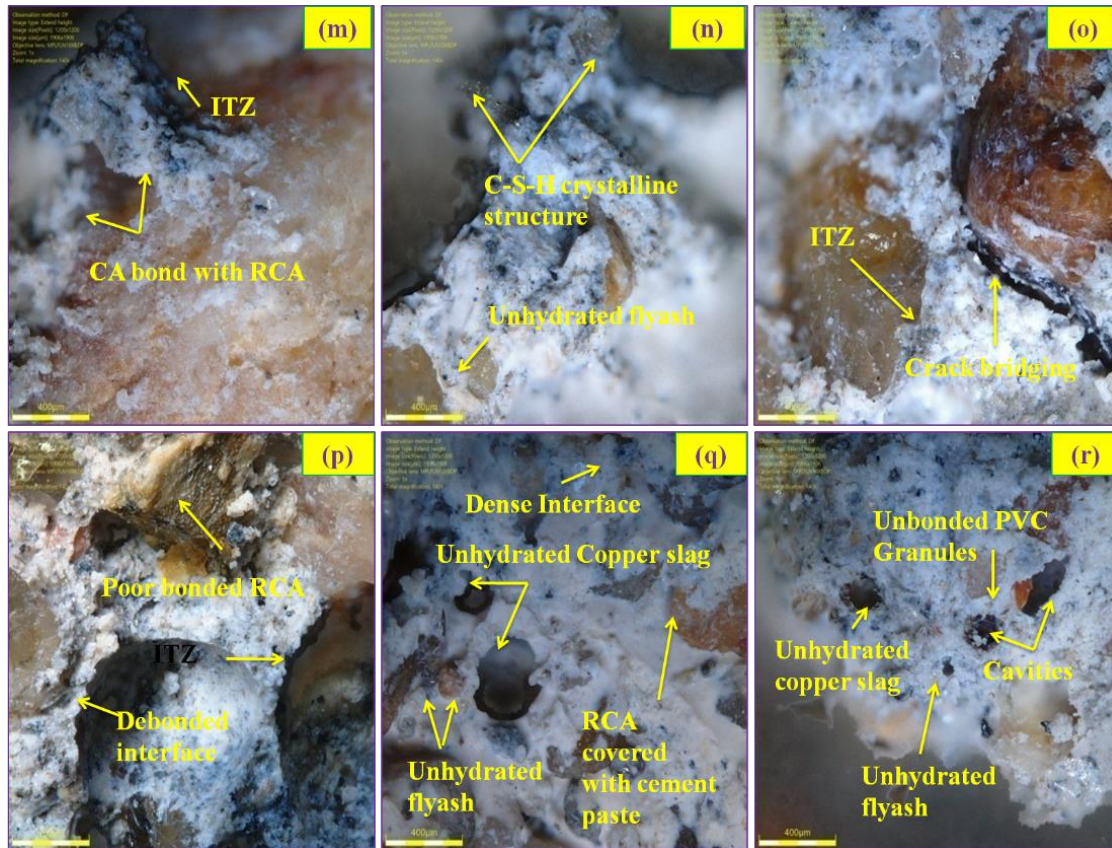
In the context of noncontact quantitative measurement with sub nanometer resolution in the z or vertical axis, the three-dimensional (3D) optical microscope based on white light interferometry is considered as a perfect tool in the field of study of surface metrology applications. In this current research, a 3-dimensional optical microscope (3D Microscope: DSX1000, Olympus Co., Japan) is used to check the concrete composite interactions at specific location to understand the interaction mechanism between its constitutions. The physical and chemical changes of cement slurry, aggregates, slag content, admixtures and some other influencing parameters are closely related to microstructure properties.



**Fig.4.20: 3D Microscope: DSX1000**

In current study six mixes i.e., Mix M0 standard mix with compressive and tensile strength of  $45.66 \text{ N/mm}^2$  and  $3.66 \text{ N/mm}^2$  at 56 days of curing age. Mix M1, M14 are highest compressive and tensile strength mixes all of 25 mixes with a compressive and tensile strength of  $43.31 \text{ N/mm}^2$ ,  $42.06 \text{ N/mm}^2$  and  $3.58 \text{ N/mm}^2$ ,  $3.55 \text{ N/mm}^2$  respectively at 56 days of curing age.





**Fig: 4.21 Three-Dimensional microscope images at 400µm of (a) M0 at 7 days (b) M0 at 28 days (c) M0 at 56 days (d) M1 at 7 days (e) M1 at 28 days (f) M1 at 56 days (g) M14 at 7 days (h) M14 at 28 days (i) M14 at 56 days (j) M20 at 7 days (k) M20 at 28 days (l) M20 at 56 days (m) M21 at 7 days (n) M21 at 28 days (o) M 21at 56 days (p) M19 at 7 days (q) M19 at 28 days (r) M19 at 56 days**

Mix M20 with average compressive and tensile strength of 30.43 N/mm<sup>2</sup> and 2.66 N/mm<sup>2</sup> at 56 days of curing age and Mix M21, Mix M19 are lowest compressive and tensile strength mixes all of 25 mixes with a compressive and tensile strength of 16.29 N/mm<sup>2</sup>, 15.94 N/mm<sup>2</sup> and 1.55 N/mm<sup>2</sup>, 1.47 N/mm<sup>2</sup> respectively at 56 days of curing age are considered for 3D optical microscopic study and obtained results are plotted in Fig 4.21(a-r).

**Table.4.9: Description of Three-Dimensional microscope images**

<b>Curing age</b>	<b>7 days</b>	<b>28 days</b>	<b>56 days</b>
<b>M0 (Standard Mix)</b>	•Well bonded cement pastes with CA	•Portlandite	•C-S-H
	•Micro cracks	•C-S-H Gel	•Hydrated Fillers developed
			•Dense interface
<b>M1 (First Highest strength)</b>	•Unreacted Fly ash	•Portlandite	•Portlandite
	•C-S-H Gel	•Well bonded cement matrix with CA	•C-S-H crystalline structure
	•Micro cracks		•Well bonded Cement Paste
<b>M14 (Second Highest strength)</b>	•Matrix bonded with CA and RCA	•C-S-H Gel	•C-S-H Gel
	•Cement paste	•Unreacted Fly ash	•Well bonded CA with RCA
		•Well bonded Copper slag with matrix	•C-S-H crystalline structure
			•Portlandite
<b>M20 (Average strengthen mix)</b>	•Copper slag bond with matrix	•Portlandite	•PVC granule bonded with matrix
	•C-S-H Gel	•PVC granule bonded with matrix	•Un hydrated Copper slag weekend bond with matrix
		•C-S-H crystalline structure	•ITZ

<b>M21 (Least strength mix)</b>	•CA bond with RCA	•C-S-H crystalline structure	•ITZ
	•ITZ	•Un hydrated fly ash	•Crack Bridging
<b>M19 (Final least strength mix)</b>	• Poor bonded RCA	•Dense interface	•Unbonded PVC Granules
	•ITZ	•Un hydrated Copper slag	•Cavities
	•Debonded interface	•RCA covered with cement paste	•Un hydrated fly ash
		•Un hydrated fly ash	•Un hydrated copper slag

The morphology of M0 and M1 mixes are similar at early stages with good bonding between cement slurry and aggregates, it seems due to the heat of hydration micro cracks are visible as represented in Fig.4.21(a),(d) , but later as curing time increased to 28 and 56 days no microcracks are visible, they started developing large number of mesh or cone shaped clusters of C-S-H gel as curing age increases to 28 days[66] as shown in Fig.4.21(b), (e). In contract, Mix1 had some un hydrated fly ash clearly visible in spherical shape at early 7 days as shown in Fig.4.21(d) but later this fly ash particles started to hydrate and act as a good filler material to promote early strength development at 28 days, in addition to strength due to its spherical shape fly ash[95] easily fills any developed voids and improved the fracture toughness of matrix also this can be clearly identified as micro cracks never appeared after 7 days of curing.

A study found the fly ash ingredient at 28 days plays a crucial role in hydration process and reacts well with  $\text{Ca}(\text{OH})_2$  to improve the growth rate of matrix which incorporates good strength development [96].For Mix M1 the early phase structure was dense and has extremely poor pore distribution compared to all other mixes morphology represented 28 days details in Fig.4.21(e). In current study, some chemical reaction between cement and other ingredients and hydration of calcium oxides at later stages

developed a clear visible appearance of white mineral crystalline structure known as Portlandite as shown in Fig.4.21(b), (e).

In general, developed portlandite belongs to silicate group minerals and its formation will be more helpful in strength development and dense interface formation results to have a good bonding between multi-ingredient of SCC Mix 0 and Mix 1 as shown in Fig.4.21(c), (f), this is consistent with obtained compressive and tensile strength test results.

Moreover, Mix M14 which is a ternary mix containing fly ash, copper slag as cement substitute and RCA as CA substitute developed a good output of higher strength of all ternary mixes and its morphology represents a good bond between CA and RCA at early stages due to well bonded cement matrix at early stage of 7 days curing[97] as shown in Fig.4.21(g).

Later due to unhydrated fly ash and copper slag powder the generated matrixes shows some spherical shaped structures as shown in Fig.4.21(h) but the hydration of cement matrix still developed good quantity of C-S-H gel at early 28 days of curing as represented in Fig.4.21(h). Later as age of curing increased to 56 days the bonding between RA and RCA visible to be good enough to bind with cement matrix and developed C-S-H crystalline structure along with portlandite as shown in Fig.4.21(i) this morphology study is consistent with obtained destructive compressive and tensile strength test results as shown in table 2.

Morphology of ternary mix M20 containing 40% of fly ash, 12% of CS as cement substitute and 10% of PW (PVC granules) as FA substitute obtained an average compressive and tensile strength of all 25 mixes shows that at early 7 days of curing, CS was well bonded with cement matrix and dense C-S-H gel formation was clearly visible in Fig.4.21(j). A few studies already stated that SCC mixes with CS up to 20% produce C-S-H gel along with Ettringite[98].

It is interesting to know that after 28 days of curing the PW made a good bonding with cement matrix and developed huge crystalline structure of C-S-H by hydration process and produced portlandite as if still it does not absorb more water in SCC as shown in Fig.4.21(k). As the age of mix increased to 56 days some unhydrated fly ash and CS made the bonding between cement matrix and aggregates weak and results to form a weak plane known as inter transition zone (ITZ) as shown in Fig.4.21(l). ITZ is a water-rich area and a weaker link in concrete. ITZ differs from the cement matrix in that it has a higher water-cement ratio, more CH, and larger crystal particles[99].

The morphology of M21 and M19 mixes are similar at preliminary stages as mix M21 contains 75% of RCA and 20% PW the unabsorbed water is observed by RCA and carried a smooth hydration process but a weak bonding between the matrix as so developed ITZ as shown in Fig.4.21(m).

Similarly, as mix 19 is a tetra binding mix with four supplementary replacements with highest percentages of RCA presence in mix made it to absorb free water in SCC mix at early stage of curing itself and developed ITZ with greater deboned interface at 7 days of curing age as represented in Fig.4.21(p).

Some unhydrated fly ash spherical particles are clearly visible under microscope at 28 days of curing age for both M21 and M19 mixes as shown in Fig.4.21(n), (q) respectively.

Because of sharp edged crystalline unbonded C-S-H structure the mix M21 tends to fail to bear loads at later ages and to develop crack bridges with large voids and ITZ as shown in Fig.4.21(o).

A clear picture of unbonded PW was visible with large cavities, unhydrated fly ash and CS in mix 19 as shown in Fig.4.21(r) thus resulting the mix to be least strengthened mix of all 25 SCC mixes this is consistent with obtained compressive and tensile strength test results.

#### **4.4 RESEARCH OBJECTIVE 4:**

To evaluate the crack propagation in structural elements (RC beams) made with fly ash, copper slag, recycled aggregate, and plastic waste.

##### **4.4.1 Crack propagation study:**

The objective of this study is to identify and characterize the types of cracks that occur in reinforced concrete beams under load application.

##### **4.4.2 Flexural strength:**

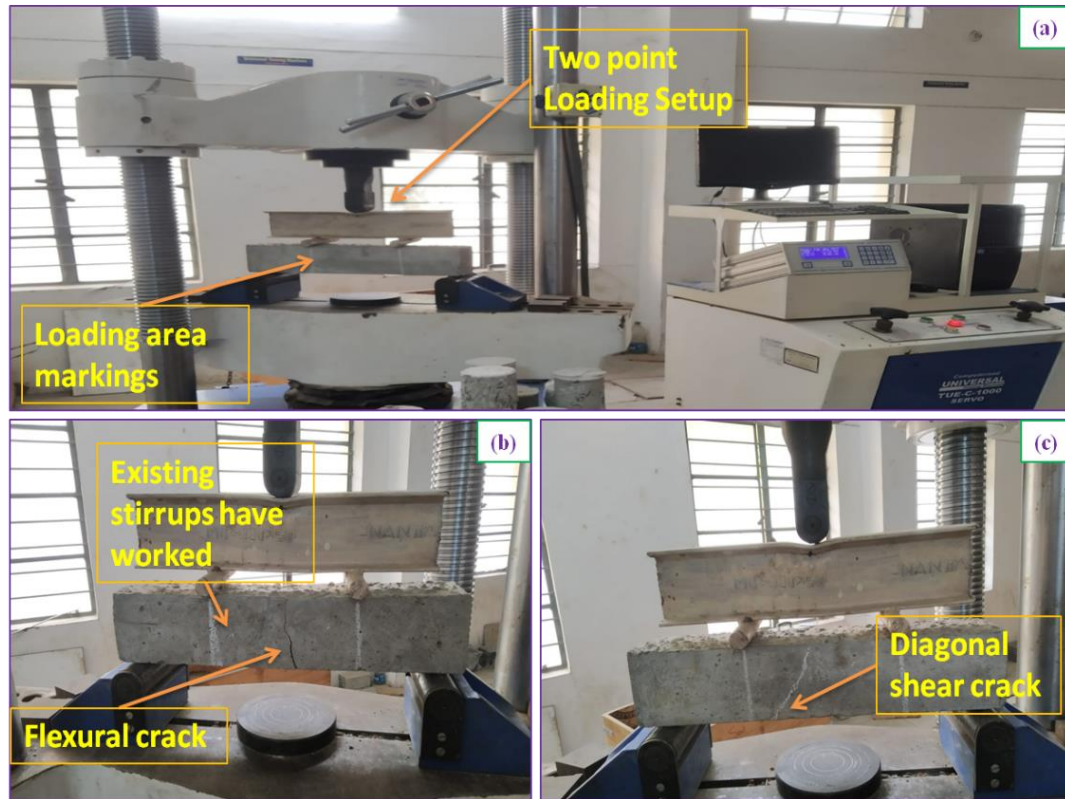
In this study doubly reinforced cement concrete (RCC) beams are casted of size 600mm\*150 mm\*150mm. Provided with an effective length of 550 mm, top, bottom and side clear cover of 20mm each. Two 10 mm diameter Fe 415 grade steel reinforcement was provided both at tension and compression zone of beam with 100mm centre to centre spacing between steel bars[57].

For shear reinforcement of beam a total of five stirrups of 6mm diameter at 100 mm centre to centre spacing are adopted in RCC beam design.

The experimental beam design was carried out according to IS 456-2000. A total of 26 beam flexural strength results (i.e., Standard M0 mix beam, M1, M2, ....., M25 mixes) are evaluated after 28 days of curing period using loading frame equipment of capacity 10 tonnes.

After placing reinforcement in position prepared SCC mixes are poured into beam moulds and kept aside for settling without any disturbance for 24 hours[100]. Later the Reinforced Cement Concrete Self-Compacting Concrete (RCC SCC) beam specimens are cured in water for 28 days. The M40 grade RCC SCC beam specimens are setup on the computerised Universal Testing Machine (UTM) TUE-C-1000 Servo with 100 tonnes of loading capacity to conduct the experiment. For the test, a two-point loading system was used as illustrated in Fig.4.22(a). Cracking failure of the test beams is depicted in Fig.4.22(b-c), where the diagonal shear crack [32] represents the crucial crack failure in the

beams at the ultimate load, which was observed for mix M19 representing the mix is weak in bearing shear stress.



**Fig:4.22: Images of (a) UTM setup (b) Flexural cracks propagation for SCC mix at final stage before failure (c) Diagonal Shear cracks formed for M19 mix at early stage**

As the mix was SCC which eliminates the vibration process most of the beams seen to exhibit shear cracks in the shear cracking zone of the tested specimens and the type of cracks developed are illustrated in Table 4.10. A study states that the Embedded Through Section strengthened beams had more fractures and a larger diagonal crack angle [100] during the shear test because of increasing the shear reinforcement[101] because the shear transfer mechanism was significantly activated [32]. Similarly, a study states that SCC beam with a full shear connection is vulnerable to longitudinal shear failure when transverse reinforcement [102] is insufficient (density of steel 0.41%), but the SCC beam

with a partial shear connection is vulnerable to stud shear failure. The initial stiffness and final flexural strength of SCC beams fall as the shear connection degree decreases, but the relative slip increases [103].

**Table 4.10: Flexural strength (FS) in N/mm<sup>2</sup> and type of crack propagation**

Mixes	Specimen ID	Flexural strength at 28 days (N/mm <sup>2</sup> )	Type of cracks developed
M0	F0C0P0R0	4.74	Flexural cracks
M1	F25C0P0R0	4.50	Flexural cracks
M14	F35C9P0R50	4.37	Flexural cracks
M6	F30C0P5R50	4.07	Flexural cracks
M17	F40C3P20R50	3.92	Flexural cracks
M12	F35C3P15R0	3.87	Flexural cracks
M2	F25C3P5R25	3.83	Flexural cracks
M10	F30C12P0R25	3.72	Flexural cracks
M9	F30C9P20R0	3.64	Flexural cracks
M16	F40C0P15R25	3.52	Flexural cracks
M13	F35C6P20R25	3.38	Flexural cracks
M24	F45C9P10R25	3.37	Flexural cracks
M3	F25C6P10R50	3.12	Flexural cracks
M20	F40C12P10R0	3.10	Flexural cracks
M23	F45C6P5R0	2.77	Web shear cracks
M7	F30C3P10R75	2.60	Web shear cracks
M8	F30C6P15R100	2.39	Web shear cracks
M4	F25C9P15R75	2.24	Web shear cracks
M15	F35C12P5R75	2.14	Web shear cracks
M11	F35C0P10R100	2.12	Web shear cracks
M5	F25C12P20R100	2.01	Web shear cracks
M18	F40C6P0R75	1.98	Web shear cracks
M22	F45C3P0R100	1.98	Web shear cracks
M25	F45C12P15R50	1.85	Web shear cracks
M21	F45C0P20R75	1.73	Web shear cracks
M19	F40C9P5R100	1.69	Web shear cracks

The comprehensive analysis of the obtained results suggests that the utilization of plastic waste, recycled aggregates, fly ash, and copper slag in SCC formulations holds

significant promise for sustainable construction practices [23],[44],[50]. The research findings highlight the potential of these alternative materials to enhance the fresh qualities, durability, microstructural properties, and crack resistance of SCC, thereby advancing the adoption of environmentally friendly and resource-efficient concrete technologies

## CHAPTER 5

### CONCLUSIONS

In the current work, the Taguchi L25 orthogonal array (OA) is chosen for the design of experiments that replace cement with industrial waste to minimize the number of attempts at the experiment and also the main moto of research is to compare with M40 grade concrete target strength using different industrial waste where the plastic waste shows more importance and the findings of this research results replicates that the obtained outcome achieved an Eco SCC with good structural performance.

#### 5.1 Key Findings:

The key findings from this study are outlined below:

##### Findings based on Objective 1:

- The optimal combination of the input parameters for high filling ability was noticed with the fly ash, copper slag, plastic waste, and RCA at 30, 3, 0, and 0%, respectively.
- The optimal combination of the input parameters for high passing ability was noticed with the fly ash, copper slag, plastic waste, and RCA at 25, 3, 5, and 50%, respectively.
- To achieve superior viscosity of the mixes, a suitable combination was drawn with fly ash, copper slag, plastic waste, and RCA at 25, 3, 0, and 0%, respectively
- For the casted SCC mixes the mechanical strength were studied under compressive and tensile loading and it was found that for mixes M1 and M14 the obtained strengths are more near to as that of conventional concrete i.e., after 90 days of curing M1 and M14 mix shows 45.02 and 43.71 N/mm<sup>2</sup> of compressive strength, 3.65 and 3.62 N/mm<sup>2</sup> of split tensile strength and 4.50 and 4.35 N/mm<sup>2</sup> of flexural strength.
- The optimal combination for both compressive and split tensile strength is at 30%FA, 3% CS, 0%PW, 0%RCA.The mean strength replicates at a curing of 56

and 90 days and shows comparatively similar to the pristine mix after binary additives.

- RCA content is the most leading controlling factor for both compressive and split tensile strength followed by FA and CS. It was found that PW does not contribute to the control of strength in higher range so incorporation of these waste will show least chances of change in properties of SCC, resulting in adoption of plastic waste incorporated SCC mixes for structural applications to achieve better performance.
- The experimental outcome reveals that for conventional concrete mix M0 an percentage increase of 3.77 was found as the curing age increase from 56 days to 90 days, but a 3.81% and 3.71% of increase in compressive strength was found for mixes M1 and M14 SCC mixes from 56 days to 90 days which represents the improvement of percentage increase in strengths are achieved for 25%FA+ 0%CS+ 0%PW+ 0%RCA incorporated SCC mix and 35%FA+ 9%CS+ 0%PW+ 50%RCA incorporated SCC mix justifying that replacement of these percentages can preserve the strength of M40 grade concrete even though it was replaced with different industrial waste.
- It is worthwhile to note that PW incorporates in improving the strength of SCC mix. For mix M6 and M20 it was observed that a compressive strength of 40.73 N/mm<sup>2</sup> and 31.19 N/mm<sup>2</sup> of compressive strength, 3.55 N/mm<sup>2</sup> and 2.71 N/mm<sup>2</sup> of split tensile strength and 4.07 N/mm<sup>2</sup> and 3.10 N/mm<sup>2</sup> of flexural strength was developed suggesting that mixes with 30%FA+ 0%CS+ 5%PW+ 50%RCA and 40%FA+ 12%CS+ 10%PW+ 0%RCA are also suitable combinations for preserving strength of M40 grade concrete with trinary industrial wastes.

### **Findings based on Objective 2:**

- The incorporation of FA shows least effect on durability property as its percentage decrease in compressive strength after 56 days of treatment with HCL shows only 7.59% reduction when compared to conventional SCC mix M0 of 9.74% of reduction.

- The addition of FA, PW and RCA in 45, 20 and 75 percentages respectively in SCC observed to be weak in durability phenomenon while treated with HCL solution. The weakening of durability could be due to various factors such as inadequate bonding between these materials, improper proportions leading to decreased strength.
- RCPT results shows us the longevity of structural performances of Sustainable SCC.

#### **Findings based on Objective 3:**

- It was found in the microscopic study that XRD analysis peak patterns shows the presence of development of  $\text{Ca}(\text{OH})_2$ ,  $\text{C}_2\text{S}$  and  $\text{C}_3\text{S}$  after hydration process for most of the SCC mixes.
- Advanced three-dimensional microscopic analyses provide insights into the occurrence of chemical reactions by visually presenting the formation of Portlandite, C-S-H gel, and the bonding interactions among all constituent materials. The visualization includes the hydration process of cement, the integration of fly ash, and the incorporation of various filler components. This clear and vibrant digital representation aligns with the experimental strength results obtained, enhancing our understanding of the underlying processes.

#### **Findings based on Objective 4:**

- Based on flexural strength test results the shear cracks are not propagated in low compressive strengthen SCC mixes representing the stability of members.
- According to statistical analyses utilizing the Taguchi experimental design along with its systematic model is the most effective strategy for maximizing efficiency, quality, and time justifying that a strong statical relationship was found between hardened properties of the SCC mixes.

In essence, the study's results affirm that the utilization of plastic waste in SCC, in conjunction with Fly Ash, Copper Slag, and Recycled Coarse Aggregate, yields commendable structural performance. This investigation serves to validate the viability

of plastic waste-incorporated SCC as a credible and sustainable alternative for structural applications, positioning it as a suitable choice alongside traditional concrete.

## 5.2 Recommendations:

Promoting the use of sustainable alternatives like plastic waste-incorporated SCC is crucial for advancing environmentally responsible construction practices. Here's a deeper look at this recommendation:

- **Environmental Impact Reduction:** Plastic waste incorporation offers a promising solution for addressing the global challenge of plastic pollution. By diverting plastic waste from landfills and oceans, civil engineers can contribute to reducing environmental harm and promoting recycling efforts.
- **Resource Conservation:** Utilizing plastic waste in concrete reduces the demand for virgin materials, such as natural aggregates, which helps conserve natural resources. This aligns with the principles of sustainability by minimizing extraction activities and preserving ecosystems.
- **Exploration of Sustainable Alternatives:** Engineers should actively explore and promote the use of sustainable alternatives, such as plastic waste-incorporated SCC, as viable options for structural applications. Collaborating with researchers and stakeholders to validate the performance and feasibility of these alternatives can support the adoption of environmentally responsible construction practices.
- **Microscopic Analysis:** Continued microscopic analysis, such as XRD analysis and three-dimensional imaging, has provided valuable insights into the hydration process, chemical reactions, and bonding interactions within SCC mixes. Stating research in this area can enhance our understanding of the fundamental mechanisms governing the performance of sustainable concrete mixes.
- **Statistical Modelling and Optimization:** Researchers should further explore the application of statistical techniques, such as Taguchi experimental design, for optimizing SCC mix designs. Developing robust statistical models can facilitate the

efficient use of materials, improve quality control, and optimize production processes for SCC.

In summary, collaborative efforts between researchers and practitioners are essential for advancing the development and adoption of sustainable concrete technologies. By leveraging the findings and recommendations from this study, both researchers and practicing civil engineers can contribute to the advancement of sustainable construction practices and the realization of more resilient and environmentally friendly infrastructure.

### **5.3 Focus on United Nations Sustainable Development Goals (SDGs):**

The Conclusions outlined focus on investigating the properties and performance of SCC incorporating plastic waste, recycled aggregates, fly ash, and copper slag. Here's how each result related to considered objectives aligns with the United Nations Sustainable Development Goals (SDGs):

#### **1. Investigating Fresh and Hardened Properties:**

Objective 1 involves studying the fresh and hardened qualities of SCC, emphasizing the utilization of sustainable materials such as plastic waste and recycled aggregates. This objective conclusion contributes to:

**Goal 9: Industry, Innovation, and Infrastructure** - By exploring innovative materials and construction techniques, the research supports advancements in sustainable infrastructure development.

**Goal 12: Responsible Consumption and Production** - By examining the use of recycled materials and waste diversion strategies, the research promotes responsible consumption and production practices within the construction industry.

**Goal 13: Climate Action:** By exploring the use of alternative materials like plastic waste, recycled aggregates, fly ash, and copper slag, the research aims to reduce the carbon footprint associated with traditional concrete production. Utilizing industrial by-products and recycled materials can potentially decrease greenhouse gas emissions linked to cement production, thus supporting climate action efforts.

## **2. Examining Durability Properties:**

Objective 2 focuses on evaluating the durability of SCC incorporating sustainable materials. This objective conclusion aligns with:

**Goal 11: Sustainable Cities and Communities** - By assessing the durability of concrete, the research contributes to the creation of resilient and sustainable urban infrastructure, essential for sustainable development.

**Goal 13: Climate Action** - By studying the durability of concrete made with fly ash (a by-product of coal combustion), the research addresses climate change mitigation efforts by promoting the use of materials that reduce carbon emissions.

## **3. Exploring Microstructural Properties:**

Objective 3 aims to explore the microstructural characteristics of concrete incorporating plastic waste, recycled materials, fly ash, and copper slag. This objective conclusion supports:

**Goal 12: Responsible Consumption and Production** - By examining the composition and performance of sustainable concrete mixtures, the research promotes responsible consumption and production practices, aligning with sustainable development objectives.

## **4. Evaluation of Crack Propagation:**

Objective 4 involves Evaluating crack propagation in structural elements made with alternative materials addresses. This objective conclusion contributes to:

**Goal 9: Industry, Innovation, and Infrastructure**- By assessing the performance and integrity of structural elements constructed with innovative materials like copper slag and recycled aggregates, the research contributes to advancements in infrastructure development and construction industry practices.



**Fig.5.1: United Nations Sustainable Development Goals Courtesy of UNESCO**

Overall, the research focuses on advancing sustainable construction practices, promoting innovation in materials and techniques, and supporting the development of resilient and environmentally friendly infrastructure, thus contributing to multiple Sustainable Development Goals, including Goals 9, 11, 12, 13 and 14.

## CHAPTER 6

### LIMITATIONS AND SCOPE FOR FUTURE RESEARCH

This chapter, critically evaluates the limitations encountered during the investigation of the structural performance of self-compacting concrete made with waste plastic. While research focus has been on elucidating the concrete's behaviour, certain constraints, such as the limited exploration fire hydrants and the absence of standardized testing for specific applications, have been acknowledged. Additionally, we outline the potential avenues for future research, emphasizing the need for extended studies on material compatibility with diverse elements, addressing real-world exposure challenges, and exploring the economic feasibility of broader applications in construction and infrastructure.

#### 6.1 Limitations:

1. **Material Compatibility with Hydrant Components:** The compatibility of SCC made with waste plastic with various components of fire hydrants (such as metals, rubbers, and seals) might not be extensively investigated. This limitation could affect the understanding of potential chemical or physical interactions that could compromise the functionality of the hydrant.
2. **Variable Plastic Characteristics:** The properties of waste plastic can vary significantly based on the type, source, and processing method. The thesis may be constrained by the inherent variability in waste plastic characteristics, making it challenging to draw broad conclusions applicable to all types of waste plastics.
3. **Long-Term Durability Assessment:** Evaluating the long-term durability of self-compacting concrete with waste plastic poses a challenge due to the time constraints inherent in research. The thesis may acknowledge the limitation of providing extensive data on the material's performance over an extended service life.

4. **Environmental Conditions:** The performance of concrete, especially with recycled materials, can be influenced by environmental conditions. Limitations may arise from the inability to conduct tests under all possible environmental scenarios, such as extreme temperatures, aggressive chemical exposures, or cyclic freeze-thaw cycles.

## 6.2 Scope for future research:

Future research on the utilization of plastic waste in sustainable construction, particularly in the context of SCC, is crucial for addressing environmental concerns and holds significant promise. Some potential research areas in this field could include:

1. **Innovative Materials:** Researching and creating novel materials for SCC applications that utilize recycled plastics or are created to be more environmentally friendly.
2. **Recycling Technologies:** Improving recycling techniques to process and incorporate plastic waste into building materials in an efficient manner.
3. **Durability and Performance:** Determining if construction materials made of plastic waste are long-lasting and operate as intended in order to ensure that they adhere to safety and quality standards.
4. **Environmental Impact Assessment:** Conduct thorough life cycle analyses to comprehend the environmental impact of employing plastic waste in SCC and evaluate it against conventional materials.
5. **Circular Economy Integration:** Exploring ways to integrate plastic waste usage in SCC within the principles of a circular economy, focusing on reducing, reusing, and recycling materials.

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## LIST OF PUBLICATIONS

1. V. Sai Neeraja, Ashutosh Sharma “Enviro safe concrete” in Procedia Environmental Science, Engineering and Management 6 (2019) (4) 565-574, September 2019. (SCOPUS)
2. V. Sai Neeraja, Vaibhav Sharma “Experimental Investigation on Fresh Properties and Optimization of Self-Compacting Concrete Reinforced with Waste Plastic” Lecture Notes in civil engineering, in Nov 2021. [https://doi.org/10.1007/978-981-19-4731-5\\_28](https://doi.org/10.1007/978-981-19-4731-5_28). (SCOPUS)
3. V. Sai Neeraja, Vaibhav Sharma “Influence of fly ash, copper slag, plastic waste, and recycled aggregate on the fresh and mechanical properties of self-compacting concrete using Taguchi technique”, Innovative Infrastructure Solutions 2023 8:1. 8 (2023) 1–11. <https://doi.org/10.1007/S41062-023-01042-8>. (SCOPUS)
4. V. Sai Neeraja, Vaibhav Sharma, “An overview of fresh and mechanical properties of recycled coarse aggregate self- compacting concrete”, Materials Today: Proceedings, Volume 93, Part 3, 2023, Pages 211-216, ISSN 2214-7853, <https://doi.org/10.1016/j.matpr.2023.07.120>. (SCOPUS)

## **LIST OF CONFERENCES**

1. Presented a paper titled “Enviro safe concrete” in international conference in Environmental innovations: Advances in Engineering Technology and management, September 23-27, 2019.
2. Presented a paper titled “Experimental Investigation on Fresh Properties and Optimization of Self-Compacting Concrete Reinforced with Waste Plastic” in first Indian Geotechnical and Geo Environmental International Conference (IGGEC 21) at department of Civil Engineering, Dr. B.R. Ambedkar National Institute of Technology, Jalandhar, Punjab, November 19-20, 2021.
3. Presented a paper titled “An overview of fresh and mechanical properties of recycled coarse aggregate self- compacting concrete” in International UKIERI Concrete Congress Sustainable Concrete Infrastructure, Hosted by Dr B R Ambedkar National Institute of Technology Jalandhar, India and Guru Nanak Dev Engineering College Ludhiana, India, held on 14 - 17 March 2023.