

STUDIES ON MICRO-CEMENT ASSISTED BLENDED CEMENTS

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By

RAJAN SURESH KAMBLE

Research Centre at
GOA COLLEGE OF ENGINEERING, Farmagudi, Ponda-GOA

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STUDIES
ON
MICRO-CEMENT ASSISTED
BLENDED CEMENTS

DECLARATION

I, ***RAJAN SURESH KAMBLE*** hereby declare that this **THESIS “Studies on Micro-Cement Assisted Blended Cements”** represents work which has been carried out by me and that it has not been submitted, either in part or full, to any other University or Institution for the award of any research degree.

Place : GEC, Farmagudi, Ponda - GOA.

Date : 4th June 2026

Shri RAJAN SURESH KAMBLE

CERTIFICATE

I, hereby certify that the above Declaration of the candidate, ***RAJAN SURESH KAMBLE*** is true and the work was carried out under my supervision.

Name of the Guide : Dr. K. G. GUPTHA

Affiliation of Guide : GOA UNIVERSITY

Dr. K. G. GUPTHA

D E D I C A T I O N

I, dedicate my entire journey of acquiring knowledge to my parents; Smt. **CHAYA SURESH KAMBLE** and Late Shri **SURESH SHAHU KAMBLE** and shall always remain indebted for seeding good qualities into me.

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Shri **RAJAN SURESH KAMBLE**

CURIOSITY enhances KNOWLEDGE

and

PASSION leads to ATTAINMENT

THESIS APPROVAL SHEET

This Thesis entitled “**Studies on Micro-Cement Assisted Blended Cements**” submitted by ***Shri RAJAN SURESH KAMBLE*** (PRN : 202012226) is approved for the award of degree of DOCTOR OF PHILOSOPHY in CIVIL ENGINEERING.

EXAMINER

SUPERVISOR

CHAIRMAN

Place : GEC, Farmagudi, Ponda - GOA.

Date : /...../ 2026

ABSTRACT

The global consumption of Ordinary Portland Cement (OPC) experienced unprecedented growth during the late twentieth century and has continued to increase significantly throughout the twenty-first century, primarily driven by rapid urbanization, population expansion, and the consequent demand for large-scale infrastructure development including high-rise buildings, transportation networks, airports, ports, dams, and irrigation systems. Despite its indispensable role in modern construction, OPC production is recognized as one of the major contributors to environmental degradation due to extensive natural resource depletion and substantial greenhouse gas (GHG) emissions generated during clinker manufacturing.

The cement industry is presently responsible for a considerable proportion of global anthropogenic CO₂ emissions, mainly arising from limestone calcination and high-temperature kiln operations. In response to growing environmental concerns and international sustainability mandates, significant research efforts have focused on reducing the clinker factor in cement through the utilization of Supplementary Cementitious Materials (SCMs), including Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash (FA), both of which are industrial by-products possessing latent hydraulic and pozzolanic characteristics.

Although the incorporation of SCMs offers substantial environmental and economic advantages by reducing clinker consumption and associated carbon emissions, their application in blended cements is frequently accompanied by technical challenges. Higher replacement levels of SCMs generally lead to reduced early-age strength, delayed hydration kinetics, increased setting times, and altered rheological behavior due to variations in particle morphology and reactivity. Additionally, increased water demand and slower formation of hydration products often affect the overall performance and durability characteristics of blended cement systems. Consequently, optimization of blended cement formulations requires a comprehensive understanding of cement chemistry, hydration mechanisms, and particle size engineering.

The present study investigates the influence of engineered Particle Size Distribution (PSD) and Bogue's compounds on the enhancement of both early-age and long-term mechanical performance of sustainable blended cement systems. Commercial Ordinary Portland Cement (OPC) was subjected to intensive mechanical grinding to achieve a high specific surface area of approximately 5390 cm²/g, thereby producing an ultrafine reactive material designated as "Stimulator (S)." This engineered material was subsequently blended with conventional OPC at a replacement level of 45% by weight to produce a modified binder system referred to as "S45".

To further improve sustainability and reduce clinker dependency, SCMs such as GGBFS and Fly Ash were incorporated in varying proportions with S45 to formulate optimized binary and ternary blended cement composites. The study systematically evaluated the physicochemical, mechanical, and durability characteristics of the developed cementitious systems through an extensive experimental program.

Comprehensive material characterization was performed using X-Ray Fluorescence (XRF) analysis for chemical composition, Laser Diffraction Analysis for particle size distribution, Heat of Hydration measurements, Autoclave Soundness tests, Standard Consistency determination, and Initial and Final Setting Time evaluations in accordance with relevant Indian and international standards.

Mechanical performance assessment included compressive strength evaluation of mortar and concrete specimens at curing ages ranging from 1 day to 365 days in order to quantify both early-age strength development and long-term strength evolution. Furthermore, durability performance was assessed through Rapid Chloride Migration Testing (RCMT), Water Permeability testing, and Sorptivity measurements on concrete specimens cured for 28 days.

The experimental results demonstrate that optimization of PSD through ultrafine grinding significantly enhances particle packing density, hydration efficiency, and nucleation effects within the cement matrix. The modified blended systems exhibited a notable reduction in standard consistency values, indicating reduced water demand and

improved workability characteristics. Accelerated hydration kinetics were observed through reduced initial and final setting times compared to conventional OPC systems.

The engineered blends achieved substantially improved early-age compressive strengths at 1, 3, and 7 days, thereby overcoming one of the principal limitations associated with conventional SCM-based blended cements. Simultaneously, superior long-term strength development was observed at 28, 56, 90, and 365 days due to continued pozzolanic and latent hydraulic reactions contributing to matrix densification and refined pore structure development.

Durability investigations further confirmed enhanced resistance to chloride ion penetration, reduced permeability, and lower sorptivity values, indicating improved microstructural integrity and long-term durability performance. The synergistic interaction between optimized PSD and SCM incorporation resulted in the formation of a denser and more homogeneous cementitious matrix with reduced capillary porosity and enhanced interfacial transition zone characteristics.

From an economic perspective, the reduction in clinker content through higher SCM replacement levels contributed to measurable cost savings in cement production without compromising structural performance or durability. The improved strength efficiency and sustainability index of the developed blends establish their suitability for high-performance and environmentally responsible construction applications.

One of the most significant outcomes of this investigation is the successful maximization of SCM utilization in both binary and ternary blended cement systems while maintaining and, in several cases, enhancing engineering performance parameters. The study thereby contributes directly toward global decarbonization initiatives within the cement and construction industries by reducing embodied carbon associated with cement manufacturing.

The findings conclusively establish that engineered Particle Size Distribution (PSD), in conjunction with optimized SCM utilization, constitutes a highly effective strategy for

developing sustainable cementitious materials exhibiting superior early-age strength, long-term mechanical performance, enhanced durability, and reduced environmental impact. The research further demonstrates that high-performance blended cements can be produced through scientifically engineered particle packing and hydration optimization without necessitating substantial modifications to conventional cement manufacturing processes.

Nevertheless, the study also identifies SCM quality variability as a critical factor influencing performance consistency. Therefore, further research is recommended toward standardization of SCM quality parameters, development of performance-based specifications, and formulation guidelines for next-generation sustainable cement systems.

This research contributes substantially to the advancement of sustainable cement technology and provides valuable scientific and practical insights for the cement industry in achieving enhanced performance, economic viability, and environmental sustainability in future construction practices.

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List of Abbreviations

CCI	-	Cement Corporation of India
OPC	-	Ordinary Portland Cement
UNFCCC	-	United Nations Framework on Climate Change
FA	-	Fly Ash
GGBFS	-	Ground Granulated Blast Furnace Slag
SCM	-	Supplementary Cementitious Material
BIS	-	Bureau of Indian Standards
PSC	-	Portland Slag Cement
PPC	-	Portland Pozzolana Cement
PSD	-	Particle Size Distribution
SSA	-	Specific Surface Area
BSSA	-	Blaine Specific Surface Area
C-S-H	-	Calcium Silicate Hydrate
BFS	-	Blast Furnace Slag
SF	-	Silica Fume
NP	-	Natural Pozzolans
UFFA	-	Ultra Fine Fly Ash
SS	-	Steel Slag
OWD	-	Optimum Water Demand
A&A	-	Andreasen and Andersen
RR	-	Ronnie Rammler
FMC	-	Fineness Modulus of Cement
XRD	-	X-Ray Diffraction
SEM	-	Scanning Electron Microscopy
OSM	-	OPC & Slag Mortar
PFA	-	Pulverized Fly Ash
RHA	-	Rice Husk Rice
IST	-	Initial Setting Times
FST	-	Final Setting Times
CS	-	Compressive Strength
UPV	-	Ultrasonic Pulse Velocity

GHG	-	Green House Gases
LCA	-	Life Cycle Assessment
FFA	-	Class-F Fly Ash
CFA	-	Combustion Fly Ash
MP	-	Mercury Porosimetry
MFA	-	Modified Fly Ash
HCFA	-	High Calcium Fly Ash
BBCM	-	Binary Blend Cementitious Material
TBCM	-	Ternary Blend Cementitious Material
SCC	-	Self-Compacting Concrete
LS	-	Ligno Sulfonates
PC	-	Portland Cement
RCPT	-	Rapid Chloride Permeability Test
UFS	-	Ultra Fine Slag
TGRA	-	Taguchi-Grey Relational Analysis
CBA	-	Coal Bottom Ash
S	-	Stimulator
CC	-	Composite Cement
RCMT	-	Rapid Chloride Migration Test
JSW	-	Jindal Steel Works
NTPC	-	National Thermal Power Corporation
SC	-	Standard Consistency
HoH	-	Heat of Hydration
ACTM	-	Automatic Compression Testing Machine
AS	-	Autoclave Soundness

Chapter 1

Introduction

1.1 Introduction to Cement

Cement is a term derived from the primeval Roman word *opus caementicium*, which refers to masonry composed of crushed rock binding with burnt lime to form a new-age concrete augmented with volcanic ash and powdered brick. In the early 19th century, cement was produced by finely mixing argillaceous limestone and clay into a slurry and calcinating in a furnace till carbon dioxide was exorcised. The resultant product was further ground into a fine powder called Cement. However, Joseph Aspdin pioneered the invention of Portland cement, a name derived from the resemblance of hardened cement to the natural stone that existed in Portland in England, and took the patency of Portland cement on 21st October 1824. In India, the Cement Corporation of India (CCI) was the first manufacturing company to introduce Portland cement for its various applications in commercial use.

Approximately 0.94 tons of carbon-di-oxide dioxide released for every tonnage of Ordinary Portland Cement (OPC) manufactured (Lee and Wang, 2016). Hence, the cement industry is the most polluting one. Efforts are on to reduce the environmental impact to curb this pollution. The Kyoto Protocol was adopted at the Third Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in Kyoto, Japan, on 11 December 1997. UNFCCC encouraged industrialized countries to stabilize GHG emissions, and the Kyoto Protocol commits them to do so. On the recommendation of the protocol, the introduction of blended cements appeared for commercial use. Amongst the industrial wastes, Fly-ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) are popular for blending with OPC. The term Supplementary Cementitious Materials (SCMs) most commonly adopts all such similar mineral admixtures for the production of blended cements. The present study is towards deriving benefits and shaping a better material for environmental sustenance.

Another governing parameter in cement concrete production is the ability to withstand and resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties without deterioration for a longer time span, popularly known as Durability. Concrete will remain durable when the cement paste structure is dense with

low permeability, the aggregate used is well graded, strong, and inert, and all ingredients in the mix contain minimal impurities. The literature cites that blended cement is more durable than OPC.

Durability is categorized mainly into two types, namely:

- A. Physical Durability, which acts against freeze-thaw action, percolation/permeability of water, and temperature stresses, i.e., high heat of hydration, and
- B. Chemical Durability acts against alkali-aggregate reaction, sulphate attack, chloride ingress, delayed ettringite formation, and corrosion of reinforcement.

Rapid increase in OPC consumption has led to depletion of natural resources due to its over-exploitation and exorbitant anthropogenic gas release in the atmosphere by cement manufacturers. Replacement of Supplementary Cementitious Materials (SCMs) in OPC is the only viable solution to the former problems. SCMs such as Fly-ash, GGBFS are substituted in OPC in binary and/or ternary form, thereby curbing the carbon emission, efficient usage of redundant industrial wastes, making concrete more durable, and most importantly, cost-effective cement production.

1.2 Binary Blended Cement

The amalgamation of two materials, mainly Ordinary Portland Cement (OPC) with one of the supplements, either Natural Pozzolons such as limestones, Scoria, or Artificial Mineral Admixtures such as Fly-Ash, Slag, Silica Fumes, Metakaolin, is named as Binary Blended Cements.

The following are the types of Binary Blended Cements manufactured in India as per the Bureau of Indian Standards (BIS).

1.2.1 Portland Slag Cement (PSC)

PSC is manufactured either with an intimately inter-grounding of Portland cement clinker and Granulated Slag with the addition of gypsum and permitted additives or an intimate and uniform blending of Portland cement and finely ground granulated slag with slag constituent not less than 25% and not more than 70% percent by mass of Portland-Slag cement, conforming to BIS: 455 (2020).

1.2.2 Portland Pozzolana Cement (PPC)

PPC is manufactured either with an intimately inter-grounding of Portland cement clinker and Fly-ash as pozzolana with the possible addition of gypsum (natural or chemical) or an intimate and uniform blending of Portland cement and fine fly-ash pozzolana with fly ash constituent not less than 15% and not more than 35% by mass of Portland-Pozzolana cement, conforming to BIS: 1489 (Part - 1) (2020).

1.3 Ternary Blended Cement

The amalgamation of three materials, mainly Ordinary Portland Cement (OPC) with either two of the Natural Pozzolons such as Limestones, Scoria, or Artificial Mineral Admixtures such as Fly-Ash, Slag, Silica Fumes, Metakaolin, is named as Ternary Blended Cements.

Based on the Bureau of Indian Standards (BIS), the ternary blended cement is also termed as Composite cement and is manufactured either with an intimately inter-grounding of Portland cement clinker, granulated slag, and fly-ash with the addition of gypsum (natural or chemical) or an intimate and uniform blending of Portland cement, finely ground granulated slag and fly-ash with the addition of ground gypsum, if required. The material proportion by weight in Composite Cement consists of Ordinary Portland clinker/cement between 35% to 65%, Fly-ash between 15% to 35%, and Granulated Slag between 20% to 50%, and has more specific advantages over Binary Cements, conforming to BIS: 16415 (2020).

Amalgamation of SCMs with OPC affects the physio-mechanical properties of the resultant cement by way of high water-demand for exothermic reaction, delayed setting times, retarded strength gain with lower values. Particle Size Distribution (PSD) of OPC and SCMs plays a significant role in the enhancement of physical and chemical properties of the blended/ternary cement.

1.4 Mineral and Chemical Admixtures

Mineral admixtures possessing similar cementitious properties and polymer-based Chemical Admixtures tend to accelerate the hydration process of cement in the initial and at later stages to achieve improved mechanical properties. However, it is always preferred to have a cement-based product or a chemical that improves the efficiency of the cement in its performance.

The present study aims at the addition of an optimized combination of OPC and Stimulator, i.e., fine ground OPC with a specific PSD supplemented with SCMs, namely Ground Granulated Blast Furnace Slag (GGBFS) and Fly-ash (FA), to form binary and ternary blended cements. A study reveals initial improvement in strength with the addition of the Stimulator and later strength by SCMs, which appears to be beneficial in making blended cements.

1.5 Stimulator

The stimulator is finely ground Ordinary Portland Cement (OPC) either in the jet or ball mill to a specific size for a pre-determined PSD. It possesses a higher specific surface area (SSA) due to finer particles and Blaine fineness ranging from about 500 to 1200 m²/kg as compared to 300 to 500 m²/kg for OPC. Smaller-sized particles react faster when mixed with water due to the significantly larger surface area that exposes more anhydrous material to the water as a result, the hydration rate increases. It also sets faster as finer particles hydrate relatively faster as compared to coarser particles, and increasing particle fineness tends to decrease the viscosity and yield stress.

The distribution of different particle sizes in any cement matrix influences the overall performance, such as particles less than 3µm attract more water for chemical reaction and influence the early strength. 28 days compressive strength is governed by particles between 3µm to 9µm, and 9µm to 25µm, while particles greater than 25µm act as fillers and do not contribute much to compressive strength.

1.6 Particle Size Distribution

Particle Size Distribution (PSD), uniformity factors, and specific surface area (SSA) are important physical parameters affecting cement service properties. These parameters define the proportion of fine and coarse particles in the cement. Particle size distribution can be measured with automatic or manual sieves. The most frequently followed parameters in the cement are 45 and 90-micron sieve residue and BSSA (Blaine Specific Surface Area) values. Blaine value is a numerical value of the area covered by 1g of material.

The PSD curve for any cement needs to be S-shaped, which means that the particles are distributed homogeneously in different dimensions within the sample. While investigating

the properties of cement grain, not only the size but also the shape parameter is important because these two variables are essential to determining the total surface area.

1.7 Commercial Production of Stimulator

In cement manufacturing companies, grinding of OPC is generally carried out by ball milling, and further refining to finer particles is executed in the jet mill on a larger production scale.

1.7.1 Jet Mill

In a jet mill, materials are ground using a high-speed jet of compressed air or inert gas to impact particles into each other and are separated from the gas stream by cyclonic separation. Particles below a certain size can be attained while continuing to mill particles above that size, resulting in a narrow size distribution of the resulting product. Figure 1.1 shows a typical jet mill.



Figure 1.1: Jet Mill (Source: Wikipedia)

1.7.2 Ball Mill

In the ball mill, a hollow cylindrical shell rotates about its horizontal axis or at a small angle to the horizontal. The mill is partially filled with grinding media i.e., balls made of steel (chrome steel), stainless steel, ceramic, or rubber. It works on the principle of impact and attrition: size reduction is done by impact as the balls drop from near the top of the shell. Figure 1.2 shows a typical ball mill.

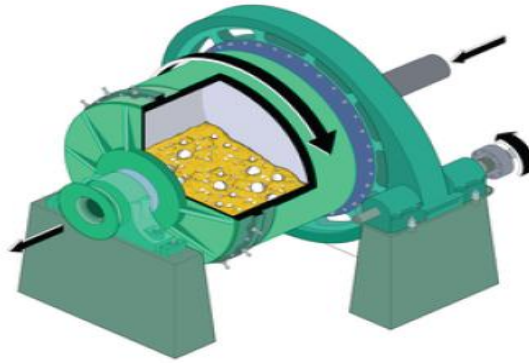


Figure 1.2: Ball Mill (Source: Wikipedia)

1.8 Ground Granulated Blast Furnace Slag (GGBFS)

Ground Granulated Blast Furnace Slag (GGBFS) is a by-product of iron and steel-making industries obtained by quenching molten iron slag in water or steam from a blast furnace to produce a glassy, granular product, which is dried and ground into a fine powder. Ground granulated blast furnace slag is highly cementitious, having high calcium silicate hydrates (C-S-H) that improve the strength and durability.

Based on the specifications listed in BIS: 455 (2020), Slag-based Portland Slag Cement (PSC) is manufactured either with inter-grinding or blending of Portland cement with Slag supplement ranging between 25% to 70%. The study, as Part-1 on Binary Blended Cement Incorporating Slag ranging between 25% to 75% with Stimulator, is explained in Chapters 4 and 5.

1.9 Fly-ash (FA)

Fly ash is a heterogeneous residual powder formed from non-combustible matter in coal, with a small number of carbons remains from incomplete combustion obtained from burning pulverized coal in electricity generation power plants. It is a substance containing aluminous and siliceous material that shows cementitious behavior with the addition of water.

Based on the specifications listed in BIS: 1489 (Part - 1) (2020), fly-ash-based Portland Pozzolana Cement (PPC) is manufactured either with inter-grinding or blending of Portland cement with fly ash supplement ranging between 15% to 35%. The study, as Part 2 on Binary Blended Cement incorporating fly-ash ranging between 15% to 55% with Stimulator, is explained in Chapters 4 and 5.

1.10 Ternary Blend

Based on the specifications listed in BIS: 16415 (2020), Slag and fly-ash based Composite Cement is manufactured either with inter-grinding or blending of Portland cement, ranging between 35% to 65% with Granulated Slag ranging between 20% to 50% and fly ash supplement ranging between 15% to 35%. The study, as Part-3 on Ternary Blended Cement incorporating Slag ranging between 25% to 55% and fly ash ranging between 15% to 45% with Stimulator, is explained in Chapters 4 and 5.

Based on the literature survey, it was learnt that replacing supplementary cementitious materials in OPC tend to retard strength gain with lower values for early as well as later curing ages. Also, the resultant blended cement showed poor setting times with high water requirements for chemical reaction. Also, re-orientation of PSD was limited to OPC. This was the overall research gap and is presented in detail in Chapter 2. Based on the literature gap, the objectives proposed are listed in Chapter 3. On careful execution of the research work, the thesis has been organized in the following format.

1.11 Organization of the Thesis

The work is summarized into Seven Chapters, namely.

Chapter 1 gives the Introduction

Chapter 2 with updated Literature Review incorporating the available literature towards blending and activation, to bridge the research gap identified with the Objectives of the study proposed,

Chapter 3 includes the Materials and Methodology adopted to achieve the proposed objectives,

Chapter 4 elaborates on the Experimental Procedures in line with Chapter 3,

Chapter 5 summarizes Results and Discussions, and

Chapter 6 derives the Conclusions based on the experimental study.

Proposed objectives to bridge the research gap incorporating literature review, is presented in the Chapter 2.

Chapter 2

Literature Review

The increase in demand for Portland cement over a couple of decades led to the over-extraction and exorbitant utilization of natural resources. The emission of carbon dioxide was one of the issues related specifically to the cement industry towards the sustainability of the environment.

The entire literature review has been subdivided into four categories, namely Sections 1 to 4. This classification is based on the objectives proposed at para 2.6 after identifying the research gap brought out at para 2.5 and listed below.

- (a) Section-1: Particle Size Distribution (PSD)
- (b) Section-2: Binary Blended Cement
- (c) Section-3: Ternary Blended Cement
- (d) Section-4: Durability

The chemical composition of Ordinary Portland cement is generally classified based on the Oxide compounds and Bogue compounds. Table 2.1 shows the oxide and bogue compounds with a typical percentage range in OPC.

Table 2.1: Oxide and Bogue compounds in OPC

Chemical Composition	Percentage
Oxide Compounds	
CaO	60-67
SiO ₂	17-25
Al ₂ O ₃	3-8
Fe ₂ O ₃	0.5-0.6
MgO	0.5-4.0
SO ₃	0.3-1.2
K ₂ O/Na ₂ O	2.0-3.5
Others	0-1
Loss of Ignition	1-2
Insoluble residue	0-0.5
Bogue Compounds	
Tri-calcium silicate (C ₃ S)	30-50
Di-calcium silicate (C ₂ S)	20-45
Tri-calcium aluminate (C ₃ A)	8-12
Tetra-calcium alumino-ferrite (C ₄ AF)	6-10

(Source: JKCL Plant, Muddapur-Karnataka)

For specialized application conditions, these bogue compounds can be controlled by changing raw material feed, changing the temperature in the kiln, altering the duration of reaction in a kiln, and adjusting the amount of gypsum.

For preserving the natural resources, reducing carbon dioxide emissions, and making the cement cost-effective, Ordinary Portland Cement is blended either with Natural Pozzolons such as Free limestones, Scoria or Artificial Mineral admixtures such as Fly-Ash, Slag, Silica Fumes, Metakaolin.

Taylor (2014) experimented with the use of Ternary Mixtures in Concrete and summarized that for most concrete applications cement content should be more than 40% with supplementary cementitious materials (SCMs) of Silica Fume up to 10%, Fly-ash up to 30% and Granulated Slag up to 50%. Figure 2.1 shows the particle size with values of specific surface area (SSA) for different materials used in concrete preparation.

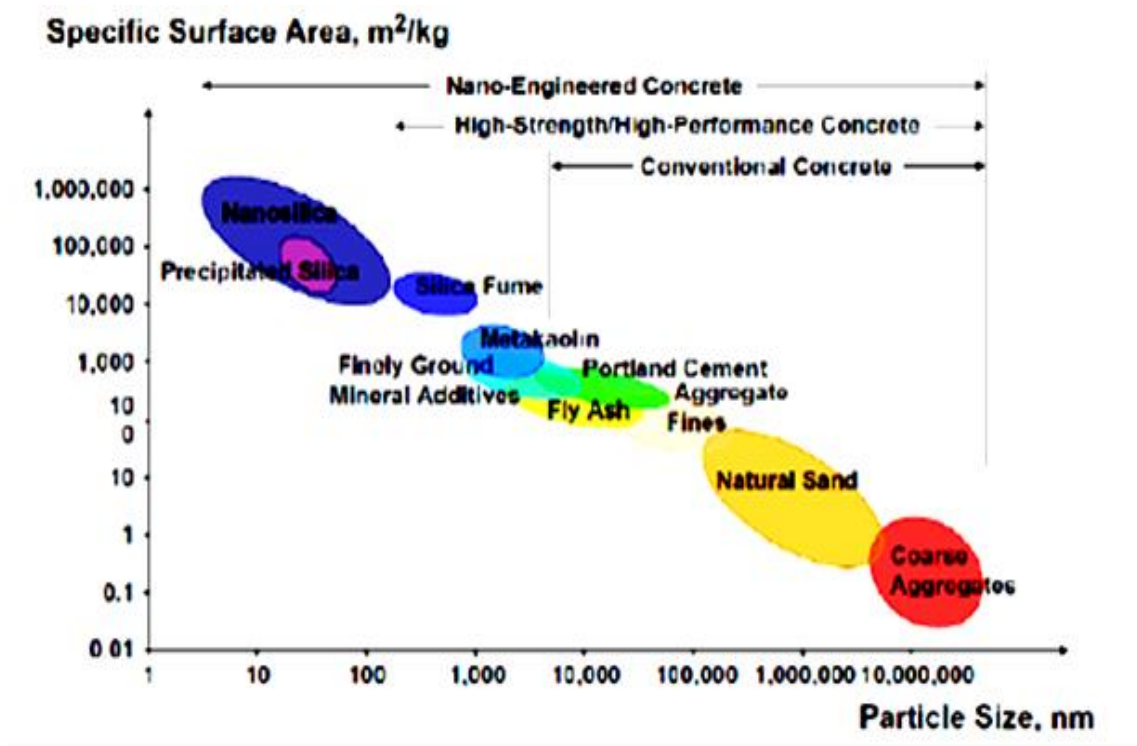


Figure 2.1: Particle size with SSA of different materials used in Concrete
(Source: Sanchez, F. and Sobolev, K. "Nanotechnology in concrete – A review")

The PSD of OPC ranges from 1 micron to 90 microns and approximately 95% of cement particles are smaller than 45 microns and the average particle size is 15 microns. The fineness of OPC with a specific surface area range between 300 to 500 m²/kg. The OPC

particles less than 5 microns initiate active reaction while particles between 5 microns to 12 microns impart strength and 13 microns to 90 microns particles fill the voids in the cement paste.

The PSD of Stimulator Cement ranges from 1 micron to 25 microns and the average particle size is 10 microns. The fineness of Stimulator cement with a specific surface area range between 500 to 1200 m²/kg. Figure 2.1 indicates the particle sizes with its SSA for different concrete materials.

The main cement properties affected by Particle Size Distribution, are:

- a. Strength
- b. Setting Time
- c. Permeability
- d. Hydration Temperature
- e. Water Demand and
- f. Microstructure

The literature collected under four different headings is as follows:

2.1 Section-1: Particle Size Distribution (PSD)

Bentz et al. (1999) investigated the effects of cement particle size distribution on performance properties with a computer simulation based on the NIST microstructural model and also experimental studies. The effect on setting time, heat release, capillary porosity percolation, diffusivity, chemical shrinkage, autogenous shrinkage, internal relative humidity evolution, interfacial transition zone, flocculation, and dispersion of cement particles, was experimented with two cement fine-nesses i.e. 640 sq.m./kg and 210 sq.m./kg for three different water-cement ratios of 0.50, 0.30 and 0.246. They concluded that finer cement needs more hydration to build more particle to particle to form a percolated pathway with a higher initial rate of heat release which may cause thermal stresses and early-age cracks. Coarser cements enhance curability by more hydration processes for the capillary porosity to de-percolate. The overall result indicated that finer cement took less setting time and more early strength gain than coarse cement. However, the heat of hydration, chemical shrinkage, autogenous shrinkage, and internal relative humidity evolution was less in coarser than finer cement resulting in controlled thermal cracking and enhanced curability. As regards diffusivity, the coarser cement

showed higher values than finer cement and for interfacial transition zone microstructure, the coarser cement resulted in higher porosity with large pores.

Park et al. (2004) investigated rheological properties using a Rotovisco RT 20 rheometer (Haake) with a cylindrical spindle, of cementitious materials containing fine particles namely finely ground blast furnace slag, fly ash and silica fume, designed as one, two and three component systems by replacement of ordinary portland cement (OPC). They concluded that an increase in dosage of super-plasticizer in OPC paste, increased the yield stress and plastic viscosity thereby improving the rheological properties. For a two-component system of replacing OPC with blast furnace slag (BFS), the yield stress and plastic viscosity decreased with an increase in Slag content while in the OPC-fly ash (FA) system, there was an increase in yield stress and plastic viscosity with increase in FA content and for OPC-silica fume (SF), yield stress and plastic viscosity steeply increased with increasing SF. The rheological properties improved for the OPC-FA-SF system in comparison to OPC-BFS-SF. Overall, the higher component system showed better results than the lower component system, and the addition of SF controlled yield stress and plastic viscosity in cementitious materials and acted as a filler material. In a two-component system, OPC-BFS showed better rheology properties and in three components systems, the addition of SF is preferred for high-performance concrete.

Binici et al. (2007) experimented on Pure Portland cement (PPC), Natural Pozzolans (NP) i.e. scoria, and GGBFS to obtain blended cements that contain 10, 20, 30% additives by inter-grinding and separate grinding and then blending with two Blaine fineness of 280 m²/kg and 480 m²/kg and studied the effect of particle size distribution on its properties. They concluded that the average compressive strength at 28 days of separately ground blended cement was 8% higher than inter-ground ones. Fineness modulus of finer specimens was about 13% higher than coarser specimens. The sulfate resistance at 24 months was higher by about 7.7% in separately grounded blended cement specimens than inter-ground ones. More number of mineral admixtures, better fineness, and a narrower particle size distribution decrease the cumulative heat of hydration of cement, and separately ground blended cements release less heat of hydration than the inter-ground ones mainly attributed to the abrasive effect of GBFS during grinding. Separately ground blended cements are finer than inter-grounded blends for the same Blaine values which means that particle size distribution difference between inter-grinding and separate

grinding decreases when the size considered gets smaller and is attributed to fewer interactions among the ingredients of inter-ground cements at small particle sizes and more among larger particle sizes in separately ground blended cements. Overly, grounded separately were relatively finer and had higher sulfate resistance and compressive strength with the lowest heat of hydration as against inter-ground ones. They also observed that the separately ground finer specimens passed 34, 69, 81, and 99% through 5, 20, 30, and 55 μm sieves, respectively as against 32, 68, 75, and 94% passing values for the inter-ground specimens, which had the same fineness.

Li et al. (2008) experimented on four different Slag particles of 5~10 μm , 10~15 μm , 15~20 μm , and 20~26 μm and analyzed the influence of particle size distribution of slag on the compressive strength and pore structure of low-temperature concrete cured for 3 days, 7 days and 14 days. They concluded that concrete with slag particles of 10~15 μm PSD showed the highest compressive strength followed by 5~10 μm , 15~20 μm , and 20~26 μm slag PSD. The compressive Strength of Concrete increased with an increase in curing temperature. Overall, slag with 10~15 μm PSD outperformed regardless of curing temperature, and pore structure with the density of concrete improved as slag granularity decreased.

Bentz D. P., et al. (2008) conducted comprehensive studies of a variety of early-age properties of coarse and fine cement pastes and mortars including compressive strength, isothermal calorimetry, semi-adiabatic temperature rise, setting time, chemical shrinkage, autogenous deformation, restrained ring shrinkage, and acoustic emission with cement fineness possessing two Blaine values of cement viz. 380 m^2/kg and 311 m^2/kg . They concluded that finer cement consistently showed higher compressive strengths at all testing ages due to a combination of smaller inter-particle spacing and their increased reactivity while coarser cement releases less heat with substantially lower semi-adiabatic temperature rise. Coarser cement showed earlier setting time due to greater early-age reactivity, initial development of compressive stress with lower residual stress, and lower risk of cracking at early ages than finer cement mainly attributed to the lower magnitude of autogenous deformation with the decrease in autogenous stresses. Overall concluded that high early-age strength cement with finer particles increases thermal and autogenous deformation with early-age cracking as compared to coarser cement particles.

Celik (2008) experimented on OPC particle samples having size distributions viz. $-10\ \mu\text{m}$, $-20\ \mu\text{m}$, $-30\ \mu\text{m}$, $-45\ \mu\text{m}$, $-32+3\ \mu\text{m}$ and $-20+5\ \mu\text{m}$ obtained by laboratory scale 3rd generation separator and studied the effect of physical parameters such as Particle size distribution, uniformity of the distribution and specific surface area (SSA) on strength of cement by adding $-32+3\ \mu\text{m}$ and $-20+5\ \mu\text{m}$ fractions to the original PC 42.5 R in varying amounts. He concluded that hydration in early stages is affected by finer OPC particles in development of strength and coarser particles at later ages.

Peng et al. (2009) studied influence on packing density with respect to minimum water requirement and its association with hardened mortars compressive strength of binders in binary, ternary and quaternary forms comprising of ultra-fine fly ash (UFFA), steel slag (SS) and silica fume (SF) as cementitious materials. They concluded that mineral admixtures addition improved packing density in binders with enhanced compressive strength especially in composite form with two to three cementitious materials by dense packing of material particles at low water-binder ratio due to increase in packing density of resultant binders.

Bentz et al. (2011) experimented with the influence of Cement PSD, Fly-ash PSD, and Fly-ash volumetric supplement by working on PSD for four cements with target D90 values of $7.5\ \mu\text{m}$, $10\ \mu\text{m}$, $15\ \mu\text{m}$, and $20\ \mu\text{m}$, PSD for four fly ashes with target D10 values of $5\ \mu\text{m}$, $10\ \mu\text{m}$, $15\ \mu\text{m}$, and $20\ \mu\text{m}$ and fly ash volumetric proportion percentage ranging from 20% to 60%. They concluded that finer cement accelerates hydration at early ages, contributing to strength enhancement but at a later age the effect was nominal due to the achievement of complete hydration by finer cement particles. Coarser fly-ash particles do not react as readily as finer ones and later age strength is best enhanced by utilizing finer fly ash particles. Fly-ash blended cements showed a prolonged period in achieving cumulative heat release of $50\ \text{J}/\text{cm}^3$ and delayed to set. Wholly, they concluded that finer cement and coarser fly ash blend boosted early-age strengths and replacement of 20% to 35 % fly ash showed equivalent to higher values of mechanical properties in comparison to OPC.

Bentz et al. (2012) investigated the influence of Cement PSD, fly ash PSD, and the ratio of fly ash to cement on yield stress and viscosity of blended pastes. They concluded that replacement of cement by fly ash decreases yield stress as it proportionally decreases cement particle density thereby reducing the number of flocculated cement particle to

cement particle connections. While for plastic viscosity, both cement and fly ash particles contributed to the measured value. Wholly, they concluded that yield stress is controlled by cement particle density with fly ash acting as a diluent, and viscosities are influenced by both cement and fly ash particles, with approximate linear relationships.

Bentz et al. (2012) studied the impact of cement PSD, flyash PSD and flyash to cement ratio on yield stress and viscosity of blended pastes. They concluded that cement particle density control yield stress and viscosity is influenced by both cement and flyash particles with approximate linear relationships between plastic viscosity values to total particle surface area/density.

Kashani et al. (2013) investigated the effects of three slags PSD with particle size less than 53 μm , between 53-90 μm an average particle size between 53 μm and 53-90 μm . They experimented on GGBFS powder by using a pulverizing mill (Labtechnics) to crush and reduce the particle size and then two sieve fractions viz. <53 μm and 53-90 μm , were collected by separating the particles using 90 μm and 53 μm sieves. Based on the test results conducted for yield stresses and the flow curves of the pastes, they concluded that a higher fraction of larger particles showed lower yield stress as compared to a higher fraction of smaller particles due to the changes in the packing factor of the powders in concentrated suspensions as a function of particle size distribution and that there is a direct relationship between the modal particle size and the yield stress of the paste based on YODEL model.

Sabdon et al. (2014) investigated the effect of nano-cement in mortar of two cements viz. PCC (Portland Composite Cement) and PPC (Portland Pozzolana Cement) by substituting normal cement with nano-cement in the range from 0%, 20%, 40%, 60%, 80%, to 100% by weight and studied the parameters such as setting times, particle size distribution and compression strength of final blends. They concluded that nano-cement increased strength at 28 days and PPC was aggressive in nature for initial setting time with hydration as compared to PCC. Also, at initial stage PPC showed moderate strength at 40% substitution and steeply increased while PCC demonstrated relatively small intensification between the content of 40% to 80%, with a sharp slope at a nano-cement content lower than 40% and higher than 80%.

Hua et al. (2014) investigated hydration by conducting isothermal calorimetry tests on portland cement mortars prepared at four different water-to-cement ratios (w/c) viz. 0.35, 0.40, 0.50 and 0.60 with three different finenesses viz. 399 m²/kg, 364 m²/kg and 302 m²/kg. They concluded that higher fineness cement generated higher heat at faster pace in early ages. Also, lower w/c ratio produced higher hydration heat at early ages and the total heat generation remained same regardless of w/c ratio. Setting Times viz. initial and final increased with increase in w/c ratio and with decrease in cement fineness.

Guynn et al. (2015) based on several independent laboratory studies, have developed a framework for optimizing the substitution of cement with SCMs in concrete by paying attention to the PSDs of cement and SCM and the corresponding packing density of the combined ingredients for an optimization. This framework can be adapted as a base for evaluating and optimizing any combination of Cement and SCMs. They have conceptualized that in blended cements, SCMs can be increased by (1) a simple analytical framework for predicting permissible SCM replacement levels; (2) case studies that validate the analytical framework; and (3) industrially feasible manufacturing systems for making optimized blended cements with three fundamental design principles to be followed for optimizing SCM contents, namely (1) Maintain a broad particle size distribution (PSD) (e.g., a Fuller distribution) (2) Minimize the quantity of coarse Portland cement particles (>24 µm) and (3) Minimize the quantity of overly fine Portland cement particles (<8 µm).

Mehdipour et al. (2017) experimented on binary and ternary binder systems with OPC, Flyash, Silica Fume and Granulated Blast Furnace Slag and studied the influence of PSD and calculated SSA on flow characteristics, packing density, and compressive strength development of cement paste. Further, they determined (i) optimum water demand (OWD) by wet packing density method to achieve maximum wet density, (ii) optimized PSD by using modified Andreasen and Andersen (A&A), RosineRammmler (RR), and power law grading models to achieve maximum packing density with low water demand. They concluded that increasing SSA from 425 to 1600 m²/kg enhanced packing density from 0.58 to 0.72, while further increase in SSA from 1600 to 2200 m²/kg reduced packing density from 0.72 to 0.62. Also, combined effect of lower OWD, greater packing density, and higher SCM reactivity showed higher compressive strength in binders and

considerable correlations between A&A distribution modulus, SSA, RR spread factor, and power law distribution exponent were proven.

Karimi et al. (2018) investigated the effect of the modification of the physical structure of cement on workability, early-age strength, and autogenous shrinkage of cement pastes. They worked with no particles larger than 90 μm and smaller than 0.3 μm having its modal value as 20 μm , on two cement PSD viz. one with more volume fractions of particles smaller than 20 μm and the other with more volume fractions of particles bigger than 20 μm . They concluded that cement with coarser particles showed better workability than finer cement. However, finer particle cement gave better compressive strength results at all ages than coarser cement. The autogenous shrinkage of cement pastes made with coarser cements is less than that of finer cements. Wholly, they concluded that coarser cement particles prevailed over smaller ones with better rheological features, less autogenous shrinkage, and greater value of creep due to lower early-age compressive strengths.

Kim (2018) experimented by collecting several sizes of cement particles from different filters at a cement plant and conducted the adjustment of cement particle-size distribution to enhance the properties of concrete based on ASTM Type I cement. They studied the effects of the distribution of cement particles on chemical properties and physical tests such as setting time and compression tests based on the fineness modulus of cement (FMC) and concluded that as FMC increased, the setting time was delayed in proportion due to presence of coarse particles with a smaller surface area that can contact water thereby delaying the rate of hydration. Also, as FMC increased compressive strength remained relatively low at an early age and the difference became smaller at a later age due to continuous hydration of unhydrated cement with the progress of age.

2.2 Section-2: Binary Blended Cement

Olorunsogo (1998) investigated the influence of particle size distribution (PSD) of ground granulated blast furnace slag (GGBS) on the bleeding characteristics of slag cement mortars by separating and recombining to a targeted PSD of GGBS using Rosin-Rammler distribution parameters, further blending targeted GGBS with OPC for 0, 30 and 70% replacement and carried out the mixes for two water-cement (w/c) ratio of 0.35 and 0.45. He concluded that a blend incorporating slag with a medium range of PSD i.e. 18.5 μm showed the highest values of bleeding rate and capacity. Overall, he concluded that the

bleeding increased significantly with an increase in slag replacement for an equal w/c ratio and no relationship was established between PSD and bleeding rate for slag replacement.

Bouzoubaâ et al. (1999) reviewed the effects of grinding fly ashes on their physical and chemical properties and their effect on the properties of mortars and concretes incorporating the blended fly ash cements. They concluded that specific gravity, fineness, and pozzolanic activity increase with a reduction in water requirement up to an optimum grinding time, beyond which all parameters do not increase significantly. Grinding of fly ashes for a short period breaks some plerospheres, cenospheres, and carbon particles, however, for a longer period it breaks other spherical particles with an increase in irregular-shaped particles. Chemical composition does not change much after grinding fly ash. With the increase in fineness and reactivity, the autogenous temperature rise of the fly ash concrete is increased, however setting times and bleeding decrease with an increase in fineness of Fly-ash particles. Wholly, they concluded that more grinding increased fineness, reactivity, and compressive strength, however the initial and final setting time and bleeding decreased but their chemical composition was not affected.

Chindaprasirt et al. (2005) studied the flyash fineness effect on compressive strength, porosity, and pore size distribution of hardened cement pastes adopting original Class-F flyash with median particle size of $19.1\mu\text{m}$ and classified flyash with $6.4\mu\text{m}$, respectively by replacing OPC with flyash at 0%, 20%, and 40% by weight of binder keeping w/b=0.35 for all blended pastes. They concluded that finer flyash showed higher compressive strength as against coarse flyash. Also, porosity and pore size were primarily influenced by replacement levels of flyash and its fineness. Classified flyash decreased porosity, average pore size while original flyash increased porosity however average pores size decreased.

Chindaprasirt et al. (2007) experimented replacing OPC with original Class-F flyash with median particle size of $19.1\mu\text{m}$ and classified flyash with $6.4\mu\text{m}$, respectively at 0%, 20%, and 40% by weight of binder keeping w/b=0.35 and conducted tests such as mercury intrusion porosimetry, x-ray diffraction (XRD), scanning electron microscopy (SEM). They concluded that pore size in blended cement paste with original flyash decreased in comparison to Portland cement and it further decreased in classified flyash blend. Also, XRD revealed classified flyash blended cement paste to be more effective in

reduction of $\text{Ca}(\text{OH})_2$ intensity as against original fly ash and finer flyash produced dense structure than coarse flyash.

Sajedi (2012) experimented on mechanical activation of OPC and Slag mortars (OSM) by optimizing grinding of 6 hours to attain specific surface area (SSA) of around $3 \text{ m}^2/\text{g}$ for OPC and of 91/2 hours to attain SSA of around $4.3 \text{ m}^2/\text{g}$ for Slag, keeping the Slag substitution level at 50% for all mortar mixes. Tests on blended mortars were carried out on three groups viz. (i) Both ground OPC and Slag, (ii) Ground Slag and ungrounded OPC, and (iii) Ground OPC and unground Slag. He concluded that the first group showed the highest compressive strength over other groups with value of 80.1 MPa at 28 days. Also, loss in strength was observed at later ages due to phase separation caused by excessive fineness leading to increased water requirement and grounded slag showed better effect on strength enhancement than grounded OPC.

Zhu et al. (2012) investigated the effect of the particle size distribution (PSD) of slag on water requirement, setting time, and compressive strength by making a reference and 17 cement samples containing different blast furnace slag and testing their properties. They reported that Slag was separated into three parts based on particle size and replaced OPC ranging from 10% to 40% with combinations of three PSD. They concluded that bending and compressive strength increased as the Slag particle size decreased and finer slag particles compact the microstructure of the hydration sample with an increase in normal consistency while the setting time is prolonged.

Pacewska et al. (2013) experimented with using binders with high cement replacements of fly-ash up to 80% and studied physical and chemical processes occurring in such systems after the addition of water with its effect on hydration of cement paste. They concluded that the introduction of high amounts of fly ash results in retardation of hydration, especially in its early periods with elongation of setting and reduction of early strength. In high-volume fly ash binders, admixtures such as NaOH, Na_2SO_4 shorten the induction period and intensify hydration.

López et al. (2014) experimented with mechanical and durability properties on cement mortars of portland cement blended with finer and coarser particles of blast furnace slag separately with replacement ranging from 20% to 80%. They concluded that cement blend with coarse slag particles showed more elongation as compared to finer slag blend

mainly attributed to the formation of ettringite which is elongated crystals responsible for the expansive behavior of slag and also bigger granulometry, causing a bigger porosity and bigger incidence of the sulfates. However, expansion decreased with an increasing percentage of slag. Overall, they concluded that compressive strength and durability increased as slag grain size decreased in cement blends.

Sevim et al. (2016) investigated the effect of fly ash particle size distribution on strength of the cement mortars due to its filler effect and chemical reactions caused by an increase in the amount of fly ash. Based on the optimization of fly ash PSD rendering to the modified Andreasen and Andersen model, they experimented on compact cement mortars for compressive and flexural strengths cured in drinking water. They concluded that the best flexural and compressive strengths are observed between 0.3 and 0.4 moduli of distribution ratio.

Debouchaa et al. (2017) experimented with substituting cement with natural pozzolana up to 40% and studied the effect of the heat of hydration by isothermal calorimetry on paste specimens and compressive strength, flexural strength and capillary water absorption of cement mortars by Mercury intrusion porosimetry. They concluded that a small amount of natural pozzolana improved the cement hydration in short term due to heterogeneous nucleation and the release of heat decreased with an increase in natural pozzolana substitution. Also, an increase in the amount of natural pozzolana decreased compressive and flexural strength at all ages up to 90 days and capillary water absorption reduced with an increase in NP supplement mainly attributed to a reduction in capillary pores by the formation of secondary C–S–H gel due to the pozzolanic reaction.

Cherif et al. (2017) studied the influence on the microstructure of cement separately with 25% limestone filler, 30% fly ash, 75% blast furnace slag, 10% silica fumes by measuring chloride diffusion coefficient using migration test, water and mercury porosimetry and chemical composition of pore solution of cementitious materials extracted by pressing cement pastes and analyzed in ionic chromatography. They concluded that OPC had higher water porosity as compared to other SCM blends, Overall, they reported that mineral additions modify the microstructure of cement pastes and pore solution contains significant sulfates and calcium concentration.

Samad et al. (2017) on basis of literature reviewed the environmental impact of cement manufacturing on concrete by using binary cement incorporating Ground Granulated Blast Furnace Slag (GGBS), Pulverized Fly Ash (PFA), and Silica Fumes (SF). They concluded that initial strength gain and heat of hydration are low but strength gets enhanced at later ages with enhanced durability against sulphate and chloride attack in concrete with GGBS replacement. In PFA blended concrete, early strength gains are slow as compared to OPC concrete. Overall, they concluded that a replacement level of up to 50% for GGBS, 20% for PFA, and 10% for Rice Husk Ash (RHA) is recommended.

Shubbar et al. (2017) experimented with the effect of using Ground Granulated Blast Furnace Slag (GGBS) as a partial replacement for Ordinary Portland Cement (OPC) ranging from 0% to 50% to OPC by weight. They concluded that at least 7 days of curing is crucial for the strength development in GGBS mortars and the compressive strength of cement mortar at 7 days of age was higher for GGBS replacement up to 20% and fell below the control mix value for higher GGBS replacement. However, values of strength for all GGBS replacements were more than controlled mixed with pure OPC at 28 days of age.

Shreyas (2017) evaluated the strength and efficiency factors of hardened concrete, by partial replacement to OPC with ground granulated blast furnace slag ranging from 0% to 40%, for M25 grade of concrete at various ages. He concluded that compressive, split tensile and flexural strength tests with curing times of 7 days, 14 days, 21 days, and 28 days showed a characteristic increase in its strength behavior. GGBS can be used as a replacement material in cement and up to 40% replacement will give an excellent result both in strength and quality aspects.

Yu et al. (2018) experimented with developing green structural concrete with 80% cement replaced by local Chinese fly ash to achieve the target characteristic compressive strength of 45 MPa with adjusting the water/binder ratio and/or super-plasticizer dosage. They concluded that UHVFA concrete can be prepared with a low water/binder ratio of 0.3 and OPC replacement with 80% Indian Fly-ash, for the pre-cast concrete industry. Also, the compressive strength of concrete can reach over 20 MPa at 7-day age, and over 30 MPa at 28-day age under equivalent heat curing by using a low water/binder ratio of 0.3 and properly combining raw materials. Overall, they concluded that green concrete with a reduction of around 70% in CO₂ emission, a reduction of more than 60% in

embodied energy, and a reduction of about 35% in material cost can be prepared as compared to commercial M30 grade concrete.

Moghaddam et al. (2019) experimented with the effect of fly ash fineness on the heat of hydration, microstructure, flow and compressive strength of blended cement pastes with different fineness viz. 17.4 μm classified fly ash, 11.3 μm run-of-station fly ash, and 5.7 μm grounded run-of-station fly ash from the same power station source. They concluded that an increase in fly-ash content in blended cement paste decreased cumulative heat of hydration, and also for a given cement replacement level, finer fly-ash released more heat of hydration than coarser particles. Higher consumption of calcium hydroxide at 7 and 28 days was noticed with increasing fineness of fly ash thereby reflecting pozzolanic reactivity and a denser microstructure paste. Also, the presence of fly-ash in blended paste introduced an additional hydration peak in the heat evolution curve mainly attributed to the late activation of fly-ash by calcium hydroxide renewing the C_3A reaction and converting ettringite to monosulfate and finer fly-ash improved fluidity and better compressive strength as compared to coarser fly-ash.

Sakthivel et al. (2019) investigated the evolution of compressive strength over 2 days to 1 year and elastic modulus at 28 days, for concretes with and without SCMs viz. flyash and ground granulated blast-furnace slag (GGBS or slag) and explored the influence of water-binder ratio maintaining between 0.50 to 0.65, binder type and age of exposure. They concluded that higher compressive strength was demonstrated by slag over flyash at all ages and over OPC at later ages. Also, ternary binder excelled in strength over binary binders and static elastic modulus of concrete increased as strength increased in all binary and ternary concrete systems.

Ma et al., (2021) studied three different kinds of ground fly ash from the ball mill and vertical mill on the relation of spherical destruction, fluidity of cement paste, and strength of cement mortar by observing the particle morphology in scanning electron microscopy (SEM) in order to calculate the spherical destruction i.e. ratio of spherical particles broken into irregular particles in the grinding process of fly ash thereby providing a quantification of morphology change due to grinding. They concluded that finer PSD of fly ash is obtained by vertical mill while higher spherical destruction of more than 80% is seen in ball mill grinding. The fluidity of cement paste improved in spherical particles against the ground fly ash-cement system. The strength of mortar was enhanced with

super-fine particles of fly ash grounded in the vertical mill while the pozzolanic reaction accelerated due to destroy of spherical particles by the ball mill.

Shubbar et al. (2021) evaluated the performance of high-volume fraction of GGBS in mortars through laboratory tests including initial and final setting times, compressive strength, and ultrasonic pulse velocity test by experimenting on mechanical performance at early and long-term ages with replacement of OPC by GGBS ranging from 30% to 70%. They concluded that Initial Setting Time (IST) and Final Setting Time (FST) reduced with an increase in GGBS replacement in comparison to OPC controlled mix attributed to the fineness of composed materials, compressive strength (CS) of all GGBS mixes remained below control mix up to 21 days and remained similar to control mix for the period between 28 to 90days. 30% GGBS replacement outperformed in CS after 21 to 550 curing days and Ultrasonic Pulse Velocity (UPV) reduced with an increase in GGBS replacement.

Hossain et al. (2021) studied greenhouse gases (GHG) emissions during the production of concrete using volcanic ash in comparison to fly ash and ground granulated blast furnace slag by lifecycle assessment (LCA) technique and concluded that GHG emissions by volcanic ash were more than 80% lower as compared to other SCMs. For the same grade of concrete, volcanic ash can reduce up to 25% of total GHG emissions as against Ordinary Portland cement and 19% in comparison to SCM concretes. The study also revealed that by substituting 10–50% industrial SCMs with volcanic ash, 11–37% more GHG emissions can be reduced from the concrete industry in Hong and 26% additional GHG emissions can be reduced by replacing 30% fly-ash and slag with volcanic ash from the concrete industry.

2.3 Section-3: Ternary Blended Cement

Berodier et al. (2015) studied the effect of SCMs on ternary cement paste comprising of portland cement, quartz and slag, flyash as SCMs by experimenting hydration by isothermal calorimetry and x-ray diffraction, porosity by mercury intrusion porosimetry. They concluded that slag modify porosity efficiently by filling space between hydrated cement particles upon reaction of clinker, slag and fly ash. Also, hydration reaction is limited at later ages due to higher space availability with increased water/solids ratio leading to lower reaction degree of SCMs at higher substitution levels in blended cements.

Nguyen et al. (2015) experimented on ternary binder comprising of ground granulated blast furnace slag (GGBFS), Class F fly ash (FFA), and circulating fluidized bed combustion fly ash (CFA) and studied the workability, Compressive strength, Shrinkage/expansion and microstructure to explore physical-chemical characteristics of paste and mortar of resultant binder mixes. They concluded that water to binder ratio (W/B), curing regime, and FFA addition significantly affected the engineering performances, shrinkage/expansion of SFC pastes and mortars with high workability in comparison to Ordinary Portland cement (OPC). Also, ettringite (Aft) and C-S-H/C-A-S-H were the main hydrated products of solid SFC cement with transformation of ettringite to monosulfates in longer hydration duration.

Wawrzeczyk et al. (2016) studied the modification of the cement paste structure and properties of concrete with respect to its freeze-thaw resistance on the composition of binder made with Portland cement by replacement with 30% fly-ash and 60% Slag with water to binder ratio of 0.45. The first stage was to study the effect of binder composition on cement paste microstructure using mercury porosimetry (MP) and scanning electron microscopy (SEM) and the Second stage was to determine physical characteristics namely; absorption, permeability, compressive strength, and freeze-thaw resistance of concrete. They concluded that an increase in the amount of mineral addition increased pore area and paste porosity, an increase in slag content decreased permeability while in concrete, fly ash permeability is quite high. Freeze-thaw resistance of concrete decreased with an increase in fly-ash content and mineral additions do not always provide sufficient impermeability and/or frost resistance to the structure of concrete. In any case, the concrete mix should be air entrained when mineral additions are to be used.

Laucha et al. (2016) carried out their research using OPC between 35% to 75%, Slag and Fly-ash between 10% to 30%, and Limestone filler between 5% to 45% on composite mix concrete. They concluded that the compressive strength of composite cement concrete with OPC-Slag-Limestone showed higher values with less porosity than OPC-Flyash-Limestone concrete, mainly attributed to the pozzolanic and hydraulic properties of slag. Overall, they concluded that cement up to 20% slag or Fly-ash and 30% limestone filler performed well against chloride diffusion and sulfate attack, however, these supplements showed poor performance in carbonation, freeze-thaw and compressive strength for content more than 25%.

Shubbar et al. (2017) experimented on the substitution of OPC with GGBS and Modified Fly Ash (MFA) in equal proportion with 40%, 60%, and 80% replacement and tested mechanical and durability performance of cement mortars, namely; Normal consistency, Initial and Final setting times, Compressive Strength and Electrical Resistivity of all ternary mixtures in comparison to the control binder. They concluded that normal consistency increased with a higher replacement while Initial Setting Time and Final Setting Time decreased as compared to the controlled mix. The compressive strength of all substitutions remained below the controlled mix value for all curing ages i.e. from 3 to 28 days and all ternary cement mortars showed better surface electrical resistivity performance than the controlled mix for all curing ages.

Shubbar et al. (2017) conducted experiment on replacing OPC partially with Ground Granulated Blast Furnace Slag (GGBFS) and High Calcium Flyash (HCFA) to produce low carbon cementitious material with comparable compressive strength to that of OPC. Initially, OPC was substituted with GGBS between 0% to 50% by dry mass to derive optimum binary blended cementitious material (BBCM) and subsequently this BBCM mix was mixed with HCFA between 0% to 50% to obtain ternary blended cementitious material (TBCM). They concluded that 75% OPC to 25% GGBS resulted as optimum BBCM with compressive strength of 32.2 MPa at 28 days and 25% HCFA substitution showed as ideal substitution in BBCM to derive optimum TBCM thereby reducing OPC by 56% which contribute to decrease construction materials cost with enhanced compressive strength and CO₂ emissions reduction into the atmosphere.

Varun et al. (2018) studied the fresh properties by conducting slump tests, compaction factor tests, and Vee-bee consistometer tests and hardened properties by conducting compressive and splitting tensile strength tests, on M-30 grade control concrete made of pure OPC and concrete made with partial replacement of fly-ash from 10% to 50% and GGBS from 10% to 50%. They concluded that based on the workability test carried on fresh concrete, an increase in fly-ash and decrease in GGBS content showed an increase in workability and low replacement of FA plus GGBFS yields better results of compressive strength, workability than higher ones and also in comparison to pure OPC.

Shubbar et al. (2019) investigated the effect of replacing the cement content with a high volume of GGBS and PFA on the mechanical performance of cement mortar by replacing

OPC with GGBS and Pulverised Fuel Ash (PFA) in equal proportion i.e. 40%, 60%, and 80% replacement. They concluded that compressive strength enhanced with extended age of curing and only 80% replacement showed higher value than the controlled mix at 28 days curing age.

Azmat et al. (2019) investigated the compressive strength properties of concrete with Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash in concrete by partial replacement of cement ranging from 0% to 30% for different curing days with cement to water ratio of 0.47 for all mixes and carried out the slump, compaction factor, Vee-bee and compressive strength tests on the specimen. They concluded that workability showed a rising trend corresponding to a rise in supplements up to an optimum limit of 15% and further decreased while 30% replacement of supplement obtained the highest compressive strength.

Rosa et al. (July 2020) explored on use of Clinker: Slag: Fly-ash in the proportion of Clinker varying from 20% to 50%, Fly-ash 25% and 40% and Slag 25% and 40% with two fines and carried out compressive strength test on cement mortars. They reported that synergistic action between the supplements was not noticed at an early age due to retarded pozzolanic reaction, however, GGBS outperformed FA in the later ages and concluded that synergistic action improved in long-term compressive strength of composite mortar due to denser microstructure.

Ozer et al. (2021) studied the effects of Fly-ash and GBFS fineness determined by particle size distribution (PSD) on the hydration rate and compactness of cementitious materials by working on particle size distribution (PSD) of composite cement using FA and GGBFS with no PSD and two other PSD ranges of 0-25 and 0-63 μ m using vacuum sieve for both supplements with replacement of OPC up to 20%. They summarized that finer FA/GGBS PSD showed a lower volume of permeable voids with the lowest water absorption percentage as against coarser FA/GGBS PSD. Also, FA and GGBFS with 0-25 μ m PSD excelled in mechanical and physical properties over 0-63 μ m PSD. Overall, they concluded that with suitable PSD, the replacement percentage of supplements can be enhanced over OPC usage.

Ibanez-Gosalvez et al. (2021) studied the effects on the microstructure, durability, and mechanical performance of mortars in the long term produced by ternary binders of blast

furnace slag, fly ash, and limestone compared to mortars without additions and mortars made with binary binders. The experiment revealed that there was a progressive refinement of microstructure in mortars with the rise in time of the relative volume of finer pores tested by mercury intrusion porosimetry and the increasing tendency of electrical resistivity. Also, there was a reduction of the chloride diffusion coefficient and an enhancement of the mechanical performance of the mortars. Overall, they concluded that the incorporation of slag and fly ash in the binary and ternary binders produce a higher microstructure development and better durability and mechanical properties due to the effects of the hydraulic activity of slag and pozzolanic activity of fly ash and in ternary binders, both slag and fly ash as additions outperformed compared to those with limestone.

Agrawal et al. (2021) investigated the effect on Ordinary Portland Cement (OPC) by replacing with Flyash (FA) at 10%, 20%, 30% levels and Ultra-fine Flyash (UFFA) at 10%, 15% and 20% levels to obtain nine different ternary mixes. They studied the cost analysis, workability and compressive strength and concluded that ultra-fine flyash particle size shows improved early strength as against normal flyash. Also, use of FA and UFFA at optimized substitution can reduce cement consumption by 45% and deal with disposal issues of industrial waste.

Mohammed et al. (2022) experimented on self-compacting concrete (SCC) containing fly ash (FA), ground granulated blast furnace slag (GGBFS) and both (FA + S) with lignosulphonates (LS) as chemical admixtures replaced by weight between 10% to 60% of Portland Cement (PC) and conducted tests such as slump flow diameter, T50 time, V-funnel time, and L-box height ratio. They concluded that fresh concrete density decreased as flyash content increased and vice-versa with slag. Also, T50 time and V-funnel time results showed decreasing trend as FA and S contents increased. Compressive strength continuously decreased with increase of flyash while it increased in slag upto 40% substitution and in both upto 30% substitution. Overall, slag showed better results in comparison to flyash as mineral admixture.

2.4 Section-4: Durability

Lukowskia et al. (2015) dealt with corrosion resistance in the environment corresponding to the aggressive factors acting on concrete in agricultural areas containing acids and sulphates of cement mortars with different proportions of ground granulated blast-furnace

slag (GGBFS) ranging from 0% to 70%. Based on the test results conducted on specimens stored in three environments viz. tap water, magnesium sulfate (MgSO_4) solution with 10% (by mass) in water and artificial silage acid comprising of Lactic acid, Acetic acid and formaldehyde, they concluded that losses in their strength, mass, and linear changes are less as compared to only Portland cement, after storing in sulfate and silage acid environment mainly attributed to more compacted, tightness and diminishing porosity of the hardened cement paste microstructure, caused by GGBS presence.

Kuterasińska-Warwas et al. (2017) aimed at determining the suitability of new cements for neutralizing harmful substances in the obtained matrices and studied the leaching of harmful substances viz. Lead (Pb), Copper (Cu), (Zinc) Zn, and Chromium (Cr) and their degree of immobilization in cement matrices comprising a large proportion of cement clinker replaced by other non-clinker components - industrial wastes, ie. siliceous fly ash and granulated blast furnace slag. They concluded that cements with high addition of non-clinker components are suitable for stabilization of toxic substances and the obtained cement matrices retain a high degree of immobilization of heavy metals at the level of 99%.

Saraswathy et al. (2017) experimented tests such as compressive strength, effective porosity, coefficient of water absorption, short-term accelerated impressed voltage, rapid chloride permeability test (RCPT) on M30 and M40 concrete cured for 28, 90 days derived from OPC, PPC and PSC cements. They also performed microcell and electrochemical evaluation on rebar corrosion behaviour embedded in concrete and concluded that PSC concrete outperformed over PPC and OPC with minimum current flow, low chlorides, less porosity and low water absorption, chloride diffusion, corrosion thereby delaying the time taken for initiation of crack in concrete.

Anwar et al (2020) experimented on the resistance of concrete containing Ordinary Portland cement and using fly-ash (FA) and silica fume (SF) as by-products materials, to the combined influence of carbonation and chloride ingress. Specimens were prepared by replacing OPC with fly ash between a range of 15% to 25% and Silica Fume between 5% to 10% and with a ratio of water/cementitious blend materials of 0.40 with the same degree of workability. They concluded that a combination of FA and SF showed better results with SF improving concrete performance at early age and FA continuously purifying the properties of fresh and hardened concrete as it matures. Also, using FA or

SF in a binary system or ternary with OPC leads to very small values of S chloride from depth 20~30 mm thereby stating that cementitious blends of concrete require less cover depth to protect the reinforcement. Overall, they concluded that cementitious blend mixes showed a lower percentage of soluble/total chloride than the control mix for three stages of different environments exposures namely; artificial seawater for 5 months, 20°C + 60%RH + 5% CO₂ for 18 weeks, and 20°C + 60% RH for 18 weeks.

Hren et al. (2021) examined and evaluated the corrosion properties by monitoring the propagation phase, determining the microstructural properties of cements, and assessing the final corrosion damage in carbonated and non-carbonated states with chlorides introduced through cyclic ponding on multiple blended cements. All specimen at 100% relative humidity and 20 ± 2°C temperature was cured for 28 days. After curing, 50% of specimens were subjected to accelerated carbonation for 11 weeks with a 3.1% CO₂ concentration, 57% relative humidity and at 25°C, while the balance 50% were left to air dry at room temperature during the same 11-week period at an air temperature of 22 ± 2 °C and relative humidity of 50 ± 5%. After acceleration, all specimens were introduced to chloride ions through cyclic ponding with a 3.5% NaCl solution. Upon examination, they concluded that the steel in the blended cements showed relatively high corrosion activity in the initial stage but later decreased as compared to OPC due to the beneficial changes to the pore structure, and blended cements exhibited greater susceptibility to carbonation with carbonated mortars revealing shallower damage over a larger surface area.

Aiken et al. (2021) investigated porosity by mercury intrusion porosimetry, compressive strength on blended mortars, leaching behaviour and microstructure under hydrochloric acid attack on geopolymer binders containing 100% flyash and various blends of flyash-blast furnace slag blends without incorporating Portland cement. They concluded that flyash-slag blends showed better acid resistance than 100% flyash and traditional Portland cement mixes, mainly attributed to strength loss in 100% flyash mixes due to acid ingress in high porosity microstructure and faster surface deterioration in Portland cement mixes. Also, flyash-slag blends showed improved resistant to hydrochloric acid attack with increased in slag content, while increased fly ash content demonstrated more resistant to sulfuric acid attack.

Agrawal et al. (2021) experimented on replacing OPC partially with SCMs viz. flyash (FA) between 20% to 40% to derive binary cement concrete and with ultra-fine slag

(UFS) between 5% to 20% to derive twelve ternary mix concrete. They explored the workability, strength, chloride migration, water permeability with cost factor for all composite mixes and concluded that properties such as workability, compressive strength, flexural-split tensile strength, chloride migration resistance and water permeability improved in FA-UFS-OPC ternary binder over FA binary binder. Also, optimized mix was derived using Taguchi-grey relational analysis (TGRA) technique that suggested 55% OPC, 30% FA, and 15% UFS to be the best ternary combination.

Singh et al. (2022) reviewed the carbonation resistance of blended mortar comprising silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBFS), and coal bottom ash (CBA) and concluded that Silica Fume blended cement mortars showed the highest resistance to carbonation followed by FA, GGBFS, and CBA with a decrease in carbonation depth up-to 10%. Also, the Compressive Strength of blended cement concrete was highest in FA by an improvement of 7% – 12% at the age of 28 days due to the pozzolanic and hydraulic activity followed by SF and CBA.

Chakurkar et al. (2023) experimented on optimization of particle size distribution of OPC amalgamated with Stimulator and concluded that a specific blend of 55% OPC to 45% Stimulator showed better physio-mechanical properties considering overall cost-factor including milling of OPC.

2.5 Research Gap Identified

A comprehensive review of the available literature indicates that existing studies have predominantly focused on the performance evaluation of Ordinary Portland Cement (OPC)-based systems. In particular, the work reported by Shraddha et al. is limited to OPC cement and does not address the behaviour of blended cement systems incorporating multiple supplementary cementitious materials. Furthermore, the literature reveals a lack of systematic investigations on binary and ternary blended cements, especially with respect to their mechanical, durability, and microstructural performance characteristics. Consequently, a significant knowledge gap exists regarding the synergistic effects of two-component and three-component cement blends. The present study is therefore intended to bridge this gap by evaluating the performance of blended cement systems and establishing their suitability as sustainable alternatives to conventional OPC-based materials.

The research carried out by Chakurkar et al. (2023) was limited only to OPC and was not extended to binary/ternary blended cements with SCMs. This research gap is now taken up as experimental study extending to binary/ternary blends with fly ash and GGBFS as SCMs with the objectives listed below. The materials and methodology adopted in the present work are presented in Chapter 3.

2.6 Objectives of the Study

A systematic study has been proposed with the following objectives:

- a) Study and review of results of Ordinary Portland Cement (OPC) with Stimulator (S).
- b) Study of Physical and Chemical parameters of Binary Blend with S45 and Ground Granulated Blast Furnace Slag (GGBFS) as SCM.
- c) Study of Physical and Chemical parameters of Binary Blend with S45 and Fly-ash (FA) as SCM.
- d) Study of Physical and Chemical parameters of Ternary Blend with S45 and Slag, Fly-ash as SCMs.
- e) Comparison of optimized Binary and Ternary blends of S45, Slag, and Fly-ash with present commercial cements viz. Portland Slag Cement (PSC), Portland Pozzolana Cement (PPC) and Composite Cement (CC).
- f) Study of Durability aspects of the optimized Binary and Ternary Cement Blends.
- g) Environmental Sustainability Analysis and Conclusion of the parameters studied.

In order to achieve the objectives cited above, detailed analysis of the materials and methodology to carry out the experimentations corresponding to the procedures laid down as per relevant Indian standards has been presented in Chapter 3.

Chapter 3

Materials and Methodology

Studies on Binary and Ternary Blended Cements incorporating S45 with Slag and Fly-ash as supplementary cementitious materials (SCMs) are carried out at JK Cement Works, Muddapur, Karnataka based on the specifications and procedures postulated in the relevant BIS codes. Figure 3.1 shows scene of JKCL Plant while Figure 3.2 indicates accreditation of JKCL plant.



Figure 3.1: JKCL Plant at Muddapur, Karnataka



Figure 3.2: JKCL Plant at Muddapur, Karnataka accredited with GreenCo Platinum Rating

The materials used for the study work, are as follows:

3.1 Materials

3.1.1 Ordinary Portland Cement (OPC)

JK OPC 43 grade cement (Week No: 48/2021) is used for all analyses in the study, conforming to BIS 269 (2020). The typical test parameters certificate of JK OPC 43 grade cement (Week No: 48/2021) is presented at Figure 3.3 below.

TEST REPORT				
Customer Name & Address	Packing Plant – JKM	Sample ID	JKCS/OPC-21/48	
Test Report No. (ULR)	TC844121000000191F	Sample Recived Date	3-Dec-21	
Date of Performance of Testing	3-Dec-21 To 9-Dec-21	Completion Date	31-Dec-21	
Location of Test Performed	Chemical Lab & Mechanical Lab	Date of Issue	1-Jan-22	
Customer Identification	W. No.48/2021	CM/L Number	3401033	
CHEMICAL REQUIREMENTS				
SAMPLE TEST TYPE	REQUIRMENT IS 269:2015	IS Method	Test Results	UOM
A. Ratio of % of Lime to % of Silica, Alumina & Iron Oxide (CaO-0.7*SO3)/(2.8*SiO2+1.2*Al2O3+0.65*Fe2O3)	0.66 to 1.02	IS:4032:1985 (RA 2019)	0.86	--
B. Ratio of percentage of alumina to that of iron oxide	0.66 (Min)	IS:4032:1985 (RA 2019)	1.44	--
C. Magnesia	6.0 (Max)	IS:4032:1985 (RA 2019)	4.41	[% by mass]
D. Total Sulphur content as SO3	3.5 (Max)	IS:4032:1985 (RA 2019)	2.57	[% by mass]
E. Insoluble Residue	5.0 (Max)	IS:4032:1985 (RA 2019)	1.27	[% by mass]
F. Loss on Ignition	5.0 (Max)	IS:4032:1985 (RA 2019)	1.94	[% by mass]
G. Chloride Content	0.10 (Max)	IS:4032:1985 (RA 2019)	0.04	[% by mass]
H. Total Alkali Content as Na2O	0.60(Max)	NCCBM: MS-13-2010	0.45	[% by mass]
PHYSICAL REQUIREMENTS				
1. Fineness	225 (Min)	IS:4031 [PART-2] (RA 2018)	297	[M2/Kg]
2.Soundness:				
By Autoclave Method	0.8 (Max)	IS:4031 [PART-3] (RA 2019)	0.12	[%]
By Le Chatelier Method	10.0 (Max)	IS:4031 [PART-3] (RA 2019)	1.0	[mm]
3.Setting Time				
Initial	30 (Min)	IS:4031 [PART-5] (RA 2019)	160	[Minute]
Final	600 (Max)	IS:4031 [PART-5] (RA 2019)	240	[Minute]
4. Compressive Strength (MPa)				
72 ± 1 hr.(3 days)	23 (Min)	IS:4031 [PART-6] (RA 2019)	33.0	[Mpa]
168 ± 2 hr.(7 days)	33 (Min)	IS:4031 [PART-6] (RA 2019)	46.0	[Mpa]
672 ± 4 hr.(28 days)	43 (Min) 58 (Max)	IS:4031 [PART-6] (RA 2019)	52.0	[Mpa]
Environmental Condition: Temperature: - 27±2 0C: Humidity: - Not less than 65%				

Environmental Condition: Temperature: - 27±2 0C; Humidity: - Not less than 65%

Figure 3.3: OPC Test Report

3.1.2 Stimulator (S)

Stimulator is produced by grinding JK OPC 43 grade cement (W-15/04/2022) in jet mill (Figure 1.1) for 30 minutes to attain desired Blaine value having a specific surface area of 539 m²/kg.

3.1.3 S45 (BM)

The optimized fractioned combination of commercial OPC with Stimulator in the ratio of 55% to 45%, respectively is nomenclature as S45 and is treated as the Base Material (BM) viz. prime cement for the present study.

3.1.4 Ground Granulated Blast Furnace Slag (GGBFS)

Ground granulated blast furnace slag incorporated as one of the SCM for the present study is of Jindal Steel Works (JSW) make.

3.1.5 Fly-ash (FA)

Fly-ash used as the other SCM is from National Thermal Power Corporation (NTPC) make.

3.1.6 Standard Sand

Standard Sand conforming to BIS-650 (2018) is used for the present work to cast mortar cubes for relevant test analyses.

3.1.7 Water

Potable water conforming to BIS 456 (2021) is used for various analytical tests.

The physical properties and chemical compositions of the raw materials incorporated for the study are enlisted in Table 3.1 and Table 3.2, respectively.

Table 3.1: Physical Properties of OPC, S, S45, FA and GGBFS

Parameter	Unit	Material				
		OPC	S	S45	FA	GGBFS
Sp. Gravity	-	3.10	3.10	3.10	2.20	2.90
Fineness	(m ² /kg)	297	539	430	350	440

Table 3.2: Chemical Composition of OPC, S, S45, FA and GGBFS

Material	Chemical Composition (%)							
	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O
OPC	57.53	20.58	6.08	3.34	4.23	2.67	1.40	0.09
S	59.17	20.76	5.70	3.82	5.61	2.34	0.90	0.18
S45	55.64	21.13	6.33	4.22	4.09	2.97	1.43	0.19
FA	3.95	59.10	20.33	5.22	0.59	0.08	-	-
GGBFS	37.63	34.81	17.92	0.66	7.80	0.20	-	-

3.2 Methodology

Cement in the commercial form is produced as Ordinary Portland Cement (OPC), binary blended with OPC and one supplementary cementitious material (SCM) viz; slag as

Portland Slag Cement, fly-ash as Portland Pozzolana Cement, ternary blended with OPC, Slag and Fly-ash as Composite Cement and quaternary blend with OPC and any three SCMs like Slag, Fly-ash, Silica Fume, Metakaolin.

Chakurkar et al. (2023) experimented with optimization of locally available Ordinary Portland Cement (OPC) incorporating Stimulator (S) obtained from grinding OPC to a desired PSD with a Blaine value of $539 \text{ m}^2/\text{kg}$ and concluded that the proportion of OPC to S in the ratio of 55%: 45% is the optimized mix and is considered as S45 in the present study.

Referring to the Objectives, the methodology adopted for research execution is shown in Figure 3.4. The experimental procedures are narrated in Chapter 4.

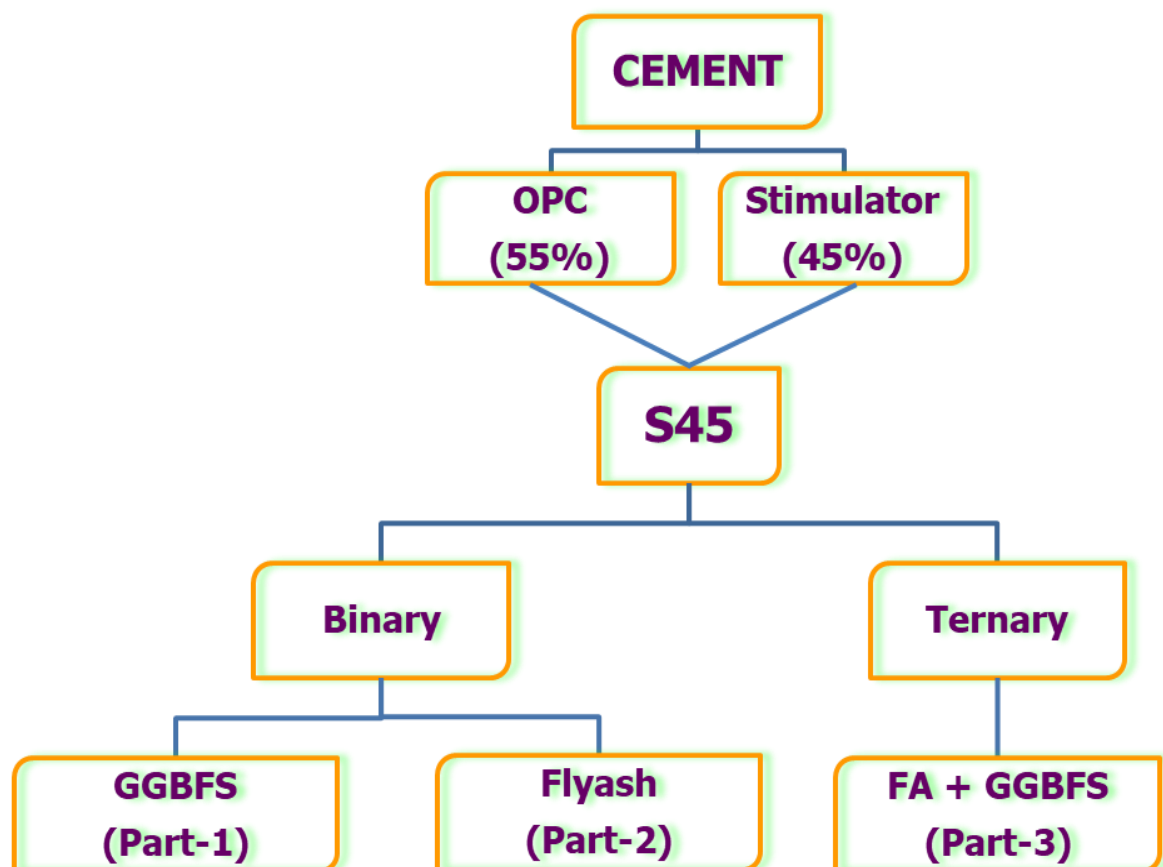


Figure 3.4: Methodology of Research Execution

Chapter 4

Experimental Procedures

The research work is conducted in three parts comprising of binary blend of S45 with granulated slag as Study-1, with fly-ash as Study-2 and ternary blend of S45, GGBFS and fly-ash as Study-3. Specimen of all cement blends are derived in three forms, namely powder, mortar and concrete form to ascertain the chemical, physical and durable properties of the cement mixes.

The preparation of specimens for requisite tests is elaborated below:

4.1 Study-1: Binary Blend with S45 and Ground Granulated Blast Furnace Slag (GGBFS) as SCM

As accentuated in BIS 455 (2020) and supported by the literature surveys, GGBFS shall be supplemented in Slag Blended Cement in the range of 25% to 70%.

Considering the above facts in the present work, GGBFS substitution in S45 is taken at an incremental interval of 10%, starting from 25% to the highest replacement of 75%. Table 4.1 shows the calculations for fractioning of S45 and GGBFS percentages in the blended cement and is graphically sketched in Figure 4.1.

Table 4.1: Calculation for proportioning of S45, GGBFS

Blend	Proportion (%)	
	S45	GGBFS
G25	75	25
G35	65	35
G45	55	45
G55	45	55
G65	35	65
G75	25	75

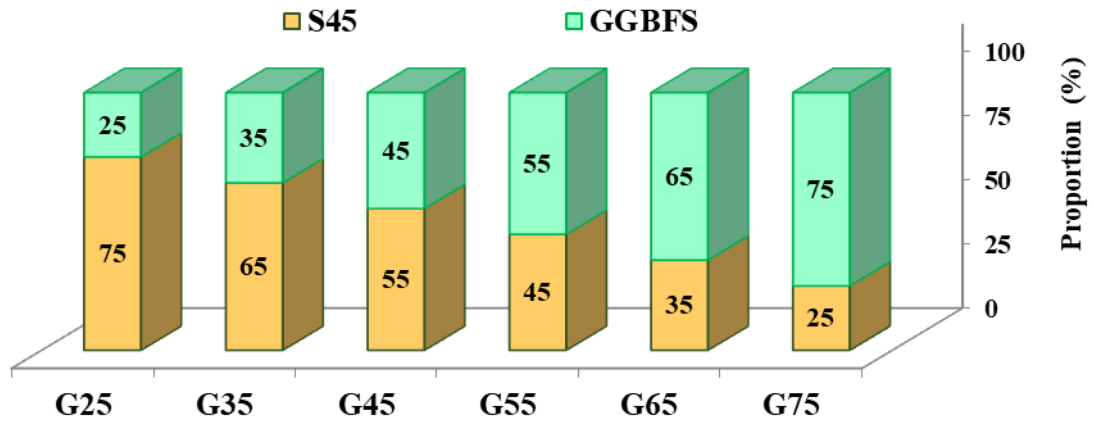


Figure 4.1: S45+GGBFS Blends

4.2 Study-2: Binary Blend with S45 and Fly-ash (FA) as SCM

As emphasized in BIS 1489-1 (2020) and supported by the literature surveys, Fly-ash shall be supplemented in Fly-ash Blended Cement in the range of 15% to 35%.

Considering the above facts in the present work, Fly-ash substitution in S45 is taken at an incremental interval of 10% starting from 15% to the highest replacement of 55%. Accordingly, S45 comprising of OPC and Stimulator (S) are proportionately calculated for each fly-ash substitution level. Table 4.2 indicate the calculations for fractioning of OPC, S, fly-ash percentages in the blended cement and graphically sketched at Figure 4.2.

Table 4.2: Calculation for proportioning of S45, FA

Blend	Proportion (%)	
	S45	FA
F15	85	15
F25	75	25
F35	65	35
F45	55	45
F55	45	55

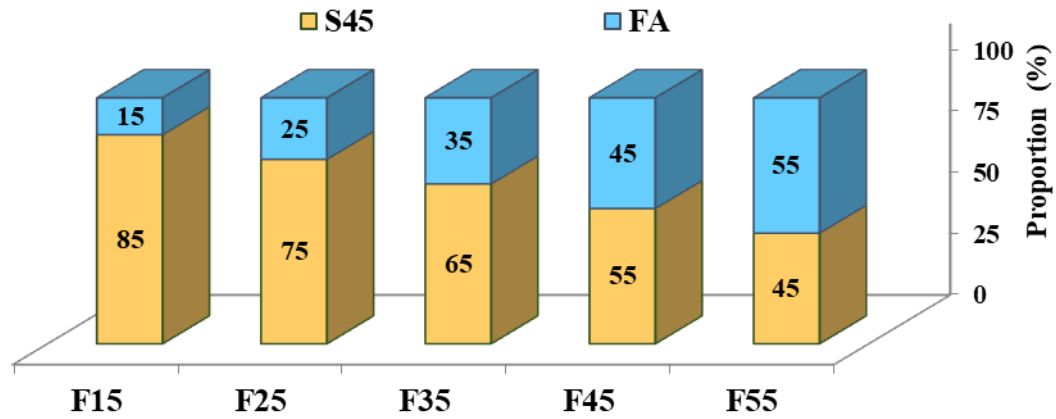


Figure 4.2: S45+FA Blends

4.3 Study-3: Ternary Blend with S45 and Slag, Fly-ash as SCMs

As highlighted in BIS 16415 (2020) and supported by the literature surveys, the raw materials in Composite Cement shall range between 35% to 65% with OPC and Fly-ash, GGBFS supplements between 15% to 35% and 20% to 50%, respectively.

Considering the above facts in the present work, Fly-ash replacement is taken at an incremental interval of 10% from 15% to 35% and GGBFS from 25% to 55%, respectively. Accordingly, S45 comprising of OPC and Stimulator (S) are proportionately calculated for each combined SCMs substitution level. Table 4.3 show the calculations for fractioning of OPC, S, FA, GGBFS percentages in the ternary blended cement and graphically sketched at Figure 4.3.

Table 4.3: Calculation for proportioning of S45, FA, GGBFS

Blend	Proportion (%)		
	S45	FA	GGBFS
F15G25	60	15	25
F15G35	50	15	35
F15G45	40	15	45
F15G55	30	15	55
F25G25	50	25	25
F25G35	40	25	35
F25G45	30	25	45
F35G25	40	35	25
F35G35	30	35	35
F45G25	30	45	25

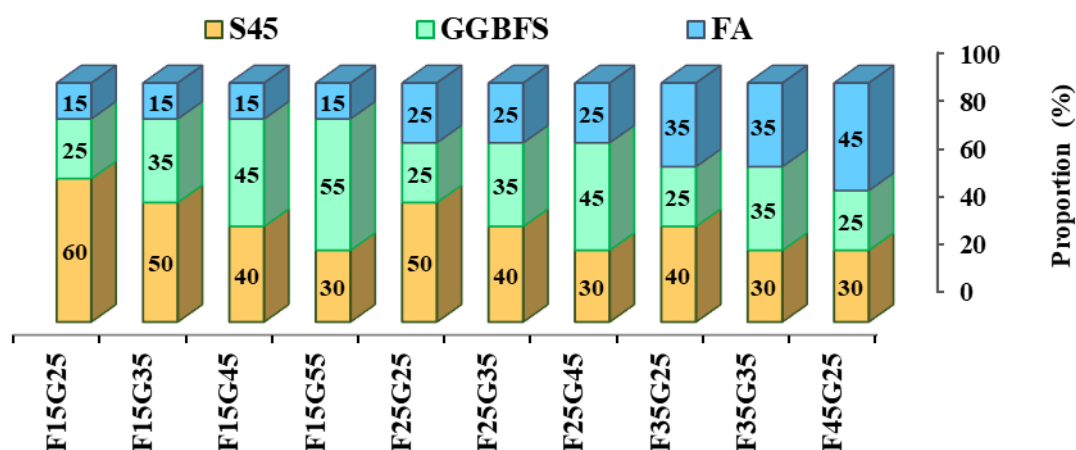


Figure 4.3: S45+FA+GGBFS Blends

4.4 Preparation of Specimen samples

Specimen samples for PART-1, 2, 3 enlisted at article 4.1, 4.2, 4.3 were prepared by mixing S45, slag and fly ash in proportions listed in Table 4.1, 4.2, 4.3 initially hand-mixed and further in blender for 10 minutes and represented the samples for the study.

4.5 Experiments Conducted

The specimen samples were tested for the below listed physio-mechanical properties and with the test results obtained, further interpretations and conclusions were derived.

4.5.1 X-ray Fluorescence

X-ray Fluorescence Spectrometric analysis in adherence to BIS 12803 were conducted on OPC, S, and FA for their chemical compositions. Binder specimen was prepared in form of tablets after drying the samples by using a pressed pellet or fused bead method. Chemical concentration of compounds present in the binder series were determined by emission intensities of secondary fluorescent rays passing through the powder upon exposure to primary X-rays.

4.5.2 Particle Size Distribution by LASER Diffraction

Confirming to ISO 13320 and ASTM E-3340, LASER diffraction method determined the Particle Size Distribution (PSD) of fly-ash binders. Using Malvern Mastersizer 3000, S45, slag, fly-ash and composite binder series were subjected to laser beam in wet medium. Inverse proportion of the intensity of angular dispersion through powder particles measured the different sizes.

4.5.3 Soundness by Autoclave Method

Soundness test by Autoclave method was conducted on S45, slag, fly-ash and composite binders as stipulated in BIS 4031 (Part-3) (2019). Each binder sample weighing 500gms

was mixed with adequate distilled water (derived by normal consistency) to form uniform cement paste and later-on filled in mold of internal size 282mm x 25mm x 25mm with forefinger compaction in two layers. Molded specimen was rested for 24 hours in moist room and afterwards exposed to steam boiling under 2.10 MPa pressure in autoclave machine for 3 hours. Upon cooling for one hour with pressure falling to 0.10 MPa inside the machine, the specimen was removed from the mold and further cooled for 15 minutes in water to bring down the specimen to ambient temperature i.e. $27\pm 2^{\circ}\text{C}$. Subsequently, its length was measured after surface drying and the difference in length viz. pre and post autoclaving was recorded as expansion of that binder sample.

4.5.4 Standard Consistency

All binder powders were tested for Standard Consistency (SC) conforming to BIS 4031(Part-4) (2019). Uniform paste of each binder sample was attained by adding water in accordance to BIS 456 (2021) and hand-mixing continuously for gauging time between 3 to 5 minutes. Consistency was then tested by Vicat apparatus by placing the paste in mold rested on non-porous plate to measure the penetration depth. Vicat plunger's penetrated depth between 5mm to 7mm from the bottom of mold was measured as the given value of SC for that test. Trials were repeated for each sample with varying water percentages and average of three passed tests was recorded as SC value for the said binder sample.

4.5.5 Initial and Final Setting Times

BIS 4031 (Part-5) (2019) stipulates the procedural guidance to determine Setting Times viz. initial and final and accordingly, sets of all binders were derived. Initial Setting Time (IST) was recorded as the time gap between the moment when water was added to the binder powder and when the Vicat's needle failed to penetrate the test block beyond 5.0 ± 0.5 mm from bottom of the mold. Similarly, Final Setting Time (FST) was noted as the time spell between the impression made by Vicat's needle on test block surface while the annular attachment failed to do so.

4.5.6 Heat of Hydration

S45 and all binders were subjected to Heat of hydration (HoH) test for un-hydrated and hydrated conditions. Uniform paste was prepared by hand-mixing 60gms of specimen binder with 24ml distilled water for 4 minutes and later filled in paraffin sealed glass/plastic vials. These vials were rested in vertical position at $27\pm 2^{\circ}\text{C}$ ambient temperature. Subsequently, 7gms of specimen paste was subjected to $900-950^{\circ}\text{C}$ heat for 5

minutes and cooled in desiccator containing anhydrous calcium chloride for 21/2 to 5 hours. Using calorimeter, temperature was recorded and corresponding heat of hydration was worked out using formulae stipulated in BIS 4031 (Part-9) (2019).

4.5.7 Compressive Strength

In accordance to procedure guide-lined in BIS 4031 (Part-6) (2019), three mortar cubes were casted using 70.6mm x 70.6mm x 70.6mm mold for every fly-ash binder series in laboratory at a controlled environment of 25-27°C temperature and 65-70% humidity. 200gms of binder and Standard sand conforming to BIS 650 (2018) with three fines viz. fine, medium, and coarse (200 gms each) were mixed with potable water conforming to BIS 456 (2021) derived by standard consistency (SC) in percentage by weight of the blended binder. This mortar paste was then filled in the mold and compacted using vibratory machine conforming to BIS: 10080 (2018) to derive three mortar cubes for every age which were subsequently tested for desired curing ages of 1, 3, 7, 14, 28, 56, 90, 180, 270 and 365 days on Automatic Compression Testing Machine (ACTM) for their compressive strength.

4.6 Various Experimental Activities

Activities carried out at JK Cement Works, Muddapur, Karnataka, are depicted in Figures 4.4 to 4.9, below:

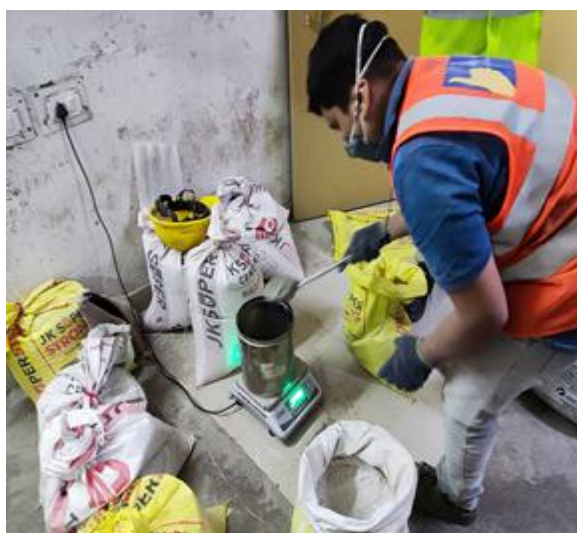


Figure 4.4: Weighing of each element of Blends



Figure 4.5: Spreading of elements in a Large Tray



Figure 4.6: Thorough Hand Mixing of Blends



Figure 4.7: Weighing of Standard Sand



Figure 4.8: Tests carried by Vicat's Apparatus



Figure 4.9: Blended Cement Mortar cubes

Based on the methodology followed and experimental procedures carried out, the results are presented in the Chapter 5 in part 1, 2, 3 respectively in the sequence followed in the Chapter.

Chapter 5

Results and Discussions

This Chapter presents the results obtained based on the experimentation carried out on the proposed methodology. The results are classified based on 6 categories, viz., Part-1, 2, 3, 4, 5, and 6, respectively on S45 and GGBFS blend, S45 and Fly-ash blend, and, S45, Fly-ash, and GGBFS Composite blend. Comparison of optimized Binary and Ternary blends of S45, Slag and Fly-ash with present commercial cements viz. Portland Slag Cement (PSC), Portland Pozzolana Cement (PPC) and Composite Cement (CC) is also presented. Durability and Environmental Sustainability studies on Optimized Slag and Fly-ash Binary Blend and Composite Cement with Fly-ash and Slag are also presented in the later part of the Chapter.

5.1 PART-1: S45 and GGBFS blend

All the tests conducted on specimens of S45+GGBFS mixes are elaborated as below:

5.1.1 Physical and Chemical Composition

The physical and chemical test results for the combinations of the blends referred to in Table 4.1 are tabulated in Table 5.1.1 as below:

Table 5.1.1: Physical and Chemical Composition of GGBFS Blends

		S45		GGBFS				
				G25	G35	G45	G55	G65
				25%	35%	45%	55%	65%
								G75
								75%
<i>Physical Composition</i>								
Specific Gravity			3.15					GGBFS-2.90
Blaine value	m ² /kg	OPC-297						GGBFS-441
		S-539						
<i>Chemical Composition</i>								
Calcium oxide (CaO)	%	55.64	48.78	50.43	47.46	45.31	43.19	41.07
Silicon dioxide (SiO ₂)	%	21.13	28.92	24.97	29.83	31.26	32.72	34.32
Aluminum oxide (Al ₂ O ₃)	%	6.33	12.48	9.53	12.26	13.55	14.78	16.43
Ferric oxide (Fe ₂ O ₃)	%	4.22	0.00	2.08	0.00	0.00	0.00	0.00
Magnesium oxide (MgO)	%	4.09	5.64	4.82	5.51	5.83	6.10	6.50
Sulfur oxide (SO ₃)	%	2.97	3.17	2.80	2.34	2.02	1.74	1.42
Potassium oxide (K ₂ O)	%	1.43	1.15	1.17	1.01	0.91	0.81	0.71
Sodium oxide (Na ₂ O)	%	0.19	0.31	0.26	0.26	0.27	0.27	0.25

5.1.2 Particle Size Distribution (PSD)

Particle Size Distribution (PSD) of all six slag blends was carried out by Laser Diffraction (LSD) using Malvern Mastersizer 3000 in water as dispersant medium (wet method) and plotted by 'Mie' Scattering Model Distribution.

Table 5.1.2 indicates the different particle diameter values, viz. Dv (10), Dv (50), Dv (90), Dv (95), and Dv (100) of all six blends, and Figures 5.1.1 to 5.1.6 show the volume density to particle size. Figure 5.1.7 is the graphical representation of the Cumulative passing % v/s Particle Diameter in μm .

Table 5.1.2: Particle Diameter values

Series	Particle Diameter in μm				
	Dv (10)	Dv (50)	Dv (90)	Dv (95)	Dv (100)
S45	1.720	9.921	54.291	-	-
G25	3.325	18.059	54.971	69.538	143.473
G2	3.321	17.618	53.232	67.421	143.393
G3	3.473	18.957	54.940	69.006	143.268
G4	3.605	19.114	54.927	69.087	143.442
G5	3.466	18.880	53.935	67.657	143.273
G6	3.428	18.682	53.675	67.581	143.397

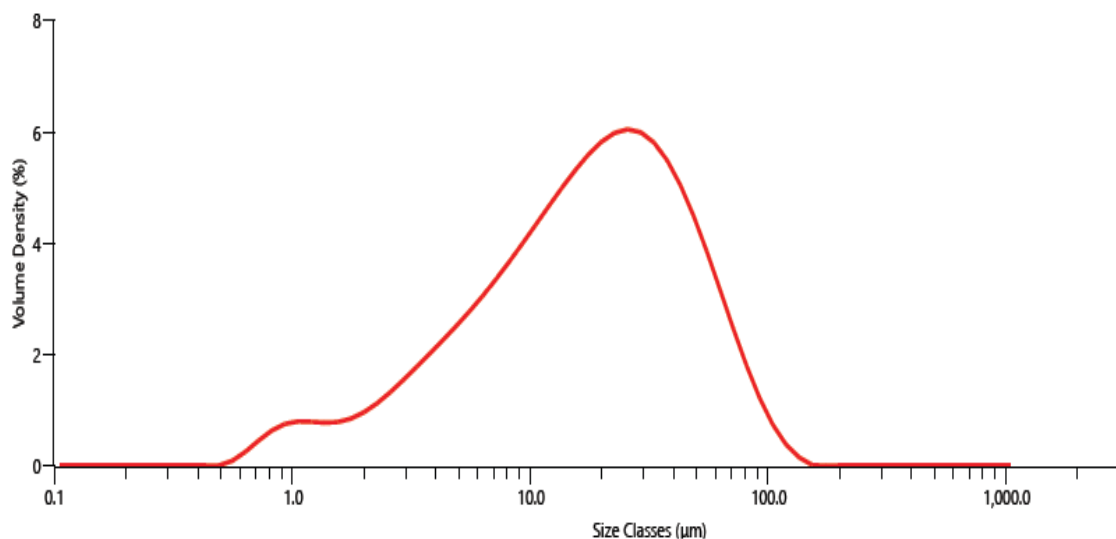


Figure 5.1.1: G25 (S45+25% GGBFS)

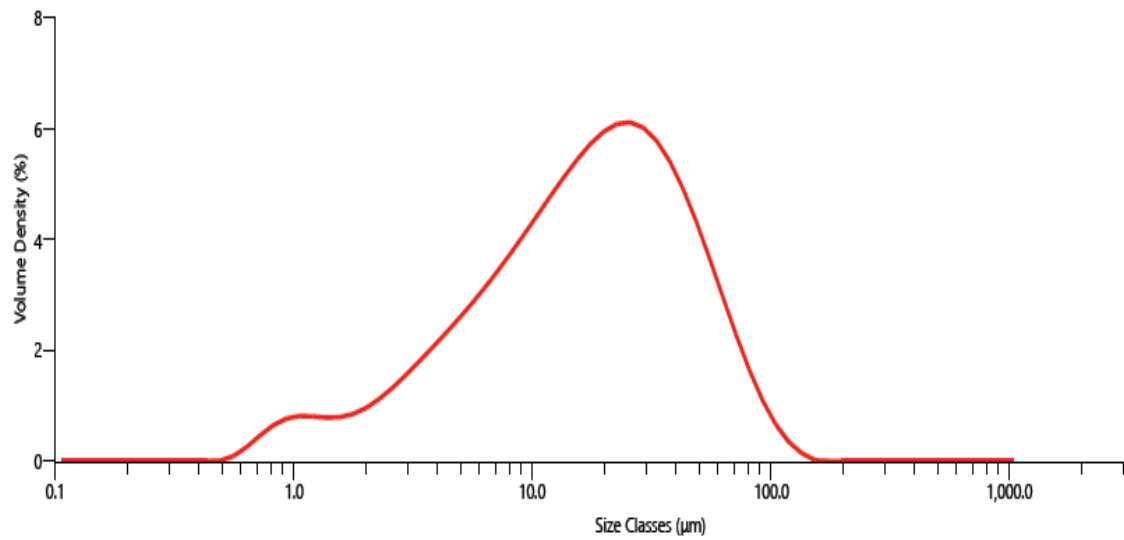


Figure 5.1.2: G35 (S45+35% GGBFS)

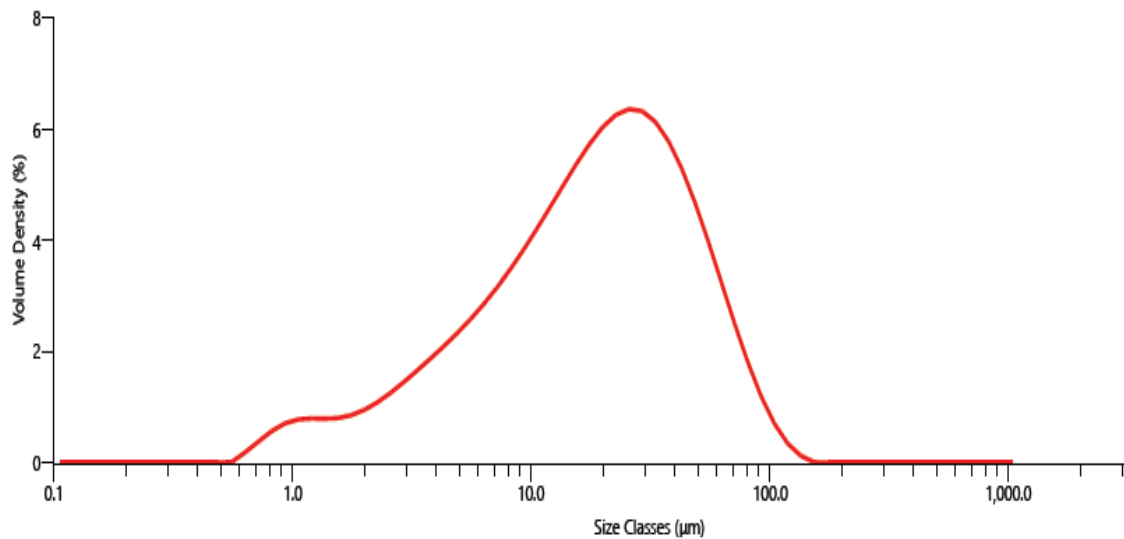


Figure 5.1.3: G45 (S45+45% GGBFS)

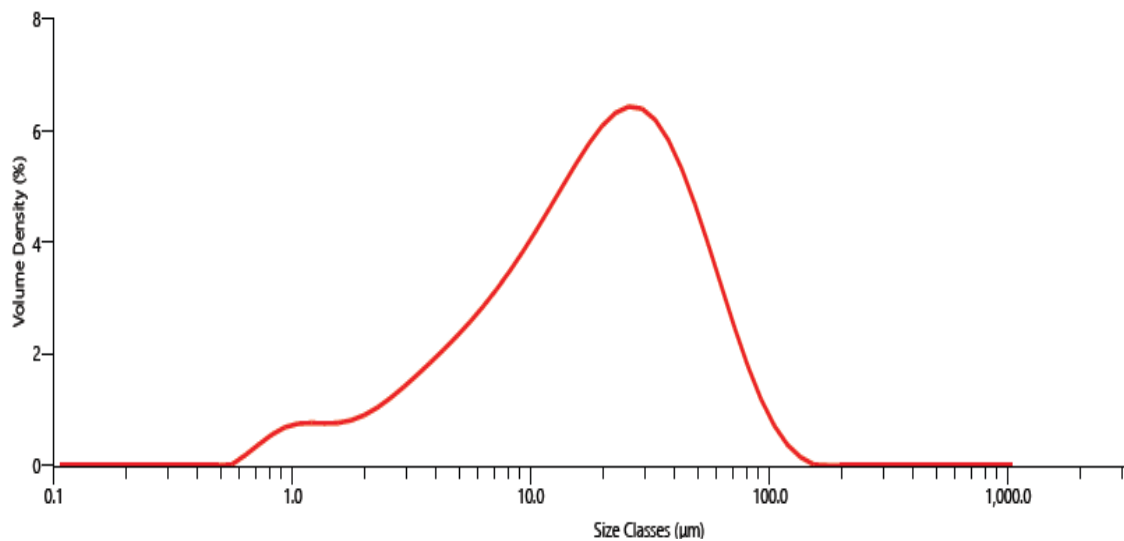


Figure 5.1.4: G55 (S45+55% GGBFS)

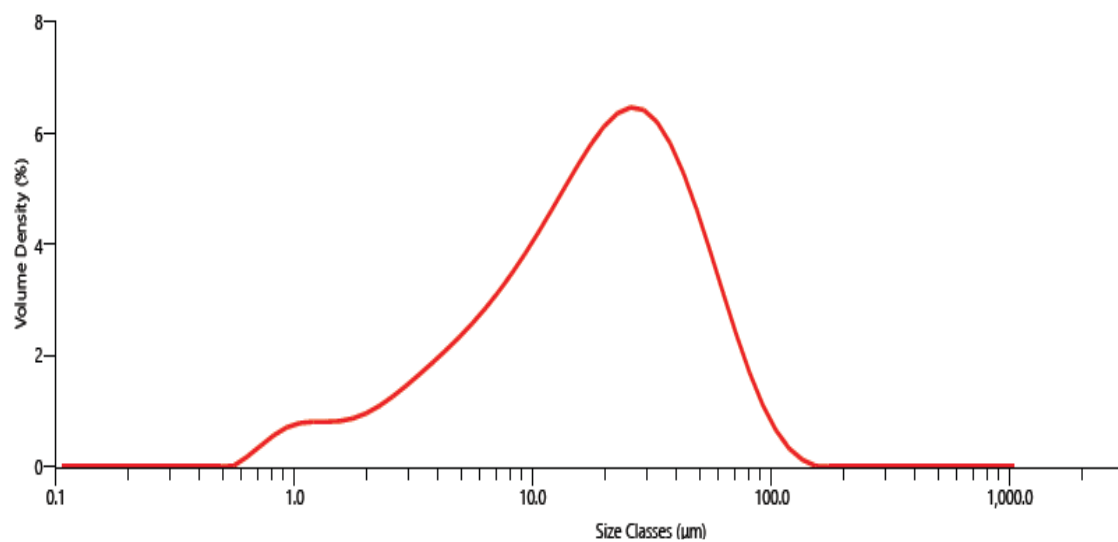


Figure 5.1.5: G65 (S45+65% GGBFS)

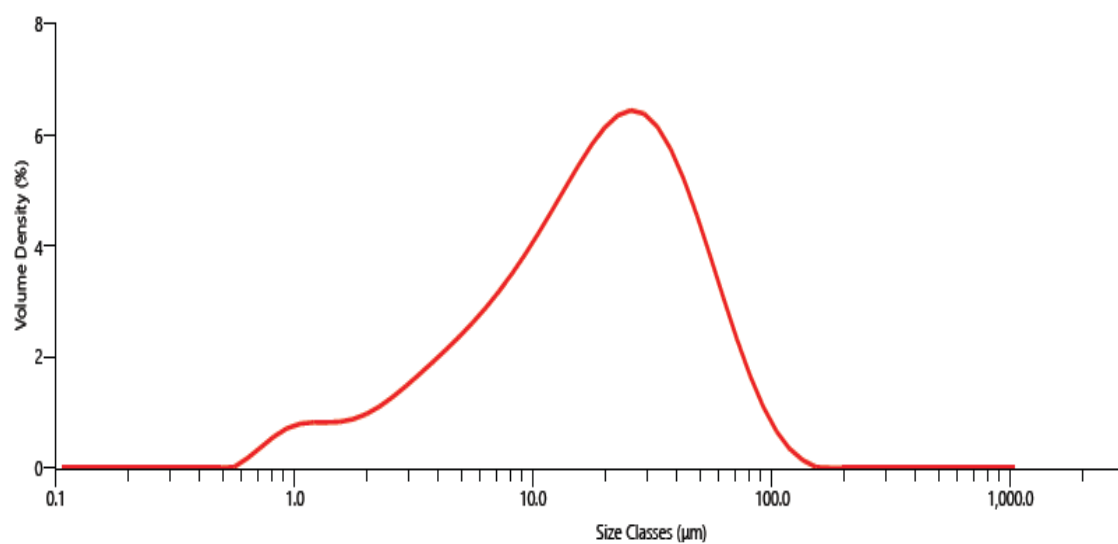


Figure 5.1.6: G75 (S45+75% GGBFS)

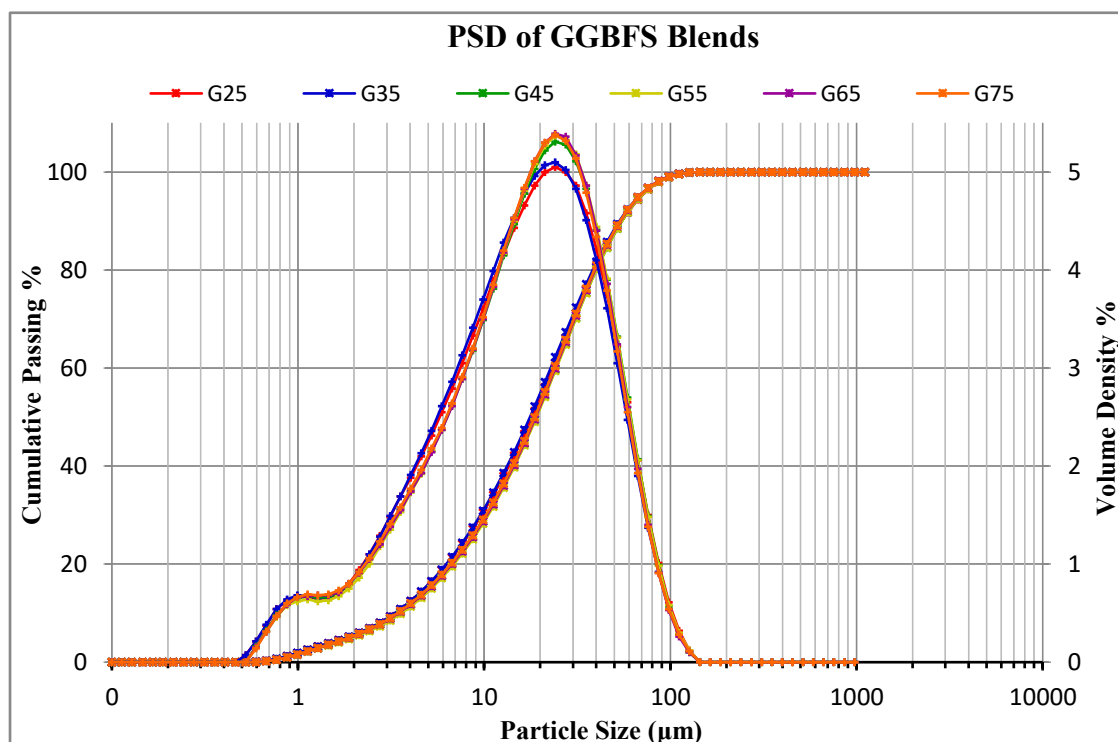


Figure 5.1.7: Cumulative passing % v/s Particle Diameter in μm

5.1.3 Soundness

Determination of Soundness by Autoclave Method with procedures conforming to BIS: 4031 (Part-3) was carried out for all six blends and the values are tabulated in Table 5.1.3.

Table 5.1.3: SC, AS, IST, FST values

Series	Standard Consistency (SC) %	Autoclave Soundness (AS)	Initial Setting Time (IST) (minutes)	Final Setting Time (FST) (minutes)
S45	26.0	0.104	125	205
G25	27.5	0.076	145	225
G35	27.5	0.052	160	240
G45	27.5	0.032	175	255
G55	28.0	0.012	190	270
G65	28.5	-	205	295
G75	30.0	0.032	185	275

It is evident from the results presented in the table that the soundness values of the cement blends decrease progressively with an increase in the proportion of fine supplementary cementitious materials (SCMs), including the S45 blend and mixtures ranging from G25 to G75. The incorporation of finer particles enhances the particle packing density of the cementitious matrix, thereby reducing internal voids and promoting a more uniform microstructure.

The reduction in soundness values can be attributed to the dilution of free lime (CaO) and magnesia (MgO) present in Ordinary Portland Cement (OPC), which are primarily responsible for undesirable delayed expansion. Furthermore, the fine particles act as micro-fillers and provide additional nucleation sites for hydration products, leading to a denser and more stable cement matrix. The pozzolanic and latent hydraulic reactions of the blended constituents consume calcium hydroxide generated during cement hydration, producing additional calcium silicate hydrate (C-S-H) gel that contributes to volumetric stability.

Consequently, the incorporation of fines improves the dimensional stability of the cement blends by minimizing expansion-related effects and reducing the likelihood of microcracking. Improved soundness is therefore indicative of enhanced cement quality and is often associated with superior durability characteristics, including lower permeability, reduced ingress of aggressive agents, and improved long-term mechanical performance. The observed decrease in soundness values for both binary and ternary blended cement systems demonstrate the beneficial role of fines in producing a denser, more durable, and volumetrically stable cementitious composite compared to conventional OPC.

5.1.4 Standard Consistency

Determination of Consistency by Vicat Apparatus with procedures conforming to BIS: 4031 (Part-4) was carried out on all blends and the values are tabulated in Table 5.1.3 and graphically represented in Figure 5.1.8.

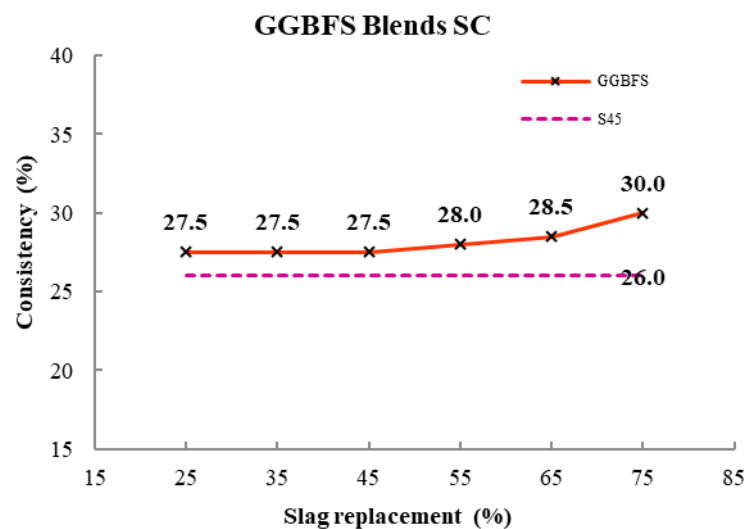


Figure 5.1.8: Standard Consistency

Figure 5.1.8 illustrates the variation in water requirement (standard consistency) of the blended cement systems with increasing slag content. The results indicate that the water demand remains nearly constant up to approximately 45% slag substitution, beyond which a gradual increase in water requirement is observed. This behavior can be attributed to the increasing proportion of finer particles within the cementitious matrix, which possess a larger specific surface area and consequently require additional water for surface wetting, hydration, and pozzolanic reactions.

The consistency test is one of the most significant characterization tests for cement as it directly influences hydration kinetics, setting behavior, strength development, soundness, and long-term durability. The observed trend demonstrates that up to 45% replacement, the fine particles effectively enhance particle packing without significantly increasing the water demand. The micro-filler effect improves the packing density of the cement matrix, reduces capillary voids, and promotes the formation of a dense and homogeneous microstructure. Consequently, the hydration process proceeds efficiently while maintaining acceptable workability characteristics.

Beyond 45% slag substitution, the increased concentration of ultra-fine particles results in a marginal increase in water demand due to the larger surface area available for hydration and adsorption of water molecules. Nevertheless, the increase remains within acceptable limits, indicating that the blended systems continue to exhibit favorable hydration characteristics. Similar observations have been reported in previous studies, wherein increased fineness was found to moderately elevate water demand while simultaneously enhancing the quality of hydration products and microstructural refinement.

The incorporation of fines also plays a critical role in improving the soundness of cement blends. The finer slag particles dilute the concentration of free lime (CaO) and magnesia (MgO), which are the principal constituents responsible for delayed expansion in Ordinary Portland Cement (OPC). In addition, the pozzolanic and latent hydraulic reactions of the fines consume calcium hydroxide liberated during hydration and convert it into additional calcium silicate hydrate (C-S-H) gel. This reaction mechanism reduces the availability of expansive compounds and improves volumetric stability.

Furthermore, the enhanced particle packing and pore refinement achieved through the incorporation of fines reduce internal stresses associated with hydration and moisture movement. The resulting dense microstructure minimizes microcracking and expansion, thereby lowering soundness values and improving dimensional stability. Consequently, binary and ternary cement blends containing an optimum proportion of fines exhibit superior soundness characteristics compared with conventional OPC. Improved soundness is further reflected in enhanced durability, reduced permeability, greater resistance to aggressive environmental exposure, and improved long-term mechanical performance.

Therefore, the results confirm that the controlled incorporation of fines not only maintains acceptable consistency characteristics but also significantly enhances the soundness of cement blends through microstructural densification, reduction of expansive constituents, and the development of a stable and durable hydration matrix.

5.1.5 Initial and Final Setting Times

Determination of Initial and Final Setting Times by Vicat Apparatus with procedures conforming to BIS: 4031 (Part-5) were carried out on all blends and the values are tabulated in Table 5.1.3 and graphically represented in Figure 5.1.9.

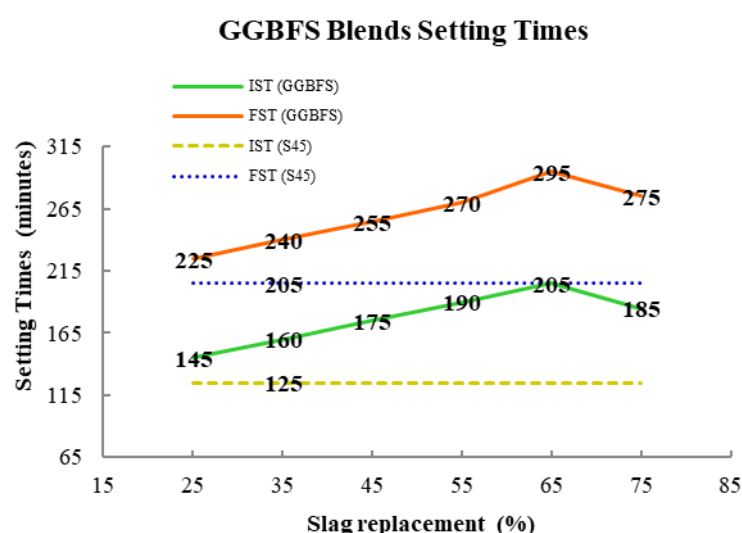


Figure 5.1.9: Initial (IST) and Final Setting Time (FST) values

The test results indicate the effect of PSD in terms of the Consistency results and the Setting Times for the reasons cited above for Binary and Ternary Blends with GGBFS and Fly-ash.

5.1.6 Compressive Strength (CS) for curing ages at 1, 3, 7, 14 and 28 days

Determination of Compressive Strength on blended cement mortar cubes with procedures conforming to BIS: 4031 (Part-6) was carried out, as follows:

Three specimen samples each for every blend were cast in 70.6mm x 70.6mm x 70.6mm mold conforming to BIS: 10080 with Base Material (i.e. S45) and GGBFS blended cement, Standard Sand (fine and coarse) was used for cement testing conforming to BIS: 650 in equal proportion of 200gms each and mixed with a percentage of water derived by standard consistency and compacted with vibratory machine conforming to BIS: 10080, for the desired curing ages of 1, 3, 7, 14, 28, 56, 90, 180, 270 and 365 days.

The average values of Compressive Strength (CS) of all six blends for curing ages of 1, 3, 7, 14 and 28 days are tabulated in Table 5.1.4 and graphically represented from Figures 5.1.10 to 5.1.14.

Table 5.1.4: Compressive Strength (CS) values

Series	Compressive Strength (CS) in MPa				
	1 day	3 days	7 days	14 days	28 days
S45	32.5	39.2	45.5	48.7	55.0
G25	21.4	34.2	38.9	46.6	55.0
G35	18.9	34.1	40.3	44.9	49.7
G45	15.4	31.0	38.3	47.1	51.5
G55	11.1	28.3	37.0	41.9	46.5
G65	8.1	24.6	32.8	35.3	39.6
G75	6.2	16.7	19.1	22.7	28.2

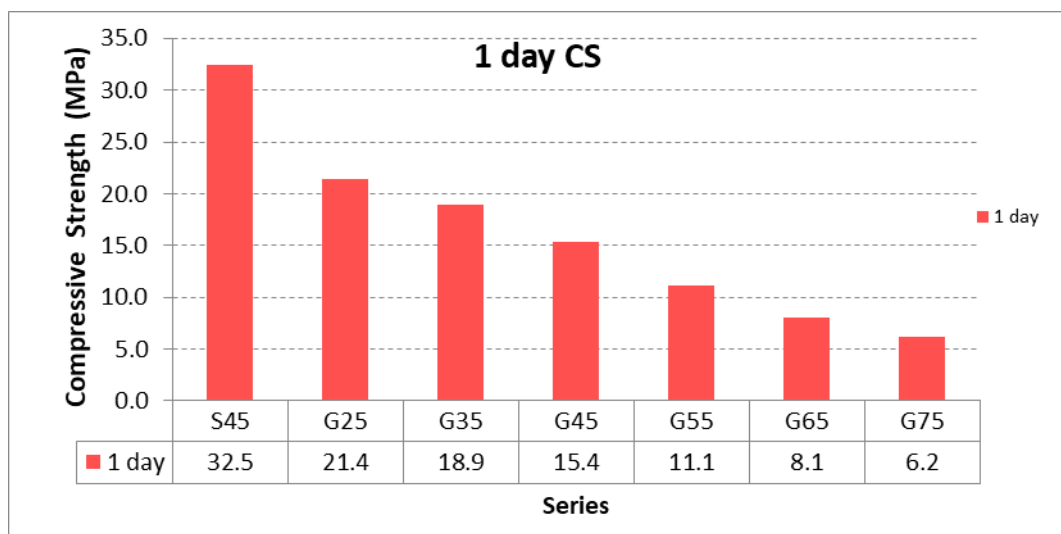


Figure 5.1.10: 1-day Compressive strength

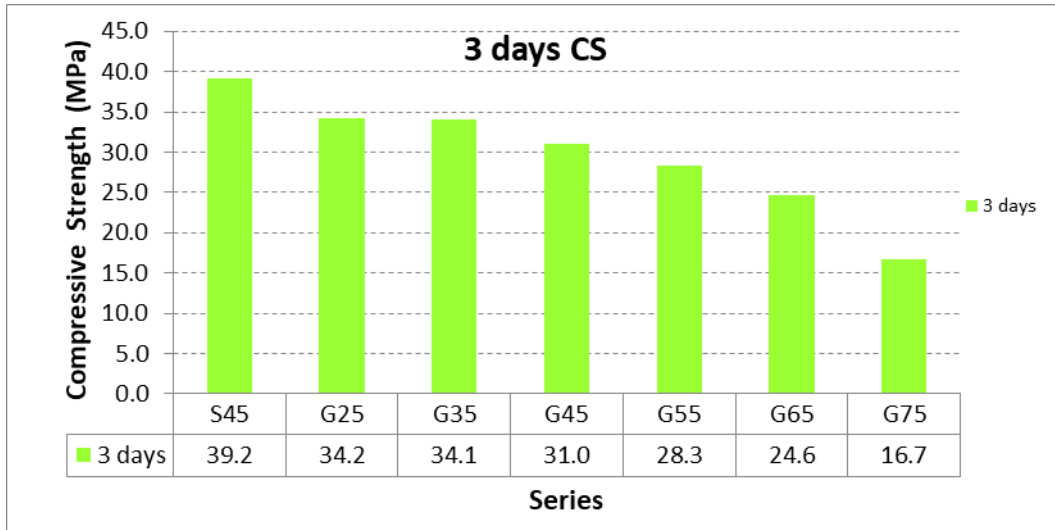


Figure 5.1.11: 3 days Compressive strength

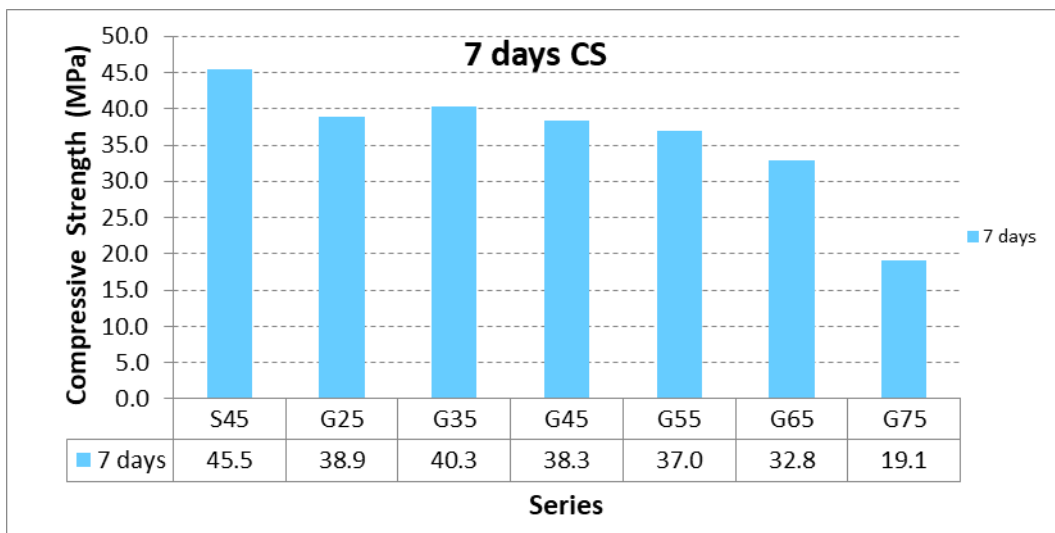


Figure 5.1.12: 7 days compressive strength

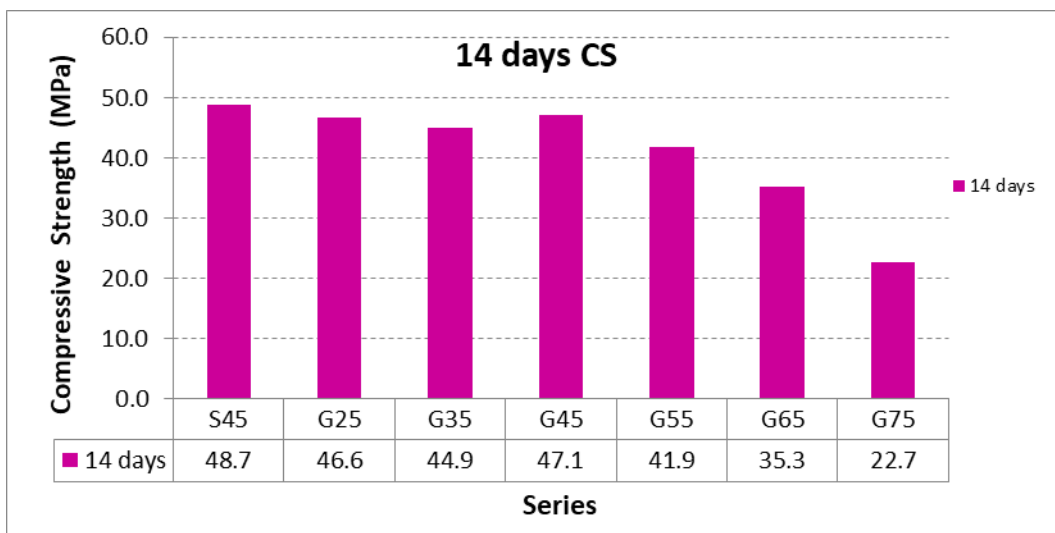


Figure 5.1.13: 14 days Compressive strength

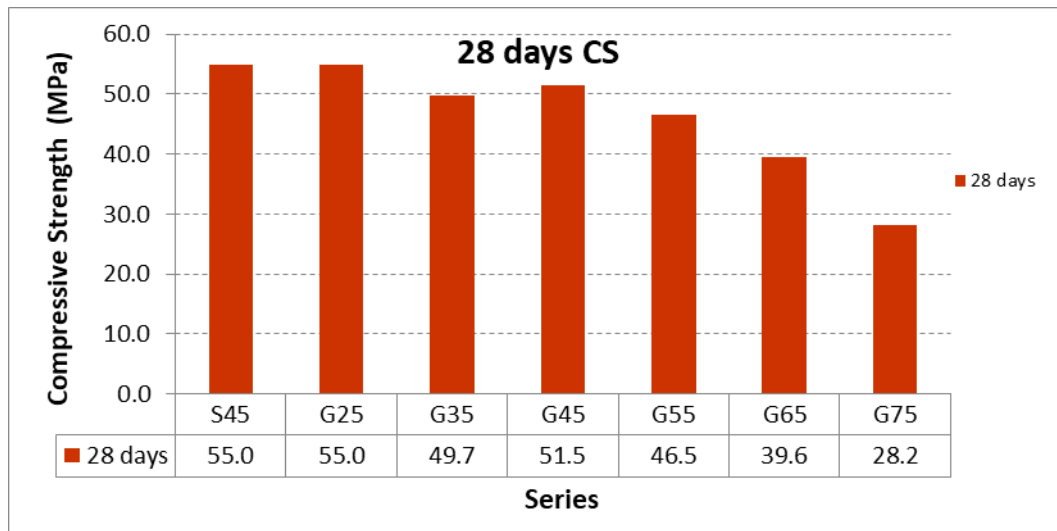


Figure 5.1.14: 28 days Compressive strength

5.1.7 Compressive Strength (CS) for curing ages at 56, 90, 180, 270 and 365 days

The average values of Compressive Strength (CS) of all six blends for further curing ages of 56, 90, 180, 270 and 365 days are tabulated in Table 5.1.5 and graphically represented in Figures 5.1.15 to 5.1.19.

Table 5.1.5: Compressive Strength (CS) values

Series	Compressive Strength (CS) in MPa									
	1 day	3 days	7 days	14 days	28 days	56 days	90 days	180 days	270 days	365 days
S45	32.5	39.2	45.5	48.7	55.0	-	-	-	-	-
G25	21.4	34.2	38.9	46.6	55.0	61.8	63.7	63.0	61.6	64.0
G35	18.9	34.1	40.3	44.9	49.7	59.9	61.5	66.4	62.1	64.4
G45	15.4	31.0	38.3	47.1	51.5	52.6	56.9	57.7	59.2	62.0
G55	11.1	28.3	37.0	41.9	46.5	49.2	53.6	55.5	55.1	58.0
G65	8.1	24.6	32.8	35.3	39.6	39.9	39.0	43.3	47.7	50.3
G75	6.2	16.7	19.1	22.7	28.2	27.8	26.9	29.2	34.6	39.9

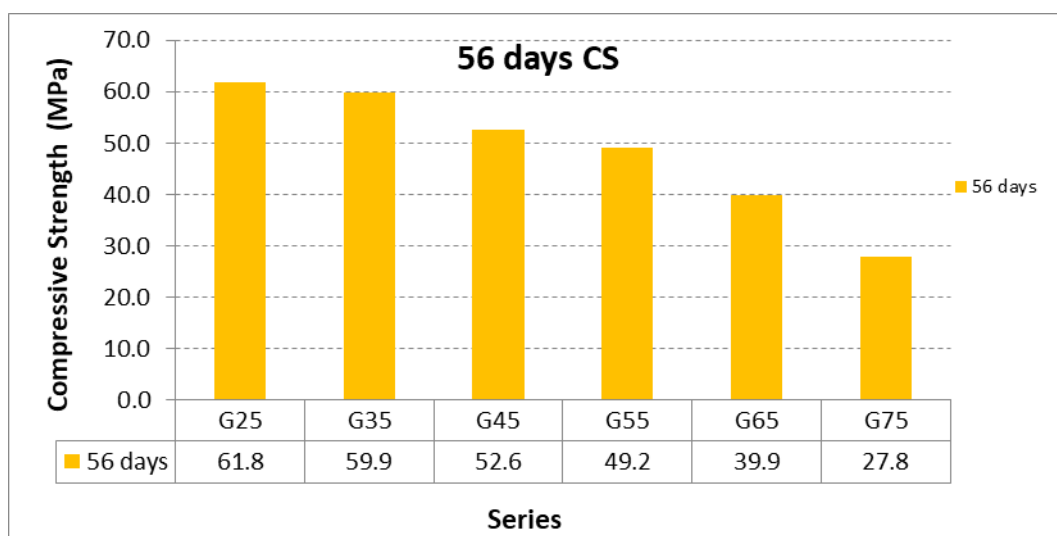


Figure 5.1.15: 56 days Compressive strength

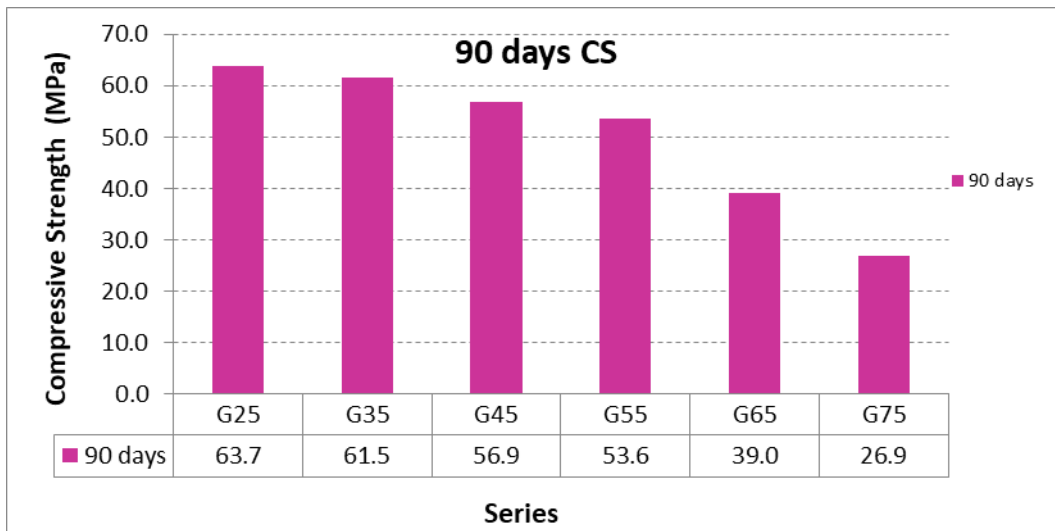


Figure 5.1.16: 90 days Compressive strength

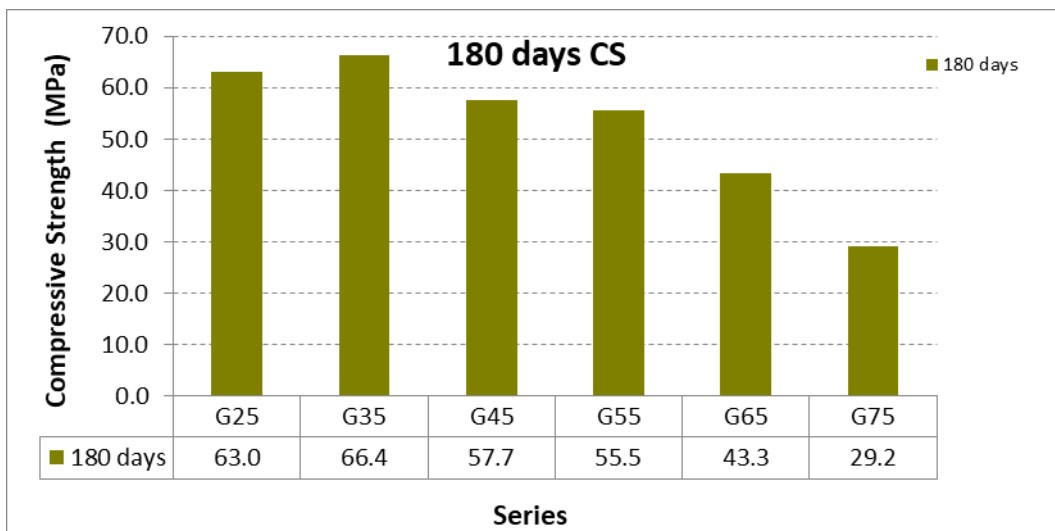


Figure 5.1.17: 180 days Compressive strength

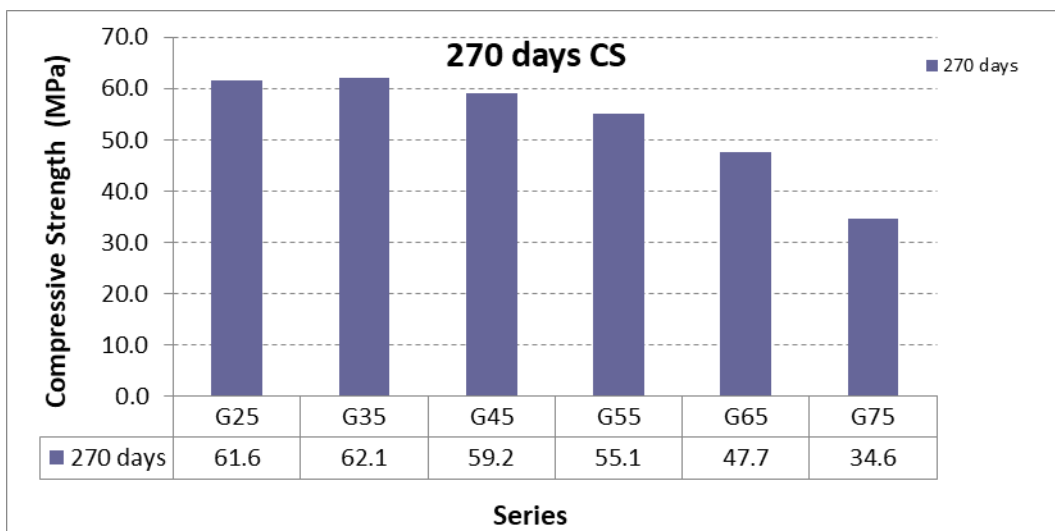


Figure 5.1.18: 270 days Compressive strength

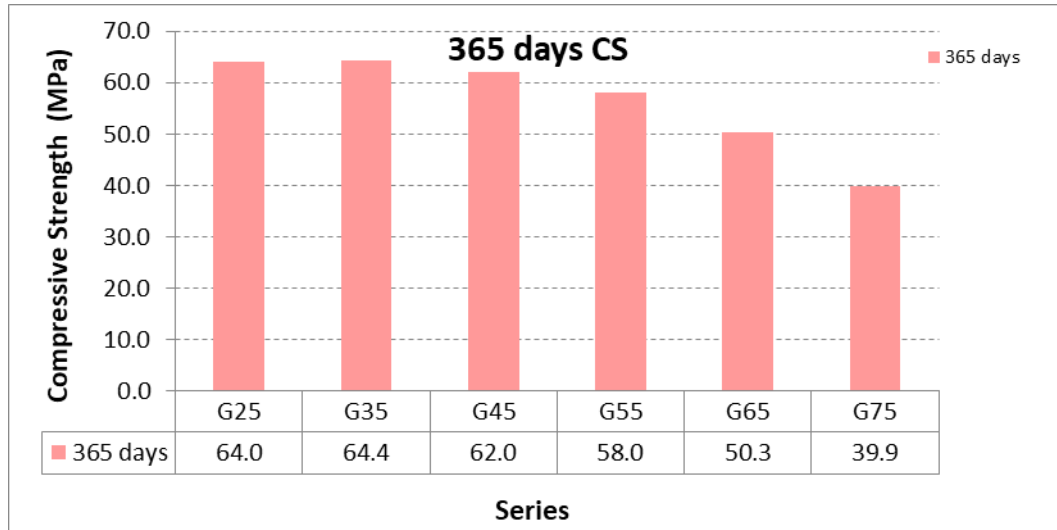


Figure 5.1.19: 365 days Compressive strength

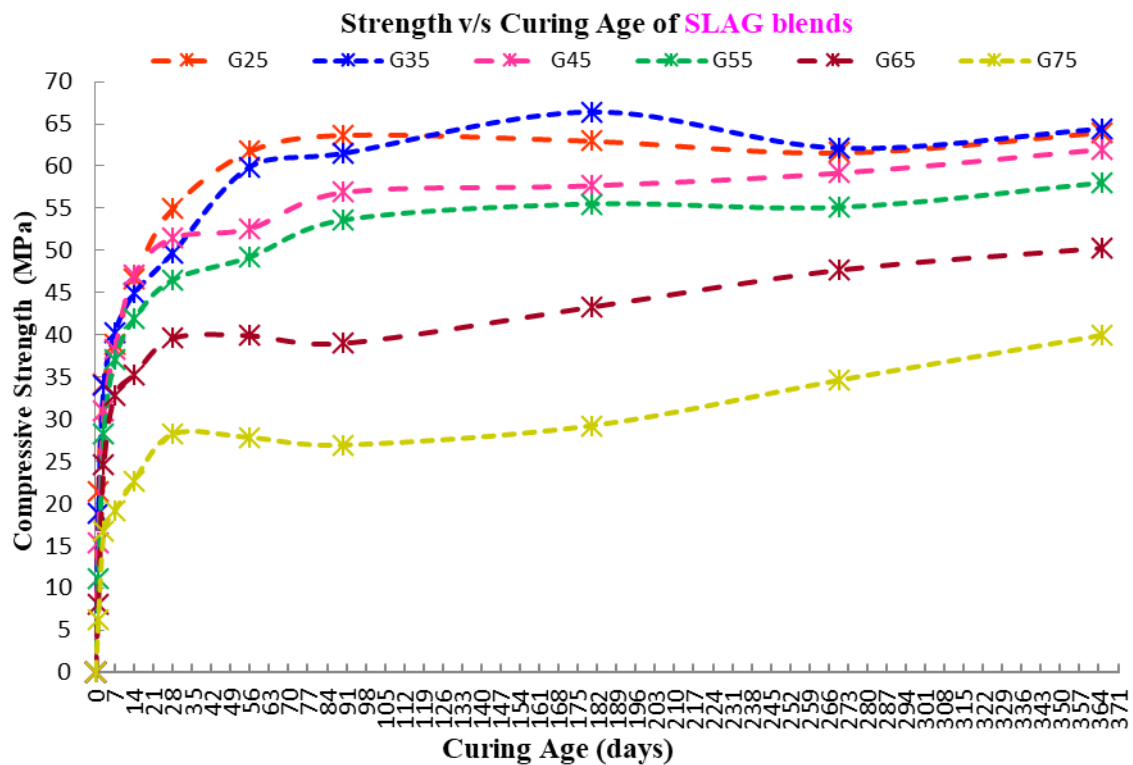


Figure 5.1.20: Compressive strength (CS) v/s Curing age up to 365 days

5.2 PART-2: S45 and Fly-ash blend

All the tests conducted on specimens of S45+FA mixes are elaborated below:

5.2.1 Physical and Chemical Composition

The physical and chemical test results for the combinations of the blends referred to in Table 4.2 are tabulated in Table 5.2.1 as below:

Table 5.2.1: Physical and Chemical Composition of Fly-ash Blends

Table 2.2.1: Physical and Chemical Composition of Fly-ash Blends							
		S45	Fly-ash				
			F15	F25	F35	F45	F55
			15%	25%	35%	45%	55%
<i>Physical Composition</i>							
Specific Gravity		3.15			FA-2.20		
Blaine value	m ² /kg	OPC-297 SC-540			FA-386		
<i>Chemical Composition</i>							
Calcium oxide (CaO)	%	55.64	48.36	42.16	36.40	29.45	24.97
Silicon dioxide (SiO ₂)	%	21.13	27.33	31.23	34.86	39.44	42.19
Aluminum oxide (Al ₂ O ₃)	%	6.33	8.72	10.61	12.33	15.41	16.82
Ferric oxide (Fe ₂ O ₃)	%	4.22	3.81	3.94	4.09	4.28	4.44
Magnesium oxide (MgO)	%	4.09	3.47	3.19	2.84	2.37	2.10
Sulphur oxide (SO ₃)	%	2.97	2.53	2.11	1.71	1.20	0.89
Potassium oxide (K ₂ O)	%	1.43	1.39	1.37	1.34	1.26	1.23
Sodium oxide (Na ₂ O)	%	0.19	0.17	0.17	0.17	0.12	0.12

5.2.2 Particle Size Distribution (PSD)

Particle Size Distribution (PSD) of all five fly-ash blends is carried out by Laser Diffraction (LSD) using Malvern Mastersizer 3000 in water as dispersant medium (wet method) and plotted by 'Mie' Scattering Model Distribution.

Table 5.2.2 indicates the different particle diameter values of D_v (10), D_v (50), D_v (90), D_v (95), and D_v (100) of all five blends, and Figures 5.2.1 to 5.2.5 shows the volume density to particle size. Figure 5.2.6 is the graphical representation of Cumulative passing % v/s Particle Diameter in µm.

Table 5.2.2: Particle Diameter values

Series	Particle Diameter in µm				
	Dv (10)	Dv (50)	Dv (90)	Dv (95)	Dv (100)
S45	1.720	9.921	54.291	-	-
F15	3.694	21.114	74.827	104.678	396.874
F25	3.892	21.820	81.073	112.778	388.834
F35	3.878	21.888	84.171	117.585	348.285
F45	4.823	27.411	133.157	194.527	657.934
F55	5.252	28.102	137.691	197.720	647.841

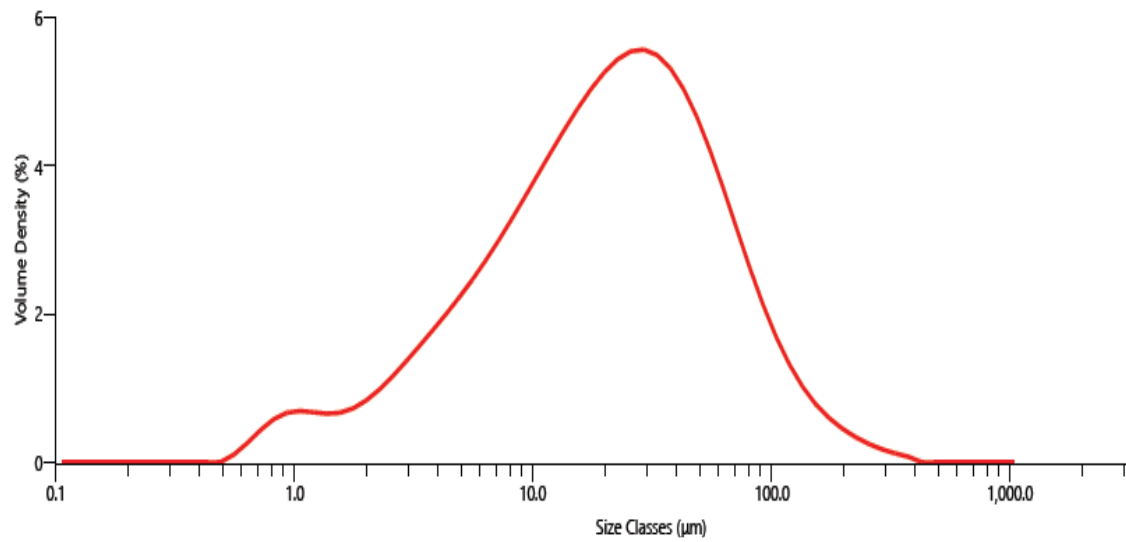


Figure 5.2.1: F15 (S45+15% FA)

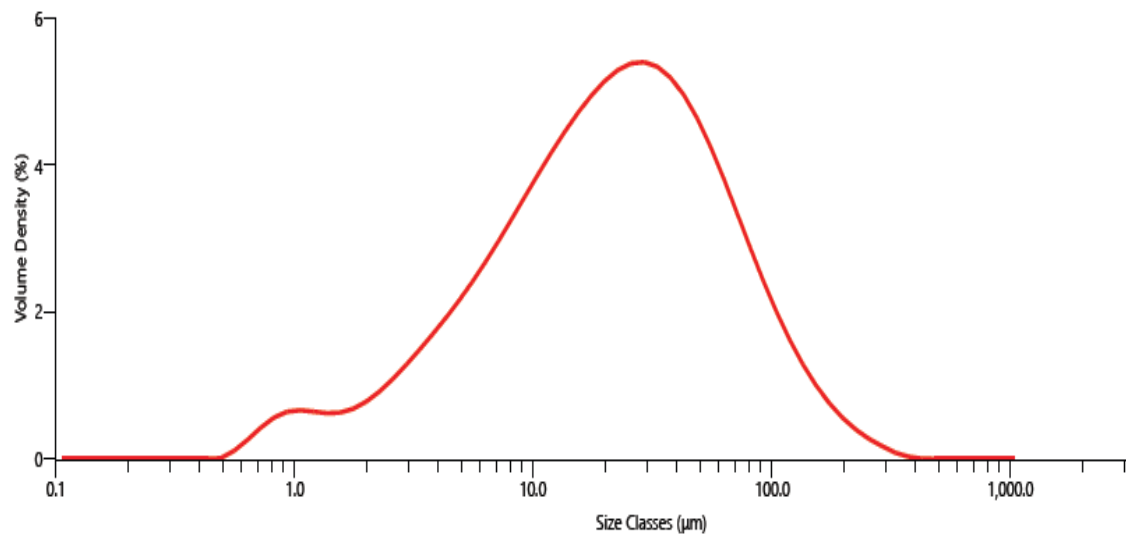


Figure 5.2.2: F25 (S45+25% FA)

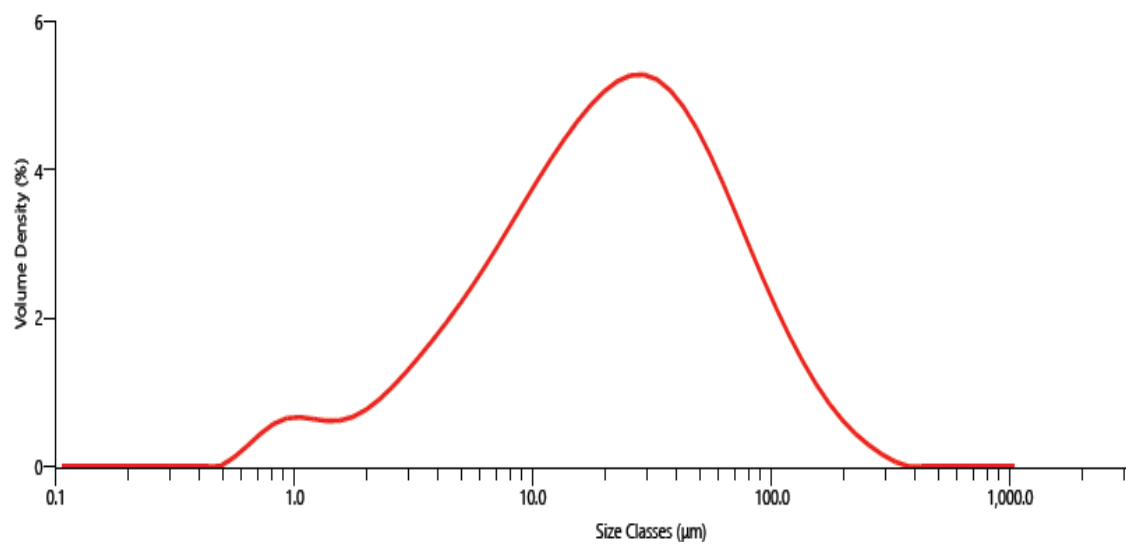


Figure 5.2.3: F35 (S45+35% FA)

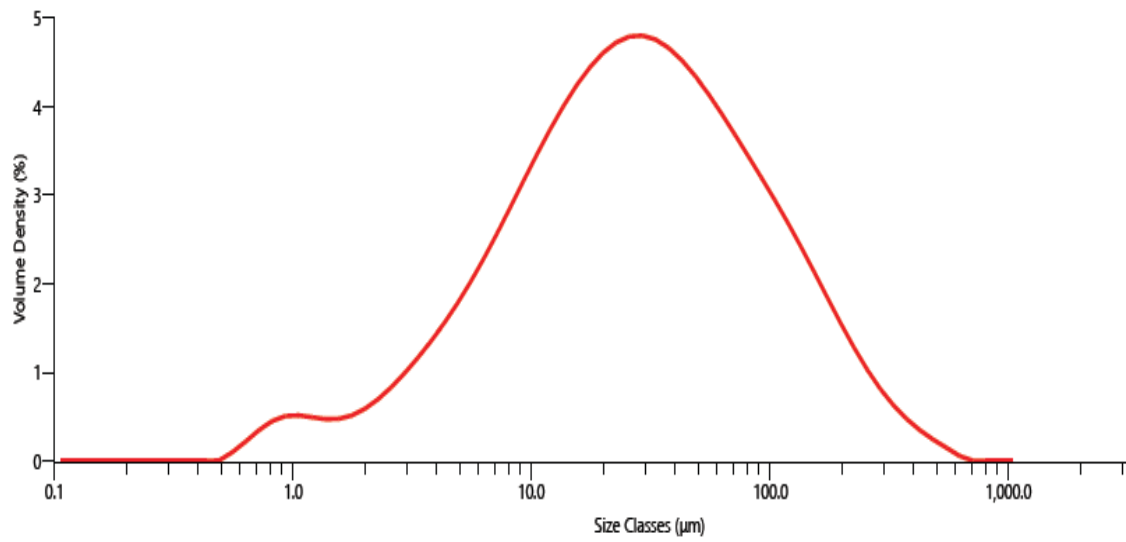


Figure 5.2.4: F45 (S45+45% FA)

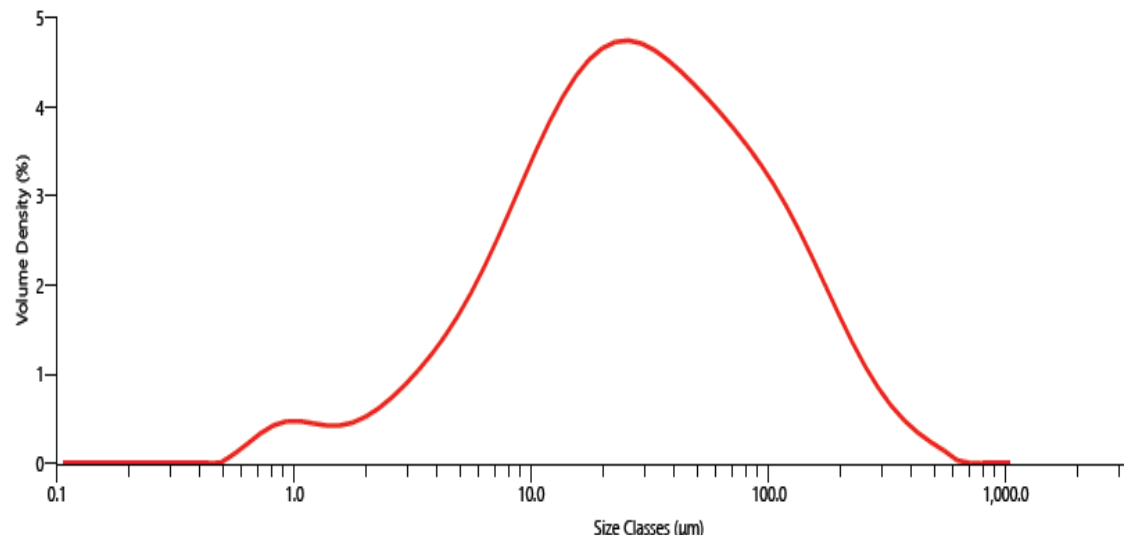


Figure 5.2.5: F55 (S45+55% FA)

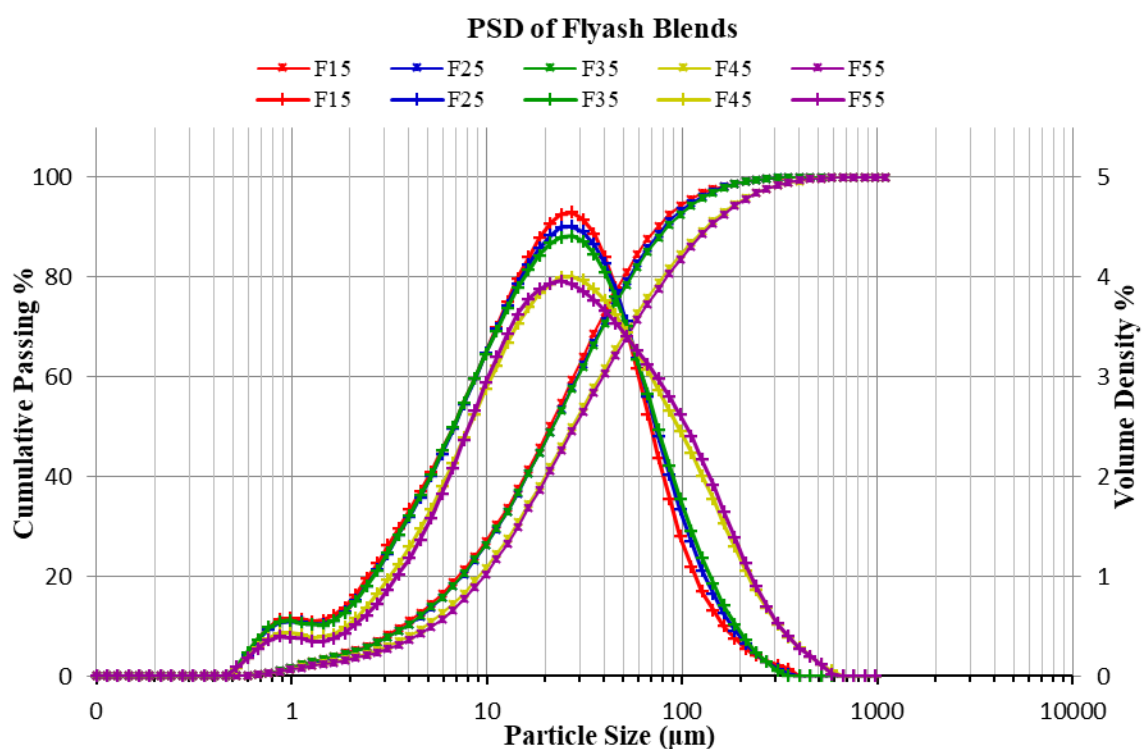


Figure 5.2.6: Cumulative passing % v/s Particle Diameter in μm

5.2.3 Soundness

Determination of Soundness by Autoclave Method with procedures conforming to BIS: 4031 (Part-3) are carried out for all five blends and the values are tabulated in Table 5.2.3.

Table 5.2.3: SC, AS, IST, FST values

Series	Standard Consistency (SC) %	Autoclave Soundness (AS)	Initial Setting Time (IST) (minutes)	Final Setting Time (FST) (minutes)
S45	26.0	0.104	125	205
F15	26.5	0.072	150	235
F25	25.5	0.064	140	220
F35	24.0	0.048	170	250
F45	25.5	0.020	175	255
F55	25.0	-	195	275

5.2.4 Standard Consistency

Determination of Consistency by Vicat Apparatus with procedures conforming to BIS: 4031 (Part-4) are carried out on all blends and the values are tabulated in Table 5.2.3 and graphically represented in Figure 5.2.7.

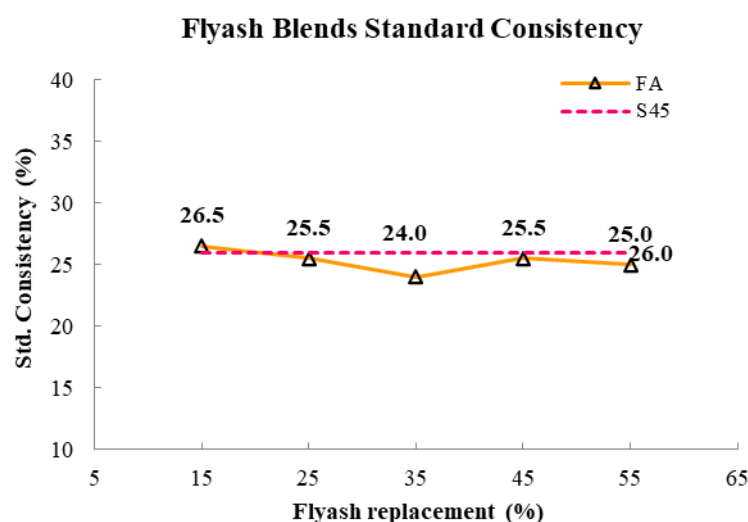


Figure 5.2.7: Standard Consistency

5.2.5 Initial and Final Setting Times

Determination of Initial and Final Setting Times by Vicat Apparatus with procedures conforming to BIS: 4031 (Part-5) are carried out on all blends and the values are tabulated in Table 5.2.3 and graphically represented in Figure 5.2.8.

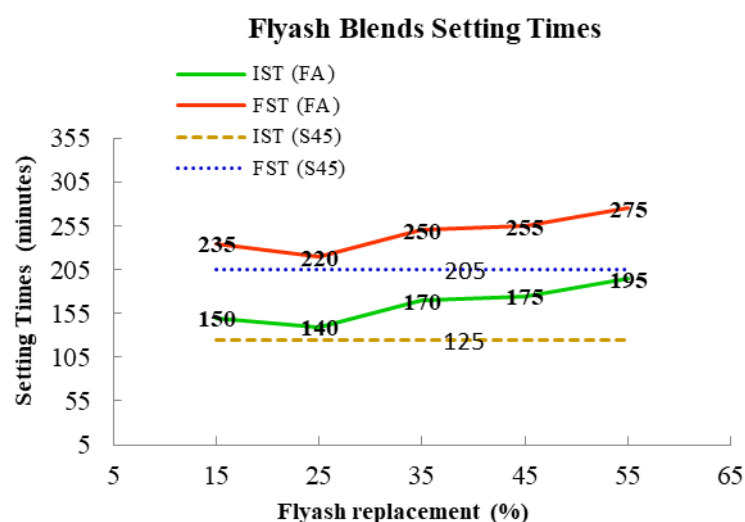


Figure 5.2.8: Initial and Final Setting Times

5.2.6 Compressive Strength (CS) for curing ages at 1, 3, 7, 14, 28, 56, 90, 180, 270 and 365 days

Determination of Compressive Strength on blended cement mortar cubes with procedures conforming to BIS: 4031 (Part-6) are carried out, as follows:

Three specimen samples each for every blend are cast in 70.6mm x 70.6mm x 70.6mm mold conforming to BIS: 10080 with Base Material (i.e. S45) and Fly-ash blended cement, Standard Sand (fine and coarse) used for cement testing conforming to BIS: 650 in equal proportion of 200gms each and mixed with a percentage of water derived by

standard consistency and compacted with vibratory machine conforming to BIS: 10080, for the desired curing ages of 1, 3, 7, 14, 28, 56, 90, 180 and 270 days.

The average values of Compressive Strength (CS) of all five blends for curing ages of 1, 3, 7, 14, 28, 56, 90, 180, 270 and 365 days are tabulated in Table 5.2.4 and graphically represented from Figures 5.2.9 to 5.2.18.

Table 5.2.4: Compressive Strength (CS) values

Series	Compressive Strength (CS) in MPa									
	1 day	3 days	7 days	14 days	28 days	56 days	90 days	180 days	270 days	365 days
S45	32.5	39.2	45.5	48.7	55.0	-	-	-	-	-
F15	24.0	30.4	38.8	43.6	48.5	52.9	51.3	53.6	56.7	58.6
F25	22.0	32.3	37.6	42.3	50.0	56.2	59.5	63.3	58.9	64.3
F35	18.9	30.4	33.8	40.1	48.1	54.5	57.4	63.7	57.8	62.4
F45	16.0	21.1	27.6	32.5	42.1	49.2	51.3	53.2	58.6	57.3
F55	10.3	16.2	21.1	26.6	36.2	40.3	44.3	49.1	47.4	49.5

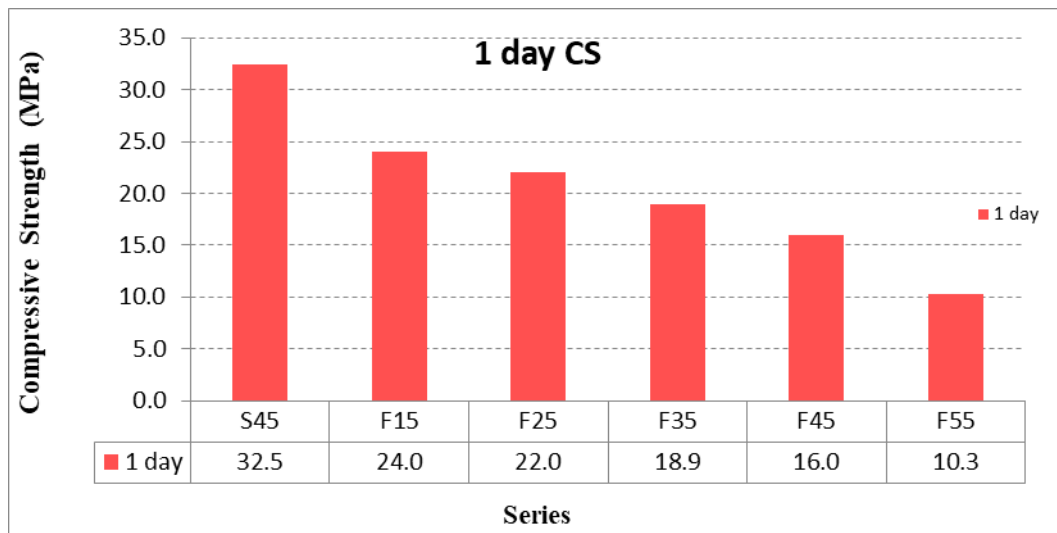


Figure 5.2.9: 1-day Compressive strength

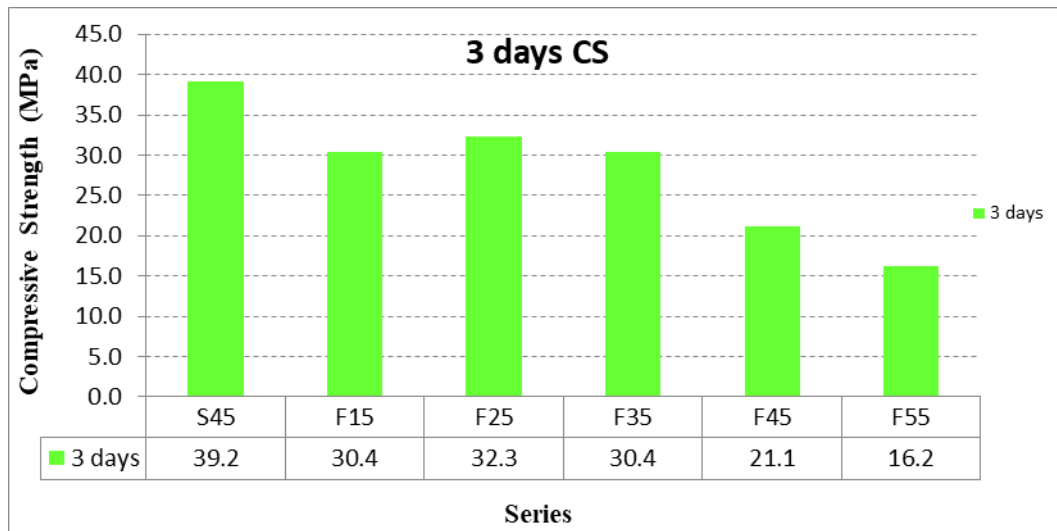


Figure 5.2.10: 3 days Compressive strength

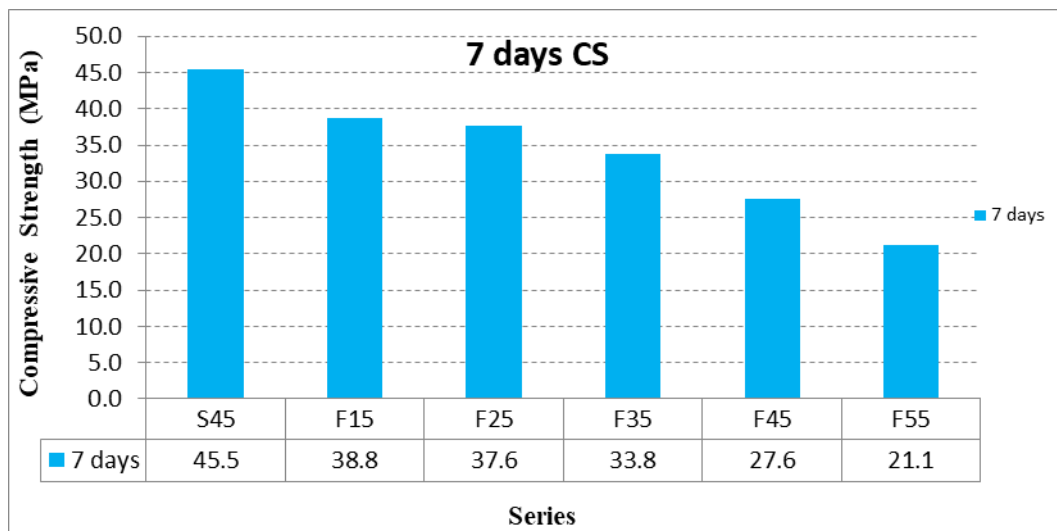


Figure 5.2.11: 7 days compressive strength

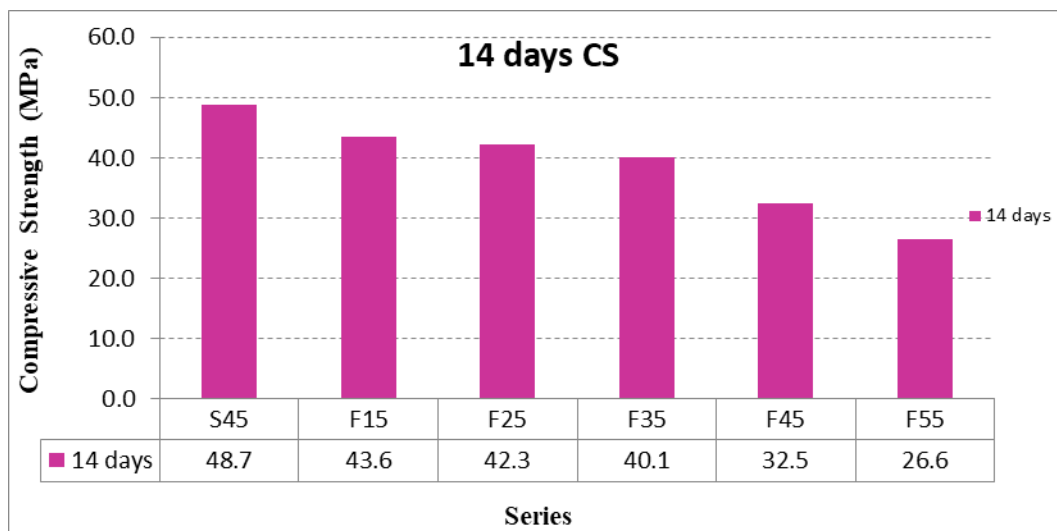


Figure 5.2.12: 14 days Compressive strength

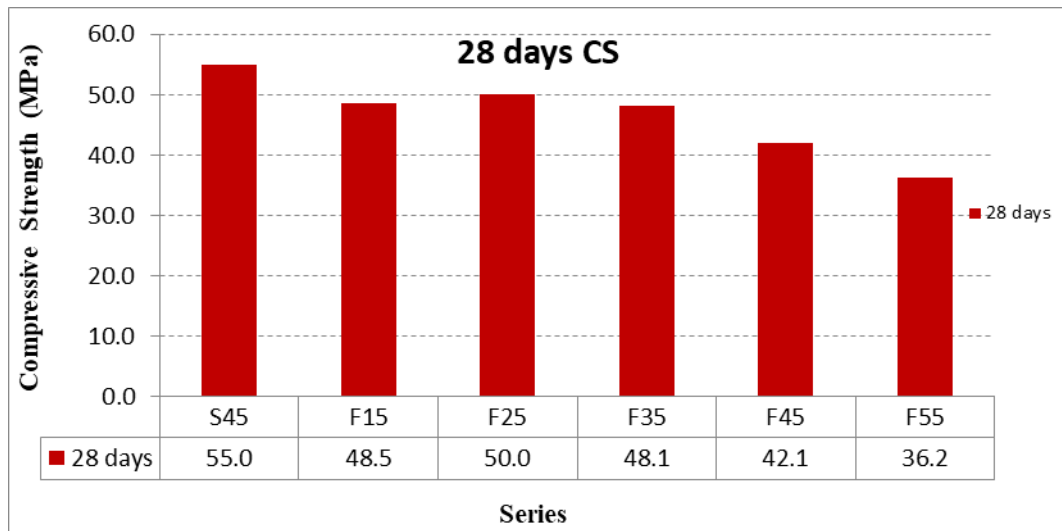


Figure 5.2.13: 28 days Compressive strength

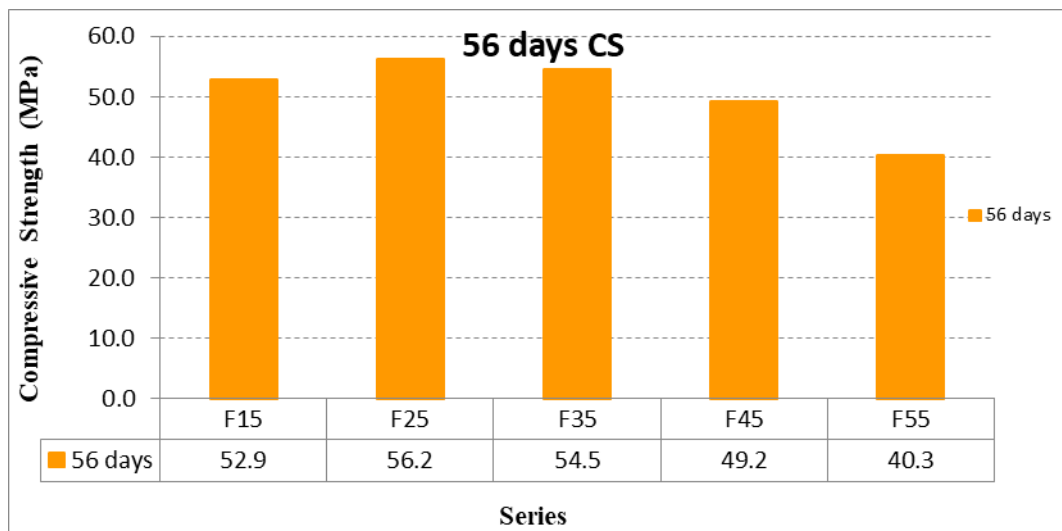


Figure 5.2.14: 56 days Compressive strength

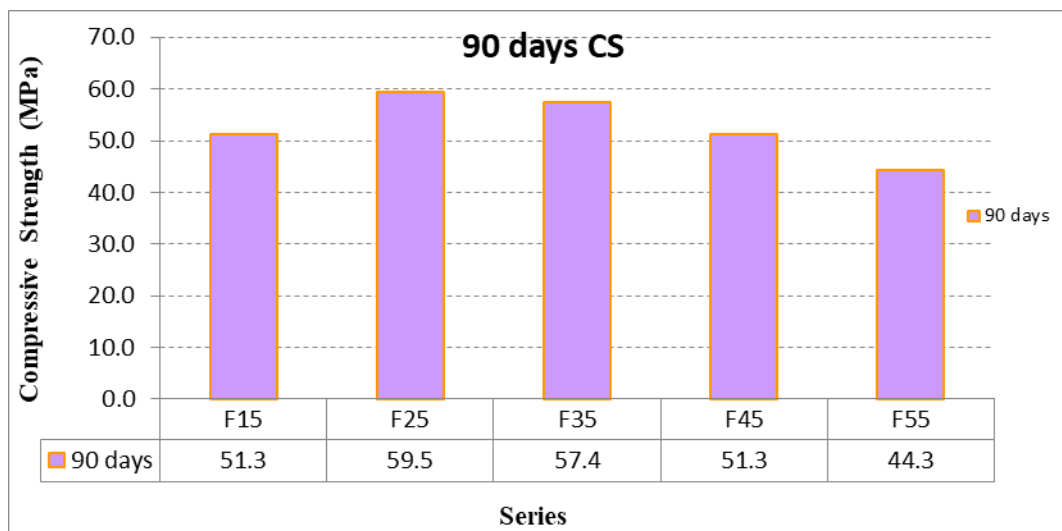


Figure 5.2.15: 90 days Compressive strength

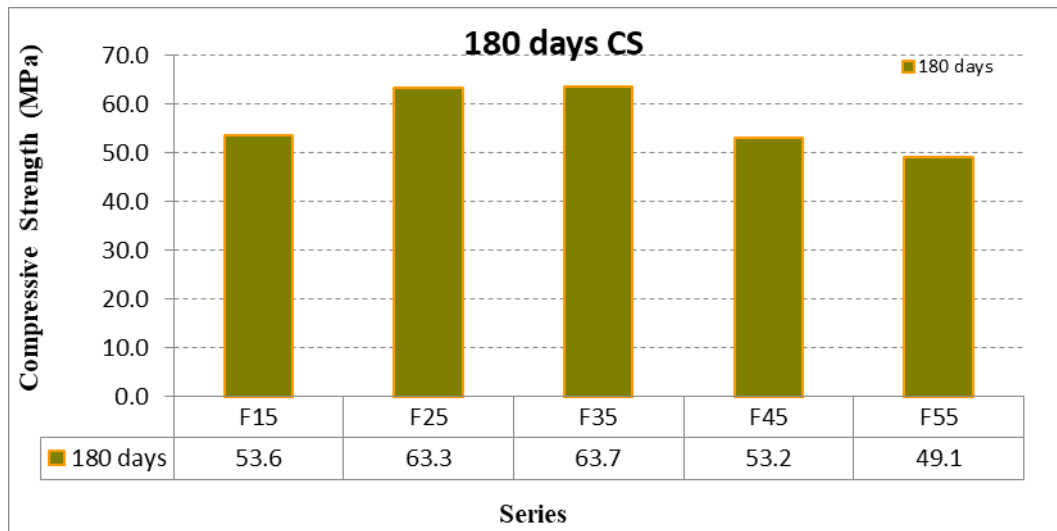


Figure 5.2.16: 180 days Compressive strength

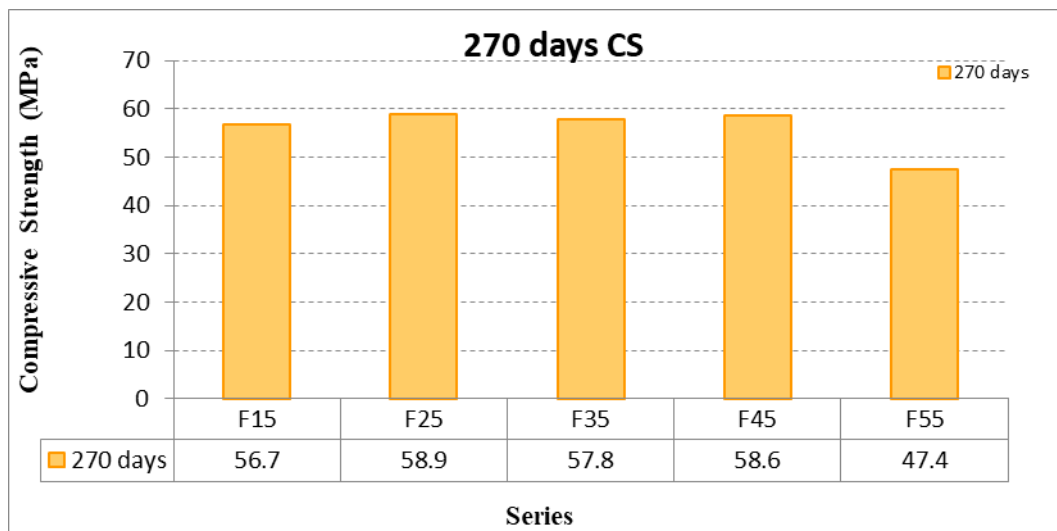


Figure 5.2.17: 270 days Compressive strength

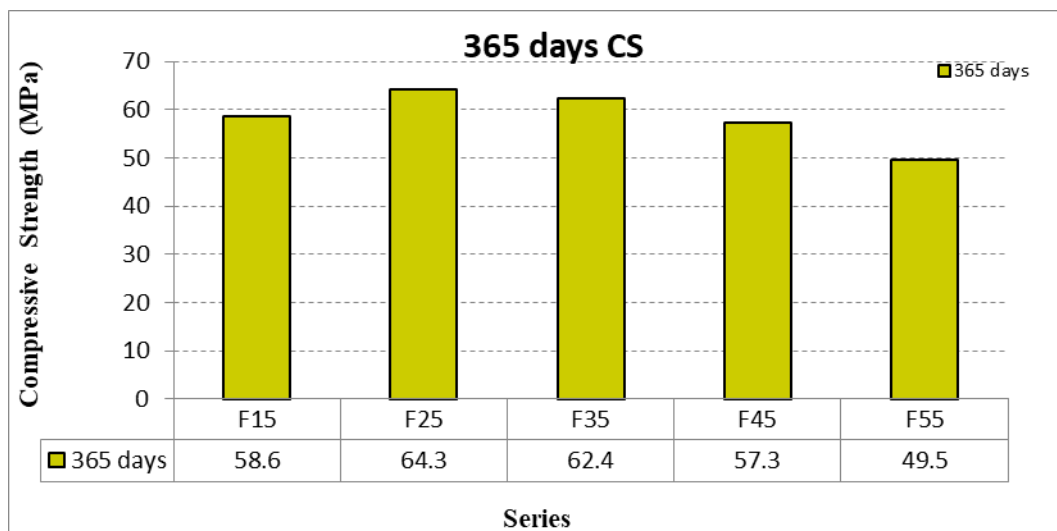


Figure 5.2.18: 365 days Compressive strength

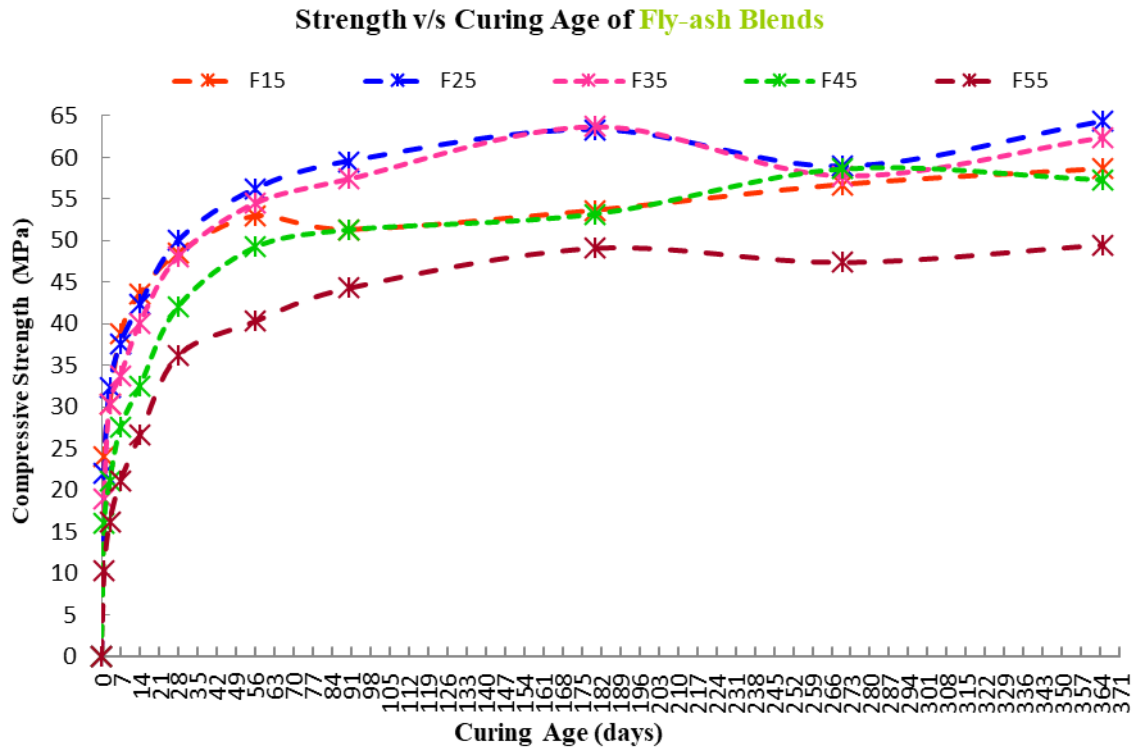


Figure 5.2.19: Compressive strength (CS) v/s Curing age up to 365 days

5.3 PART-3: S45, Fly-ash, and GGBFS Composite blend

All the tests conducted on specimen of S45+GGBFS+FA mixes are elaborated, as below:

5.3.1 Physical and Chemical Composition

The physical and chemical test results for the combinations of the blends referred to in Table 4.3 are tabulated in Table 5.3.1 as below:

Blend	Chemical Composition							
	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O
F15G25	43.83	29.62	11.26	3.51	4.48	1.90	1.29	0.17
F15G35	41.20	30.26	12.31	3.43	4.82	1.64	1.24	0.18
F25G25	37.91	33.61	13.12	3.65	4.28	1.42	1.26	0.16
F15G45	39.00	32.23	13.39	3.38	5.34	1.35	1.18	0.19
F25G35	35.50	34.33	14.10	3.58	4.60	1.24	1.21	0.16
F35G25	32.11	36.59	12.03	4.19	3.98	1.15	1.27	0.19
F15G55	36.69	33.03	14.40	3.26	5.78	1.10	1.14	0.20
F25G45	33.30	35.75	15.22	3.47	5.05	0.98	1.17	0.18
F35G35	29.74	37.94	12.60	4.14	4.54	0.91	1.22	0.17
F45G25	26.04	40.18	13.98	4.41	3.78	0.76	1.24	0.16

5.3.2 Particle Size Distribution (PSD)

Particle Size Distribution (PSD) of all ten composite blends is carried out by Laser Diffraction (LSD) using Malvern Mastersizer 3000 in water as dispersant medium (wet method) and plotted by 'Mie' Scattering Model Distribution.

Table 5.3.2 indicates the different particle diameter values of Dv (10), Dv (50), Dv (90), Dv (95), and Dv (100) of all ten composite blends, and Figures 5.3.1 to 5.3.10 shows the volume density to particle size.

Table 5.3.2: Particle Diameter values

Series	Particle Diameter in μm				
	Dv (10)	Dv (50)	Dv (90)	Dv (95)	Dv (100)
S45	1.720	9.921	54.291	-	-
F15-G25	3.862	20.268	72.455	99.262	270.467
F15-G35	3.643	19.824	70.572	97.706	271.375
F15-G45	3.587	19.431	68.895	97.107	350.241
F15-G55	3.557	19.114	65.744	91.003	307.170
F25-G25	3.910	20.985	80.150	111.041	271.898
F25-G35	4.045	20.525	77.619	108.845	271.887
F25-G45	3.736	19.901	74.386	104.232	308.232
F35-G25	4.201	22.746	94.887	132.004	343.719
F35-G35	4.166	21.918	91.495	126.566	307.271
F45-G25	4.276	23.093	97.290	132.956	349.280

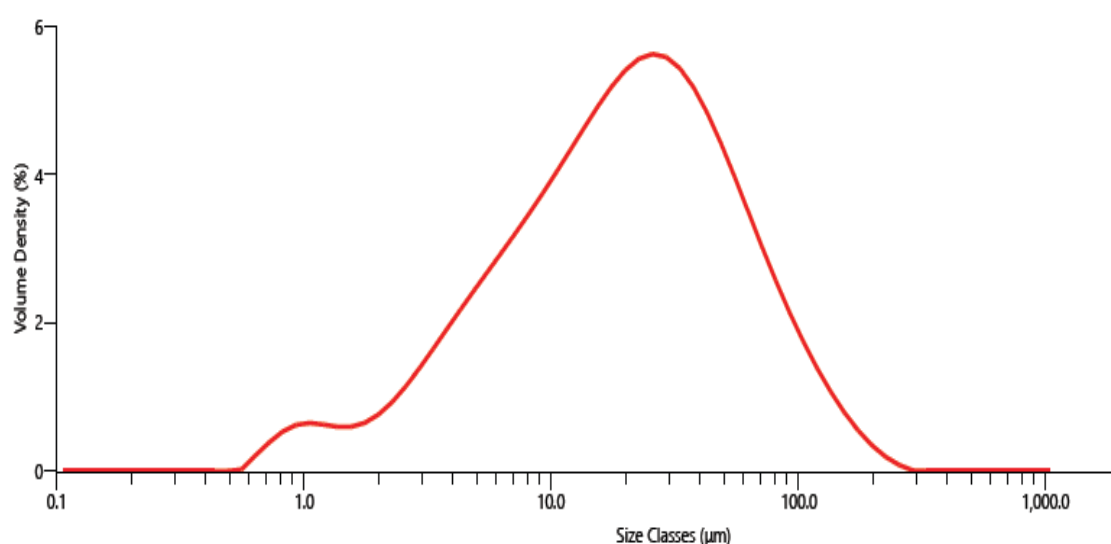


Figure 5.3.1: S45 + FA (15%) + GGBFS (25%)

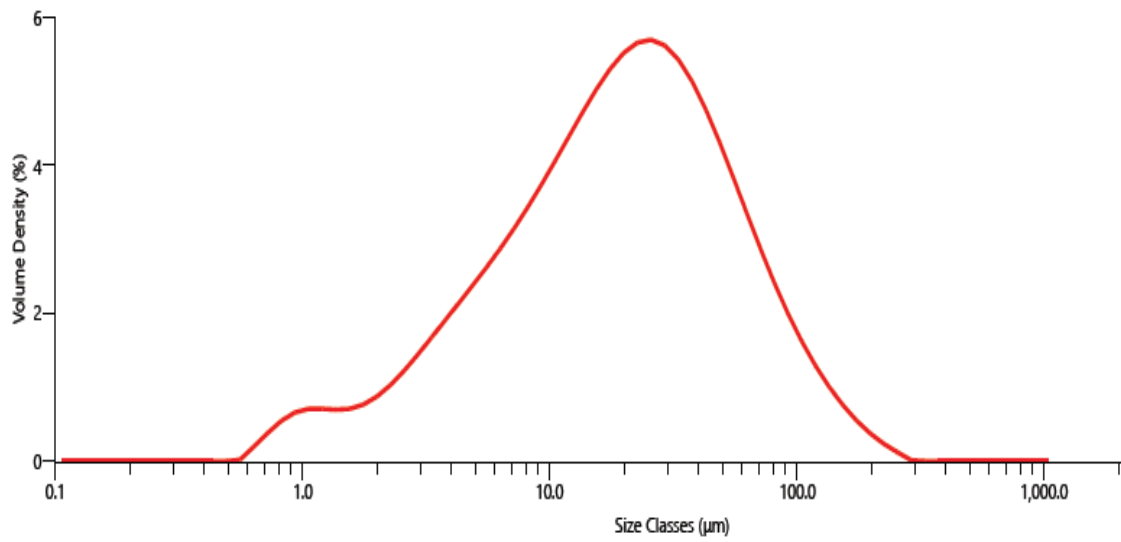


Figure 5.3.2: S45 + FA (15%) + GGBFS (35%)

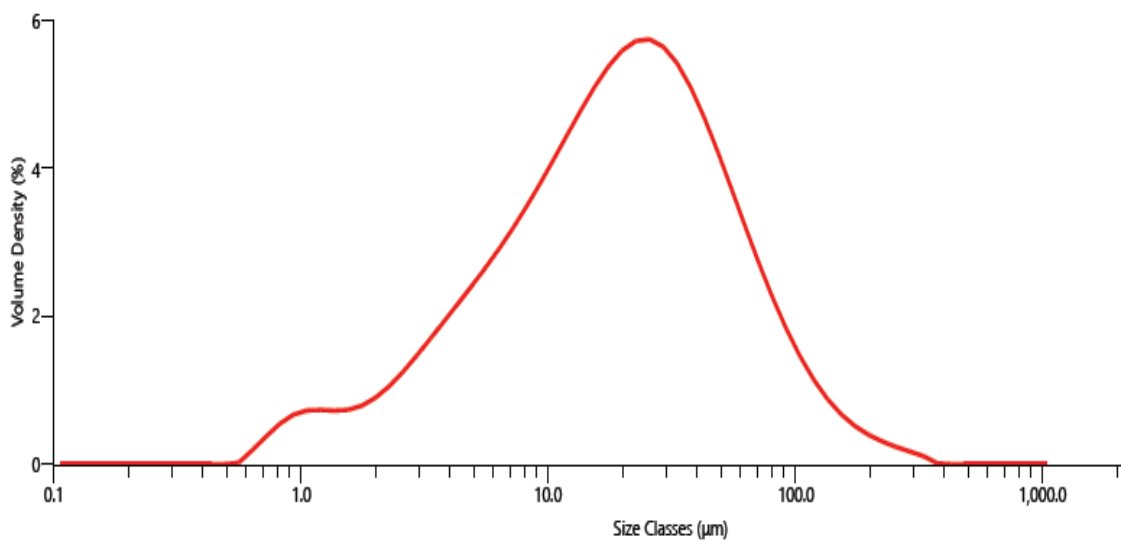


Figure 5.3.3: S45 + FA (15%) + GGBFS (45%)

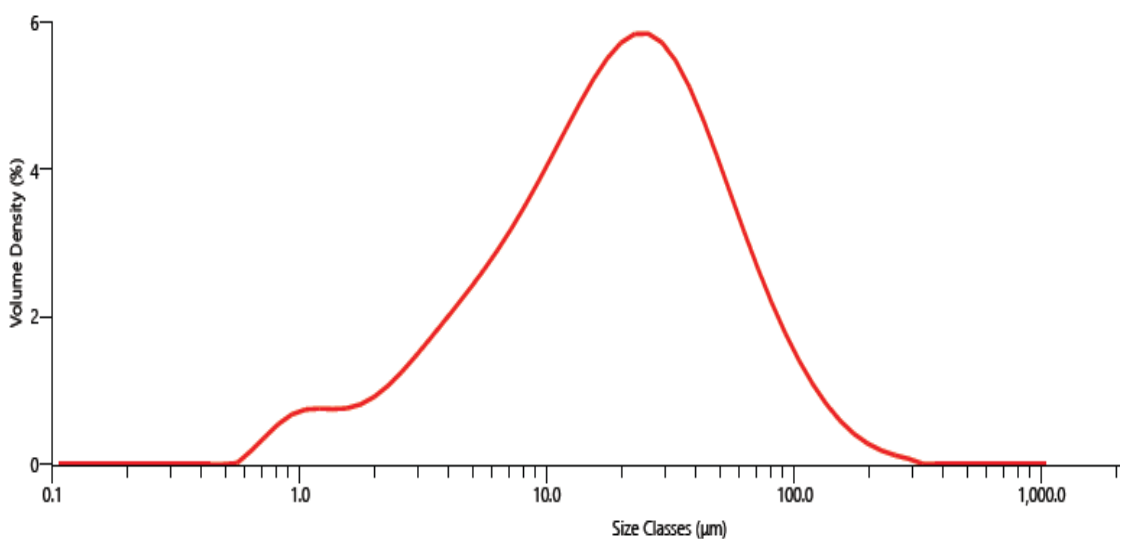


Figure 5.3.4: S45 + FA (15%) + GGBFS (55%)

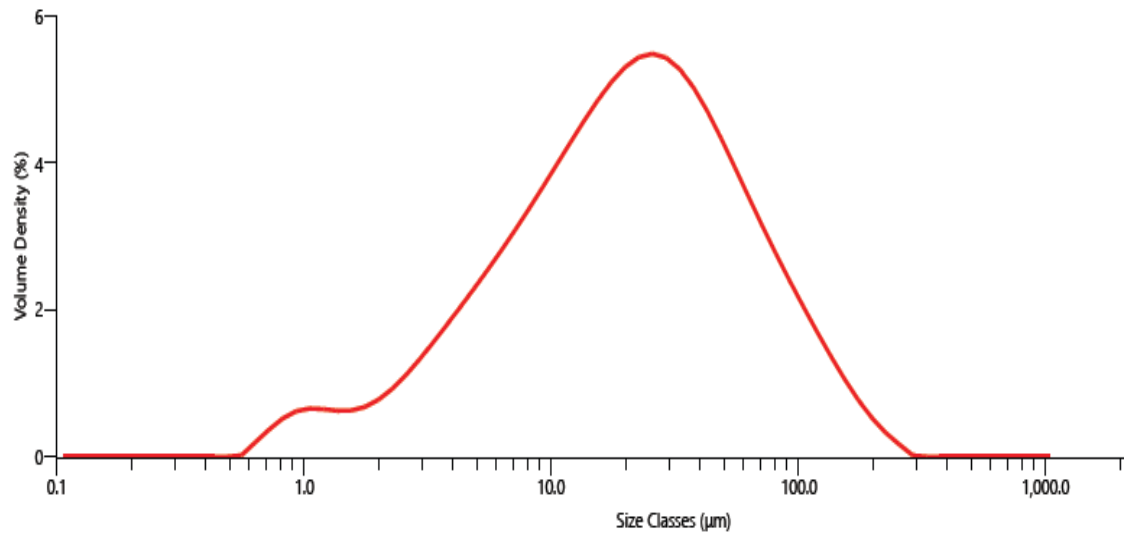


Figure 5.3.5: S45 + FA (25%) + GGBFS (25%)

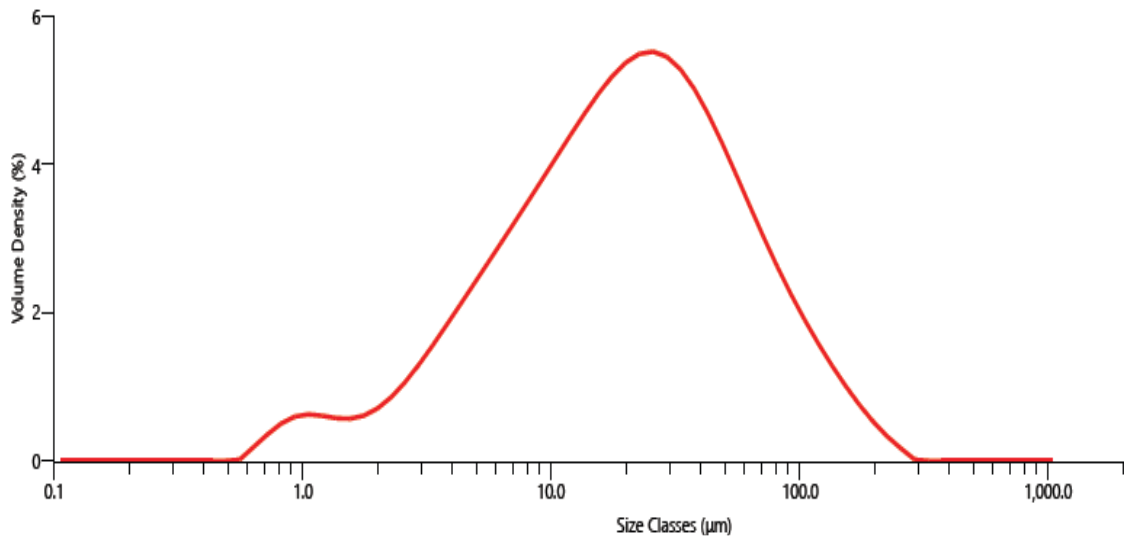


Figure 5.3.6: S45 + FA (25%) + GGBFS (35%)

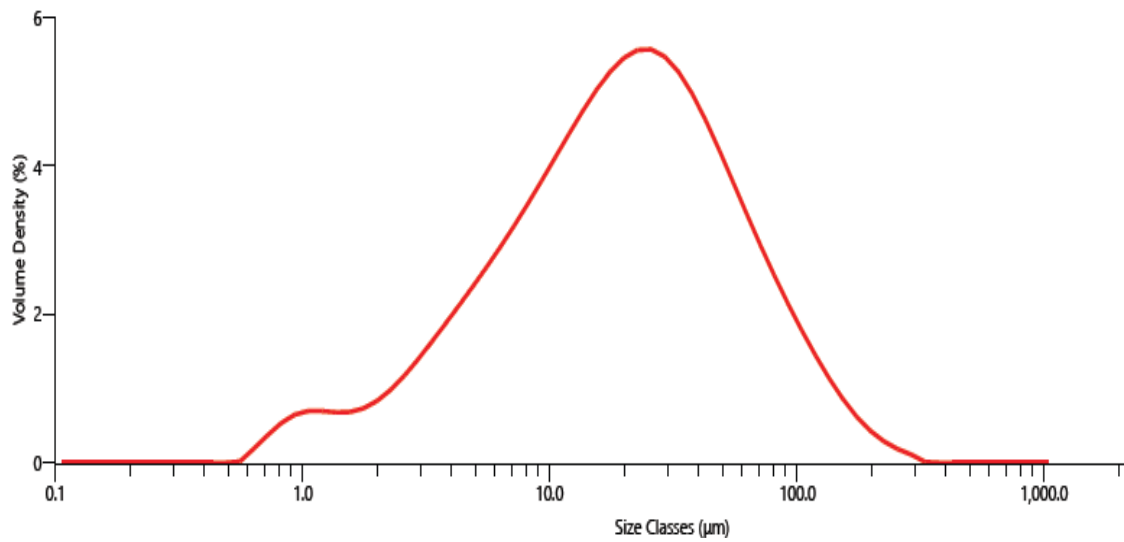


Figure 5.3.7: S45 + FA (25%) + GGBFS (45%)

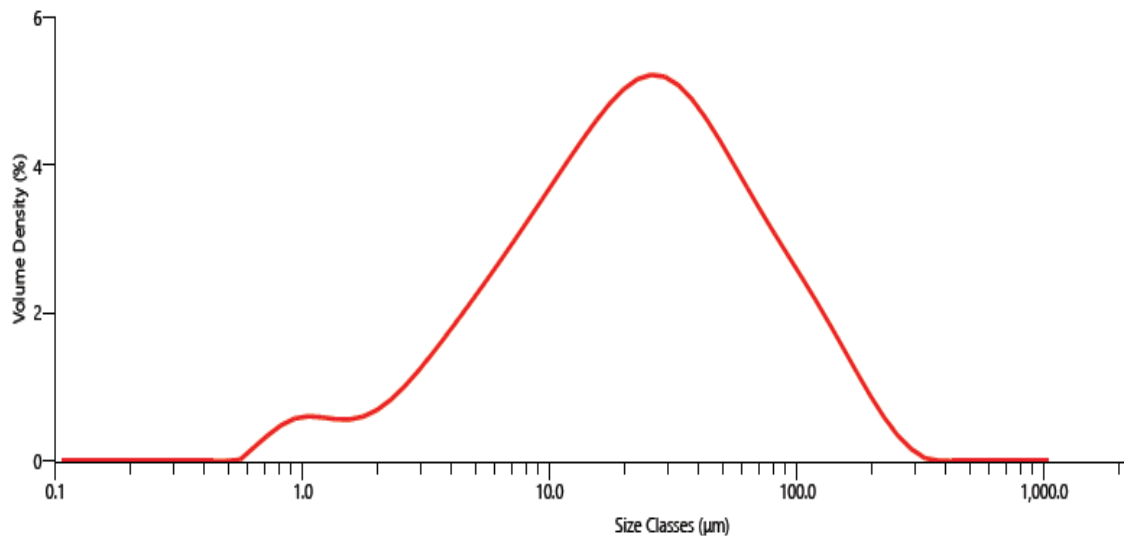


Figure 5.3.8: S45 + FA (35%) + GGBFS (25%)

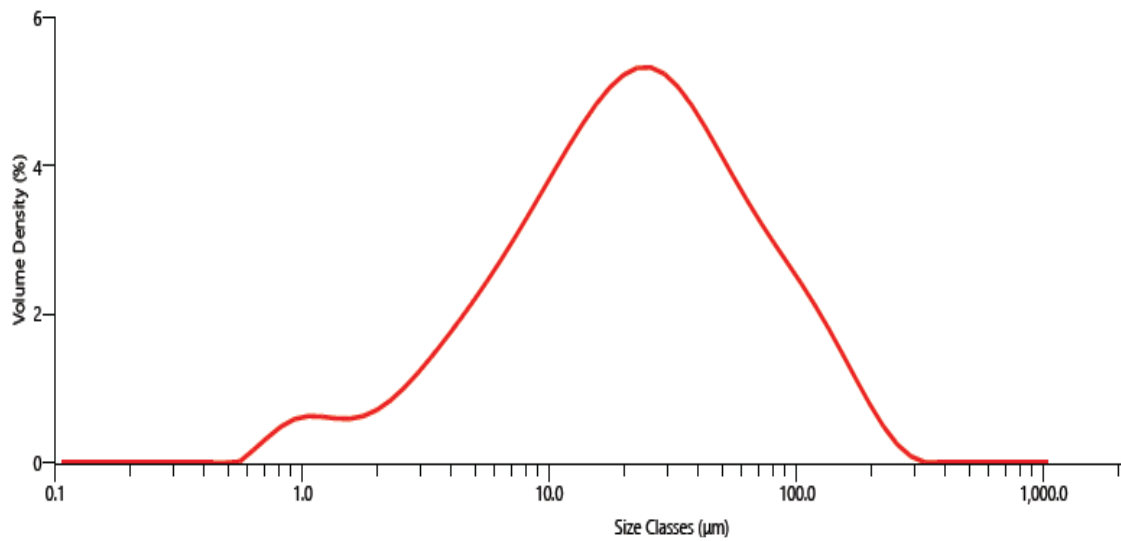


Figure 5.3.9: S45 + FA (35%) + GGBFS (35%)

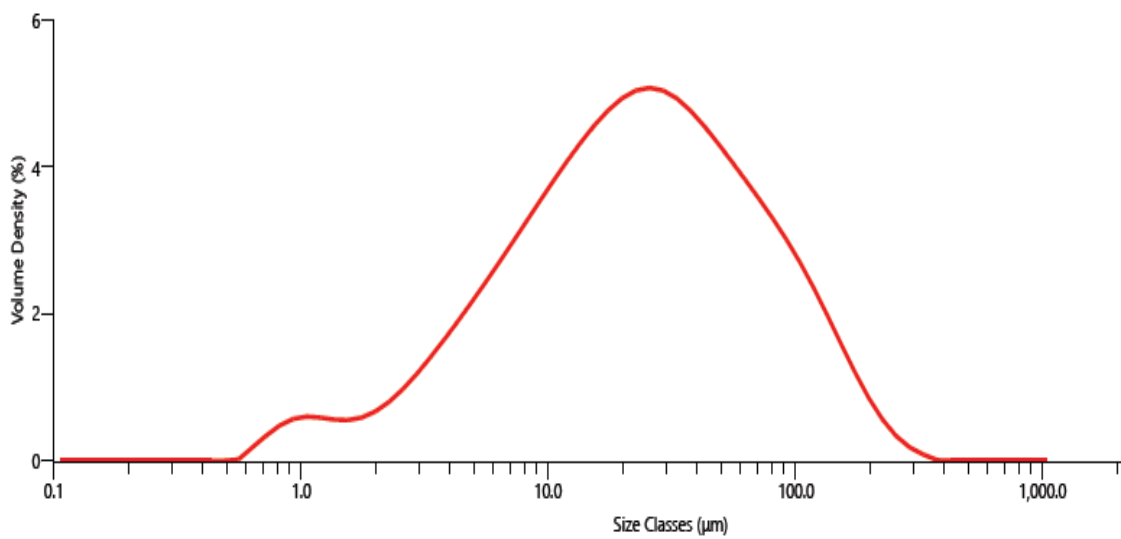


Figure 5.3.10: S45 + FA (45%) + GGBFS (25%)

5.3.3 Soundness

Determination of Soundness by Autoclave Method with procedures conforming to BIS: 4031 (Part-3) are carried out for all ten composite blends and the values are tabulated in Table 5.3.3.

Series	Standard Consistency (SC) %	Autoclave Soundness (AS)	Initial Setting Time (IST) (minutes)	Final Setting Time (FST) (minutes)
S45	26.0	0.104	125	205
F15-G25	27.5	0.040	160	240
F15-G35	28.0	0.024	140	220
F15-G45	28.0	-	145	230
F15-G55	28.5	-	135	220
F25-G25	28.0	-	180	260
F25-G35	28.0	0.120	170	250
F25-G45	28.0	-	165	245
F35-G25	27.5	-	180	260
F35-G35	28.0	-	185	265
F45-G25	27.5	-	125	215

5.3.4 Standard Consistency

Determination of Consistency by Vicat Apparatus with procedures conforming to BIS: 4031 (Part-4) are carried out on all blends and the values are tabulated in Table 5.3.3 and graphically represented in Figure 5.3.11.

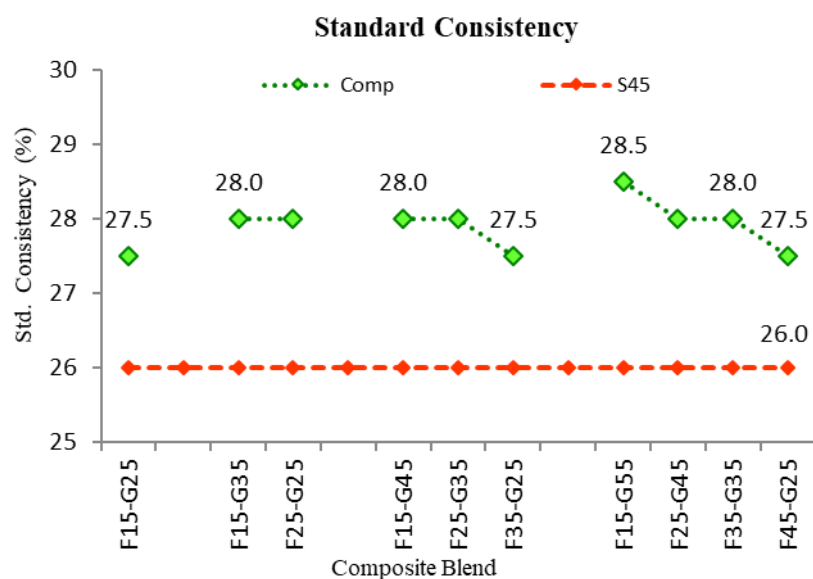


Figure 5.3.11: Standard Consistency

5.3.5 Initial and Final Setting Times

Determination of Initial and Final Setting Times by Vicat Apparatus with procedures conforming to BIS: 4031 (Part-5) are carried out on all blends and the values are tabulated in Table 5.3.3 and graphically represented in Figure 5.3.12.

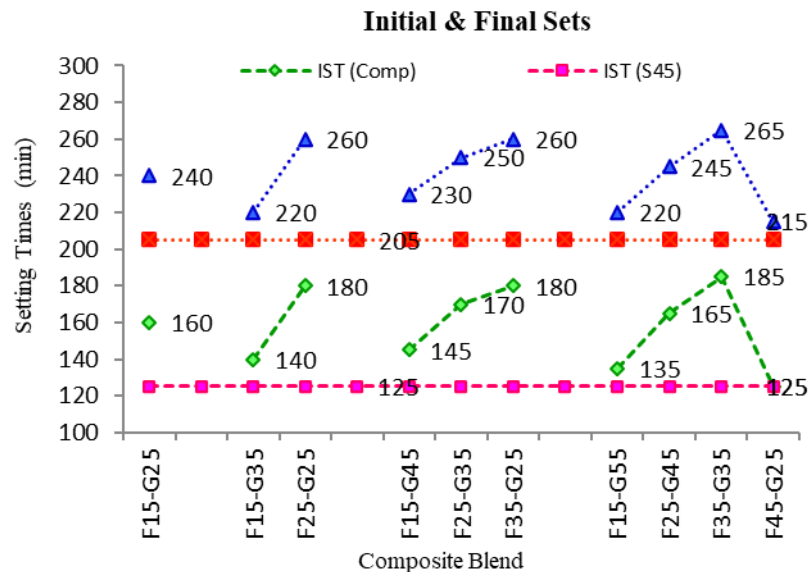


Figure 5.3.12: Initial (IST) and Final Setting Time (FST) values

5.3.6 Compressive Strength (CS) for curing ages at 1, 3, 7, 14, 28, 56, 90, 180, 270 and 365 days

Determination of Compressive Strength on composite blended cement mortar cubes with procedures conforming to BIS: 4031 (Part-6) are carried out, as follows:

Three specimen samples each for every blend are cast in 70.6mm x 70.6mm x 70.6mm mold conforming to BIS: 10080 with Base Material (i.e. S45), Fly-ash, and GGBFS composite blended cement, Standard Sand (fine and coarse) used for cement testing conforming to BIS: 650 in equal proportion of 200gms each and mixed with a percentage of water derived by standard consistency and compacted with vibratory machine conforming to BIS: 10080, for the desired curing ages of 1, 3, 7, 14, 28, 56, 90, 180, 270 and 365 days.

The average values of Compressive Strength (CS) of all ten blends for curing ages of 1, 3, 7, 14, 28, 56, 90, 180, 270 and 365 days are tabulated in Table 5.3.4 and graphically represented in Figure 5.3.13.

Table 5.3.4: Compressive Strength (CS) values

Series	Compressive Strength (CS) in MPa									
	1 day	3 days	7 days	14 days	28 days	56 days	90 days	180 days	270 days	365 days
S45	32.5	39.2	45.5	48.7	55.0	-	-	-	-	-
F15-G25	19.4	29.5	39.5	45.0	49.4	53.1	55.1	57.1	59.2	60.6
F15-G35	15.0	26.5	34.2	39.2	50.1	53.9	54.0	59.0	60.2	60.7
F15-G45	12.4	22.7	30.6	36.8	41.4	44.3	43.6	49.9	52.9	53.3
F15-G55	8.0	20.1	27.0	29.1	36.1	39.1	40.0	44.9	47.7	46.2
F25-G25	14.5	26.3	36.3	45.4	47.9	50.2	52.7	54.3	62.0	63.6
F25-G35	12.5	22.0	35.9	38.1	45.5	48.3	50.8	53.6	55.3	56.6
F25-G45	11.5	20.2	28.6	35.3	38.2	40.6	49.1	51.3	51.5	52.1
F35-G25	11.8	21.3	30.9	37.3	42.2	45.5	47.2	50.4	48.6	52.7
F35-G35	8.3	15.4	25.1	30.2	35.8	38.6	44.5	48.3	44.7	45.3
F45-G25	8.1	15.8	23.6	30.9	34.5	37.4	39.2	42.0	48.4	47.5

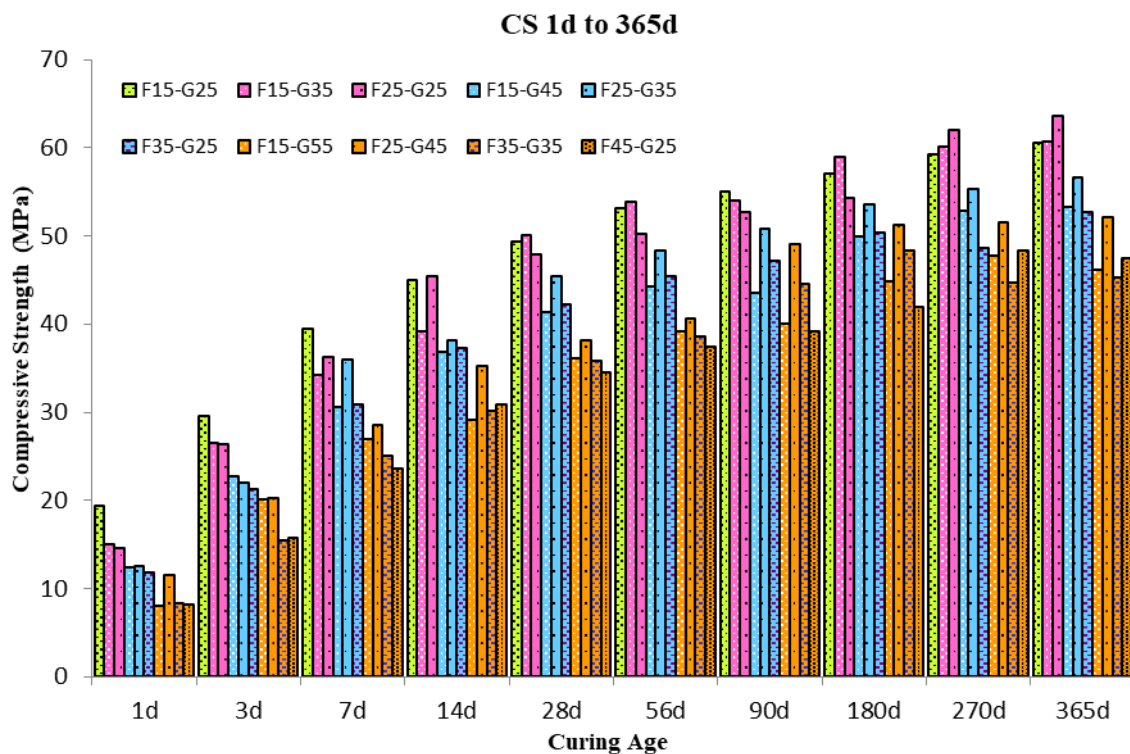


Figure 5.3.13: Compressive strength for curing ages from 1 to 365 days

5.3.7 Categorization of Composite Blends based on total combined substitution of Fly-ash and Slag for better analysis of the results obtained

5.3.7.1 Categories based on total combined substitution are tabulated in Table 5.3.5.

Table 5.3.5 shows the categorization of ternary blends based on total replacement of SCMs with fly-ash and GGBFS combined together in S45.

Table 5.3.5: Categories based on total combined substitution

Category	Series	Fly-ash Substitution (%)	GGBFS Substitution (%)	TOTAL SCM Substitution (%)
COM40	F15-G25	15	25	40
COM50	F15-G35	15	35	50
	F25-G25	25	25	50
COM60	F15-G45	15	45	60
	F25-G35	25	35	60
	F35-G25	35	25	60
COM70	F15-G55	15	55	70
	F25-G45	25	45	70
	F35-G35	35	35	70
	F45-G25	45	25	70

5.3.7.2 Particle Size Distribution (PSD)

Table 5.3.6 denote the particle size distribution of ternary blends based on categorization by combined substitution levels of SCMs in S45.

Table 5.3.6: Particle Diameter values

Category	Series	Particle Diameter in μm				
		Dv (10)	Dv (50)	Dv (90)	Dv (95)	Dv (100)
S45	S45	1.720	9.921	54.291	-	-
COM40	F15-G25	3.862	20.268	72.455	99.262	270.467
COM50	F15-G35	3.643	19.824	70.572	97.706	271.375
	F25-G25	3.910	20.985	80.150	111.041	271.898
COM60	F15-G45	3.587	19.431	68.895	97.107	350.241
	F25-G35	4.045	20.525	77.619	108.845	271.887
	F35-G25	4.201	22.746	94.887	132.004	343.719
COM70	F15-G55	3.557	19.114	65.744	91.003	307.170
	F25-G45	3.736	19.901	74.386	104.232	308.232
	F35-G35	4.166	21.918	91.495	126.566	307.271
	F45-G25	4.276	23.093	97.290	132.956	349.280

5.3.7.3 Standard Consistency, Soundness, Initial/Final Setting Times

Table 5.3.7 indicate the values of standard consistency, autoclave soundness and initial cum final setting times of ternary blends categorized on total SCMs substitution. Figure 5.3.14 sketches the standard consistency while Figure 5.3.15 denote the initial and final setting times of ternary blends in form of combined substitution categorization and compared with the controlled mic (CM) i.e. S45.

Table 5.3.7: SC, AS, IST, FST values

Category	Series	Standard Consistency (SC) %	Autoclave Soundness (AS)	Initial Setting Time (IST) (minutes)	Final Setting Time (FST) (minutes)
CM	S45	26.0	0.104	125	205
COM40	F15-G25	27.5	0.040	160	240
COM50	F15-G35	28.0	0.024	140	220
	F25-G25	28.0	-	180	260
	F15-G45	28.0	-	145	230
COM60	F25-G35	28.0	0.120	170	250
	F35-G25	27.5	-	180	260
	F15-G55	28.5	-	135	220
COM70	F25-G45	28.0	-	165	245
	F35-G35	28.0	-	185	265
	F45-G25	27.5	-	125	215

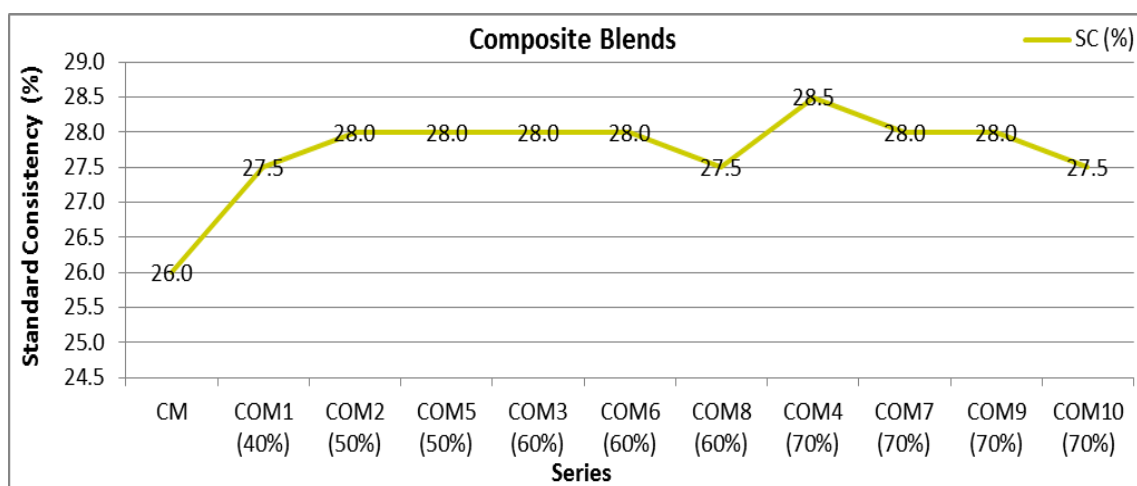


Figure 5.3.14: Standard Consistency

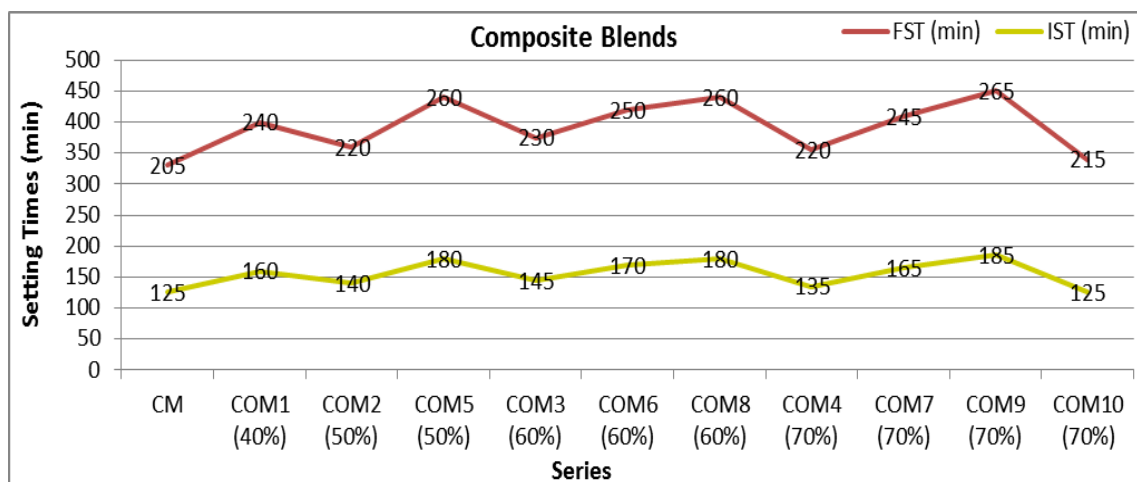


Figure 5.3.15: Initial (IST) and Final Setting Time (FST) values

5.3.7.4 Compressive Strength (CS) for curing ages at 1, 3, 7, 14, 28, 56, 90, 180, 270 and 365 days

Table 5.3.8 tabulates the compressive strength of categorized ternary blends mortar cubes for curing ages from 1-day to 28-days while Table 5.3.9 list the strength values for 56-days to 365-days curing ages.

Table 5.3.8: Compressive Strength (CS) values from 1 day to 28 days

Category	Series	Compressive Strength (CS) in MPa				
		1 day	3 days	7 days	14 days	28 days
CM	S45	32.5	39.2	45.5	48.7	55.0
COM40	F15-G25	19.4	29.5	39.5	45.0	49.4
COM50	F15-G35	15.0	26.5	34.2	39.2	50.1
	F25-G25	14.5	26.3	36.3	45.4	47.9
COM60	F15-G45	12.4	22.7	30.6	36.8	41.4
	F25-G35	12.5	22.0	35.9	38.1	45.5
COM70	F35-G25	11.8	21.3	30.9	37.3	42.2
	F15-G55	8.0	20.1	27.0	29.1	36.1
	F25-G45	11.5	20.2	28.6	35.3	38.2
	F35-G35	8.3	15.4	25.1	30.2	35.8
	F45-G25	8.1	15.8	23.6	30.9	34.5

Table 5.3.9: Compressive Strength (CS) values from 56 days to 365 days

Category	Series	Compressive Strength (CS) in MPa				
		56 days	90 days	180 days	270 days	365 days
CM	S45	-	-			
COM40	F15-G25	53.1	55.1	57.1	59.2	60.6
COM50	F15-G35	53.9	54.0	59.0	60.2	60.7
	F25-G25	50.2	52.7	54.3	62.0	63.6
COM60	F15-G45	44.3	43.6	49.9	52.9	53.3
	F25-G35	48.3	50.8	53.6	55.3	56.6
COM70	F35-G25	45.5	47.2	50.4	48.6	52.7
	F15-G55	39.1	40.0	44.9	47.7	46.2
	F25-G45	40.6	49.1	51.3	51.5	52.1
	F35-G35	38.6	44.5	48.3	44.7	45.3
	F45-G25	37.4	39.2	42.0	48.4	47.5

Figure 5.3.16, Figure 5.3.17 and Figure 5.3.18 shows the projection of strength values for various 50%, 60% and 70% combined SCMs substitution of ternary blends in S45, respectively.

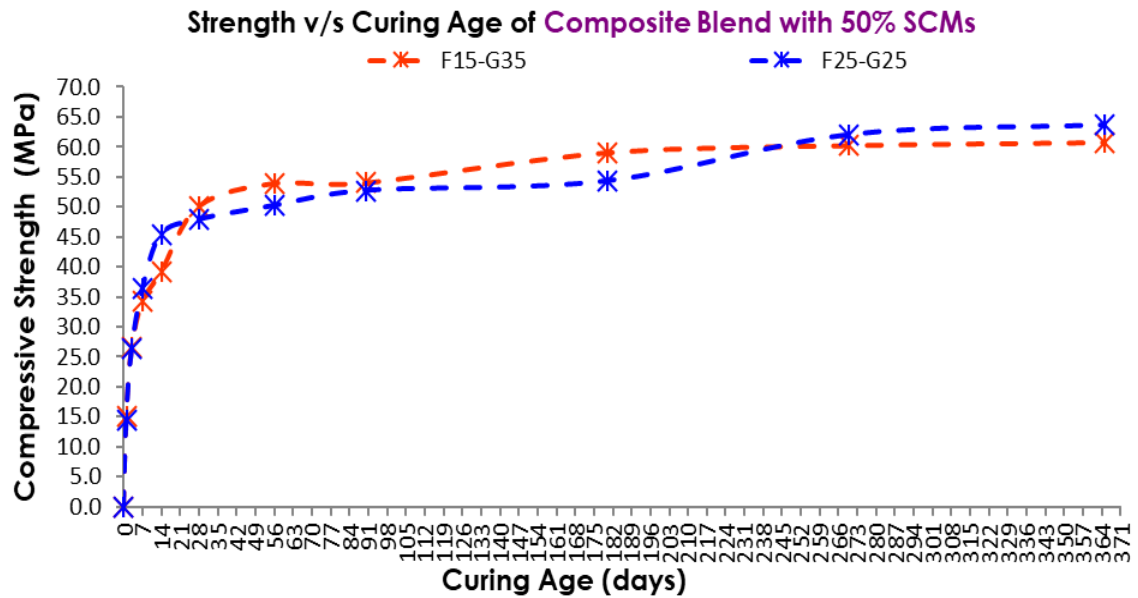


Figure 5.3.16: Compressive strength of 50% SCMs for curing ages up to 365 days

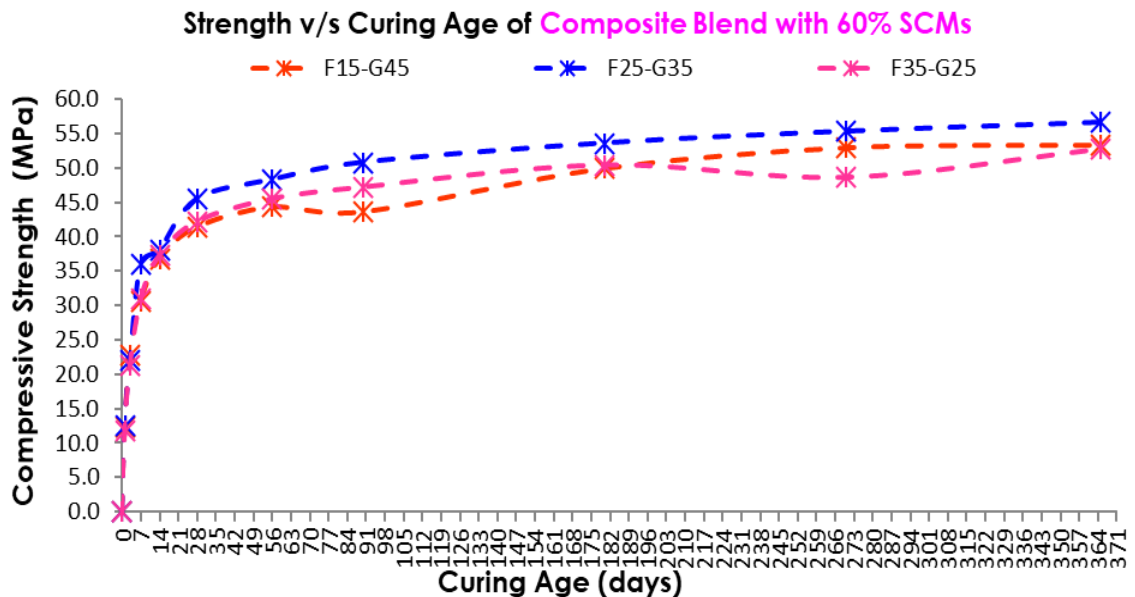


Figure 5.3.17: Compressive strength of 60% SCMs for curing ages up to 365 days

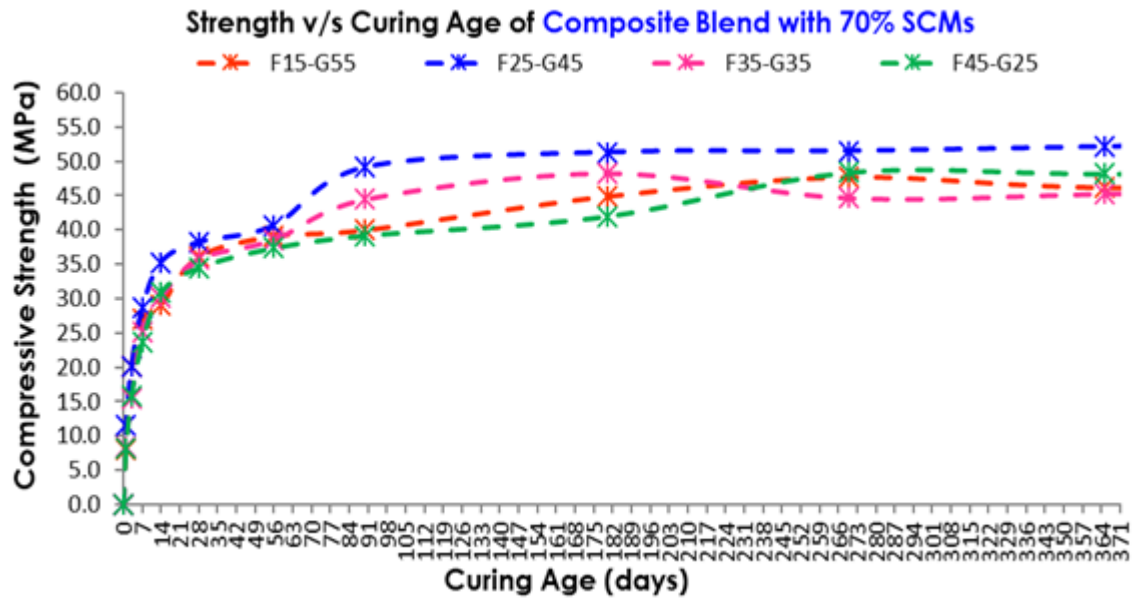


Figure 5.3.18: Compressive strength of 70% SCMs for curing ages up to 365 days

Figure 5.3.19 and Figure 5.3.20 shows the strength values of various categorized ternary blends based on total combined SCMs substitution in S45 for curing ages from 1-day to 28-days and from 28-days to 365-days, respectively.

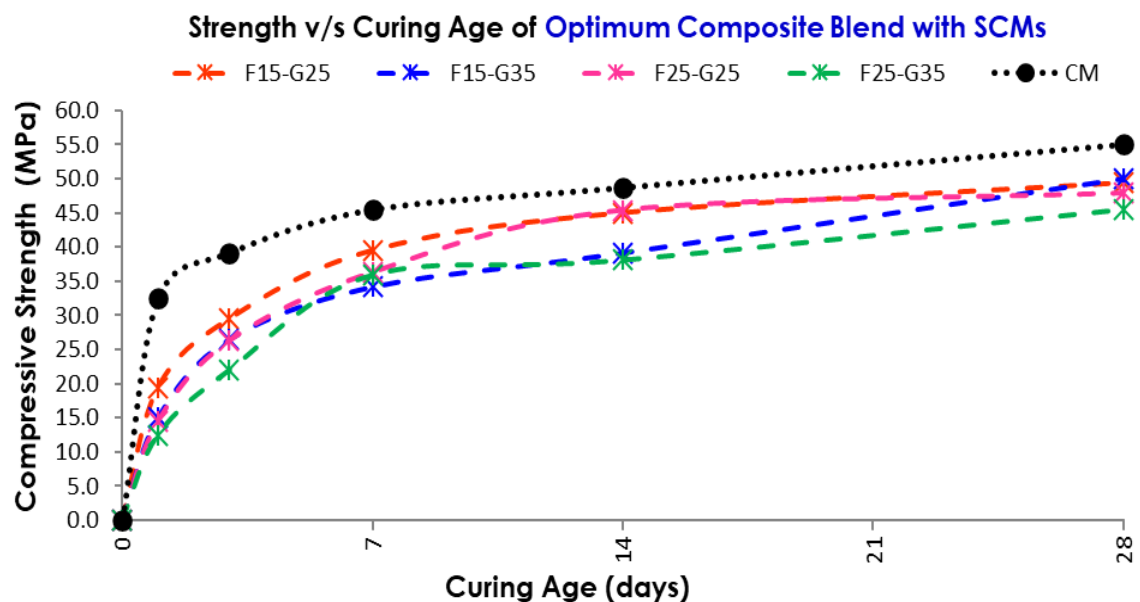


Figure 5.3.19: Compressive strength of optimum SCMs for curing ages up to 28 days

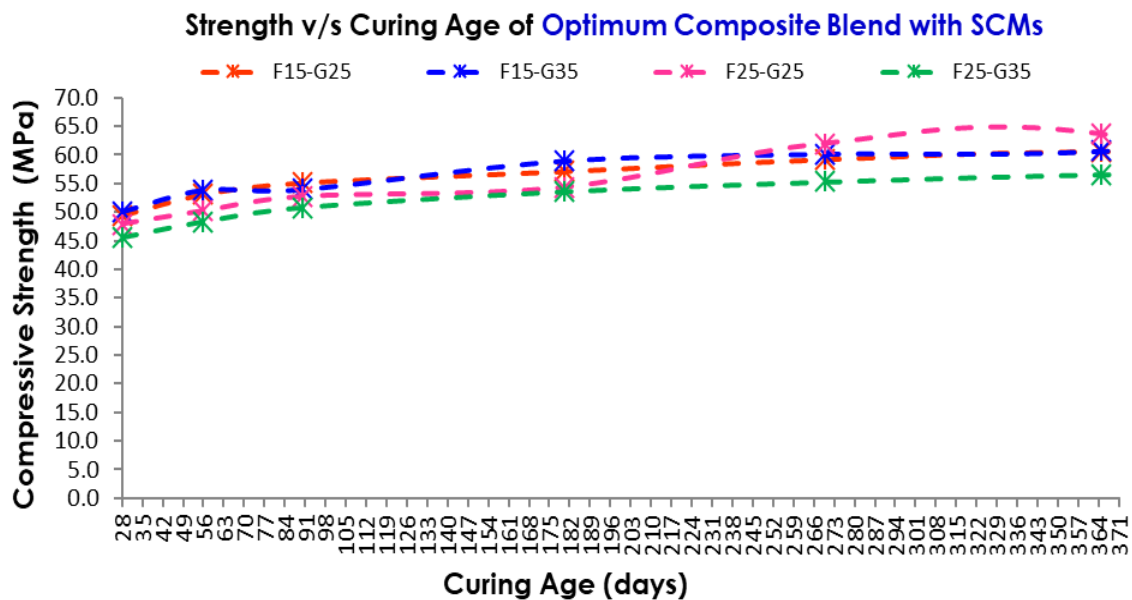


Figure 5.3.20: Compressive strength of optimum SCMs for curing ages from 28 days up to 365 days

5.4 PART-4: Comparison of optimized Binary and Ternary blends of S45, Slag and Fly-ash with present commercial cements viz. Portland Slag Cement (PSC), Portland Pozzolana Cement (PPC) and Composite Cement (CC)

The results of the improved blend in binary and ternary form with S45, GGBFS and Fly-ash are compared with commercially available cements, for understanding the nuance performance of PSD in cement matrix.

5.4.1 Comparison of S45+GGBFS blends with JK-Portland Slag Cement (PSC)

5.4.1.1 Compressive Strength of MORTAR cubes upto 28 days

Results obtained from the experimental study for S45+GGBFS blends are compared with commercially available Portland Slag Cement (PSC) of JK Cement Ltd. make.

Following are the graphical representation of compressive strength comparison for 1, 3, 7, 14 and 28 days curing ages at Figure 5.4.1.1 to 5.4.1.5 for Slag blends in comparison with S45 and commercial PSC.

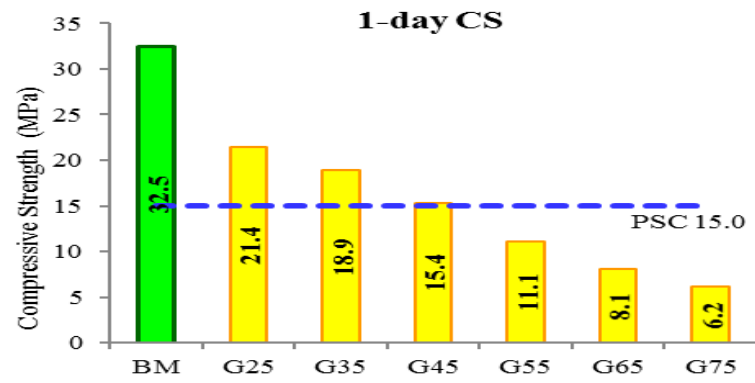


Figure 5.4.1.1: Comparison of 1-day compressive strength

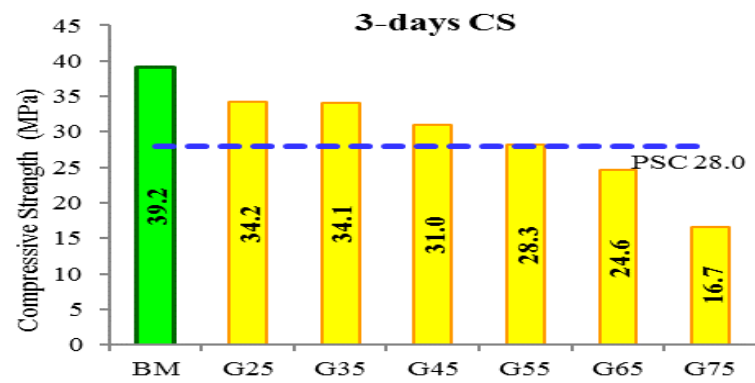


Figure 5.4.1.2: Comparison of 3-days compressive strength

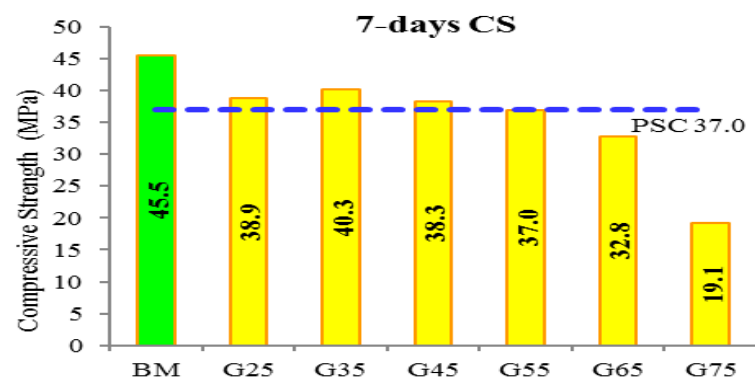


Figure 5.4.1.3: Comparison of 7-days compressive strength

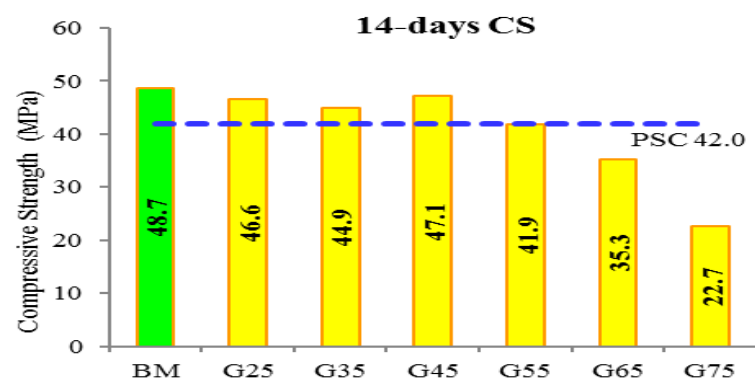


Figure 5.4.1.4: Comparison of 14-days compressive strength

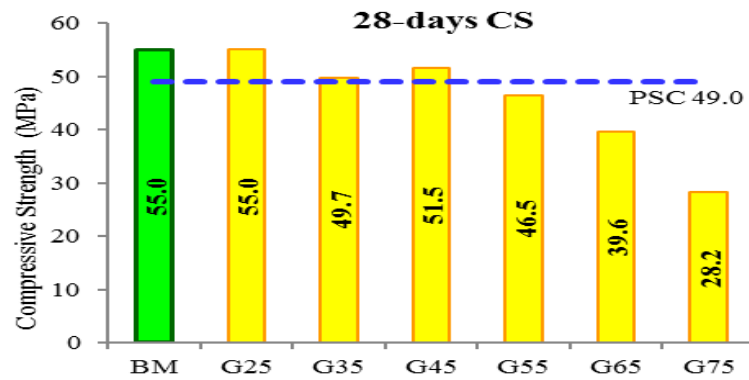


Figure 5.4.1.5: Comparison of 28-days compressive strength

The compressive strength results demonstrate that the engineered cement blends containing optimized proportions of finely ground GGBFS exhibit superior performance compared with commercially available Portland Slag Cement (PSC). Among the various combinations investigated, the S45 + 45% GGBFS blend achieved the highest overall performance, exhibiting strength improvements of approximately 11%, 4%, 12%, and 5% at 3, 7, 14, and 28 days, respectively, compared to the reference PSC. These results indicate that a 45% slag replacement level represents an optimum balance between clinker hydration and supplementary cementitious material (SCM) reactivity.

The enhanced performance of the optimized blends is primarily attributed to the modified particle size distribution and the increased proportion of reactive fines introduced through the stimulator process. The finer particles provide a larger specific surface area, which accelerates the hydration process by creating additional nucleation sites for the precipitation of hydration products. This leads to rapid formation of calcium silicate hydrate (C-S-H) gel during the early stages of hydration, thereby contributing to improved early-age strength development.

The fine slag particles also act as micro-fillers, occupying interstitial voids between larger cement grains and producing a denser particle packing arrangement. This refined microstructure reduces pore connectivity, minimizes internal stress concentrations, and restricts moisture movement within the cement matrix. Consequently, the potential for delayed expansion and microcrack formation is significantly reduced, resulting in lower soundness values and enhanced dimensional stability.

The superior soundness observed in the S45 + 45% GGBFS blend can therefore be attributed to three synergistic mechanisms: (i) dilution of expansive clinker phases, (ii)

microstructural densification through improved particle packing, and (iii) increased pozzolanic and latent hydraulic activity leading to the formation of additional C-S-H gel. These mechanisms collectively enhance volumetric stability while simultaneously improving compressive strength and durability.

The findings indicate that the optimization of particle size distribution, rather than alteration of clinker chemistry, is a highly effective approach for improving cement quality. The optimum level of 45% GGBFS replacement provides sufficient reactive fines to maximize hydration efficiency and soundness performance while maintaining excellent strength characteristics. Furthermore, such optimization offers economic and environmental benefits through reduced clinker consumption, lower production costs, and decreased carbon emissions. Therefore, the study establishes that controlled incorporation of reactive fines is a key parameter governing both the mechanical performance and soundness of binary and ternary blended cement systems.

5.4.1.2 Compressive Strength of S45+GGBFS from 56 to 365 days curing ages

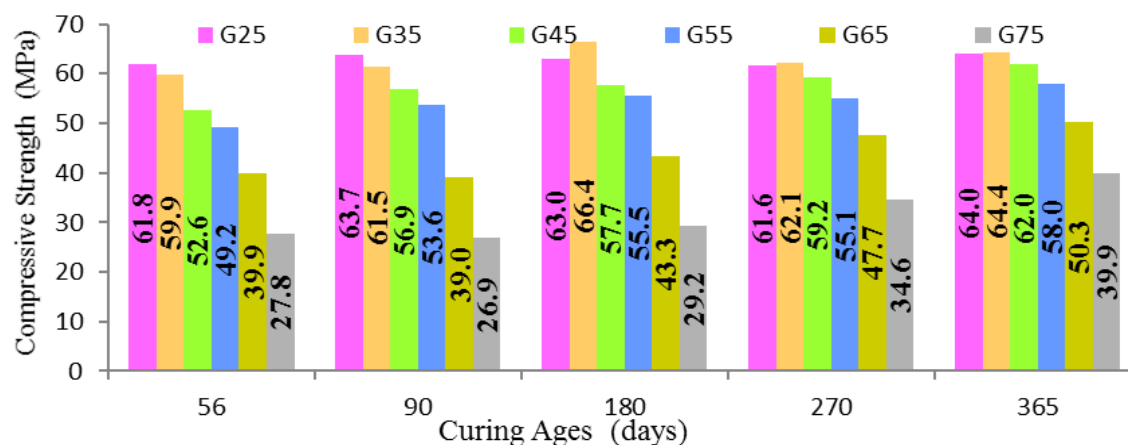


Figure 5.4.1.6: Compressive strength of S45+GGBFS from 56 to 365 days

Figure 5.4.1.6 presents the long-term compressive strength development of slag-blended cement systems from 56 to 365 days. The results reveal two distinct trends. Blends containing up to 35% slag show strength gain up to approximately 180 days, beyond which the increase becomes marginal, indicating that the secondary hydration reactions have largely ceased due to limited availability of reactive SCM particles and calcium hydroxide.

In contrast, blends containing 45% to 75% slag continue to gain strength beyond 180 days and up to 365 days. This sustained strength development is attributed to ongoing

secondary hydration reactions between GGBFS and the calcium hydroxide generated from OPC hydration, resulting in the continued formation of additional C-S-H gel and progressive matrix densification.

The enhanced long-term performance of the 45% slag blend is closely linked to its optimized particle size distribution (PSD). The improved PSD promotes efficient particle packing, reduces voids, and increases the contact area between OPC hydration products and slag particles. This facilitates prolonged secondary hydration and contributes to both physical and chemical densification of the cement matrix.

The results demonstrate that the G45 blend provides the optimum balance between clinker content and reactive slag, enabling maximum utilization of secondary hydration while maintaining superior particle packing characteristics. Consequently, G45 exhibits enhanced long-term strength, durability, and microstructural stability, confirming that optimized PSD plays a critical role in governing the efficiency of secondary hydration reactions in blended cement systems.

5.4.1.3 Compressive Strength of optimized S45+GGBFS (45%) CONCRETE cubes up-to 28 days curing ages

Results obtained from the experimental study for optimized S45+GGBFS (45%) blend is compared with commercially available Portland Slag Cement (PSC) of JK Cement Ltd. make.

Following are the graphical representation of M25 and M40 concrete compressive strength comparison for 1, 3, 7, 14 and 28 days curing ages.

Figures 5.4.1.7 and 5.4.1.8 below present the compressive strength performance of concrete produced using the optimized G45 blended cement in comparison with commercially available JK-PSC for M25 and M40 grades of concrete. The objective of this phase of the study was to evaluate whether the improvements observed at the cement level are translated into the performance of concrete.

The results indicate that the optimized blend consistently outperforms the commercial PSC, particularly during the early stages of hydration. For M25 concrete, strength gains of 43%, 69%, and 15% were achieved at 7, 14, and 28 days, respectively, whereas for M40 concrete, strength improvements of 17%, 32%, and 21% were recorded at 3, 7, and

14 days, respectively. The results clearly demonstrate that the optimized cement blend develops significantly higher early-age strength compared to the commercial PSC.

The superior early-age performance is primarily attributed to the optimized particle size distribution and improved particle packing achieved through the stimulator process. The presence of a well-graded distribution of reactive fines increases the available surface area for hydration and provides additional nucleation sites for the formation of hydration products. This accelerates the primary hydration process and promotes rapid formation of C-S-H gel, resulting in higher strength development during the first 14 days.

As hydration progresses, the contribution of secondary hydration reactions involving the slag component becomes more prominent. The finely distributed SCM particles react with the calcium hydroxide released during OPC hydration, generating additional C-S-H gel and further refining the pore structure. Consequently, the concrete matrix becomes denser and more homogeneous, contributing to sustained strength development and improved durability characteristics.

Although the rate of strength gain beyond 14 days follows the normal trend generally observed in blended cement systems, the optimized blend continues to maintain a strength advantage over the commercial PSC. This indicates that the improved particle packing not only enhances early-age hydration but also creates favorable conditions for long-term secondary hydration reactions.

Overall, the results confirm that the G45 blend represents the optimum combination of OPC and SCM content. The optimized particle size distribution ensures efficient packing of particles, enhanced hydration kinetics, superior early-age strength, and continued long-term strength development. Therefore, the improved performance of both M25 and M40 concretes validates the effectiveness of the optimized blend in achieving enhanced mechanical properties, greater stability during the early stages of concrete hardening, and improved long-term durability in accordance with codal requirements.

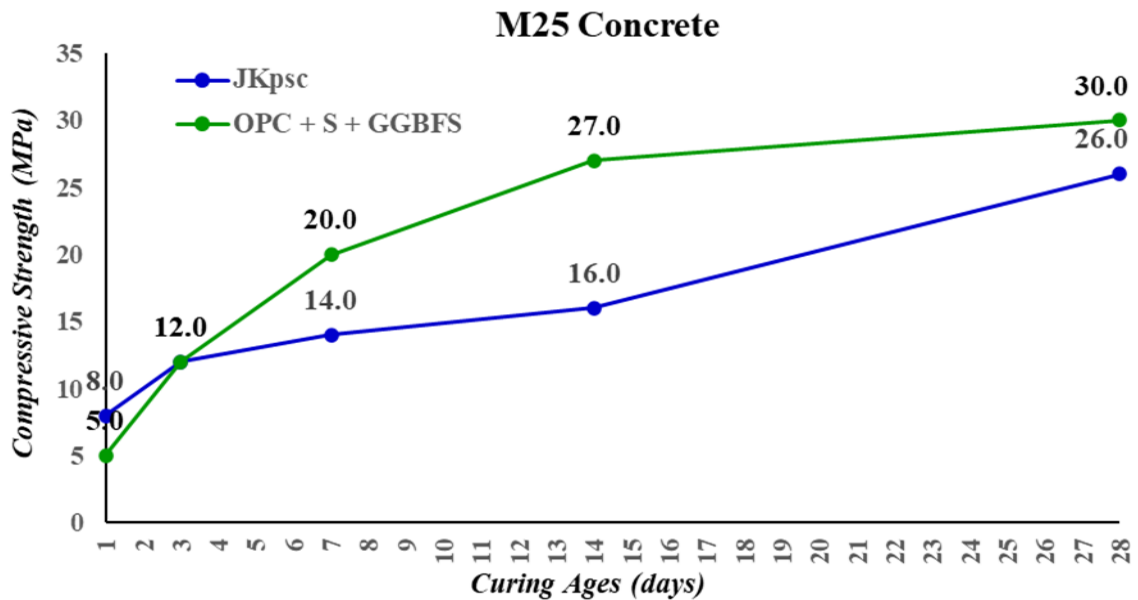


Figure 5.4.1.7: Compressive strength of S45+GGBFS M25-Concrete up-to 28 days

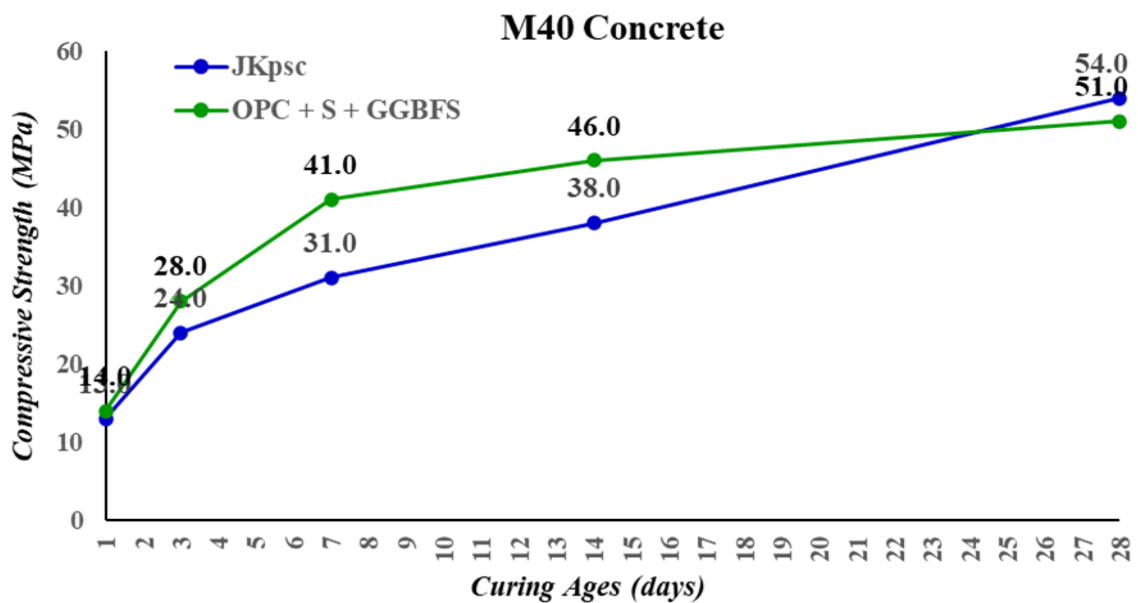


Figure 5.4.1.8: Compressive strength of S45+GGBFS M40-Concrete up-to 28 days

5.4.2 Comparison of S45+FA blends with JK-Portland Pozzolana Cement (PPC)

5.4.2.1 Compressive Strength of MORTAR cubes upto 28 days

Results obtained from the experimental study for S45+FA blends are compared with commercially available Portland Pozzolana Cement (PPC) of JK Cement Ltd. make.

Following are the graphical representation of compressive strength comparison for 1, 3, 7, 14 and 28 days curing ages at Figure 5.4.2.1 to 5.4.2.5 for Fly-ash blends in comparison with S45 and commercial Premium PPC and PPC.

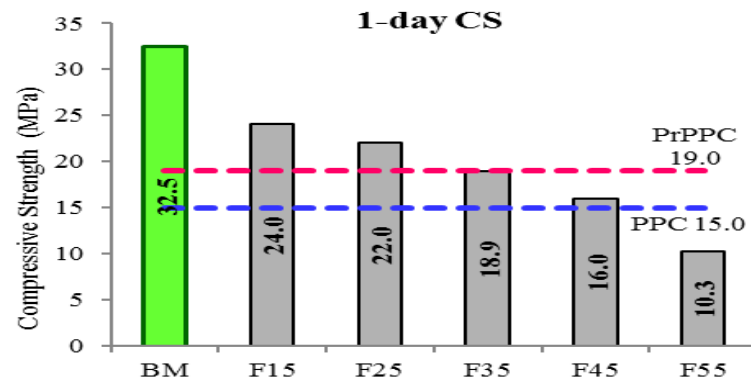


Figure 5.4.2.1: Comparison of 1-day compressive strength

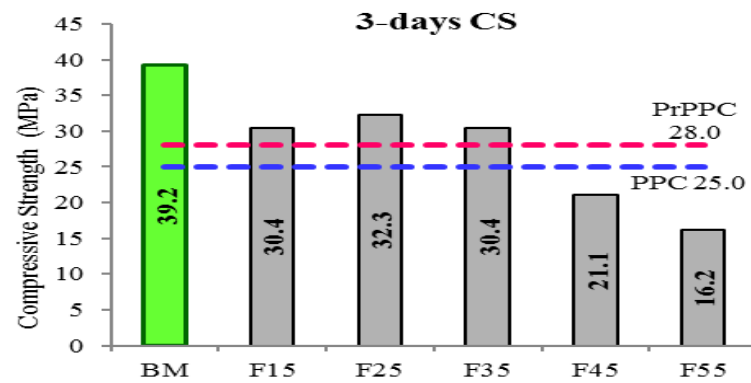


Figure 5.4.2.2: Comparison of 3-days compressive strength

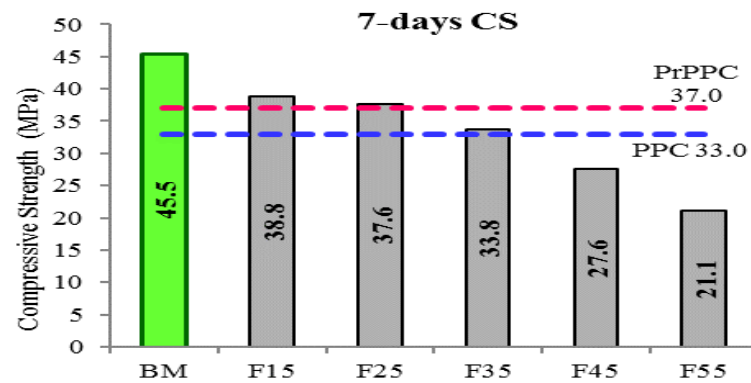


Figure 5.4.2.3: Comparison of 7-days compressive strength

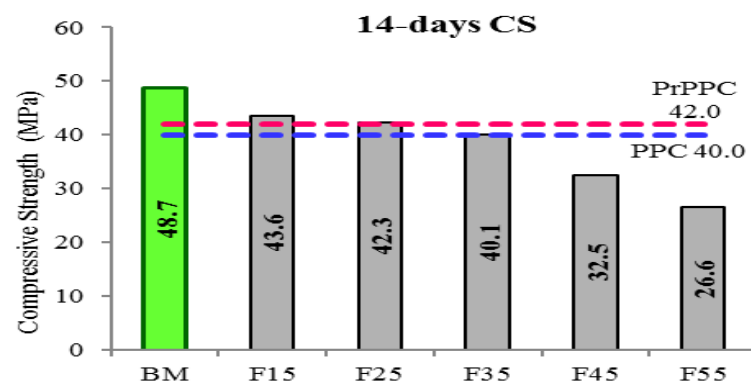


Figure 5.4.2.4: Comparison of 14-days compressive strength

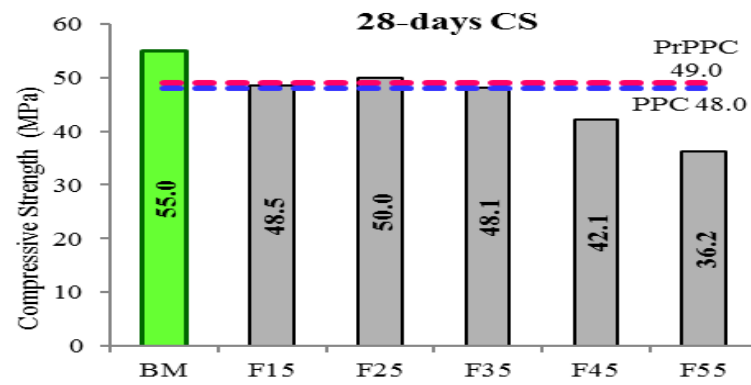


Figure 5.4.2.5: Comparison of 28-days compressive strength

The compressive strength of cements results indicates that fly ash replacement up to 35% in the S45 base material performs equally better in line with the commercially available JK-PPC and JK Premium PPC cements. The S45 + 35% fly ash blend exhibited strength improvements of 22% at 3 days and 2% at 7 days, while achieving comparable strengths at 14 and 28 days. Based on these results, 35% fly ash replacement was identified as the optimum level for the engineered OPC system.

A comparison of strength development shows that the engineered blend consistently achieved higher early-age strength than both commercial PPCs. This enhanced performance is attributed to the optimized particle size distribution (PSD), which improves particle packing, increases reactive surface area, and accelerates clinker hydration. The improved packing density also promotes better interaction between cement and fly ash particles, leading to efficient utilization of the pozzolanic reaction.

As curing progressed, the strength gain of the commercial PPCs improved due to the gradual contribution of fly ash hydration. However, the S45 + 35% fly ash blend maintained comparable performance throughout the curing period. The results demonstrate that the optimized PSD enables effective hydration of both OPC and fly ash, resulting in improved early-age strength without compromising later-age performance.

Therefore, the S45 + 35% fly ash blend represents the optimum combination, where the benefits of particle packing and pozzolanic reactivity are effectively balanced to achieve superior strength performance compared to commercially available PPC cements. The results are being only indicative as the source and quality of fly-ash was not known.

5.4.2.2 Compressive Strength of S45+FA from 56 to 365 days curing ages

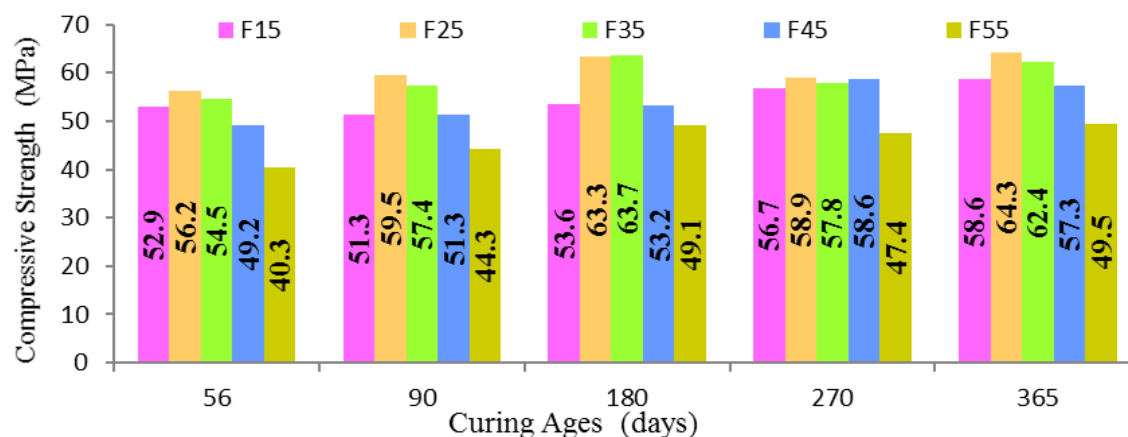


Figure 5.4.2.6: Compressive strength of S45+FA from 56 to 365 days

Figure 5.4.2.6 presents the long-term compressive strength development of fly-ash blended cement systems from 56 to 365 days. The results reveal two distinct trends. Blends containing up to 35% fly-ash show strength gain up to approximately 180 days, beyond which the increase becomes either marginal or with lower values, indicating that the secondary hydration reactions have largely ceased due to limited availability of reactive SCM particles and calcium hydroxide.

5.4.2.3 Compressive Strength of optimized S45+FA (35%) CONCRETE cubes up-to 28 days curing ages

Results obtained from the experimental study for optimized S45+FA (35%) blend is compared with commercially available Portland Pozzolana Cement (PSC) of JK Cement Ltd. make.

Following are the graphical representation of M25 and M40 concrete compressive strength comparison for 1, 3, 7, 14 and 28 days curing ages.

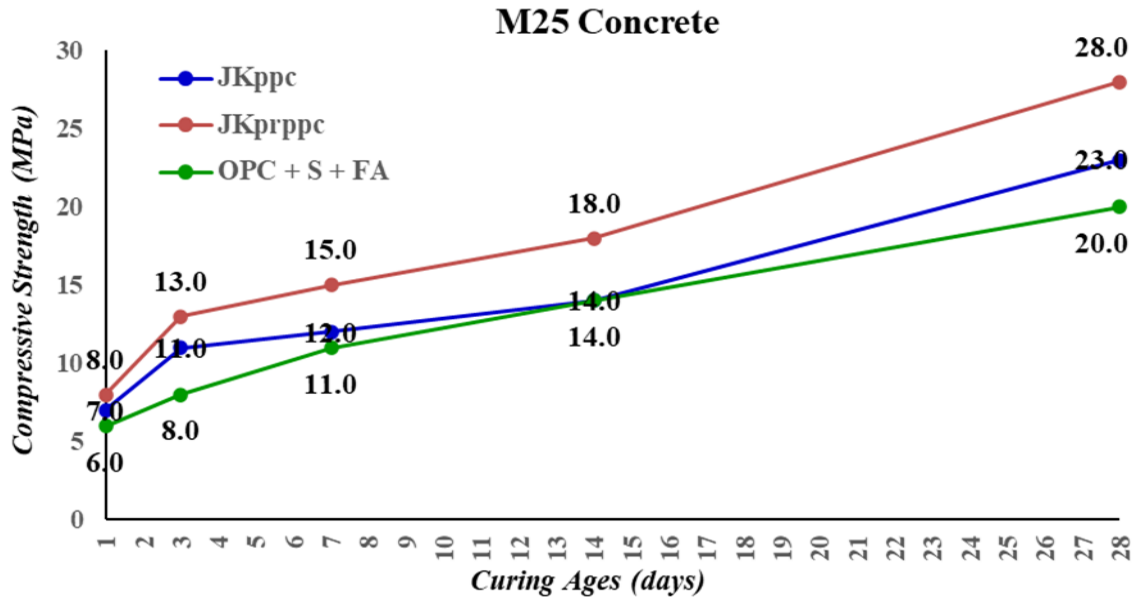


Figure 5.4.2.7: Compressive strength of S45+FA M25-Concrete up-to 28 days

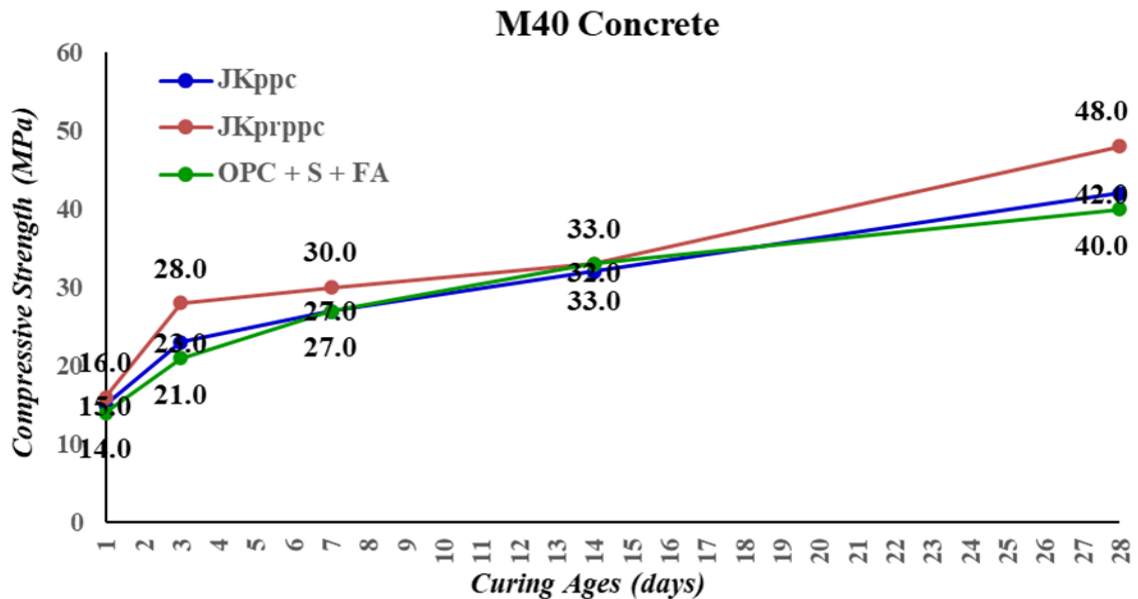


Figure 5.4.2.8: Compressive strength of S45+FA M40-Concrete up-to 28 days

5.4.3 Comparison of S45+FA+GGBFS blends with Commercial Composite Cement (CC)

5.4.3.1 Compressive Strength of MORTAR cubes up to 28 days

Results obtained from the experimental study for S45+FA+GGBFS blends are compared with commercially available Composite Cement (CC) (hidden for privacy's sake).

Following are the graphical representation of compressive strength comparison for 1, 3, 7, 14 and 28 days curing ages at Figure 5.4.3.1 to 5.4.3.5 for Ternary blends with GGBFS, Fly-ash in comparison with S45 and commercial Composite Cement (CcomC).

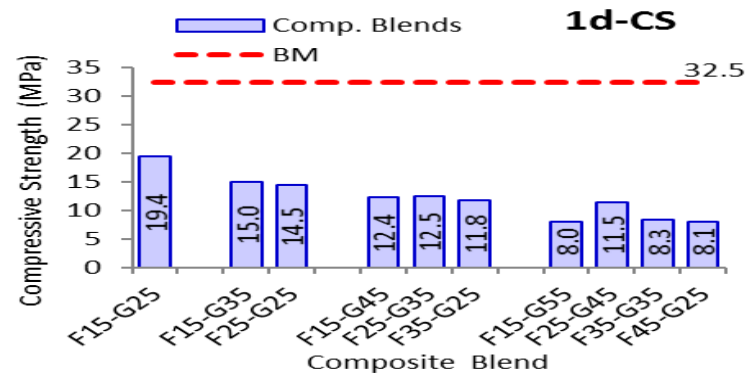


Figure 5.4.3.1: Comparison of 1-day compressive strength

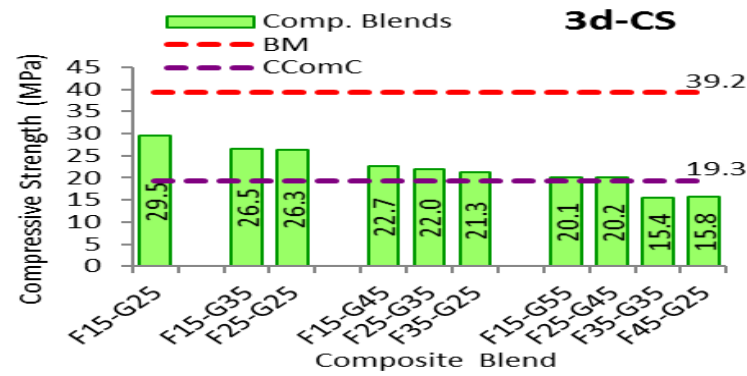


Figure 5.4.3.2: Comparison of 3-days compressive strength

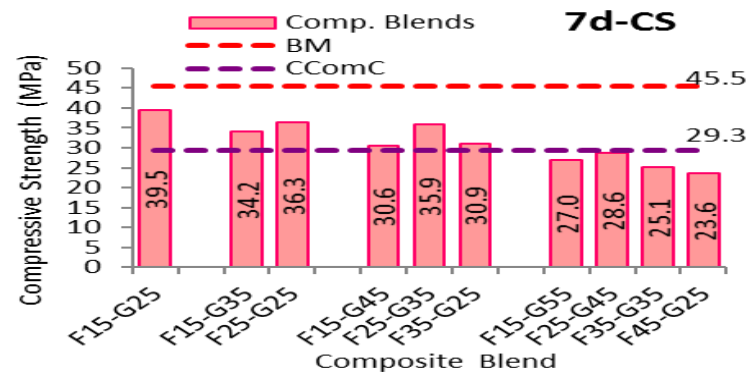


Figure 5.4.3.3: Comparison of 7-days compressive strength

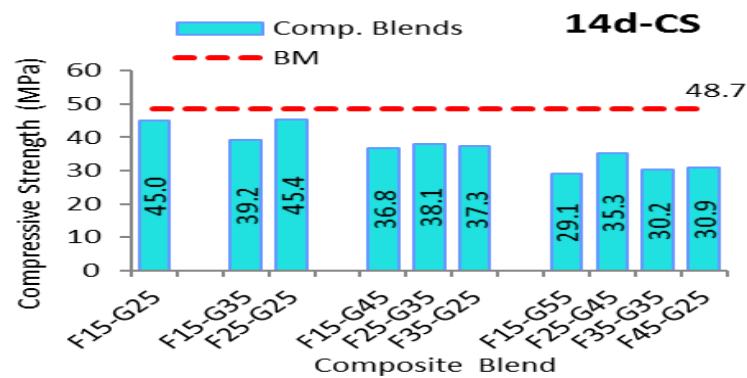


Figure 5.4.3.4: Comparison of 14-days compressive strength

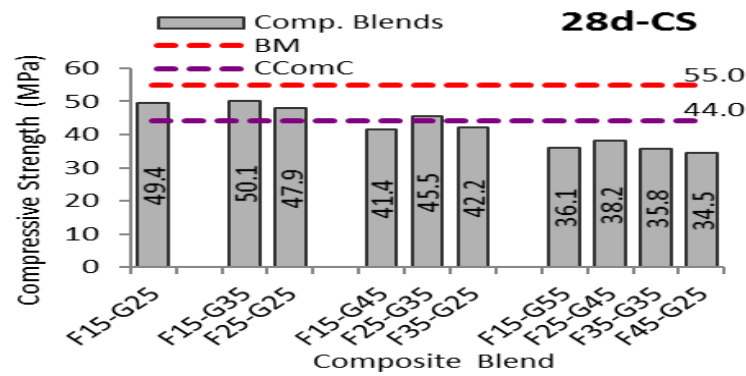


Figure 5.4.3.5: Comparison of 28-days compressive strength

From the above figures, it is noticed that FA+GGBFS combined substitution up-to 60% in Base Material (i.e. S45) showed better performance than commercial CC at 28 days curing age. Strength improvement of 10% (minimum) at 3-days, 4% (minimum) at 7-days and 3% at 28 days are seen with S45+25%FA+35%GGBFS and therefore upto 25% flyash and upto 35% slag substitution with S45 has been considered as the optimum replacement level viz. 60% (combined) in engineered OPC.

The strength development timeline reveals a clear progression driven by the distinct mechanisms of each SCM. At three days of curing, the composite cement shows at least 10% higher strength compared to commercial cement. This early strength gain is primarily attributed to the slag's latent hydraulic properties, which react rapidly with water to form calcium silicate hydrate (C-S-H) gel early in the hydration process. By seven days, the strength improvement reduces to at least 4%, as the fly ash begins its pozzolanic reaction with calcium hydroxide produced during OPC hydration, complementing the slag's contribution. At 28 days, the composite cement achieves a 3% higher strength than commercial cement, demonstrating the full synergistic effect where fly ash refines the pore structure while slag provides early C-S-H, resulting in combined microstructure densification. This progression clearly shows that slag dominates early strength development while fly ash enhances later strength, which is a classic complementary behavior observed in ternary cement blends.

The combination of 25% fly ash and 35% GGBFS represents the optimum replacement level due to several interrelated factors. The synergy between these materials is fundamental: fly ash, being slow-reacting and pozzolanic, combines with GGBFS, which is faster-reacting and hydraulic, to create a balanced performance that delivers both early and late strength. This combined effect results in a microstructure that is significantly

denser, with reduced porosity and increased impermeability, which directly translates to improved durability characteristics. The combined supplementary cementitious materials reduce porosity, increase impermeability, and refine the overall pore structure of the cement matrix.

5.4.3.2 Compressive Strength of S45+FA+GGBFS from 56 to 365 days curing ages

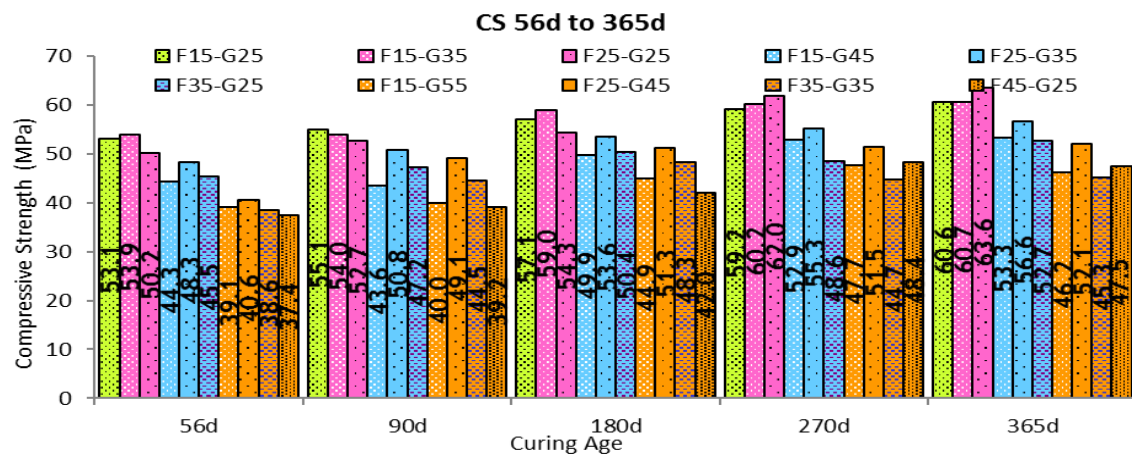


Figure 5.4.3.6: Compressive strength of S45+FA+GGBFS from 56 to 365 days

Figure 5.4.3.6 shows the compressive strength development of different composite mixes from 56 to 365 days of curing. All mixes exhibit a gradual increase in strength with age, confirming continued hydration and pozzolanic reaction over time. Among the mixes, moderate replacement combinations such as F15-G25 and F25-G25 demonstrate the highest compressive strength at all curing ages, indicating better synergy between the constituents. In contrast, mixes with higher replacement levels show comparatively lower strength, though they still gain strength steadily with prolonged curing. The results suggest that an optimum balance of replacement enhances long-term mechanical performance while excessive substitution may reduce early strength.

6.4.3.3 Compressive Strength of optimized S45+FA+GGBFS between 50% to 60% combined SCMs CONCRETE cubes up-to 28 days curing ages:

Following are the graphical representation of M25 and M40 concrete compressive strength comparison for 1, 3, 7, 14 and 28 days curing ages for optimized SCMs viz Fly-ash between 15% to 25% and GGBFS between 25% to 45%:

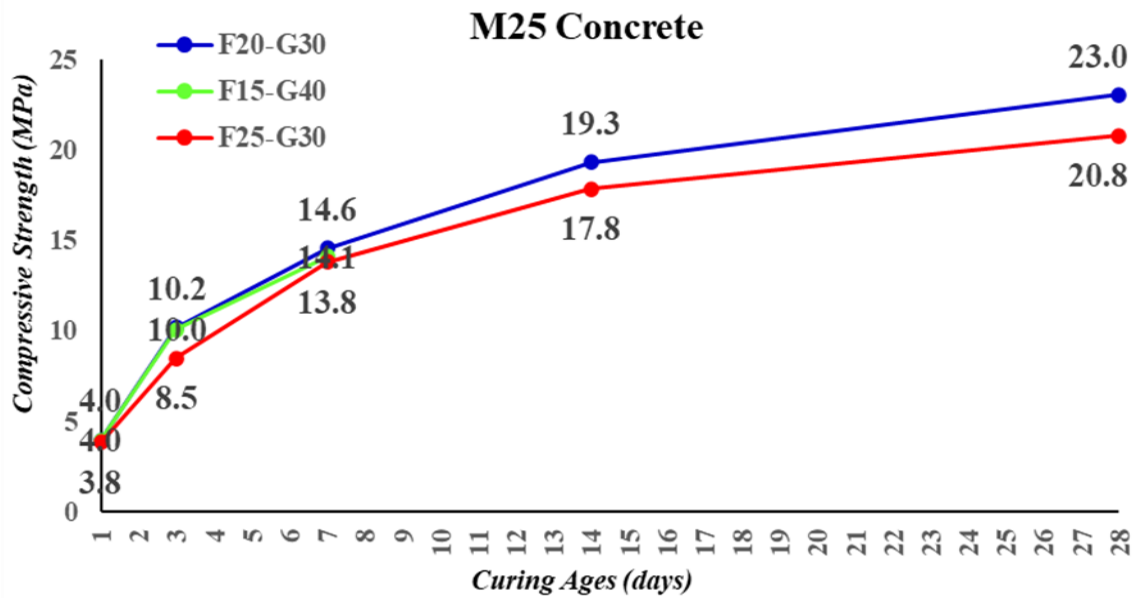


Figure 5.4.3.7: Compressive strength of S45+FA+GGBFS M25-Concrete up-to 28 days

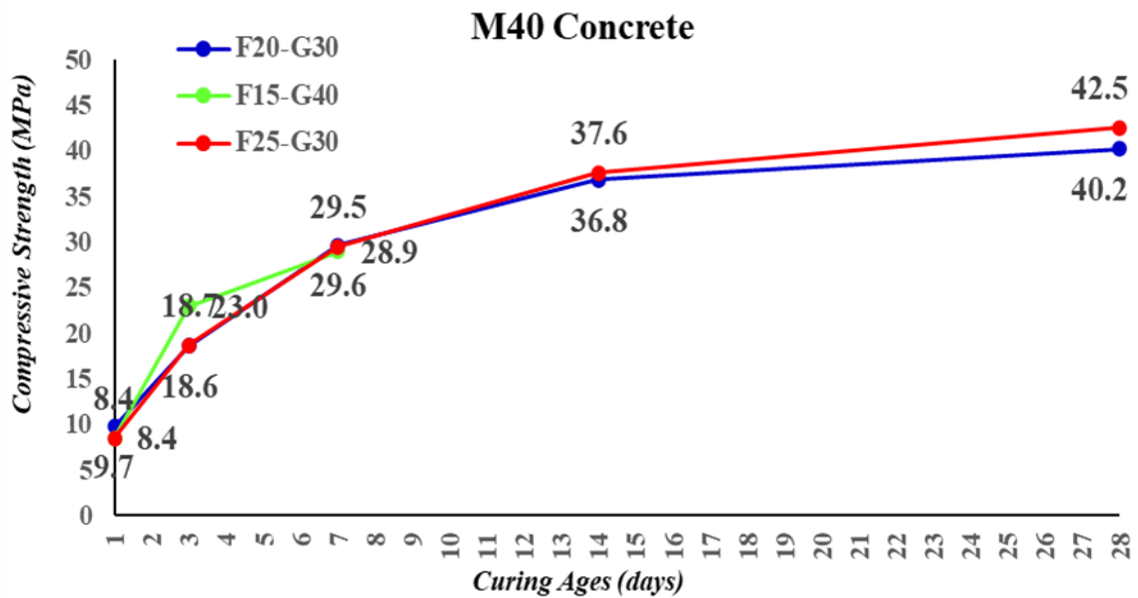


Figure 5.4.3.8: Compressive strength of S45+FA+GGBFS M40-Concrete up-to 28 days

Figure 5.4.3.7 and Figure 5.4.3.8 exhibit that compressive strength increased progressively with curing age for all concrete mixes, reflecting the continued hydration of cementitious materials. For M40 concrete, F25-G30 achieved the highest 28-day compressive strength (42.5 MPa), indicating enhanced long-term performance while for M25 concrete, F20-G30 consistently produced the highest compressive strength values and reached 23.0 MPa at 28 days. Early-age strength development (1–7 days) was generally more pronounced in the F20-G30 mix, while F25-G30 demonstrated greater strength gains during later curing periods, particularly in M40 concrete.

The observed strength gain in both concrete grades can be directly linked to the hydration behavior of cement. During the first few days, rapid hydration of C_3S produces significant quantities of C-S-H gel and calcium hydroxide, resulting in steep increases in compressive strength. Between 7 and 14 days, hydration continues at a moderate rate, leading to further densification of the microstructure. Beyond 14 days, strength development becomes more gradual as hydration reactions slow and the remaining un-hydrated cement particles react progressively.

The higher strengths recorded for M40 concrete indicate a denser cementitious matrix and a lower effective water–cement ratio, which promote greater formation and retention of hydration products. In contrast, the M25 mixes exhibit lower compressive strengths because of their comparatively less dense microstructure and reduced capacity to develop a highly compact C-S-H network.

Overall, the results confirm that compressive strength development is governed by the extent of cement hydration, with the most significant strength gains occurring during the first seven days of curing. Adequate curing ensured continuous hydration, reduced pore volume, enhanced matrix densification, and ultimately improved the long-term mechanical performance of both M40 and M25 concrete mixes.

5.5 PART-5: DURABILITY studies on Optimized Slag and Fly-ash Binary Blend and Composite Cement with Fly-ash and Slag

Durability tests were conducted on M25 and M40 concrete cubes at 28 days curing age for the following optimized Binary and Ternary Blended Cements, namely:

- 1) Slag Blend : S45(55%) + GGBFS (45%)
- 2) Fly-ash Blend : S45(65%) + FA (35%)
- 3) Composite Blend : S45(50%) + FA (25%) + GGBFS (25%)

The DURABILITY tests conducted were, namely:

- 1) RAPID CHLORIDE MIGRATION TEST (RCMT), as per NT Build 492

The principle of the method is to drive chloride ions through a saturated concrete specimen by applying an electrical potential across it for a specified period. The specimen is usually obtained from a standard concrete cylinder or from a drilled core, then trimmed to the required thickness and vacuum saturated so that the internal pore structure is in a reproducible condition before testing. During the test, one side of the specimen is exposed to a sodium chloride solution acting as the catholyte, while the opposite side is exposed to

a sodium hydroxide solution acting as the anolyte. The applied voltage is selected with reference to the initial current and specimen characteristics, and the duration of the test is controlled to produce measurable chloride penetration while avoiding excessive temperature rise. After completion of the migration period, the specimen is removed from the cell and split axially into two halves. The freshly fractured surface is then sprayed with a silver nitrate solution, which reacts with penetrated chloride ions and creates a visible boundary between chloride-contaminated and uncontaminated zones. The depth of chloride penetration is measured at several points on the fracture surface, and the average penetration depth is used in the prescribed NT Build 492 equation together with specimen thickness, applied voltage, test duration, and average test temperature to calculate the non-steady-state chloride migration coefficient. This coefficient is generally expressed in square metres per second and is treated as an indicator of the resistance of the material to chloride transport.

2) WATER PERMEABILITY, as per BIS 516 (2018)

With compliance to BIS 516 (Part-2/Section-1), the test specimen is cured in accordance with BIS 1199 (Part 5) for at-least 28 days. After de-molding the specimen, the surface exposed to water pressure is roughened with wire brush and placed in the apparatus. Water pressure of 500 ± 50 KPa for the duration of 72 ± 2 h is then applied and faces not exposed to pressure is periodically observed during the test to note the traces of water. After the test duration, the specimen surface exposed to pressure is wiped to remove excess water and immediately riven perpendicularly to the face on which the pressure was applied. Once dried, the water permeation front seen on the split face is marked and compared with the acceptable value. The maximum penetration depth of water is then measured to the nearest millimetre of the acceptable specimen. The final depth of penetration is taken as the average of three results.

3) SORPTIVITY, as per ASTM C 1585-13

Concrete cubes (3 nos) are casted and moist cured, commonly in cylindrical form. After 28 days of curing, a disc or slice, generally about 50 mm thick, is cut from the specimen. The specimen is then conditioned in a controlled environment, typically at elevated temperature and relative humidity, until a stable internal moisture state is achieved. After conditioning, the curved side and one face of the specimen are sealed with an impermeable material so that water can enter only through the designated test surface. Before exposure to water, the specimen is weighed to obtain its initial mass. It is then

placed on supports in a tray so that the unsealed face is in contact with water maintained at a shallow depth, sufficient to ensure contact without full immersion. The specimen is removed at specified intervals, surface water is wiped off, and the mass is recorded quickly to minimize evaporation effects. Measurements are taken more frequently during the early stage and at longer intervals later, because absorption is faster initially and slows with time. The cumulative water absorbed per unit exposed area is calculated from the recorded mass gain and plotted against the square root of elapsed time. The slope of the first linear portion of the curve represents the initial sorptivity, while the slope of the later linear portion represents the secondary sorptivity.

Table 5.5.1: Durability Tests

Tests	Code	Unit	45% SLAG		35% Flyash		50% SCM Composite	
			M25	M40	M25	M40	M25	M40
RCMT	NT BUILD 492	m ² /s	5.84 x 10 ⁻¹²	3.65 x 10 ⁻¹²	2.56 x 10 ⁻¹²	2.34 x 10 ⁻¹²	2.87 x 10 ⁻¹²	2.73 x 10 ⁻¹²
Water Permeability	BIS 516	mm	10	9	10	45	10	20
Sorptivity								
Initial	ASTM C 1585-13	mm/s ^{1/2}	0.012273	0.006184	0.005588	0.004859	0.011115	0.004707
Secondary	ASTM C 1585-13	mm/s ^{1/2}	0.000193	0.000738	0.000729	0.000671	0.000213	0.000818

Durability Tests on the optimized Binary and Ternary blends tabled at Table 5.5.1 revealed that Fly-ash as SCM showed better resistance to penetration of chloride ions than GGBFS. GGBFS excelled over Fly-ash in resistance to water penetration under pressure, attributed to GGBFS been finer element than Fly-ash. Fly-ash displayed better resistance than GGBFS in sorptivity test.

5.6 PART-6: ENVIRONMENTAL SUSTAINABILITY Analysis of Optimized Slag and Fly-ash Binary and Ternary Blends

Table 5.6.1 provides a comparative analysis of carbon emissions by OPC, Stimulator, S45, G45, F35 and F25-G25 cement binders while Table 5.6.2 indicates the environmental efficiencies of the Optimized Binary and Ternary Blends.

Table 5.6.1 shows drastic reduction in carbon-di-oxide emissions by Ternary Blend i.e. F25-G25 followed by Binary Blends of Slag and Fly-ash respectively, as compared to OPC and S45. Table 5.6.2 below demonstrates the Environmental Efficiencies of Binary

and Ternary blends exhibiting F25-G25 Ternary Blend as the most efficient in carbon-dioxide release with respect to 28 days compressive strength trailed by G45 & F35, in line with Table 5.6.1. These superior outcomes are largely attributed to the engineered Particle Size Distribution (PSD) thereby emphasizing upon a much greener cement which is eco-friendly and leading to the achievement of sustainability goals.

Table 5.6.1: Quantities of Carbon Emissions from Optimized Binary & Ternary Blends

Details (per tonne)	Amount of CO ₂ released (tonne)
OPC	0.8000
CO ₂ released during “Stimulator” production using 30KWh electricity for grinding OPC to Stimulator	0.0285
STIMULATOR	0.8285
Modified Cement - S45	0.8128
Optimized SLAG Binary Cement at 45% GGBFS	0.4500
Optimized FLY-ASH Binary Cement at 35% Fly-ash	0.5300
Optimized GGBFS+FA Ternary Cement at 50% combined replacement	0.4100

Table 5.6.2: Environmental Efficiency of Optimized Blends

Details	OPC	S45	G45	F35	F25-F25
28-days Strength (MPa)	53.00	66.05	51.50	48.10	47.90
Carbon released (per tonne)	0.80	0.8128	0.45	0.53	0.41
Environmental Efficiency (%)	66%	81%	114%	91%	117%

Chapter 6

Conclusions

6.1 General Conclusions

1. A comprehensive review of the literature revealed that previous investigations, particularly those reported by Chakurkar et al. (2023) and Shraddha et al., were primarily limited to Ordinary Portland Cement (OPC) systems. Systematic studies on binary and ternary blended cements incorporating multiple supplementary cementitious materials (SCMs) were lacking. The present study successfully addressed this research gap by extending the concept of Particle Size Distribution (PSD) optimization to binary blends (S45-GGBFS and S45-Fly Ash) and ternary blends (S45-GGBFS-Fly Ash) while maintaining constant clinker chemistry and Bogue's composition.
2. The study demonstrated that PSD optimization through the stimulator process is a governing parameter influencing hydration kinetics, particle packing, soundness, strength development, durability, and long-term performance of cementitious systems without altering clinker chemistry. The results establish that physical optimization of cement particles can be as effective as chemical modification in enhancing cement quality.
3. Incorporation of finely ground SCMs significantly improved volumetric stability. Autoclave soundness reduced from 0.104% for S45 to as low as 0.024% for the F15-G35 ternary blend, representing a reduction of approximately 77%. This improvement was attributed to dilution of free lime and magnesia, improved particle packing, reduced pore connectivity, and formation of additional C-S-H gel through pozzolanic and latent hydraulic reactions.
4. Consistency and setting characteristics remained within acceptable limits despite high SCM replacement levels. Standard consistency varied between 26.0% and 28.5%, while initial and final setting times ranged from 125–185 minutes and 205–265 minutes, respectively. Water demand remained nearly constant up to 45% slag replacement and increased only marginally beyond this level due to the increased surface area associated with finer particles.

5. Among the binary slag blends, S45 + 45% GGBFS was identified as the optimum combination. Compared with commercial Portland Slag Cement (PSC), compressive strength improvements of approximately 11% at 3 days, 4% at 7 days, 12% at 14 days, and 5% at 28 days were achieved. The superior performance resulted from enhanced particle packing, increased nucleation sites, accelerated primary hydration, sustained secondary hydration reactions, and formation of additional C-S-H gel.
6. Long-term strength studies up to 365 days confirmed the importance of secondary hydration and PSD optimization. Slag replacement levels up to 35% exhibited limited strength gain beyond 180 days, whereas blends containing 45–75% slag continued to gain strength up to 365 days. The G45 blend provided the optimum balance between clinker hydration and slag reactivity, resulting in maximum utilization of secondary hydration products, superior microstructural densification, and enhanced durability.
7. Concrete produced using the optimized G45 blend significantly outperformed commercial PSC. Compared with JK-PSC, M25 concrete exhibited strength gains of 43%, 69%, and 15% at 7, 14, and 28 days, respectively, while M40 concrete exhibited strength gains of 17%, 32%, and 21% at 3, 7, and 14 days, respectively. These results confirmed that improvements achieved at the cement level were successfully translated to concrete performance through enhanced hydration kinetics, improved particle packing, and efficient secondary hydration.
8. For fly ash-based binary systems, S45 + 35% Fly Ash was identified as the optimum blend. Compared with commercial PPCs, the blend achieved 22% higher strength at 3 days, 2% higher strength at 7 days, and comparable strengths at 14 and 28 days. The optimized PSD compensated for the traditionally slower early-age strength development associated with fly ash systems by improving packing density and enhancing interaction between cement and fly ash particles.
9. Among all ternary blends investigated, F25-G25 (25% Fly Ash + 25% GGBFS) emerged as the optimum composite blend. This blend achieved a compressive strength of 47.9 MPa at 28 days and 63.6 MPa at 365 days, corresponding to a

32.8% increase in strength between 28 and 365 days, which was the highest among all ternary systems studied. The COM50 category (50% total SCM replacement) provided the best balance between early-age strength, long-term strength development, hydration efficiency, and durability performance.

10. Durability investigations demonstrated the complementary roles of Fly Ash and GGBFS in binary and ternary blended systems. Fly ash-rich blends exhibited superior resistance to chloride ion penetration and improved sorptivity characteristics, whereas GGBFS-rich blends showed lower water permeability under pressure. The synergistic action of both SCMs produced denser microstructures, lower permeability, enhanced durability, reduced clinker consumption, lower carbon emissions, and improved sustainability. The study conclusively establishes PSD optimization as a scientifically validated and industrially viable technology for producing next-generation high-performance, low-carbon blended cements with superior mechanical, durability, volumetric stability, and environmental performance.

6.2 Major Contributions of the Study

A. Technical Contributions

1. Developed and validated a PSD-based optimization methodology for binary and ternary blended cement systems while maintaining constant clinker chemistry and Bogue's composition.
2. Extended the stimulator concept, previously limited to OPC systems, to:
OPC–GGBFS binary blends,
OPC–Fly Ash binary blends,
OPC–GGBFS–Fly Ash ternary blends.
3. Identified **45% GGBFS replacement** as the optimum slag content for maximizing strength, durability, and long-term hydration efficiency.
4. Identified **35% Fly Ash replacement** as the optimum fly ash content for achieving balanced early-age and later-age strength performance.
5. Demonstrated that optimized PSD can significantly enhance early-age strength development in blended cements, overcoming one of the major limitations traditionally associated with SCM incorporation.

6. Established the direct relationship between particle packing characteristics and the efficiency of secondary hydration reactions in blended cement systems.
7. Quantified the influence of reactive fines on soundness, consistency, compressive strength, and long-term durability.
8. Validated laboratory findings through concrete performance studies on M25 and M40 grades, demonstrating practical applicability of the optimized cement systems.

B. Sustainability Contributions

9. Demonstrated the feasibility of reducing clinker consumption by up to 45% through GGBFS incorporation and up to 35% through fly ash incorporation without compromising engineering performance.
10. Established a pathway for reducing carbon emissions associated with cement manufacturing through increased utilization of industrial by-products.
11. Promoted the beneficial utilization of GGBFS and fly ash, supporting circular economy principles and sustainable construction practices.

C. Scientific Contributions

12. Provided experimental evidence that PSD optimization alone can significantly improve cement performance without altering chemical composition.
13. Established the synergistic role of particle packing and secondary hydration in governing long-term strength development.
14. Generated a comprehensive database on physical, chemical, mechanical, and durability characteristics of optimized binary and ternary blended cements.
15. The findings provide a strong scientific foundation for future development of high-performance, low-carbon blended cement systems and contribute significantly to the advancement of sustainable cement technology, consistent with the research direction reported in the published Wiley journal study.

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List of Publications

1. International Journal

Sr. No.	Title	Authors	Where Published	Month and Year of Publication
1	Impact of Engineered Particle Size Distribution of Ordinary Portland Cement on Slag Supplemented Cement: A Comparative Performance Analysis with Commercial Portland Slag Cement	Rajan Suresh Kamble, Krishnasetty Govindaraja Guptha, Ashish Kumar Nayak, and Jagadish Vengala	Volume 2025, Article ID 5442750, Wiley The Scientific World Journal https://doi.org/10.1155/tswj/5442750 IF : 3.65, Q2 Journal	April 2025

2. National Journal

Sr. No.	Title	Authors	Where Published	Month and Year of Publication
1	Performance Enhancement of Binary Cement with Fly-ash using Particle size Re-orientation of Ordinary Portland Cement	Rajan Suresh Kamble and K. G. Guptha	Indian Concrete Journal (ICJ) IF : 0.44, Q4 Journal	Submitted in January 2026 and under review

3. International Conferences

Sr. No.	Title	Authors	Where Presented	Month and Year of Presentation	Remarks
1	Effect of Particle Size Distribution (PSD) on Binary Cements – Studies on Fly-ash based Cement	Rajan Suresh Kamble and K. G. Guptha	3 rd International Conference on Recent Developments on Sustainable Infrastructure (ICRDSI 2022-23), KIIT – Bhubaneswar	March 2023	Published as Lecture Notes in Civil Engineering - Springer Nature
2	Influence of Grain Size Distribution (GSD) on GGBFS-Based Binary Cement	Rajan Suresh Kamble and K. G. Guptha	International Conference on Sustainable Infrastructure : Innovations, Opportunities and Challenges (SIIOC 2023), NITK-Surathkal	April 2023	Published as Lecture Notes in Civil Engineering - Springer Nature
3	Performance Influenced by Particle Size Distribution (PSD) of Composite Cement Incorporating Fly-ash and Ground Granulated Blast Furnace Slag as SCMs	Rajan Suresh Kamble and K. G. Guptha	International Conference on Interdisciplinary Approaches in Civil Engineering for Sustainable Development (IACESD 2023), JIT-Bangalore	July 2023	Published as Lecture Notes in Civil Engineering - Springer Nature