CHAPTER 1 - INTRODUCTION AND LITERATURE REVIEW

1.1 General

Energy, greenhouse and economy are major issues of present century, the world is confronting today. Conventional concrete technology is considered to be energy intensive and a huge source of CO_2 release in our environment. Self-Consolidated Concrete (SCC) has revolutionized construction industry and enabled it to have high strength, economy, time and space reduction in high rise buildings & modern structures. Major applications involve massive placements with heavily reinforced sections such as tunnel linings, bridges piers, transportation structures, high rise buildings, rafts, pre-stressed concrete members and repairs of structures.

1.2 Self Consolidating Concrete (SCC)

SCC is invention of the decade. Three essential properties of SCC are filling ability, passing ability, and segregation resistance. ACI 237 defines SCC as "Highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation". High Range Water Reducing Agent (HRWRA) is an essential ingredient in SCC mixtures that imparts high flow under its own mass. In addition, the water-powder ratio is reduced or a viscosity modifying admixture (VMA) is used to control segregation. SCC mixes can be distinguished from conventionally placed concrete mixes by following:-

- Higher paste volume
- Higher powder contents
- Lower water-cementitious materials or water powder ratio
- Lower coarse aggregate contents
- Smaller maximum aggregate size

Secondary Raw Materials (SRMs) and mineral fillers are commonly utilized to decrease cost, improve workability, and improve hardened properties of SCC. It requires increased quality control since it is highly sensitive to changes in material properties and proportions. Consequences of deviations in workability are more significant for SCC. For instance, a slight change in water content may have minimal effect on conventionally placed concrete but may lead to severe segregation and rejected work in SCC. In general, the advantages of SCC may include:

- Improved ability of concrete to flow into intricate spaces and between congested reinforcement normally encountered in applications like tunnel linings, bridge piers, rafts, transportation structures and high rise buildings.
- Reduced construction costs due to reduced labor & maintenance cost.
- Increased construction speed and hence reduced completion time.

- Improved working conditions with fewer accidents due to elimination of mechanical vibrators and the noise.
- Improved durability and strength of hardened concrete.
- Improved form surface finish and reduced need to repair defects such as bug holes and honey combing.

1.3 Research Focus & Objectives

Construction industry of Pakistan is very vibrant but is ignorant of the latest developments which have taken place in modern concrete systems in developed world. So the replacement of conventional construction materials and practices is the need of the time in order to make mega structures economical, durable and environment friendly. Efforts to use self-consolidating cementitious systems with locally available secondary raw materials as partial replacement of cement is a step in right direction and surely it will increase construction speed and hence bring cost savings in short term and will improve structural properties both in short term and long term. In design office, compressive strength and concrete slump are generally specified by structural engineers only while ignoring certain important properties like creep, shrinkage, rheology, micro structural development uniform durability and easy placement resulting in service life problems. In this study, these factors have been given due importance.

In the present study of SCC & SCP Systems, Ground Granulated Blast Furnace (GGBF) Slag, a pozzolanic SRM was used as partial replacement of cement. Lime Stone Powder (LSP) & Quarry Dust (QD) were used as partial replacement of fine aggregates. Objectives of current research were:

- To look at possible changes / improvement in SCC response by partially replacing sand with inert SRMs (LSP & QD).
- To study the changes in response of SCCS by partially replacing cement with pozzolanic SRMs (GGBF Slag).

1.4 Progressive Development

Upto 1940, the field concrete strength was around 25 MPa which rose to about 34 MPa by mid of twentieth century. In the early 1970's, experts were of opinion that this limit would be upto 43 Mpa [1]. Burning issue in the developed world in 1980s were shortage of skilled labor and the requirement of high uniform durability of concrete. In early 80's, superplastizer were in invented in Japan & Germany which made HPC / SCC systems possible as shown in Fig 1.1. Japan took the initiative to develop SCC. Okamura is amongst the pioneers who identified need of SCC and developed first prototype in 1986. This technology spread from Japan to Europe where a lot of research work has been done, "Technical Committees" were made and Symposiums were held to give maturity to this excellent technology. From Europe, this concept travelled to North America.

The use of SCC has gradually increased throughout the world since the 1980s, gaining particular momentum in the late 1990s. Towards first step of standardization, ACI, ASTM, and other international concrete Institutions have adopted phrase of SCC. Major international symposia on SCC were held in 1999, 2001, 2003 & 2005. A state-of-the art report on SCC has been published in April 2007 by ACI committee 237. ACI 363R defines SCC as concrete with compressive strength more than 41 Mpa [1].

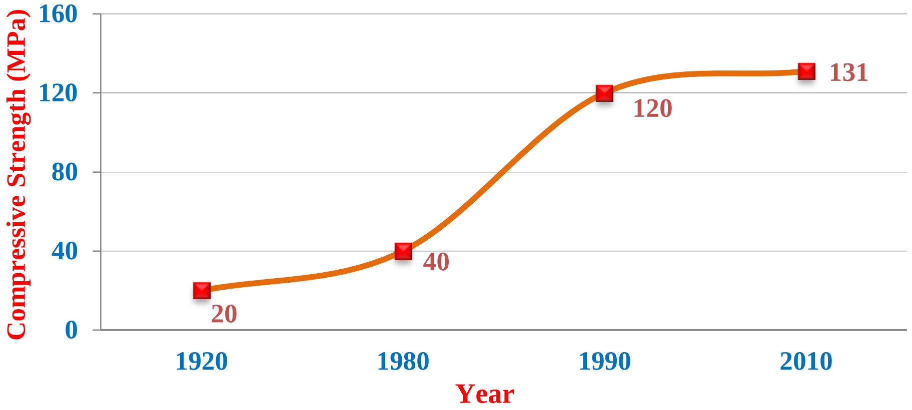


Fig 1.1 : Progressive Development of Concrete Compressive Strength [Rizwan 2006]

One of the first high profile applications of SCC was the Akashi Kaikyo Bridge in Japan [2]. In USA total production of Self-compacting concrete reached one million cubic meters in 2002[3]. Few years ago, USA has erected tall buildings with a concrete compressive strength upto 131 MPa.

1.5 Pozzolans

Origin of pozzolan is believed to be volcanic ash mined near Pozzuoli. ACI 237 R defines Pozzolan as "*A siliceous or siliceous & aluminous material, which in itself possesses little or no cementitious properties but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties*." [4] Pozzolans may be divided into:-

- Natural Pozzolan is the material which possesses pozzolanic properties. The naturally occurring materials and their processing are usually limited to crushing, grinding and sieving. These materials are raw or Calcined naturally developed (e.g. volcanic ash, shale, tuffs & diatomaceous earths.)
- Artificial Pozzolans are the by-products of industries producing them. The most commonly used by-product Pozzolans today are fly ash, silica fume and GGBF Slag etc. [4].

1.5.1 Pozzolanic Reaction

"The reaction of calcium hydroxide usually a byproduct of hydration of C_3S and C_2S with pozzolan is termed as pozzolanic reaction". When water is added in OPC forms calcium silicate hydrate (CSH) gel along with calcium hydroxide (CH) and ettringite. In the presence of a pozzolan, liberated CH in hydrated cement paste reacts with silica component of pozzolan in presence of water to form extra calcium silicate hydrate (CSH) gel. Pozzolans also add volatile alumina in addition to react with calcium hydroxide of the matrix to form tetra CAH (C_4AH_x, where x is from 9 to 13), tri-calcium aluminate hydrate (C_3AH_6), di-calcium aluminate silicate hydrate (C_2ASH_8), calcium carbo-aluminate ($C_3A.CaCO_3.H_{12}O$), high sulfo-aluminate-ettringite ($C_3A.3CaSO_3.32H_{12}O$) and low sulfo-aluminate ($C_3A.CaSO_3.12H_{12}O$) termed as cementitious products [5,6,7].

Ordinary Portland Cement [8]

$C_3S + H_2O \xrightarrow{\text{Fast}} C - S - H + CH$ -------------- (1.1)

Portland – Pozzolan Cement [8]

$\text{Pozzolan} + CH + H_2O \xrightarrow{\text{Slow}} C - S – H$ -------------- (1.2)

1.5.2 Effects of Pozzolanic Reactions.

Effects of pozzolanic reactions can be summarized as under:-

- Shape and size of pozzolanic particles along with their surface morphology influence properties of concrete both in fresh and hardened state even in replacement mode. It includes change in WD, setting time, SP demand, flow and early and later strengths.
- Controls heat of hydration initially, may affect early age strength but later age strength is enhanced as the reaction consumes calcium hydroxide, reducing the weaker crystals.
- Hydration products are effective in filling up large capillary pores. So porosity is reduced and strength is improved. Thus microstructure will be improved and durability will be enhanced especially for aggressive acidic environment including sulphate and sea water attack. [9]
- Selection of curing regime and shrinkage

1.6 Use of SRMs in SCCS

Secondary Raw Materials (SRMs) are less energy intensive materials, mainly industrial byproducts, requiring little or no pyro processing. These are also known as Supplementary Cementitious Materials (SCMs), fillers and powders depending upon the way these are produced & properties they exhibit. Some of them do not hydrate themselves but improve the hydration of cement rather indirectly like LSP / MP. These are pozzolanic or inert powders, used to enhance concrete properties both in fresh and hardened state. When SRMs replace cement, three effects can be quantified including, dilution, heterogeneous nucleation (physical) and pozzolanic reaction (chemical) depending on contents of amorphous silica along with solubility. Nano size particles of SRMs provides sites for nucleation (heterogeneous nucleation), It is a physical process followed by a chemical activation of hydration of cement which gives growth (N+G) enhancing cement hydration [10]. Today these have become an essential component of SCCS due to advantages mentioned below:-

- Better packing.
- Optimization of flow.
- Enhancement of strength.
- Improvement of microstructure.
- Better environmental effects.
- Economy and the durability of cement based systems.
- Control of early heat evolution, thus reduction in shrinkage.

1.6.1 Ground Granulated Blast Furnace Slag (GGBF Slag)

GGBF Slag is a derivative of the steel industry. Loriot, during his experiments formed a mortar with GGBF Slag in slaked lime in 1774 [11]. It is considered an economical and ecological resource for modern concrete. It has enormous use both in slag cements as well as a mineral admixture. Its composition is resolute by various factors including ores, fluxing stone and impurities in the coke charged in furnace. Its color varies from off-white to white depending on the moisture content, chemistry and efficiency of granulation. [11]

$SiO_2 + CaO + Al_2O_3 + MgO \geq$ 95% ------------- (1.3)

ASTM C 219-94 defines GGBF Slag as "*the glassy granular material is formed when molten blast-furnace slag is rapidly chilled when immersed in water or in liquid nitrogen (also known as thermal shock) thus milling it to fine powder [11]".* It is made up of both glassy and crystalline phases but only glassy phase is responsible for its cementitious properties. It shows lower SP demand as compared with cement alone and lesser shrinkage. Its specific gravity is generally less than cement. In mix, cement hydration produces CSH gel (contribute to strength) and calcium hydroxide (CH). GGBF Slag reacts with water and produces CSH from its available supply of calcium oxide and silica. A pozzolanic reaction occurs between SiO_2 from the slag source and $Ca(OH)_2$, a hydration product to form more CSH and thus makes GGBF Slag a beneficial SRM for durability purposes. GGBF Slag reduces permeability of concrete thus enhancing resistance to sulphate attack and preventing / minimizing alkalis and other deleterious to penetrate into the main core. It also reduces alkali-silica reactivity by consuming alkali (CH) of cement in the formulation during hydration. Physical packing effect is dominant for GGBF Slag systems during first 28 days

[12] and pozzolanic effect becomes more pronounced thereafter, the pozzolanic reaction of GGBF Slag decreases with increase in its particle size.

1.6.2 Lime Stone Powder (LSP)

Limestone Powder (LSP) has been reported to be an excellent adaptable to cement which is being used as cement admixtures since long in Europe and U.S. In 2004, ASTM C150 was modified for incorporation upto 5% limestone in OPC by mass fraction. It has already been concluded that upto 5% limestone rather improves properties of OPC. In U.S currently LSP contents from 10 to 15% are under experimental stage. Canadian standards have already approved LSP contents upto 15% in OPC [1,8]. In Germany, CEM II/A-LL also contains 6-14 % of LSP. However in this study, efforts have been made to consider this SRM as a partial replacement of fine aggregate i.e. sand in SCC.

LSP particles are rough, highly abrasive, irregular surface texture with flakey and angular particle shape. Its characteristics from previous studies [1,8,13] can be summarized as under:-

- High SP demand to overcome internal friction during flow due to highly abrasive morphology.
- Increased water demand when used in replacement mode.
- Causes more segregation resistance and less bleeding.
- Accelerates setting and reduce setting time.
- Gives filler and nucleation effect during hydration process.

Physical or chemical effects of LSP as partial replacement of cement or fine aggregates are given below:

- Physical effects: Nano size particles of LSP, enhance packing thus interstitial voids, are reduced [9]. Also provide sites of nucleation for hydration products.
- Chemical effects: It includes supplying of ions by fillers / SRMs in pore solution and there by influencing (accelerating) hydration kinetics. It also effects on surface morphology of products of hydration which will preferentially deposit on LSP particles which act as center of nucleation [42].

Carlsward et al, reported that LSP increases the yield stress possibly due to internal friction but has insignificant influence on slump flow and plastic viscosity [18]. Limestone powder is the only filler in the SCC which does not participate in cement hydration [16] but has some chemical action as well. On the other hand, it has been reported that although limestone is not pozzolanic, it can still contribute to strength [17], because: finely ground LSP particles act as sites for nucleation of hydration products there by accelerating early age reaction and hence strength development; limestone reacts with cement hydrate products producing a cementitious gel. [18]

1.6.3 Quarry Dust (QD)

The difference between LSP and QD is SiO_2 contents which are present in the dust and get added into rock powder from environment during natural course of action.

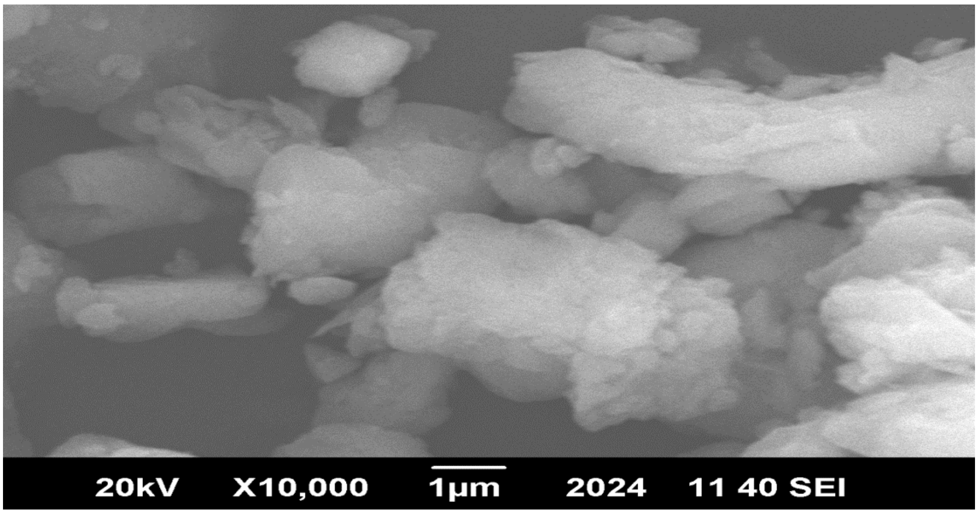


Fig 1.2: SEM Characterization of QD Particle Shape & Size

1.7 Chemical Admixtures

1.7.1 Super Plasticizers (SP).

“Chemical admixtures used to increase workability of the concrete at low mixing water content are known as super plasticizers (SP) or high range water reducing agent (HRWRA)”. They enhance durability and strength indirectly reducing required mixing water contents for a given level of workability. A significant achievable concrete strength after 1980 is contributed mainly to the invention of SP simultaneously in Japan & Germany [13].

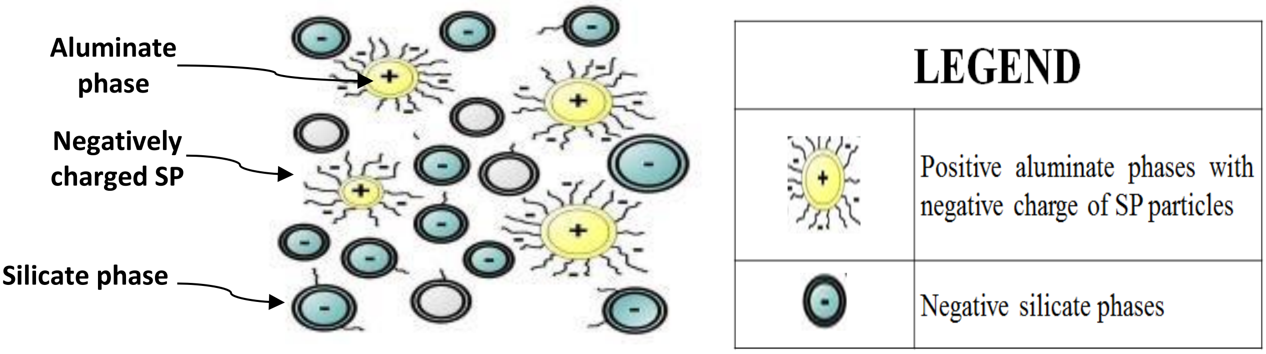


Fig 1.3: Mechanism of SP

Major clinker phases of cement are C_2S, C_3S, C_3A & C_4AF. In fresh cement paste, C_2S & C_3S have a negative zeta-potential while C_3A & C_4AF have a positive zeta-potential. When SP is added along with mixing water, SP with negative charge is attached in substantial amount to aluminate phases. Gypsum mixture leaving only small amounts for the dispersion of silicate phases. By late addition SP, is absorbed to a lesser extent on already wet powder particles, may be due to faster C_3A reaction with initial water leaving enough SP in the solution to promote dispersion of silicate phases and to lower the viscosity of the system [1].

Time of addition of super plasticizers (SP) to concrete is critically important as this factor alone influences fresh and hardened properties of concrete. They are available both in liquid and powdered form. They are based on modified polycarboxylic ether. They have excellent dispersion properties at lower W/C ratio and ensure highest durability & performance. During hydration process, they get absorbed on cement particles and electrostatically provide negative charge on all clinker phases. Thus, cement particles are disposed by electrostatic dispersion. Their dosage range is normally provided by manufacturer.

1.7.2 Viscosity Enhancing Agents (VEA)

Two types of viscosity agents are found in literature [1]. Adsorptive attaches itself onto powder grains thus reducing flow to some extent whereas non- adsorptive acts in water. It is possible to control viscosity by using non-adsorptive viscosity agents without reducing flow but SP demand will go up slightly. Details on such types of VEA's can be found elsewhere [1,19]. Viscosity and workability are contradicting properties which have to be ensured in SCC by jugglery of SP & VEA.

1.8 Fresh Properties of Self-Consolidating Concrete

1.8.1 Workability

Workability requirements for SCC are characterized by passing ability, segregation resistance & filling ability [20].

- Ability to flow under its own weight & completely fill formwork by concrete is called filling ability [21].
- Passing ability is related to ability to flow through congested reinforcement by concrete.
- Both phases (aggregate & paste) shall remain uniform during placement & until setting of concrete is known as segregation resistance.

1.8.2 Setting Time

The Setting Time of SCC typically resembles to conventionally concrete; however, given the use of high dosages of chemical admixtures and the possible use of SRMs in SCC, setting time could increase or decrease based on ingredients. Polycarboxylate based HRWRAs generally result in less delay in setting time than sulphonate-based HRWRAs. Measurement of setting time can be accomplished with conventional methods, including Vicat needle for cement paste or the penetration resistance test for the sieved mortar fraction of concrete [23]

1.9 Hardened Properties of SCC

1.9.1 Microstructure

SCC has superior microstructure than conventional concrete due to the increased packing density due to (N+G) effect and reduction in size & porosity of the interfacial transition zone (ITZ). Low water-powder ratios, necessary to achieve adequate workability, are responsible for much of the improvement in microstructure.

1.9.2 Strength

SCC is generally designed for higher strengths. Although low water-powder ratios are usually dictated by workability requirements, the water-cement ratios can be varied much more widely depending on the quantities of fillers used, including fly ash, GGBF Slag and LSP / QD. The rate of strength development & their ultimate values depend on the amount and activity of these fillers.

1.9.2.1 Compressive strength

Compressive strength is associated with porosity which relates to W/C, type of powders used and degree of hydration. Aggregate characteristics play vital role in compressive strength. Strength of aggregates becomes important in moderate to high-strength concretes. The size, shape, angularity, texture, and mineralogy can affect the quality of ITZ thus influence paste-aggregate bond. Angular and rough textured aggregates tend to exhibit improved bond to the cement paste.

1.9.2.2 Flexural strength

Flexural strength is often related to compressive strength. ITZ tends to affect strengths especially flexural to a large extent compared to compressive strength [24]. Flexural strengths of SCC are typically improved relative to conventional concrete as a result of improved microstructure / ITZ. Roziere found that the flexural strength was slightly higher for SCC than a conventional mixture of comparable compressive strength [25].

1.9.3 Durability and Transport Properties

The potential for improved durability was one of the main original motivations for the development of SCC. The improved microstructure and better consolidation associated with SCC relative to conventionally placed concrete often results in improved durability. The transport properties of concrete depend primarily on the paste volume, pore structure of the paste, and ITZ [26]. Although SCC has higher paste volume, the pore structure of the bulk paste and ITZ characteristics are often improved due to low water-cementitious materials ratios and the use of

SRMs. Improved stability, reduction in bleeding, and elimination of vibration can lead to a denser ITZ and improved durability.

1.9.3.1 Permeability

Permeability and diffusivity of concrete are related to the total porosity and size of voids & their continuity in the matrix. Pore structure of the paste is enhanced by reducing W/C, reducing the water content, providing proper curing, and using SRMs. Permeability is reduced with increased hydration. The capacity of the cement paste to bind ions is enhanced with the use of SRMs due to smaller size than cements. In particular, the hydration products of GGBF Slag are known to bind chloride ions effectively [27]. Low water-cementitious materials ratio and use of SRMs are favorable for improving permeability.

1.9.3.2 Abrasion Resistance

Abrasion resistance is linked primarily to f'_c, type of aggregate and surface finish [4]. Compressive strength is generally considered to be the most important parameter, associated with higher abrasion resistance. Abrasion resistance is also improved by using hard, dense aggregates and also silica fume.

1.10 Calorimetry

Calorimetry is a versatile technique used to know hydration kinetics of SCC. Using this technique, effect of w/c ratio, S.P content and addition of SRMs as a partial replacement of cement & fine aggregate on the heat evolved from the system can be investigated. In the present study calorimetry is used to study the effect of LSP, QD and GGBF Slag on hydration kinetics of SCCS.

1.11 Study of Micro Structure by Scanning Electron Microscopy (SEM)

SEM is an excellent versatile technique for studying the microstructure, ITZ, various phases and their interconnectivity. It provides a better view of surface morphology, microstructure and hydration products of selected specimens. Application of scanning electron microscopy enhances our ability to characterize cement and concrete microstructure, evaluate the influence of secondary raw materials, estimate the concrete durability and indirectly predict the service life [28,29].

CHAPTER 2 – PREPARATION OF MATERIALS

2.1 General

Although SCC can be made with a wide range of materials, the proper selection of materials is essential for optimizing the properties of SCC. It is generally much more sensitive to changes in material properties as compared to conventionally placed concrete. In this chapter procedures adopted for collection, preparation, storage of the materials and their characteristics including their chemical composition have been elaborated.

2.2 Collection, Preparation & Storage of Materials used in Research

2.2.1 Lime Stone & Quarry dust

In Pakistan, research is not user friendly due to nonexistence of research facilities and non-availability of research materials**.** Collection & preparation of materials were highly time consuming activities due to non-availability of materials, milling machinery in the local market and storage facility in the laboratory before starting the experimental work. A survey had to be carried out especially for milling of the materials to the required size and ultimately unconventional procedures were adopted for the subject activity. Summary of various activities is as under:-

- Lime Stone Powder and Quarry Dust were collected from parent sources Margalla deposits to ensure better quality.
- Lime Stone Powder was washed to remove dust and then dried for 24-hrs at a temperature of 105^{o}C in the laboratory whereas Quarry Dust was further processed in "as obtained "state (without washing).
- Both the materials were grinded up to 5-100 (µm) particle size in locally available "Grinding China Machine".

Fig 2.1 (a): Deposits of Lime Stone at Margalla Hills.

Fig 2.1 (b): Washing &Drying of Lime Stone Powder

- To bring the particle size to desired level i.e., ≤ 10µm , further milling was done by Los Angles abrasion machine in Transportation Lab at NICE, NUST Islamabad. Each batch of 5 kg was given 20,000 revolutions.
- Material was then sieved through #350 sieves.
- The resulting sample after sieving was preserved in air-tight polythene bags as shown in Fig 2.2 and later on used for producing different mixes.

2.2.2 GGBF Slag

GGBF Slag was selected as SRM for partial replacement of cement after non-availability of Fly Ash (German) in huge quantity (150 Kg) for SCC. The author arranged "Water Quenched" GGBF Slag from Pakistan Steel Mills Karachi. Its size was not as per requirement and had to be ground from locally available "Grinding China Machine". It is worthy to mention that grinding of GGBF Slag was more difficult than Lime Stone due to presence of glassy phases of steel.

Fig 2.2 : Storage of Materials in Laboratory

2.3 Properties of the Materials

2.3.1 Cement

Ordinary Portland Cement (OPC) of Bestway brand was selected and stored in plastic jars in accordance with the requirements of research to keep it moisture free.

Brand:	Bestway Cement Grade 53,
Type:	Type I (ASTM C 150, EN-197-1/200, PS232-2008(R))
Specific Gravity	3.10
Avg. Particle size:	20µm (By particle size analysis)
Water Demand	26.5% (ASTM C 187& EN-197)

- Surface Area 1650 cm^2/gm [8].

XRF analysis of the cement was carried out with a view to determine its chemical composition. The results are tabulated below along with comparison between Pak OPC and German CEM 1 42.5 R from previous literature [26].

Table 2.1: Comparison of Chemical Composition of Cements

Constituents	% age By weight	
	OPC (Bestway) (Pak)	CEM1 42.5 R (German)
SiO_2	17.15	16.46
Al_2O_3	5.60	4.18
Fe_2O_3	3.21	3.51
MgO	1.44	1.23
CaO	64.09	66.56
Na_2O	1.86	-
K_2O	1.19	1.65
SO_3	2.66	6.41
D50	20µm	14.77

2.3.2 Ground Granulated Blast Furnace Slag (GGBF Slag)

GGBF Slag is a by-product of the steel manufacturing industry. Iron ore, coke and limestone are fed into the furnace and the resulting molten slag floats above the molten iron at a temperature of about 1500 °C to 1600°C [11].

Table 2.2: Comparison of Chemical Composition – GGBF Slag (Pak &German)

Oxides (%)	% age By weight	
	Pak GGBF Slag	German GGBF Slag [13]
SiO_2	31.57	34.30
Al_2O_3	12.17	10.07
CaO	43.45	42.04
Fe_2O_3	2.71	0.43
TiO_2	0.85	0.94
MnO	1.75	Not detected
ZrO_2	0.03	"
SrO	0.163	"
SO_3	1.49	3.833
Na2O	Not detected	0.41
Particle size 50 (µm)	15	8.603

The production of GGBF Slag requires little additional energy as compared with the energy needed for the production of Portland cement. OPC if replaced with GGBF Slag will lead to significant reduction of carbon dioxide gas emission. GGBF Slag is therefore an environment friendly construction material [11]. It can be used to replace as much as 80% of the Portland cement used in concrete like CEM III/B of EN-196. Water quenched GBFS was obtained from Pakistan steel mills Karachi in granulated form. To obtain material up to the desired particle size i.e., less than 20 µm, (GBFS) was milled in Los Angeles Abrasion Machine by 20,000 revolutions as well as in local floor grinding machine. A comparison of XRF analysis of GGBF Slag (Pak) and German GGBF Slag [13] is given in Table 2.2.

2.3.3 Lime Stone Powder (LSP)

Lime Stone is greyish in color, rich in $CaCO_3$ (97.64%) with no contents of SiO_2. It has been popular in construction industry due to oblivious benefits as aggregate. LSP from the crushing plant was washed to remove dust particles which are usually added as impurity in the form of clay during dumping the material at quarry site.

2.3.4 Quarry Dust (QD)

QD is about 1% of the total rock mass being crushed [8]. This definitely contributes into atmospheric pollution. Efforts have been made in this study to utilize this dust in SCC as a partial replacement of fine aggregate / cement. It will not only save our environment if found useful but also can affect properties of SCCS both in fresh and hardened state. The XRF analysis results are tabulate in Table 2.3 with details at Annexure C. It is worthy to mention that composition of LSP and QD is almost same except high contents of crystalline SiO_2 in QD due to clay contents.

Table 2.3: Comparison of Chemical Composition of LSP & QD

Constituents	LSP	QD
SiO_2	Not detected	23.175
Al_2O_3	"	Not detected
CaO	97.64	70.31
Fe_2O_3	1.7125	4.34
SrO	0.646	0.46
TiO_2	Not detected	0.396
MgO	“	Not detected
K_2O	“	1.19
SO_3	“	Not detected
Na_2O	“	"
D50 (µm)	9.5	8.25
Density(g/cm^3)	2.75	2.696

2.3.5 Fine Aggregate

2.3.5.1 Lab Testing

Sand is an important component of SCC. It is recommended to use 0-2mm sand in SCC systems. Lawrancepur sand was procured for this study and it was still wet once collected. It was brought to laboratory and was oven dried at 105^0C for 24 hrs and was placed in containers before use. All the tests were carried out in the lab to check its suitability for research. Properties of Fine Aggregates have been summarized in Table 2.4.

Table 2.4: Properties of Fine Aggregates

Test	Specifications	Result
Specific gravity (SSD)	ASTM C 128	2.88
Specific gravity (Bulk)	"	2.86
Specific gravity (Apparent)	"	2.96
Absorption capacity	"	1.40%
Fineness modulus (FM)	ASTM C 136	2.19
Gradation	"	Table 2.5 & Fig 2.3

2.3.5.2 Gradation of Fine Aggregates

Standard sieves of ASTM designation # 4, 8, 16, 30, 50, 100 & 200 were used to separate the sand particle and given them a particle designation as shown in Table 2.5. Sand particles retained on #8 sieves or passing through #200 sieves were discarded. Thus the sand used was finer in size range of 1.18~0.3mm compared with ASTM range. Separated sand particles were stored in different containers as per their designation. Results of the tests conducted to ascertain the properties of sand are given in Table 2.5.

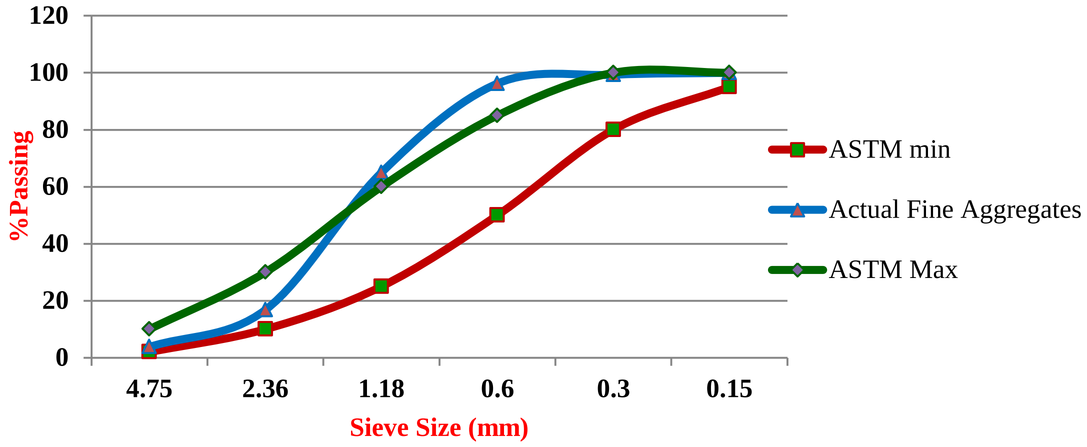


Fig 2.3: Gradation Curves of Fine Aggregates

Table 2.5: Sieve Analysis of Fine Aggregates

Sieve No	Sieve Size (mm)	Weight Retained (gm)	% age Retained	Cumulative % age Retained	% age Passing	ASTM min % age Passing	ASTM Max % age Passing
4	4.75	2	0.021	0.021	99.979	95	100
8	2.36	6.4	0.671	0.692	99.308	80	100
16	1.18	29.6	3.103	3.795	96.205	50	85
30	0.6	298	31.243	35.039	64.961	25	60
50	0.3	459.5	48.165	83.204	16.796	10	30
100	0.15	124	13.001	96.205	3.795	2	10
Pan		36.2	3.795				
	Total =	**953.8**	**Total =**	**218.96**		**FM =**	**2.19**

Locally available sand which do not conform to the ASTM gradation limits and having fineness modulus lower than the minimum specified fineness modulus by ACI 211-1-91 can be successfully utilized in manufacturing good quality structural concretes with slight variations in mix proportions of constituent materials, using admixtures or by increasing the paste within the mix of desired consistency. Proportioning of constituent materials must ensure that the concrete so formed meets the requirements in both fresh and hardened state, which involves striking a balance between the proportions of constituent materials.

2.3.6 Coarse Aggregates

2.3.6.1 Laboratory Tests

Coarse aggregate was procured from Margalla quarry site. It was sieved into two categories; CA-1 (2-9 mm) & CA-2 (9-19 mm) as suggested [31]. Results of tests conducted to ascertain the properties of aggregates are presented in Table 2.6.

Table 2.6: Properties of Coarse Aggregates

Test	Specifications	Result
Bulk specific gravity (oven dry)	ASTM C 127	2.77
Bulk specific gravity (SSD)	"	2.78
Specific gravity (apparent)	"	2.785
Absorption capacity	"	0.29 %
Dry rodded unit weight	ASTM C 29	1650 Kg / m^3
Gradation	ASTM C 136	Table 2.7 & Fig 2.4

2.3.6.2 Gradation

Gradation of coarse aggregate was done according to ASTM C136. Results of sieve analysis have been tabulated along with maximum and minimum limits of ASTM to correlate with the actual aggregates.

Table 2.7: Sieve analysis of Coarse Aggregates

Sieve Size	Sieve Size (mm)	Wt Retained (gm)	% age Retained	Cumulative % age Retained	% age Passing	ASTM min %age Passing	ASTM Max %age Passing
1"	25	0	0	0	100	100	100
3/4"	19.5	50.1	5.00	5.00	95.00	90	100
3/8"	9.5	550.5	55.00	60.00	40.00	25	55
# 4	4.75	350.4	35.00	95.00	5	0	10
# 8	2.36	50	5.00	100	0	0	5
		100	**Total = 260**				

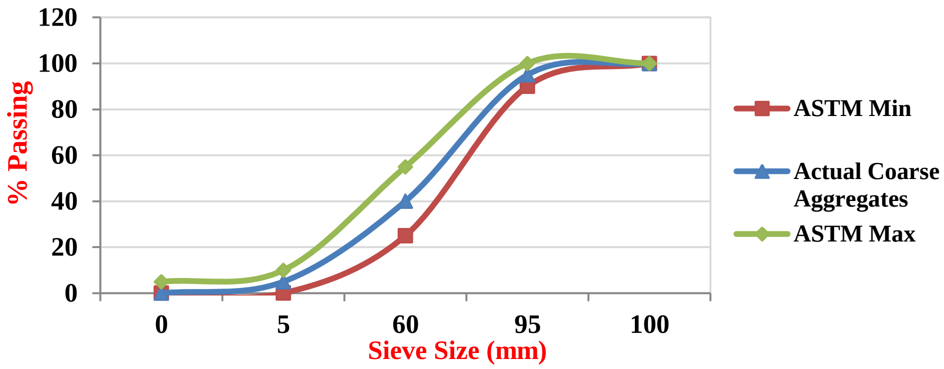


Fig 2.4: Gradation Curves of Coarse Aggregates

2.3.7 Super Plasticizer (SP) for SCC

In this study, Glenium51, liquid SP confirming to ASTM C494was used for SCC. Its recommended dosage is between 0.5 - 1.6 liters per 100 kg of cement (cementitious material) [32]. However variation is acceptable during the trial mixes depending upon the best engineering judgment. Important characteristics of Glenium 51[32] include:-

- Increases compressive & flexural strength at initial & later ages.
- Improves bond between steel & concrete.
- Reduces permeability thus enhances durability.
- Reduces shrinkage & creep.
- Enhances workability, reduces segregation & bleeding.
- Improves surface finish.

2.3.8 Super Plasticizer (SP) for SCP (Melflux 2651 F)

Melflux 2651 F is a spray dried powder of modified polycarboxylic ether. It provides excellent development of early strength and is based on latest polymer technology and has side chains based on polyethylene glycol. Powdered form of SP had been imported from Germany. pH Value of Melflux 2651F is between 6.5 to 8.5. Manufacturer recommends dosage rate of 0.05 to 0.5% of cement weight. Its shelf life is one year.

CHAPTER 3 – METHODOLOGY & EXPERIMENTAL PROGRAMME

3.1 General

After extensive survey of previous literature on SCC [1,22,35] and detailed discussions with the supervisor [1,31] careful selection of SRMs for partial replacement of cement and fine aggregate was made. No standard milling facility was available at NUST as well as in local market. A lot of effort in terms of material and expenses was made for the preparation of SRMs to the desired size by manually operated grinding machines. SCC mixer was made operational after huge efforts spanning over 4 months. Now it is the only mixer in NICE for making self-consolidating concrete. In view of objectives of the research, experimental program employed in SCP & SCC systems.

3.2 SCP Systems

3.2.1 Formulations

In Cement-Slag (CS) formulations, four contents of Ground Granulated Blast Furnace Slag were used as replacement of cement. Details are as under:

Table 3.1: Designation of Cement-Slag (CS) Formulations of SCP Systems

Formulation	Description	WD (%)
C1 – 0-WD	(Cement 100%)	26.50
0.95C1 + .05BFS – WD	(Cement 95 % & GGBF Slag 5%)	26
0.9C1 + 0.1BFS – WD	(Cement 90 % & GGBF Slag 10%)	25.50
0.85C1 + 0.15BFS – WD	(Cement 85 % & GGBF Slag 15%)	25
0.8C1 +0.2 BFS – WD	(Cement 80 % & GGBF Slag 20%)	24

In SCP formulations having blends of powders, partial replacement of cement was made with blends of SRMs ie GGBF Slag along with 10 & 20 % of LSP & QD respectivley. Details are as under:

Table 3.2: Designation of SCP Formulations having Blends of Powders

Formulation	Description	WD (%)
0.8C1 + 0.1BFS + 0.1LSP -WD	(Cement 80% & GGBF Slag 10% , LSP 10%)	26
0.7C1 +0.1BFS+ 0.2LSP- WD	(Cement 70 % & GGBF Slag 10%, LSP 20%)	25.75
0.8C1 + 0.1BFS+0.1 QD - WD	(Cement 80 % & GGBF Slag 10%, QD 10%)	25.75
0.7C1 + 0.1BFS+0.2 QD - WD	(Cement 70 % & GGBF Slag 10%,QD 20%)	25.50

3.2.2 Mixing Regime & Proportions

Constituents including cement, SRMs and powdered SP were weighed in desired quantity. Dry mixing by 30 vertical & 30 horizontal revolutions for 60 sec was done manually in plastic jar. Hobart Mixer of 5L capacity in NICE Laboratory was used for mixing of constituents of SCP as shown in Fig 3.1. The mixed powder is then fed into the bowl of Hobart Mixer followed by putting desired amount of water. Mixer is then run at mode 1 i.e. slow mixing (145 rpm) for 30 sec. Interior of bowl is cleaned with the help of mixing spatula / spoon. Slow mixing for 30 sec at mode (1) and finally, fast mixing at mode 2 (285 rpm) for 90 sec was applied. Total time for mixing is 3 minutes (180 sec) as dictated by EN-DIN 197.

Fig 3.1 (a): Hobart Mixer

Fig 3.1 (b): Moulds of SCP Prism

3.2.3 Water Demand & Setting Time

For durable SCC mix, water contents should be very close to WD of the system. European Guidelines for SCC also indicate calculation of WD of a system's be first step for SCCS design. WD and setting times of various SCP were determined by Vicat apparatus shown in Fig 3.2. At (28±2)^{o}C and (25±3) % relative humidity at WD of the formulations. SP contents for a target flow of 30±1 cm was determined by Hagerman's mini slump cone as shown in Fig 3.3.

Fig 3.2 : Vicat Apparatus

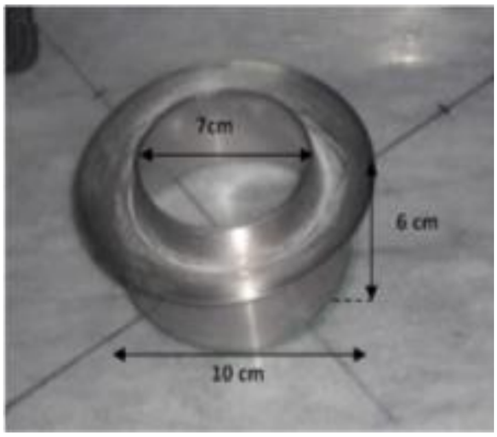


Fig 3.3 : Hagerman's Flow Cone

3.2.4 Flow Measurements

Hagerman's mini slump cone was used to determine flow behavior of SCP at WD. Quantity of SP Melflux 2651F (3rd generation powder type) PCE is required at target flow spread (30$\underline{+}$1) cm at WD using Hagerman's mini slump cone. T25 (time for 25 cm spread) & T30 (time for 30 cm spread) was determined along with total spread.

3.2.5 Calorimetry

Calorimetry is a technique to study hydration kinetics of a cement based system using Calmetrix F-Cal 8000 instrument. For SCP measurements were made for 72 hrs. F-Cal consists of 8 channels (3”x6”) cylindrical in shape. Temperature gives a finger print of the hydration / chemical reactions. Samples were collected from the SCP formulations while casting prisms for strength. A 250 gm sample was put in the plastic envelope and then placed in the cylinder of calorimeter while ensuring that cylinders must be clean both inside and outside during the tests.

3.2.6 Strength

EN 196-1 of 1994 standards has been used for casting, curing and testing of SCP. Formulations prepared in Hobart mixer as per above instructions and prisms of (40x40x160) mm size were prepared as shown in Fig 3.10. Polythene sheet was used to cover moulds after casting to avoid loss of moisture. Demolding was done after 24 hrs. Prisms were placed in water curing tank at 20°C in the laboratory. At 1, 3, 7, 14, 28 & 56 day of age samples were taken out for testing in SSD conditions.

For flexural strength, average of 3 samples were tested in flexure in ADR Auto 250 machine and recorded as the strength of that sample as per DIN standards at that prescribed age as shown in the Fig 3.7. Load is applied @ 0.2 MPa / sec for flexural strength. For compressive strength, average of 5 samples as per EN-DIN standard was taken as strength of the sample. Compression test samples were obtained from broken pieces of flexure sample having X-section as (40 x 40) mm and placing two steel plates of 40 x 40 mm^2 at top and bottom sides of specimen and load is applied @ (0.15 – 0.35) Mpa / sec. One sample was broken with chisel for SEM images from SMME laboratory.

3.3 SCC Formulations

Uptill now, efforts had been made to replace cement partially with SRMs in order to economise and protect environment. In this research a new concept of partially replacing fine aggregate with nano size SRMs along with partial replacement of cement was used. The details of formulations are as under:-

Table 3.3: Designation of SCC Formulations

Formulation	Description
C1 – FA – CA -45	(Cement 100 %) + (Fine aggregate 100%) +(Coarse Aggregates 100%) at 45% W/C
C1 – (0.9FA + 0.1LSP) – CA - 45	(Cement 100 %) + (Fine aggregate 90% + LSP 10%) + (Coarse Aggregates 100%) at 45% W/C

C1 – (0.9FA + 0.1QD) – CA - 45	(Cement 100 %) + (Fine aggregate 90% + QD 10%) + (Coarse Aggregates 100%) at 45% W/C
(0.8C1 +0.2BFS) - FA– CA – 45	(Cement 80% & GGBF Slag 20%) + (Fine aggregate 100%) +(Coarse Aggregates 100%) at 45% W/C
(0.8C1 +0.2BFS) – (0.9FA + 0.1LSP) – CA - 45	(Cement 80% & GGBF Slag 20%) + (Fine aggregate 90% + LSP 10%) + (Coarse Aggregates 100%) at 45% W/C
(0.8C1 +0.2BFS) – (0.8FA + 0.2LSP)- CA – 45	(Cement 80% & GGBF Slag 20%) + (Fine aggregate 80% + LSP 20%) + (Coarse Aggregates 100%) at 45% W/C
(0.8C1 +0.2BFS) – (0.9FA + 0.1QD)- CA –45	(Cement 80% & GGBF Slag 20%) + (Fine aggregate 90% + QD 10%) + (Coarse Aggregates 100%) at 45% W/C
(0.8C1 +0.2BFS) – (0.8FA + 0.2QD)– CA-45	(Cement 80% & GGBF Slag 20%) + (Fine aggregate 80% + QD 20%)+(Coarse Aggregates 100%) at 45% W/C
(0.8C1 +0.2BFS)+0.05CH - FA– CA - 45	(Cement 80% & GGBF Slag 20%) +($Ca(OH)_2$) 5% + (Fine aggregate 100%) +(Coarse Aggregates 100%) at 45% W/C
(0.8C1 +0.2BFS)+0.1CH - FA– CA - 45	(Cement 80% & GGBF Slag 20%) +($Ca(OH)_2$) 10%+ + (Fine aggregate 100%) +(Coarse Aggregates 100%) at 45% W/C
(0.8C1 +0.2BFS)+0.2CH - FA– CA - 45	(Cement 80% & GGBF Slag 20%) +($Ca(OH)_2$) 20% + (Fine aggregate 100%) +(Coarse Aggregates 100%) at 45% W/C

Quantities were worked out in the light of discussion [1,31] and are given in table 5.3.

3.3.1 SCC Mixer

Locally developed concrete mixer for SCC (as shown in Fig 3.4) by NUST had some faults during manufacturing at Lahore. It was made operational after a lot of effort spanning over 3 months. However results were very encouraging. Important characteristics of the mixer include:-

- Easy to operate.
- Hydraulically operated cover for up and down move. The system was so designed to ensure least wastage of fines.
- Range of mixing rate is 180 to 700 rpm but recommended upto 400 rpm.
- 5 HP electrical motor for mixing purpose.
- Mixing blades were so designed to ensure proper mixing.

Fig. 3.4 : Indigenously Developed SCC Mixer

3.3.2 Mix Proportions of Aggregates in SCC

Based on the flow ability tests of concrete mixes, pre-selection of the aggregate volume & composition, particularly sand contents, was done with varying aggregates volumes and sand-to-aggregate-ratios. Initially, total aggregate contents, were taken in the range of 0.615-0.64 m^3/m^3 with sand contents of half of total aggregate mass has been found satisfactory for SCC. Using data by Rizwan (2006) on SCC [1] and valuable discussions [31] for mix proportions were kept as under:-

➢ Coarse Aggregates		
• 2-9 mm (CA-1)	(1)	25% of weight of total aggregates
• 9-19 mm (CA-2)	(1)	25% of weight of total aggregates
➢ Fine Aggregates (FA) (0-2 mm)	(2)	50% of weight of total aggregates

In view of previous literature, to increase cohesiveness and stability, the sand contents may be increased (40-45% of total aggregate contents) keeping the total aggregate content constant [1]. Good workability is usually achieved by reducing the aggregate contents (resulting in reduced internal friction) and by increasing the paste volume as has been stated earlier. This may, however, slightly increase shrinkage and reduce strength of SCC mix. In initial trial batches of SCC using GGBF Slag without VMA, bleeding & segregation of SCC was observed. Thereafter, a number of trials were made by increasing sand contents and decreasing coarse aggregate contents. Ultimately a stable SCC mix was obtained at (1:2:3.67) instead of (1:1:2).

3.3.3 Water Demand (WD)

WD of a certain concrete is defined as the amount of water required to completely cover all particles surfaces with a thin water layer near SSD condition. It is sum of individual WDs of powders & aggregate phases. Rizwan [1] describes that minimum WD of powders equates to about 95% of the SCC's total water amount so that the WD of the coarse aggregates would amount to approximately 5% of their respective masses. Procedure suggested by Rizwan is simple and different from that reported previously where WD of aggregates was determined by centrifuging water cured aggregates [1].

Table 3.4: Calculation of the WD of 1 m³ SCC [Rizwan 2006]

Material	Amount in SCC mixture (kg/m³)	WD of material (% of mass)	WD (kg/m³)
Cement: GGBF Slag (1 : 0.20*by mass)	(421.6 +105.4)= 527	29	152.83
Aggregate size 0/2 mm	906.77	2.73 [ASTM C128]	18.69
Aggregate size 2/9 mm	494.15	1.62 [ASTM C127]	8.05
Aggregate size 9/19 mm	247.08	2.06 [ASTM C127]	5.09
Total system's WD	-	-	184.67
Mixing water (w/c=0.45)	-	-	189.72
Difference	-	-	5.05

* Based on engineering judgment

Lead for calculations of WD (Table 3.4) is taken from [1]. WD of powder component can be determined by mixing cement and other SRM's in the selected mass proportions to be used in SCC composition and a test can be made with Vicat needle. ASTM C127 and 128 may be used to determine SSD water contents of coarse & fine aggregates. Adding individual WD of all phases will give WD of the system as reflected in Table 3.5.

3.3.4 Mixing Regime

Based on valuable guidelines and discussion [35], experimental work in laboratory, tunnel and ready mixed concrete manufacturing plant by Rizwan in 2006 [1], the author carried out lab tests and developed a mixing procedure. SCC mix is prepared in 5 minutes at slow as well as rapid mixing. It may not be the most efficient but it is easy to follow. Procedure is as under:

- ➢ Calculations of proportions of various constituents.
  - In this research on SCC, aggregate ratio was kept (1:2:3.67) of coarse aggregates (9-19mm), coarse aggregates (2-9mm) & fine aggregates (0-2mm) respectively. Otherwise select aggregates with reasonable accuracy by keeping in view "The European Guidelines for SCC 2005".
  - Based on the best engineering judgment, powder contents (cement, fillers and their ratio) be selected for desired target properties of SCC in fresh and hardened state.
  - After selecting powder and aggregate contents, the WD of SCC systems can be estimated as suggested and can also be compared with the mixing water available from selected w/c ratio to avoid possible bleeding and segregation. In this research W/C was kept at 0.45 [35]. However this ratio can be selected by strength of cements & codes based on service use and exposure requirements in service life of structures [1].

  - Later on plasticizer and viscosity agent contents can be adjusted considering flow targets possibly starting with the average manufacturer's specified ranges.
  - The appropriate sand content appears to be in the range of 50-55% of the total aggregate volume especially for rather elongated coarse aggregates for stability purposes [1].
- ➢ Dry mixing for 1 minute at 180 rpm (slow rate). Sequence of putting dry constituents in rotary drum is very important to ensure efficient mixing shown Fig 3.5 is as under:-
  - Coarse aggregates (2-9 mm)
  - Coarse aggregates (9-19 mm)
  - Cement with SRMs (if any)
  - Fine aggregates (0-2 mm)
- ➢ Add 80% of water in the dry constituents and mix again for one minute at 180 rpm (Slow Mixing).
- ➢ Add SP and / or Viscosity Enhancing Agent (VEA) in remaining 20% water; mix them thoroughly. Put it in rotary drum and mix it for 1.5 minutes at 360 rpm (Fast Mixing).
- ➢ Leave the mix in the drum for 5 minutes undisturbed in order to activate SP and VEA.
- ➢ Mix the ingredients again for 1 minute at 360 rpm.
- ➢ Check SCC mix for adjusting the doze of SP and VEA (if required).
- ➢ Give a final mixing at 360 rpm for ½ minute for ensuring proper SP activation.

Fig. 3.5 : Preparation of SCC Mixes

- ➢ Carry out SCC flow tests in the sequence given below but carryout mixing for 5 sec in subsequent tests.

3.3.5 SCC Flow Tests

In the fresh state, tests in the sequence given below will be carried out in around 20 minutes by 3 men party. In laboratory, mix will then be agitated again for 5 sec each before the next test. [1]

3.3.5.1 Slump Flow Test

The slump flow test is the most well-known and widely used test for characterizing SCC and is extremely easy and straight forward to perform. The slump flow (yield stress) is the main fundamental difference between SCC and conventionally placed concrete. The slump flow test provides a measure of filling ability. The horizontal spread reflects the ability of the concrete to flow under its own mass (yield stress) while the T50 time provide indications of the plastic viscosity and segregation resistance, respectively. The test does not provide a complete description of filling ability because it does not fully reflect harshness and the ability to fill all corners of the formwork. The test does, however, provide a valuable visualization of concrete flow. Based on literature study and experimental work in the lab, merits and demerits have been proposed which include:

- It is robust, repeatable & inexpensive and easily portable which provides an independent measurement of filling ability.
- The spread is related to yield stress & T50 is related to plastic viscosity [1].
- Results do not reflect all aspects of filling ability and do not indicate the harshness of mixtures [33].

Apparatus for slump flow test includes rigid, non-absorbent square plate, slump cone (ASTM C 143), scoop or bucket to load concrete into slump cone, stopwatch and measuring tape or ruler. Following procedure can be used to determine average slump spread in cm and T50, in sec [33]:

- Dampen the slump cone and plate (ensure there is no standing water). Place the plate on firm, level ground. Center the inverted slump cone (narrow end at the bottom) on the plate (use the 8-inch concentric circle as a guide) and hold down firmly.
- Fill the slump cone in one lift. Do not apply any external compaction effort. Strike off any excess concrete above the top of the slump cone. Remove any concrete on the plate.

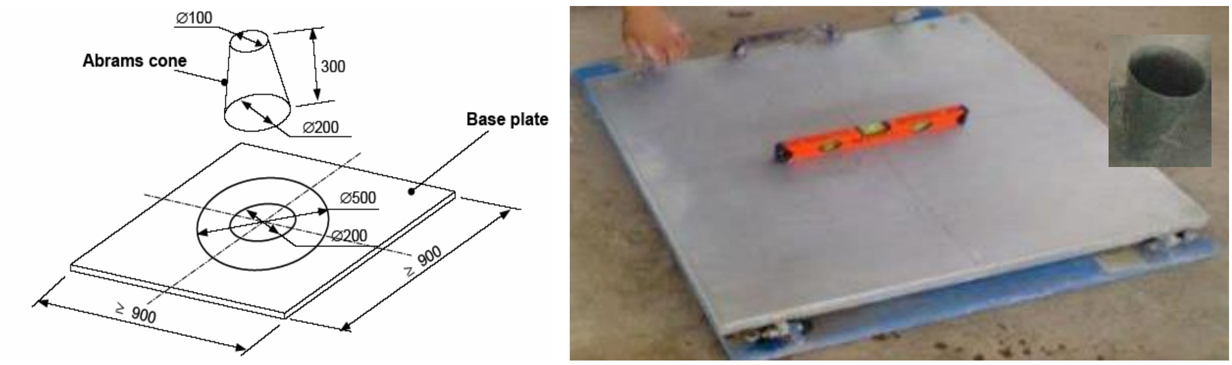


Fig. 3.6: Apparatus for Slump Flow Test [1]

- Remove the slump cone by lifting it vertically upward, being careful not to apply any lateral or torsional motion.

- Measure the time for the concrete to spread to a diameter of 50 cm (T50)
- Measure the final slump flow in two orthogonal directions after the concrete has ceased flowing.

3.3.5.2 V Funnel Test

V funnel test measures a single value that is related to filling ability, passing ability, and segregation resistance. Therefore, the test may be suitable as a pass/fail test but cannot provide an independent indication of filling ability, passing ability, or segregation resistance. Low V funnel times can be associated with good flow properties, but the test provides no information for troubleshooting mixtures with high V funnel times [33]. Merits & demerits of V funnel test include:

- The test is relatively simple to perform and results are expressed in a single value related to filling ability, passing ability, and segregation resistance.
- For paste, mortar and concrete mixtures that can be idealized as homogenous, non-segregating materials, the results are a function of yield stress and plastic viscosity. For such materials that are also self - flowing (near - zero yield stresses), the results are primarily a function of plastic viscosity [33].
- The test does not provide an independent indication of filling ability, passing ability, or segregation resistance [33].
- Large & bulky test frame must be placed on a leveled surface.

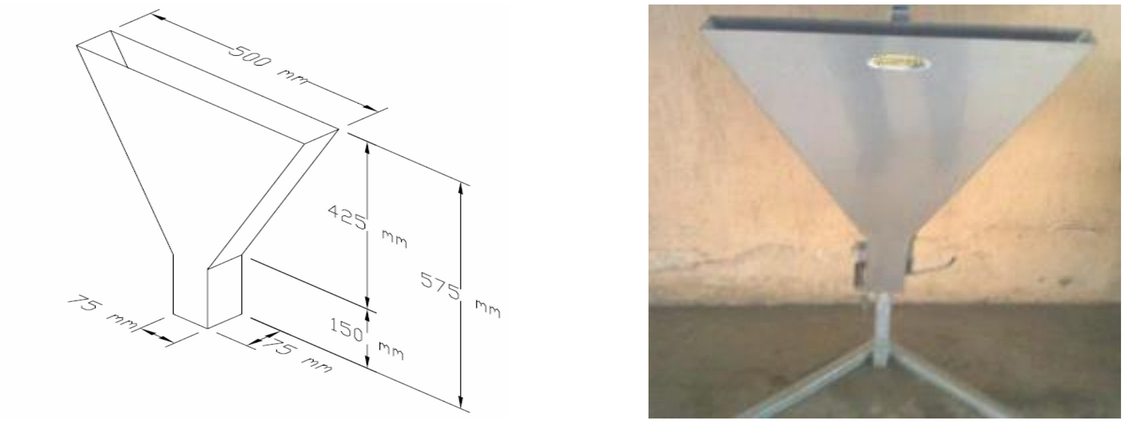


Fig. 3.7: Apparatus for V Funnel Test [64]

Apparatus of the test has been shown in Fig 3.7. It includes V Funnel, bucket (minimum capacity of 0.35 ft^3, scoop or bucket to load concrete into V funnel and stopwatch. Taking guidelines from previous literature [1,33], following procedure may be used to determine V Funnel time:-

- Place the V funnel frame on firm, level ground. Position the bucket below the opening in the V funnel.
- Dampen the inside of the V funnel. Leave the bottom gate open for sufficient time so that once the gate is closed, water does not drain and collect on the gate. Close the bottom gate.

- Fill the V funnel with concrete. Do not apply any external compaction effort. Strike off any excess concrete above the top of the V funnel.
- Allow the concrete to remain undisturbed in the V funnel for one minute.
- Open the gate of the V funnel and allow the concrete to flow into the bucket.
- Measure the time from the opening of the gate to the point when light is first visible through the bottom hole.

3.3.5.3 L Box Test

L Box test provides a measurement of passing & filling ability [1]. It has been used widely throughout the world and was selected by the European Testing SCC project as a reference test for passing ability. L Box test was chosen for evaluation in this research because it is easier to visualize the flow of the concrete in the test especially any blocking behind the bars and the apparatus is easier to clean [33]. Advantages and disadvantages of the L Box test include [33]:

- The test provides a visualization of how concrete will flow in the field.
- The amount of mass available to push concrete through the bars is more representative of field conditions than in the J Ring test.
- Relationship between test results & field performance is better established than for J Ring test.
- Test does not distinguish between passing ability and filling ability.
- The test apparatus is bulky, difficult to clean, and not well-suited for use in the field.
- The selection of rebar spacing is not well defined.
- The determination of blocking ratio requires two measurements and three separate calculations. A single measurement is not possible.
- The volume of concrete required is greater than for the J Ring test.

It includes L-Box with 3 equally spaced, 16 mm-diameter, deformed reinforcement bars, scoop or bucket to load concrete into L-Box, stopwatch and measuring tape or ruler. Following procedure may be used as reported previous literature [33] to determine blocking ratio (H_2 / H_1), T 200, T 400 and T600:-

- Place the L- Box on a firm, level surface. Close the gate.
- Fill vertical portion of the L Box with concrete. Do not apply any external compaction effort.
- Allow the concrete to remain undisturbed in L Box for one minute. Open the gate fully.
- Measure the time for the concrete to reach point marked at 400 mm (T40) down the length of the box.

- Measure the heights H_1 & H_2 at each end of the box after concrete flow has ceased.

Fig. 3.8: Apparatus of L-Box

3.3.5.4 J Ring Test

J Ring apparatus measures passing ability, segregation resistance and filling ability. While comparing it with slump test, difference should be lesser otherwise it will reflect non-continuous packing, low deformation & segregation resistance [1]. Koehler describes the J Ring test as:

- The test independently measures passing ability.
- The test represents field conditions well and accurately distinguishes between mixtures with varying degrees of passing ability.
- The equipment is low in cost and portable. Although it is mainly needed in the laboratory, it can be easily used in the field (especially when compared to the L Box).
- The use of a single spacing of reinforcing bars for all tests may overestimate passing ability for highly congested sections.

Fig. 3.9: J Ring Test

It includes J Ring 300mm diameter with 12 equally spaced,16mmdia reinforcement bars (deformed), rigid, non-absorbent plate, at least 32 inches square, with concentric circles marked at diameters of 200mm (8 in.) and 300mm (12 in.), slump cone [ASTM C 143], scoop or bucket to load concrete into slump cone, measuring tape or ruler.

3.3.6 Calorimetry

Calorimetry is a test to measure Hydration Kinetics of SCC. F Cal 8000 has been used to determine heat of hydration of various SCC formulations. For SCC, calorimetry was done for 96 hrs (4 Days) instead of 72 hrs as was done for SCP. While comparing results of SCP & SCC, parameters like dormant period & peaks of heat of hydration are found. Calorimetric results of both SCC & SCP will be shown diagrammatically along with detailed discussion in coming chapters.

3.3.7 Strength

EN 196-1 of 1994 standards has been used for casting, curing and testing of SCC. SCC mixes were prepared with details above described. Both cubes (100x100x100) mm and prisms (40x40x160) mm were poured with concrete. Polythene sheet was used to cover after casting to avoid loss of moisture. Demolding was done after 24 - 72 hrs due to delayed setting of GGBF Slag. Samples were placed in curing tank at 20^{o}C in the laboratory. At 3, 7, 14, 28 &56 days samples were taken out for testing in SSD conditions.

For flexural strength, average of three prism samples were tested in flexure in ADR Auto 250 machine and recorded as the strength of that sample as per DIN standards at that prescribed age as shown in the Fig 3.10. For compressive strength, average of 3 cubes as per EN– DIN standard

Fig 3.10 : Strength Testing Machine

was taken as strength of the sample as shown in the Fig 3.10. Sample for SEM images were prepared from prisms tested in flexural with chisel at specified ages.

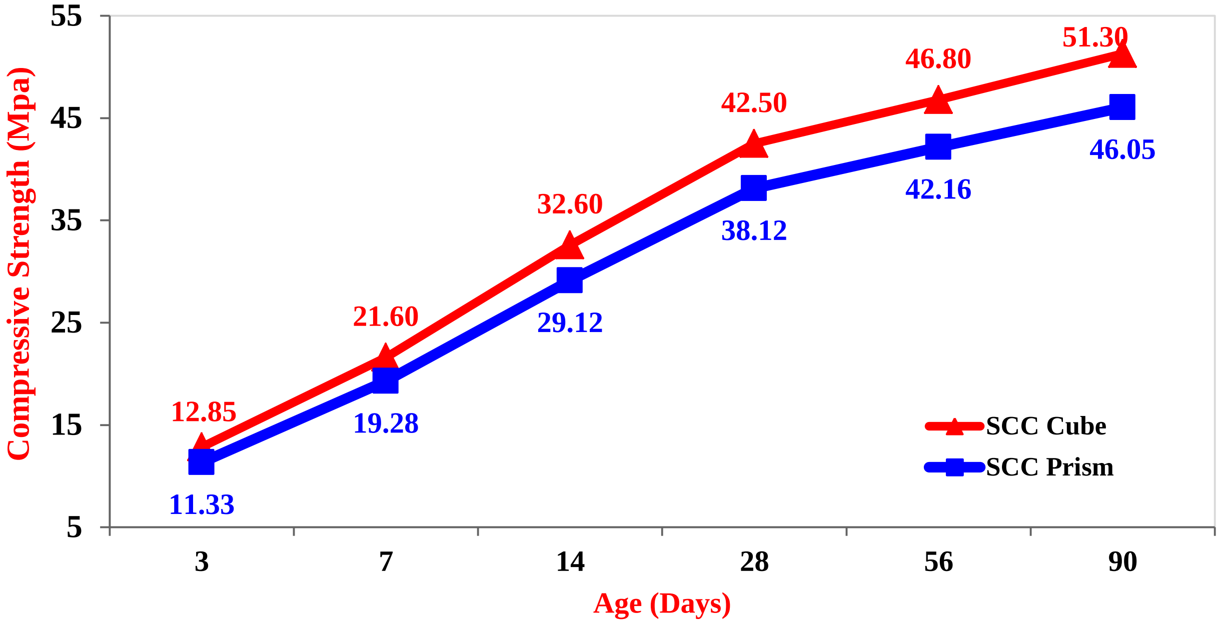


Fig 3.11: Comparison of Compressive Strength - Cube & Prism

CHAPTER 4 – RESULTS

4.1 Characterization of SRMs by Scanning Electron Microscopy (SEM)

Shape, size, surface morphology and internal porosity of SRMs are important parameters for understanding their role in flow, strength, shrinkage, calorimetry and microstructure of SCCS.

4.1.1 Limestone Powder (LSP)

Fig 4.1 shows SEM images of LSP particles under research. Average size (D-50) of LSP particles from XRF data determined by “Gaussian Curve” in “MATLAB” software is 9.25 (µm). SEM images indicate LSP particles are rough, highly abrasive, angular& flaky. Moreover, they are broken and patches can be seen in Fig (4.1).

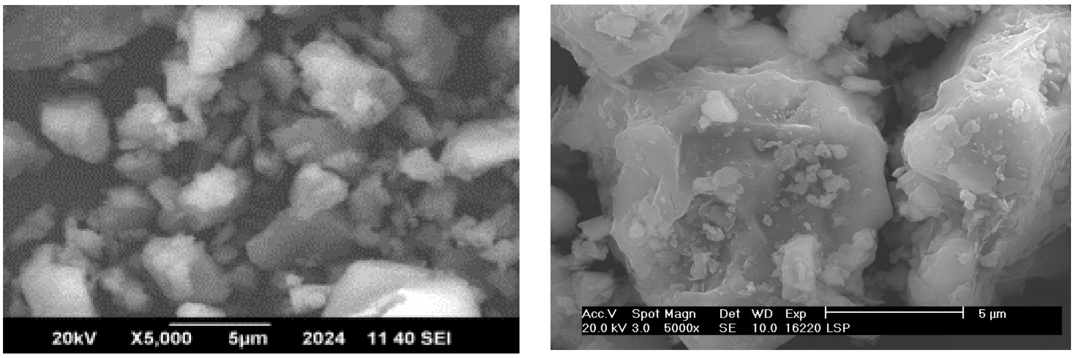


Fig 4.1: SEM Characterization of LSP Particles [Rizwan 2006]

4.1.2 Query Dust (QD)

Fig 4.2 shows SEM images of QD particles under research. Average size (D-50) of QD particles from “Gaussian Curve” is 8.25 (µm). It is evident from SEM images that QD particles are broken, abrasive in nature with rough & irregular surface texture.

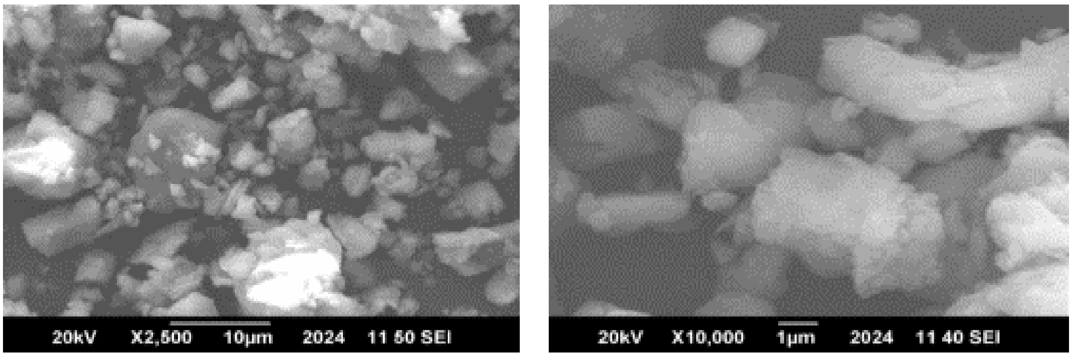


Fig 4.2: SEM Characterization of “Quarry Dust” Particles

4.1.3 Ground Granulated Blast Furnace (GGBF) Slag

Average size (D-50) of GGBF Slag particles is 14.5 (µm). Fig 4.3 shows that GGBF Slag particles are irregular, broken, with smooth and glassy surface texture.

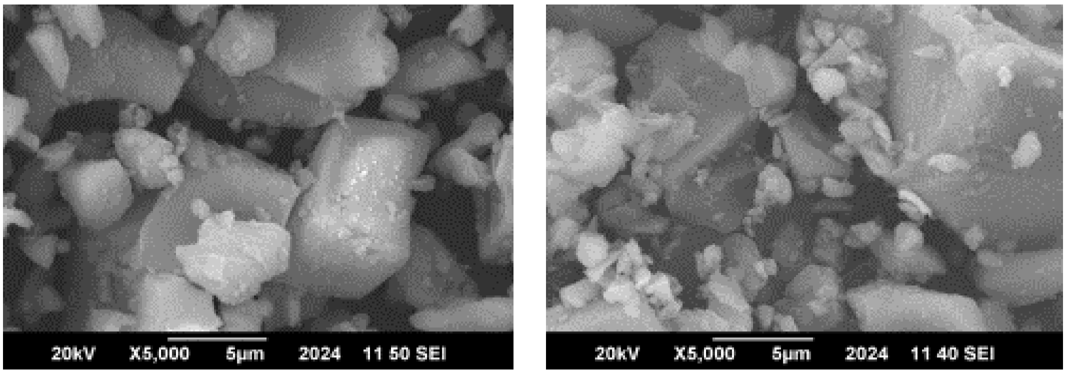


Fig 4.3: SEM Characterization of “GGBF Slag” Particles

4.1.4 Ordinary Portland Cement (OPC)

Fig 4.4 shows that particles of OPC are rough, abrasive in nature, broken & angular in shape. D-50 of cement particles is 19.5 (µm).

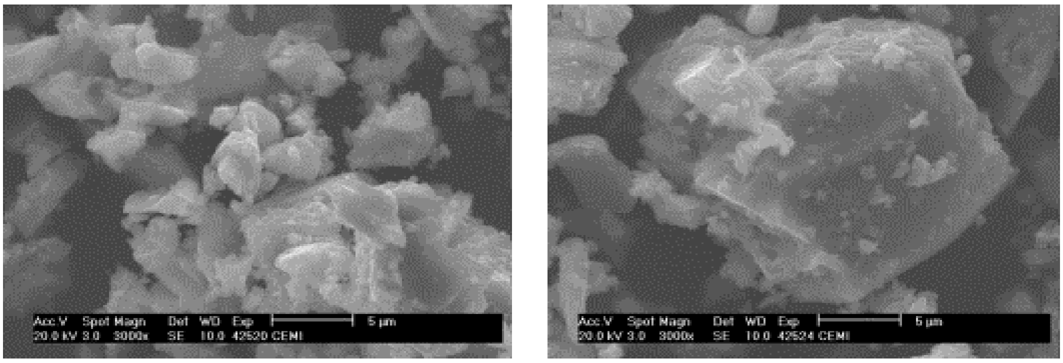


Fig 4.4: SEM Characterization of OPC Particles

4.2 Tests on Self Compacting Paste (SCP) Systems

4.2.1 WD of SCP Formulations

Surface morphology, shape, size and internal porosity of SRMs have a direct bearing on WD of a system [1]. WD of CS Formulations is shown in Fig 4.5. It constantly decreases with the increase of GGBF Slag contents. WD of SCP Formulations having blends of powder is shown in Fig 4.6.

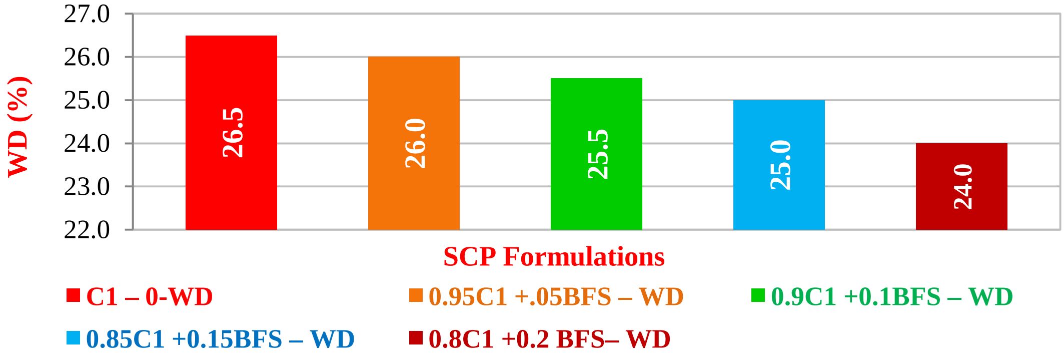


Fig 4.5: WD of CS Formulations of SCP Systems

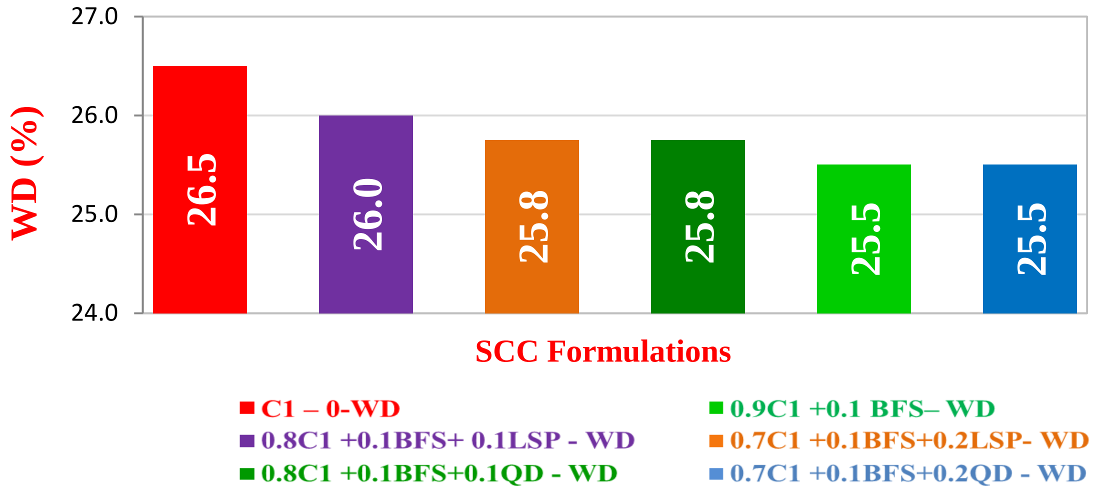


Fig 4.6: WD of SCP Formulations having Blends of Powders

4.2.2 Setting Time (ST) of SCP Formulations

Initial setting time (IST) and final setting time (FST) have always been a point of focus of researchers for placement / handling of fresh concrete in an advantageous way.

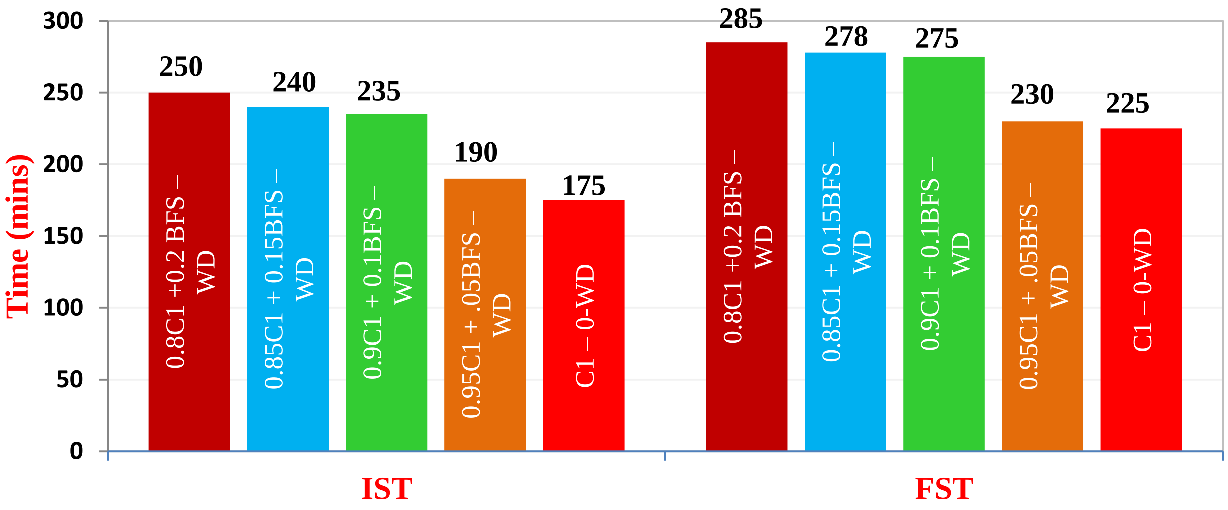


Fig 4.7 (a): IST & FST of CS Formulations of SCP Systems

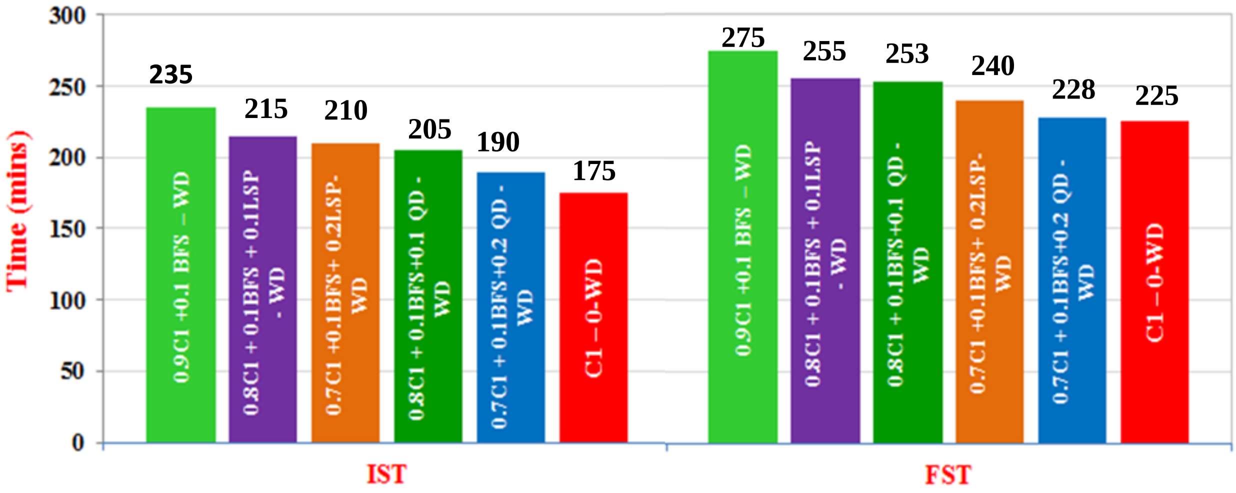


Fig 4.7 (b): IST & FST of SCP Formulations having Blends of Powders

Characteristics of SRMs have a direct bearing on IST & FST. Results have been shown graphically in Fig 4.7 (a) & 4.7 (b).

4.2.3 Flow Tests of SCP Formulations

SP requirement for a target flow (30±1) increases on addition of small SRMs content (10 & 20 % of cement mass) resultantly effecting flow properties, strength, pore structure and hydration kinetics [1].

Fig 4.8 (a): Hagermans Mini Cone Flow Apparatus (Rizwan 2006)

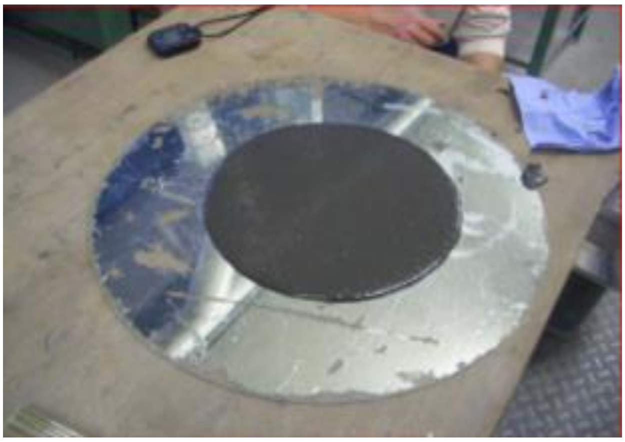


Fig 4.8 (b): Flow Spread After Removal of Cone (Rizwan 2006)

4.2.3.1 SP Demand of SCP Formulations

Fig 4.8 (c) & Fig 4.8 (d) show SP demand for a target flow (30±1 cm) / spread for CS & SCP formulations with blends of powders having GGBF Slag, LSP and QD with various contents.

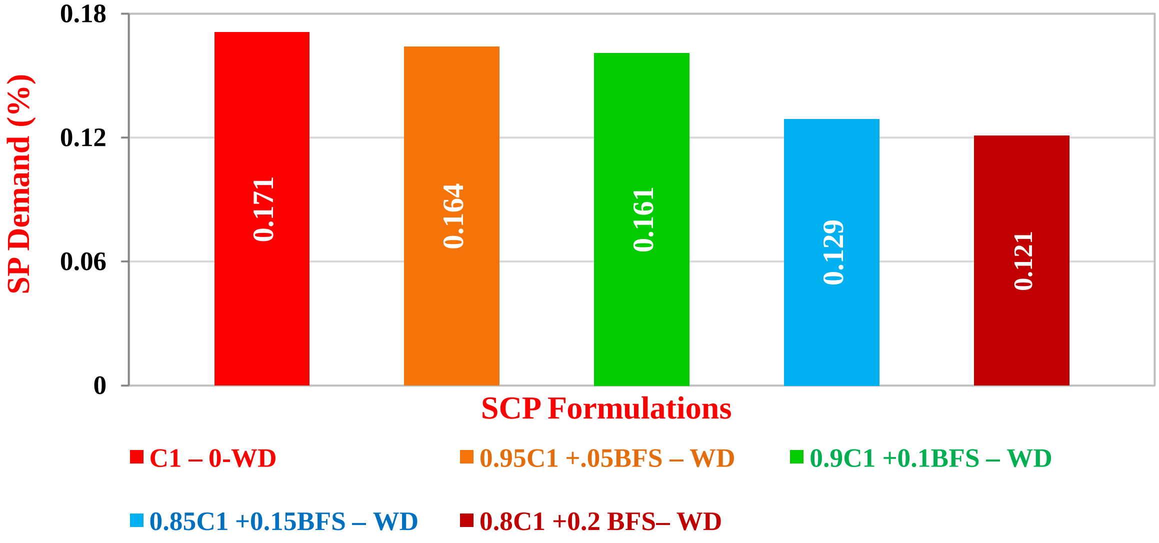


Fig 4.8 (c) : SP Demand - CS Formulations of SCP Systems

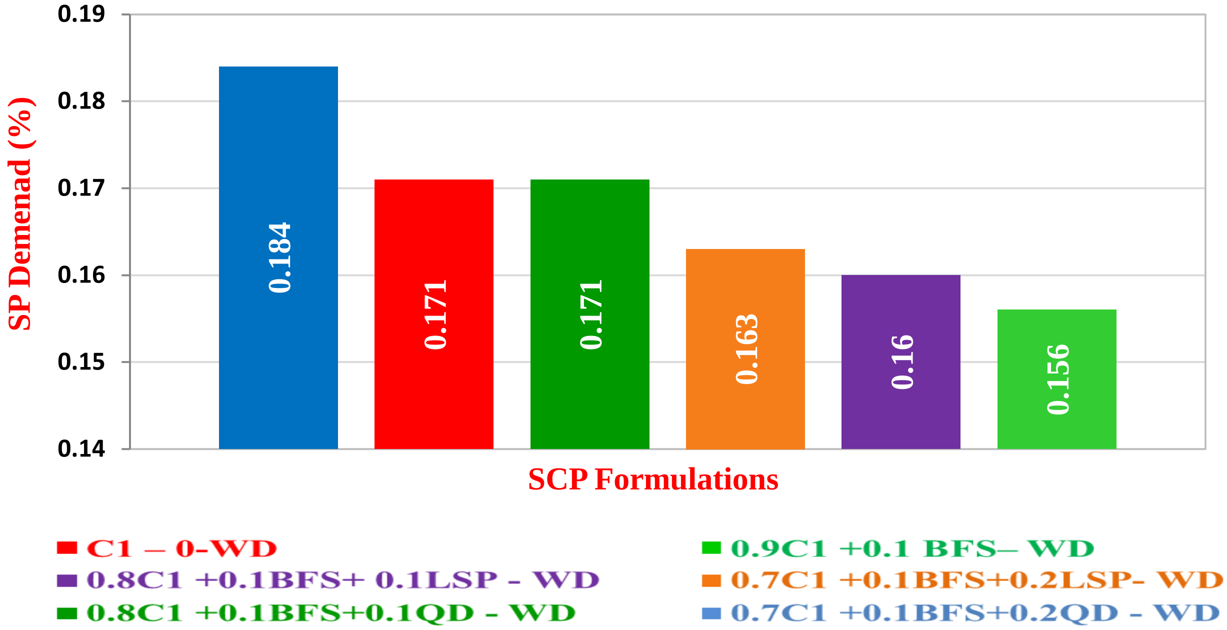


Fig 4.8 (d): SP Demand - SCP Formulations having Blends of Powders

4.2.3.2 Flow Times of SCP Formulations

4.2.3.2.1 T-25 cm &T-30 cm - SCP Formulations

Various times at 25cm ring (T 25) & 30cm spread (T 30) were determined on glass sheet by lifting Hagerman's mini slump cone while using super plasticizer Mel flux 2651 powder. Fig 4.9 (a) & Fig 4.10 (a) represent T 25 and T 30 of CS formulations while Fig 4.9 (b) & Fig 4.10 (b) graphically describes T25 and T30 of SCP formulations having blends of powders respectively.

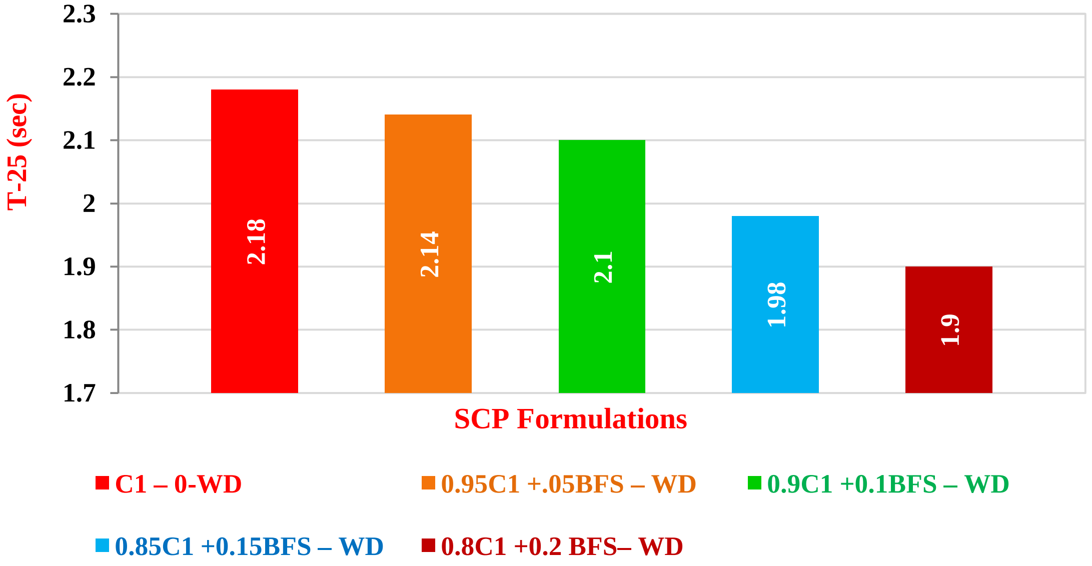


Fig 4.9 (a) : T-25 of CS Formulations of SCP Systems

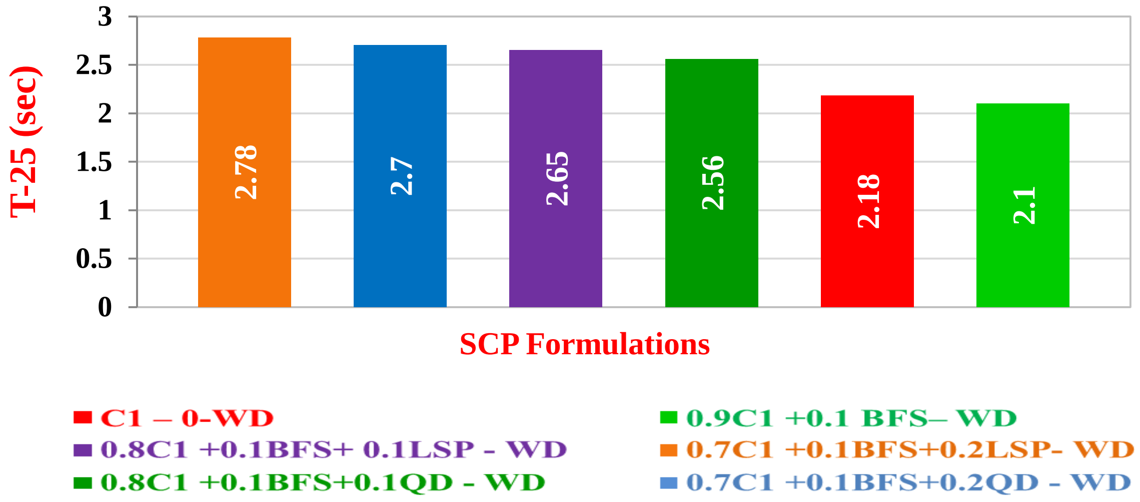


Fig 4.9 (b): T-25 of SCP Formulations having Blends of Powders

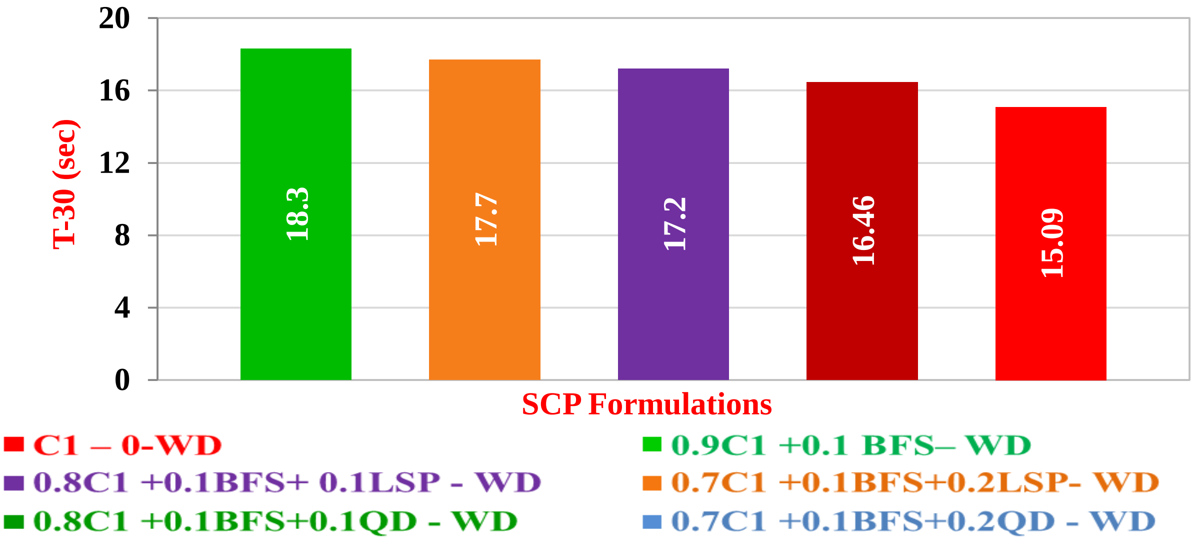


Fig 4.10 (a): T-30 of CS Formulations of SCP Systems

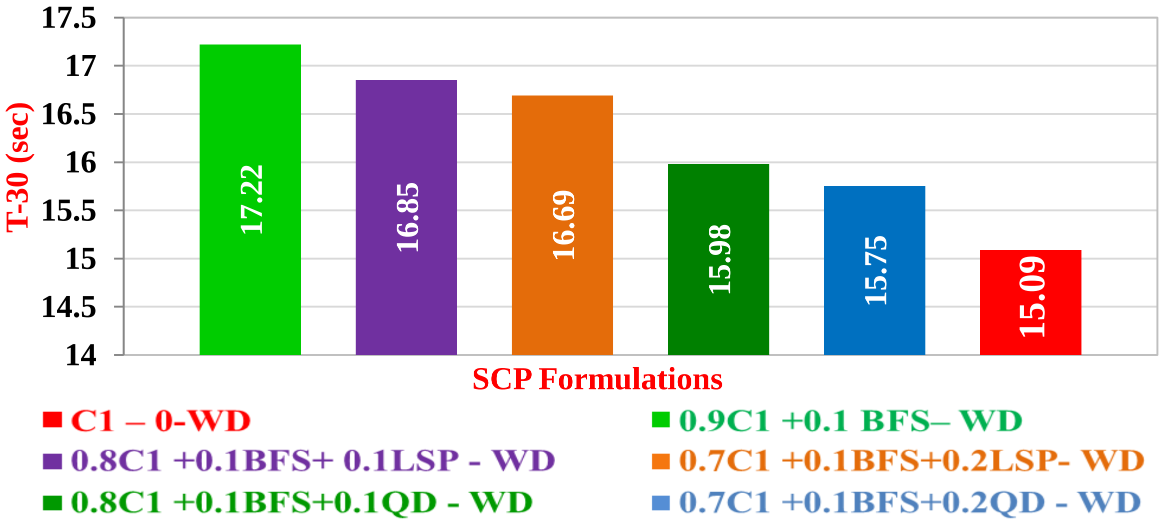


Fig 4.10 (b): T-30 - SCP Formulations having Blends of Powders

4.2.3.2.2 Maximum Flow Spread – SCP

Slump spread represent flow which depends very heavily on the shape, surface morphology and internal porosity of the SRM particles [1]. Spherical particles of various sizes get easily adjusted during flow by just rolling over each other without much internal friction.

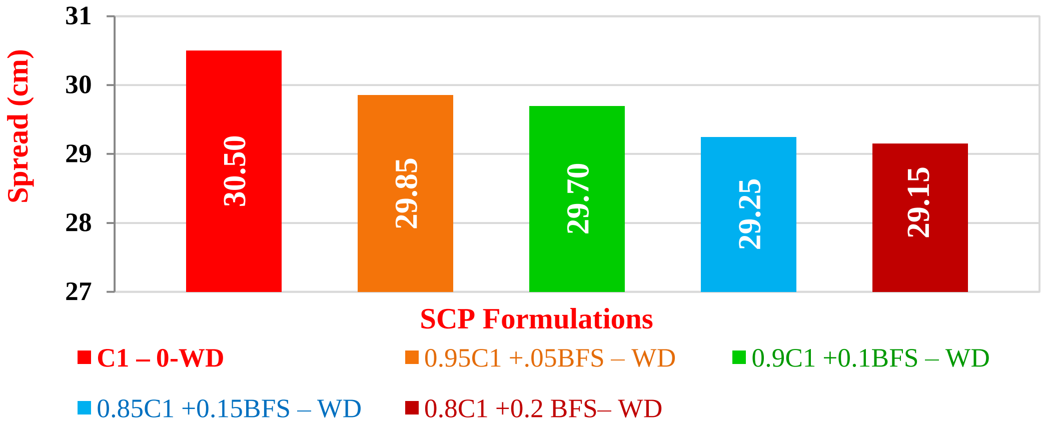


Fig 4.11 (a): Max Spread of CS Formulations of SCP Systems

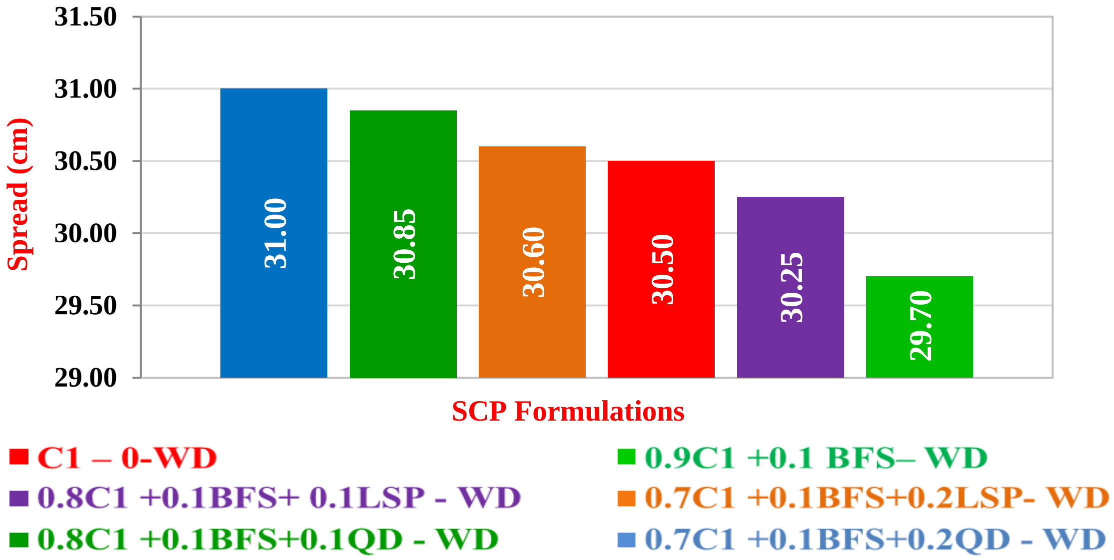


Fig 4.11 (b): Max Spread of SCP Formulations having Blends of Powders

4.2.4 Strength of SCP Formulation

Specimens were casted, demoulded after 24 hrs, cured in water and tested in SSD condition for strength at ages of 1, 3, 7,14, 28 & 56 days. Development of both the strengths i.e., flexural and compressive at specified age is shown below.

4.2.4.1 Compressive Strength – SCP Formulation

In CS formulations, there is a drop of compressive strength at early age (1 Day & 3 Days) due to delayed activation of GGBF Slag, however there is a clear trend of recovery of strength at later ages (14 Days onwards) and at 28 & 56 days compressive strength is more than (C1 – 0-WD) formulation. In SCP formulations having blends of powders, recovery has been seen

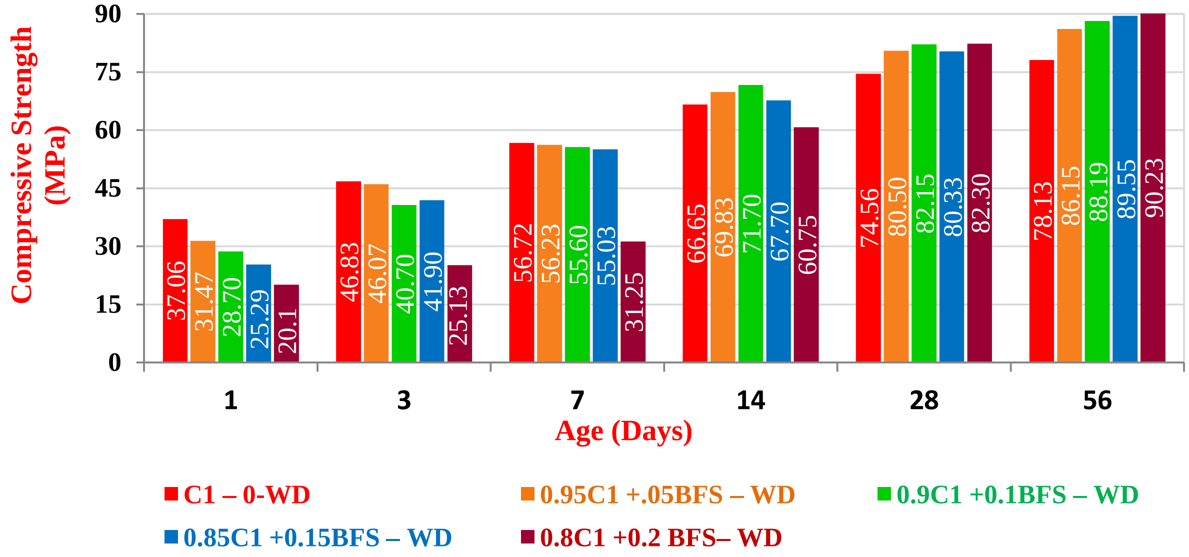


Fig 4.12 (a): Compressive Strength – CS Formulation of SCP Systems

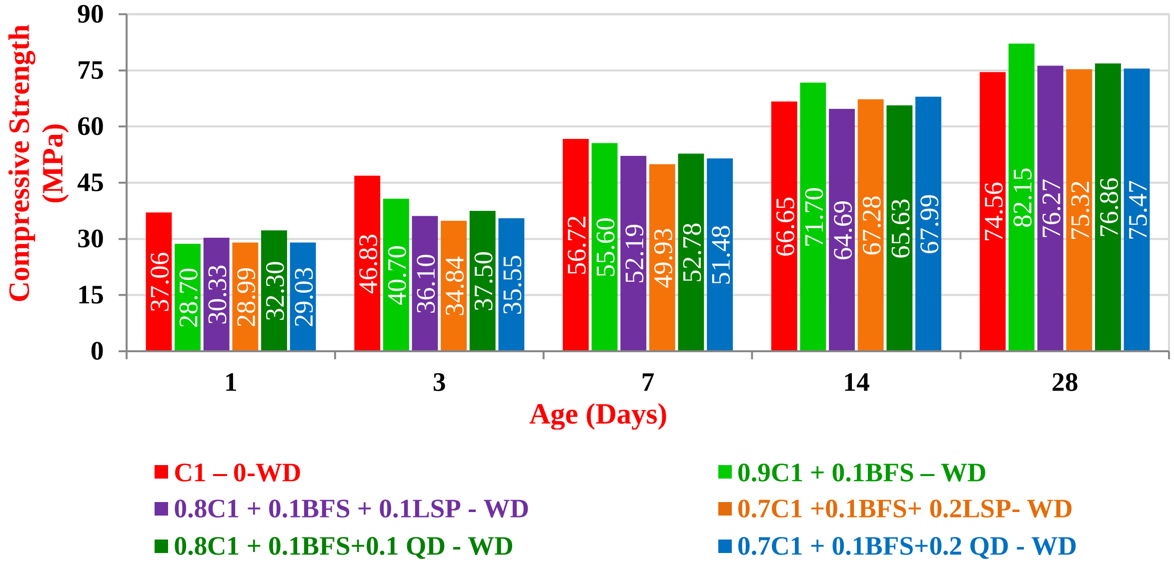


Fig 4.12 (b): Compressive Strength of SCP Formulations having Blends of Powders

with even at early ages. Fig 4.12 (a) and Fig 4.12 (b) represent compressive strengths of SCP formulations at specified ages respectively.

4.2.4.2 Flexural Strength:

Early age flexural strength of CS formulations (at 1 Day & 3 Days), is less than that of (C1 – 0-WD) formulation. At later ages (14 Days onwards) delayed activation of GGBF Slag effect is reducing and a trend of recovery of flexural strength can be seen. Flexural strength of CS formulations is more than (C1–0-WD) formulation after 28 days. In SCP formulations having

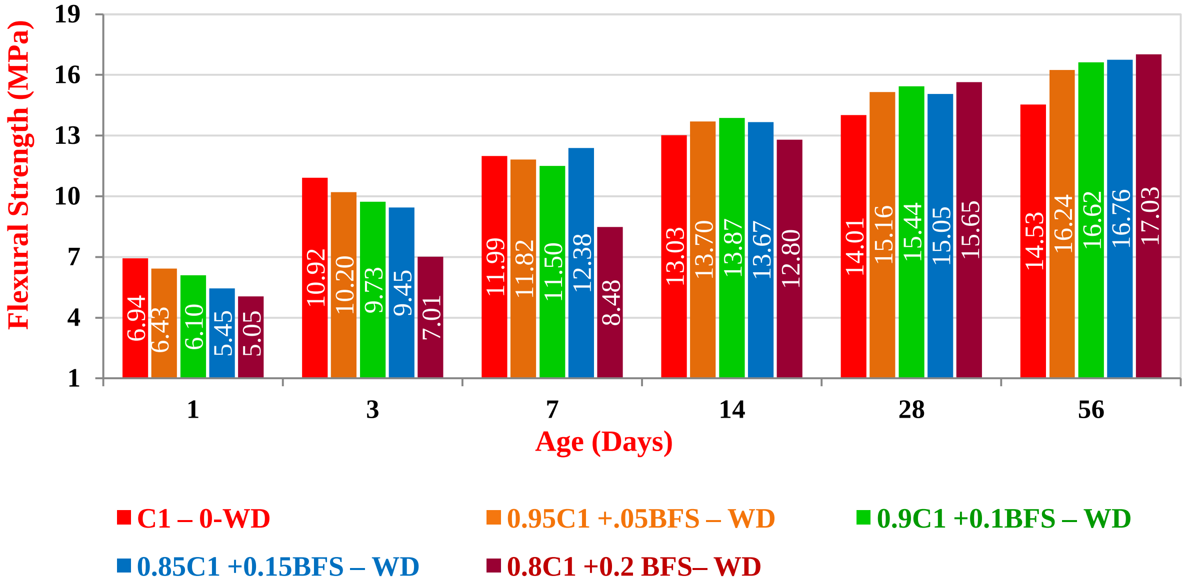


Fig 4.13 (a): Flexural Strength – CS Formulation of SCP Systems

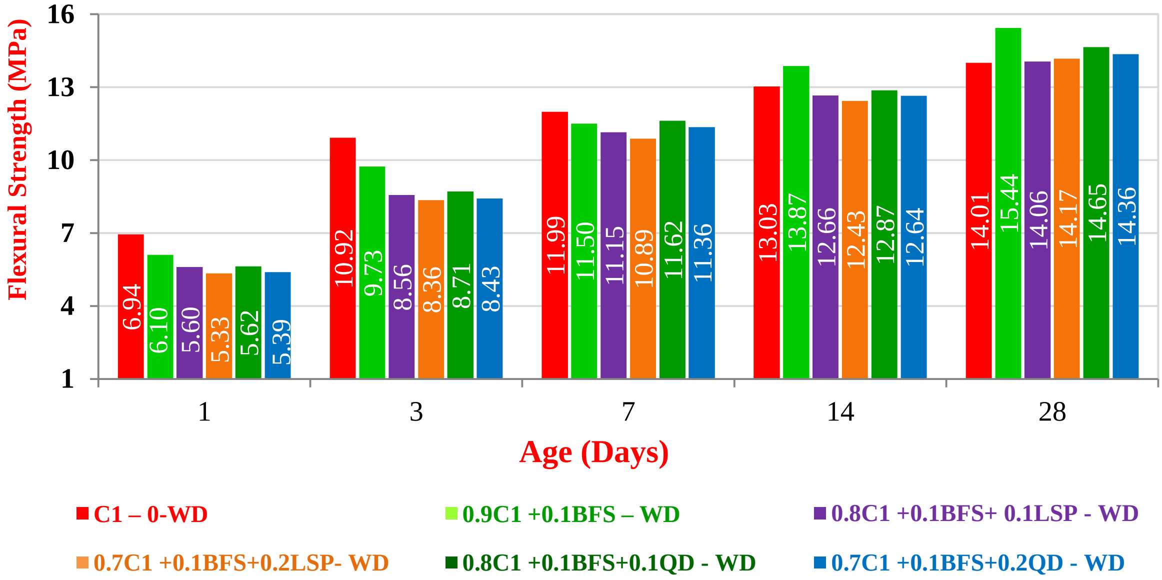


Fig 4.13 (b): Flexural Strength of SCP Formulations having Blends of Powders

blends of powders, recovery trend is visible even at early age. Fig 4.13 (a) and Fig 4.13 (b) represent flexural strengths of both categories of SCP formulations at specified ages.

4.2.5 Hydration Kinetics of SCP Formulation

Effects of addition of SRMs both in SCP formulations has been translated in terms of heat release and thus hydration kinetics of SCP. Fig 4.14 (a) and Fig 4.14 (b) represent graphically heat flow of CS formulations & formulations having blends of powders for 32 hour.

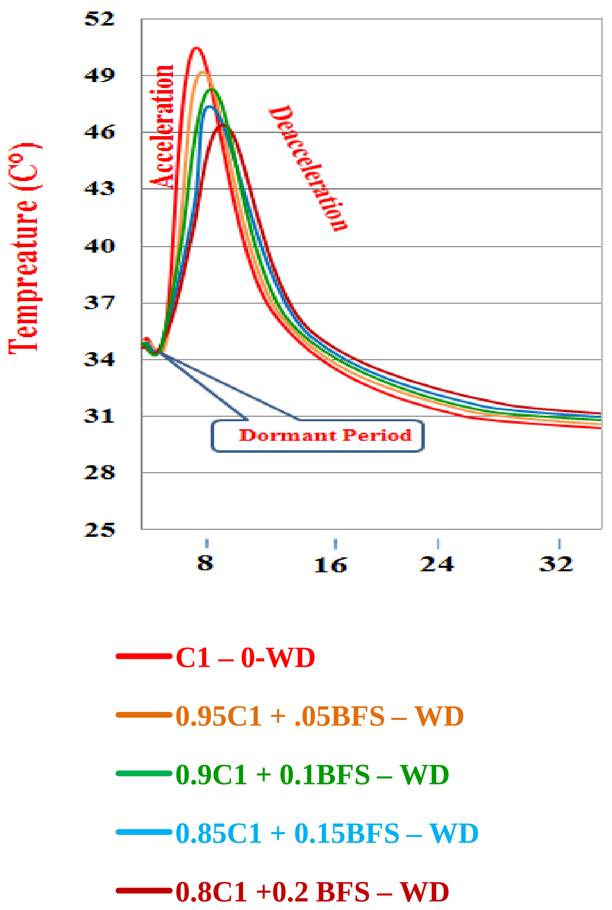


Fig 4.14 (a): Heat of Hydration - CS Formulations of SCP Systems

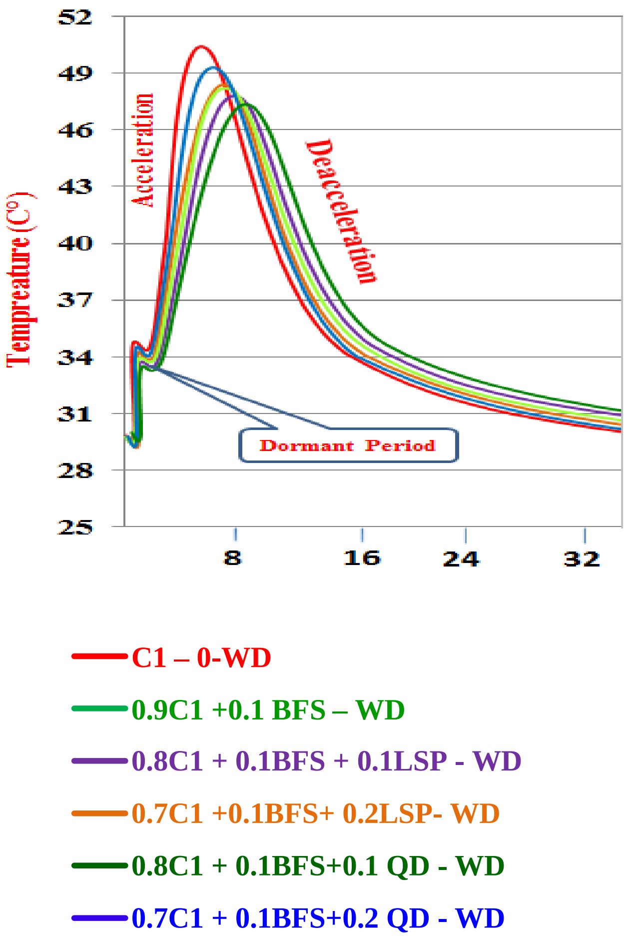


Fig 4.14 (b): Heat of Hydration of SCP Formulations having Blends of Powders

4.3 Tests on Self-Consolidating Concrete

Behaviour of SCC has been studied both in fresh and hardened state in terms of flow, strength, SEM analysis & hydration kinetics. Various recipes of SCC were tested in the light of previous research [1] & discussion [31]. Finally w/c was been kept constant as 0.45. Contents of VEA were kept as 0.6. For aggregates various grading were studied & tested in the line of previous literature [1] and finally aggregate contents ratio was kept (1:2:3.67) already described in chapter 3.

- Fine Aggregates (FA) (0-2 mm) (3.67) By weight of total aggregates
- Coarse Aggregates
    - 2-9 mm (CA-1) (2) By weight of total aggregates
    - 9-19 mm (CA-2) (1) By weight of total aggregates

4.3.1 Flow Tests of SCC.

Flow of SCCS is one of the major factors which improves self-consolidation, reduces voids, decreases porosity and gives superior concrete. Behaviour of flow of SCC was studied under slump flow, V funnel, L box, J Ring and air content tests. Better passing ability & flow ability ensure better compaction and ultimately contribute towards strength. Comprehensive details of these tests have already been elaborated.

4.3.1.1 Slump Flow Tests

Slump flow test is a well - known and widely used test to characterize SCC. It is easy to perform in the field. The slump flow (yield stress) is the main fundamental difference between SCC and conventionally placed concrete .In slump flow test, spread gives an idea of yield stress while T-50 cm time indicates viscosity of SCC systems. It is also inferred in literature that T50 cm time is an indirect measure of viscosity of SCC mixes [1].

Fig 4.15 shows T-50cm for various SCC formulations under study. T-50cm is highest for controlled formulation (C1 – FA – CA - 45) which decreases with the addition of SRM in ((0.8C1 +0.2BFS) – FA – CA - 45). On partial replacement of fine aggregates with LSP / QD T-50 increases than (C1 – FA – CA - 45) formulation. T-50 is more for LSP formulations than QD formulations both at 10 & 20 % contents respectively.

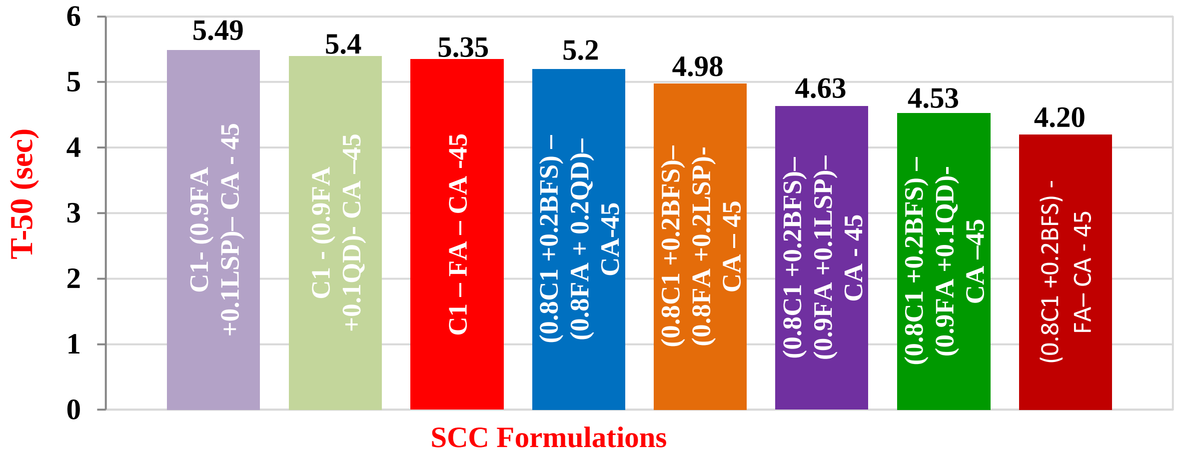


Fig 4.15: T-50cm of Slump Flow Tests (SCC)

Fig 4.16 shows slump spread D (Max) for various SCC formulations. Slump spread of ((0.8C1 +0.2BFS)-FA– CA - 45) is the highest. When fine aggregates are replaced with 10 & 20 % LSP & QD, spread is more in 10% than 20% contents of both SRMs as shown in Fig 4.16.

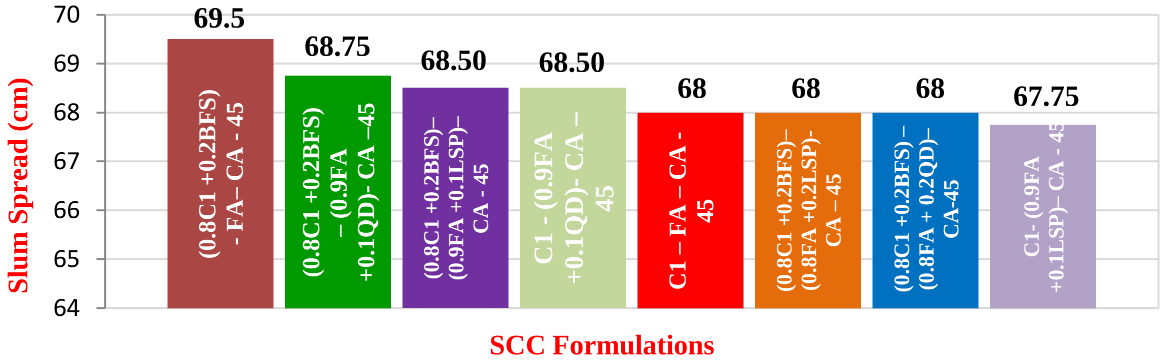


Fig 4.16: D (max) of Slump Flow Test – SCC Formulations

4.3.1.2 V Funnel Test

V Funnel time is related to passing ability, filling ability and segregation resistance. It may be suitable as a pass / fail test yet cannot provide an autonomous indication of passing ability, filling ability, or segregation resistance. Its time is an indicative of viscosity [1]. V funnel time of SCC formulations is shown in Fig 4.17. It is highest (6.25 Sec) for (C1 – FA – CA 45) and lowest (3.18 Sec) for ((0.8C1 +0.2BFS) - FA– CA – 45) formulation. Varying composition of fine aggregates in other formulations by adding LSP / QD, V funnel time increases and is more pronounced in (0.8C1 +0.2BFS) – (0.8FA +0.2LSP)- CA – 45 & (0.8C1 +0.2BFS) – (0.8FA +0.2QD)- CA – 45 where replacement of SRMs contents is 20%. Results are shown below:

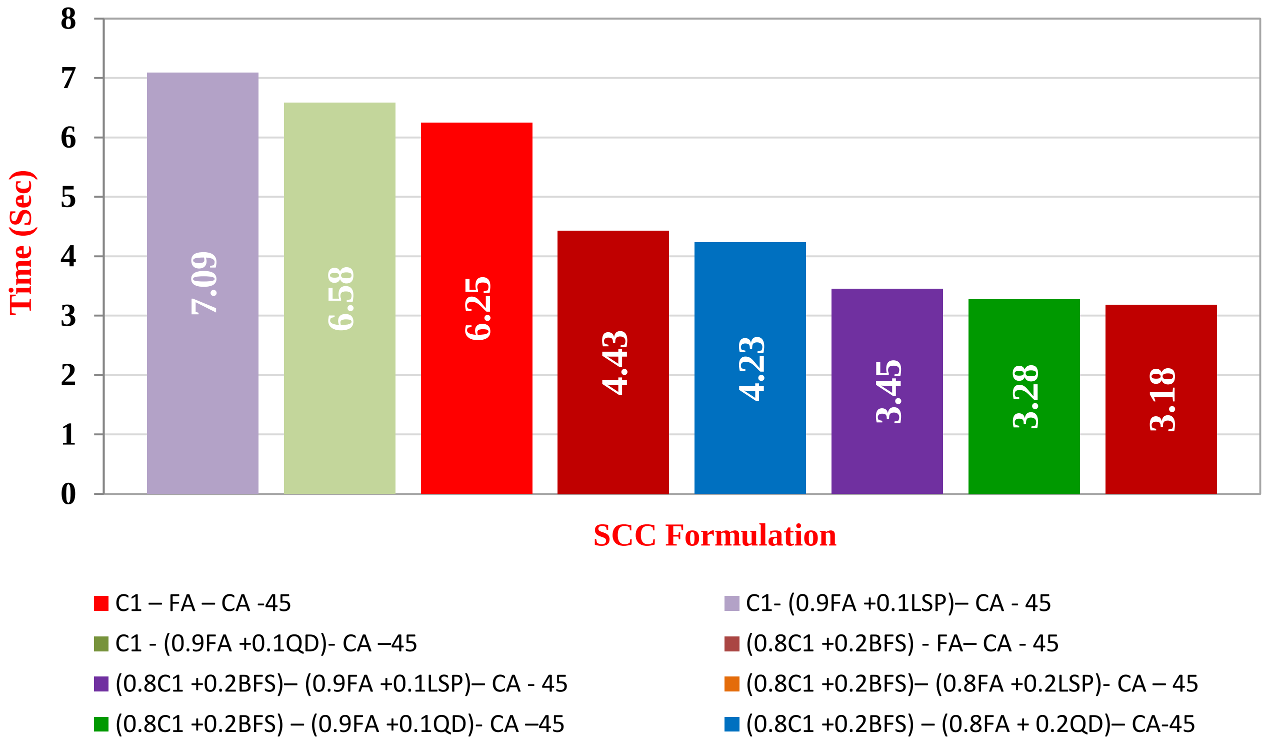


Fig 4.17: V Funnel Times of SCC Formulations

4.3.1.3 L Box Test

L Box test measures passing & filling ability of SCC mixes. Three times are taken as T-200 mm, T- 400mm, T- 600 mm along with blocking ratio (H_2/H_1). Having high deformability, blocking ratio (H_2/H_1) near unity, T-600 mm time will be reduced. Fig 4.18 below shows the comparison of T-200 mm, T-400mm, T-600 mm while Fig 4.19 indicates blocking ratio (H_2/ H_1) of various formulations.

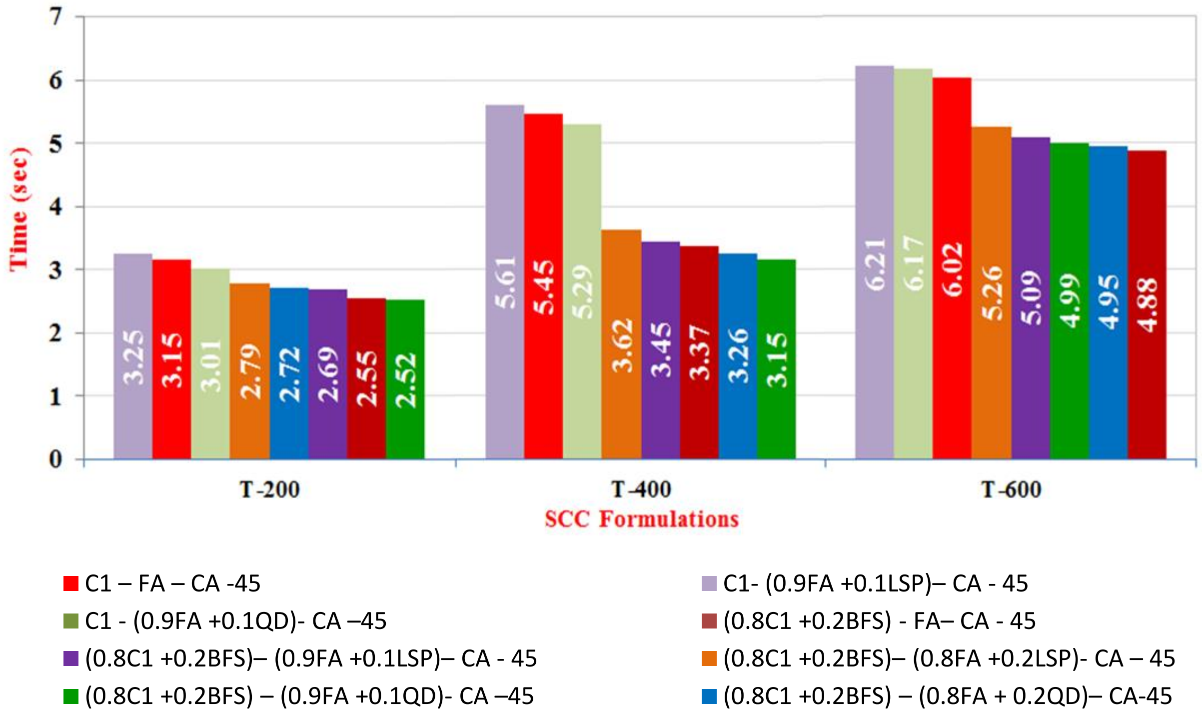


Fig 4.18: Flow Times in L Box Test - SCC Formulations

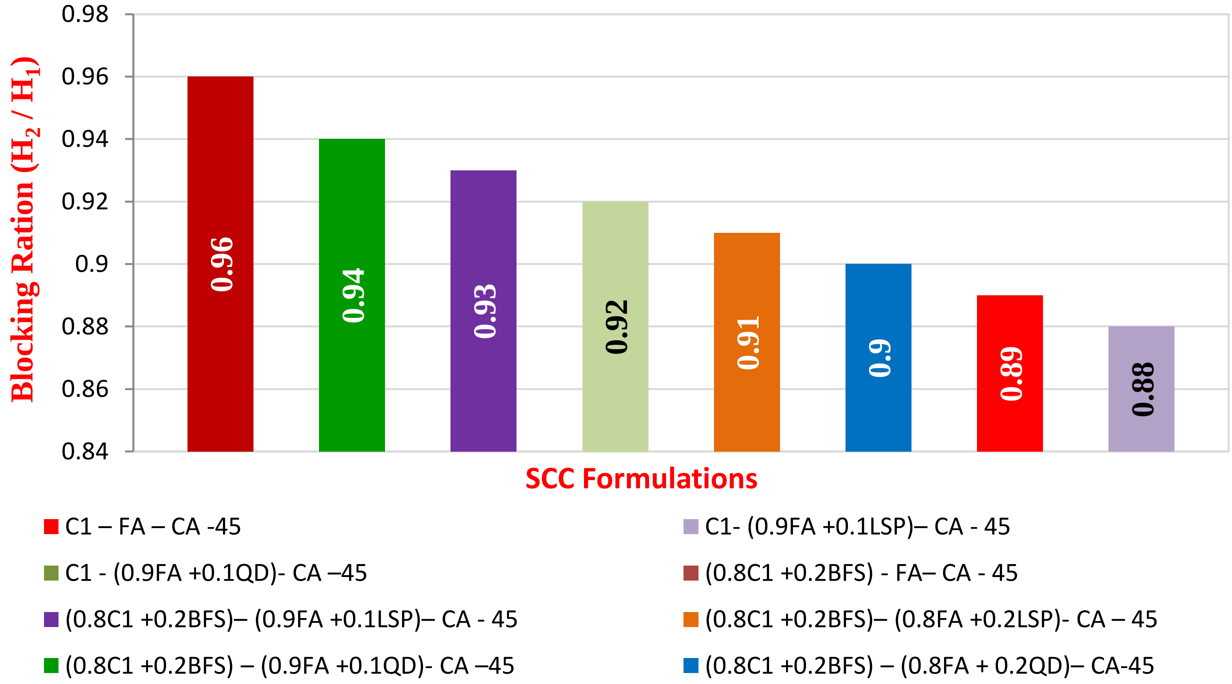


Fig 4.19: Blocking Ratio (H_2 / H_1) – SCC Formulations

4.3.1.4 J Ring Test

J Ring test gives an independent measurement of passing ability and segregation resistance. Increasing slump flow (filling ability), results in less J Ring blocking. It may not be affected by slump flow to an extent as L Box test. It is similar to slump flow test with same equipment except with an addition of intermittent peripheral ring with 12 rods which offers the obstruction and resultantly spread is less and T-50 is more compared to slump flow test.

Fig 4.20 shows T-50cm for various SCC formulations. T-50cm is highest for i.e, (C1 – FA – CA -45) formulation. Trends are similar to slump flow tests. However it is a little less due to obstruction offered by intermittent peripheral ring.

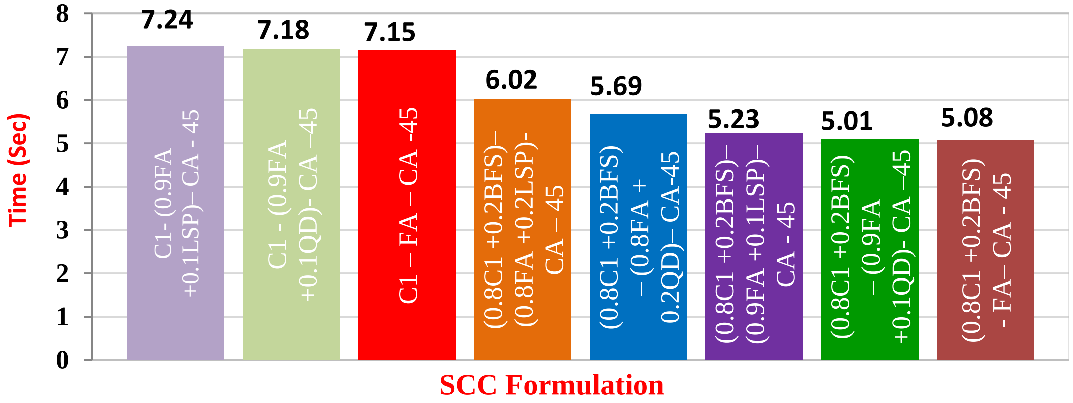


Fig 4.20: T-50 cm (J RING) – SCC Formulations

Spread of J Ring is less than that of slump flow test. Fig 4.21 shows slump spread D (Max) for various SCC formulations. With the addition of SRMs as partial replacement of cement and / or fine aggregates, flow of SCC increases resultantly flow spread also increases which can be clearly seen in ((0.8C1 +0.2BFS) -FA– CA - 45) formulation.

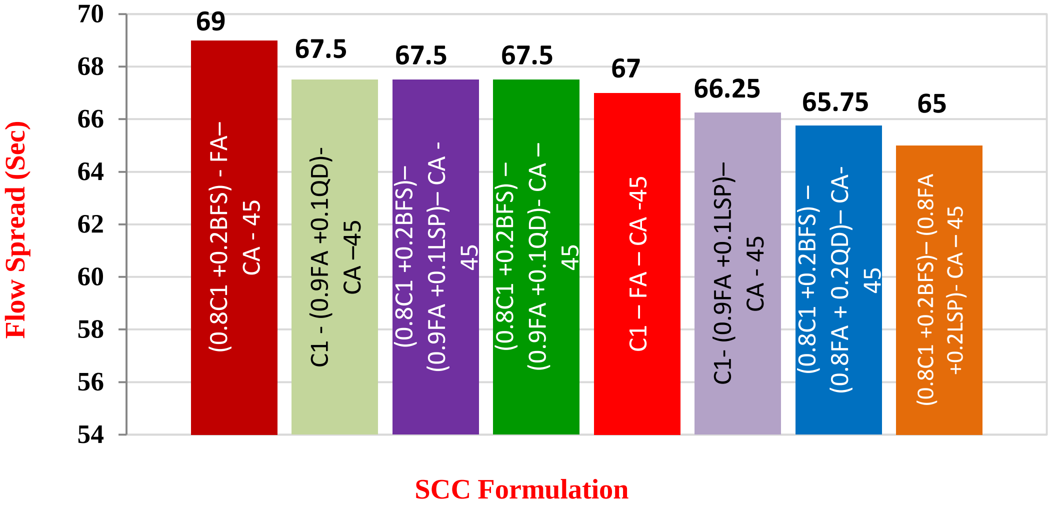


Fig 4.21: Flow Spread in J Ring Test – SCC Formulations

4.3.1.5 Super Plasticizer (SP) Contents

SP demand of various SCC formulations has been investigated with factors like W/C, aggregate contents and VEA contents as constant at the target flow of 68±2 cm using BASF super plasticizer (SP) Glenium 51. Results have been shown in Fig 4.22. Formulation ((0.8C1 +0.2BFS) –

(0.8FA + 0.2QD)– CA-45) has highest demand of SP whereas ((0.8C1 +0.2BFS)-FA– CA - 45) has lowest demand of SP.

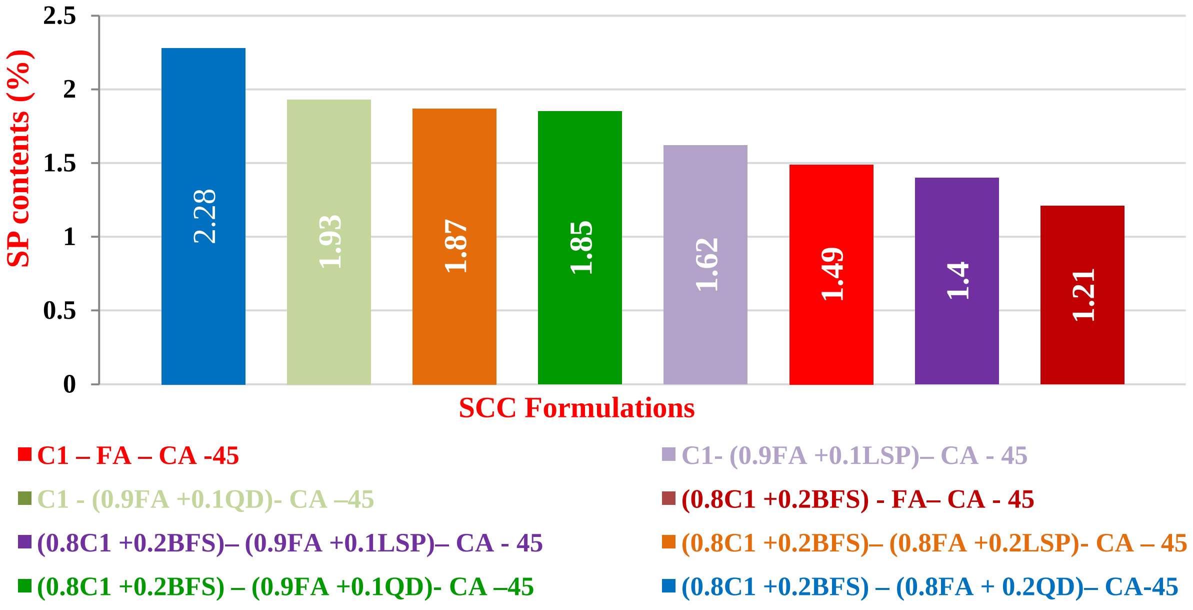


Fig 4.22: SP Contents - SCC Formulations

4.3.1.6 Air Contents Test

Average air contents for different formulations are shown in Fig 4.23. It appears that the entrapped air contents decrease with the addition of SRMs as partial replacement of cement and / or fine aggregate.

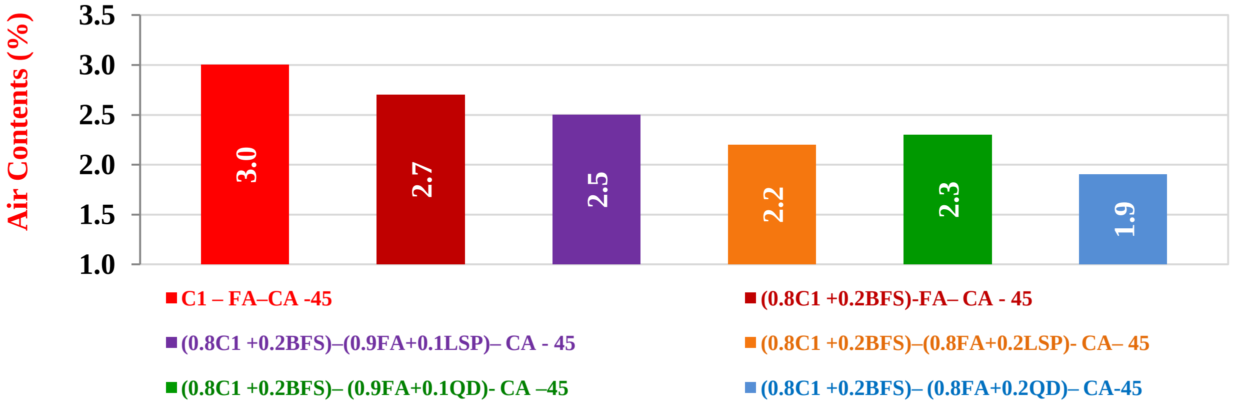


Fig 4.23: Air Contents - SCC Formulations

4.3.1.7 Calorimetric Curves - SCC mixes

Calorimetry is a test to study hydration kinetics. For SCC, calorimetry was done for 96 hrs (4 Days) instead of 72 hrs for SCP. Parameters like dormant period & peaks of heat of hydration can easily be measured. Fig 4.24 represents graphically hydration kinetics of SCC formulations where delayed setting is prominent due to GGBF Slag. Effects generated due to variation in composition of fine aggregates by adding LSP / QD are also visible.

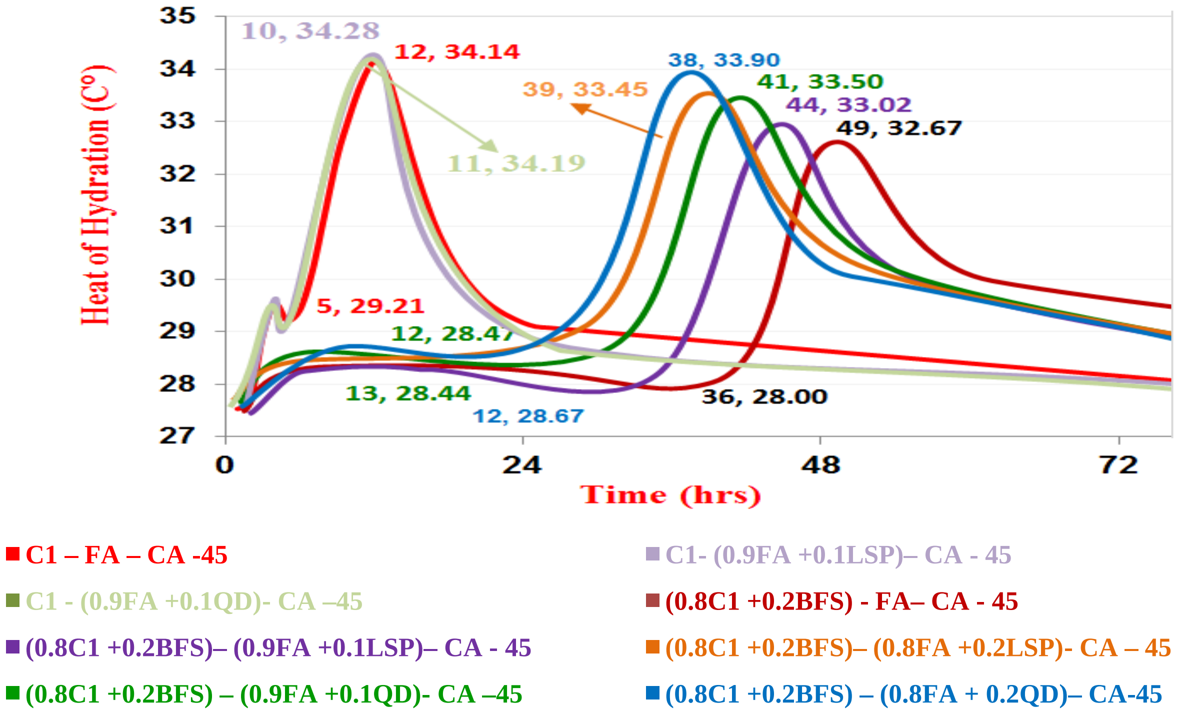


Fig 4.24: Calorimetric Curves – SCC Formulations

4.3.2 Strength of SCC Mixes

Specimens were casted, cured in SSD condition in the lab and then tested for strength at the ages of 1, 3, 7, 14, 28, 56 and 90 days. It is seen that in ((0.8C1 +0.2BFS) – FA– CA -45) formulation, there is a clear drop of early age strength but later age strength is improved and it is a bit more than (C1 – FA – CA -45) formulation. When fine aggregates are replaced partially with 10 & 20 % LSP & QD in ((0.8C1 +0.2BFS)-FA– CA - 45), compressive strength is improved both at early and later ages. Fig 4.25 and Fig 4.26 represent compressive & flexural strengths of SCC formulations at specified ages respectively.

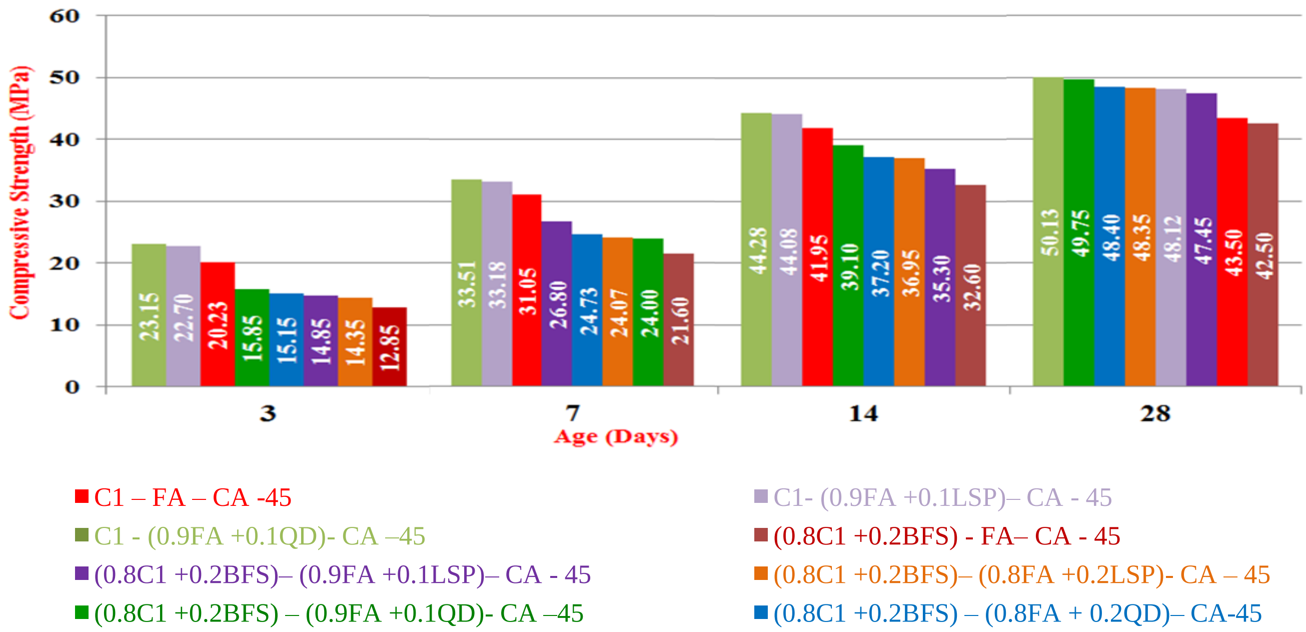


Fig 4.25 : Compressive Strength of SCC Formulations

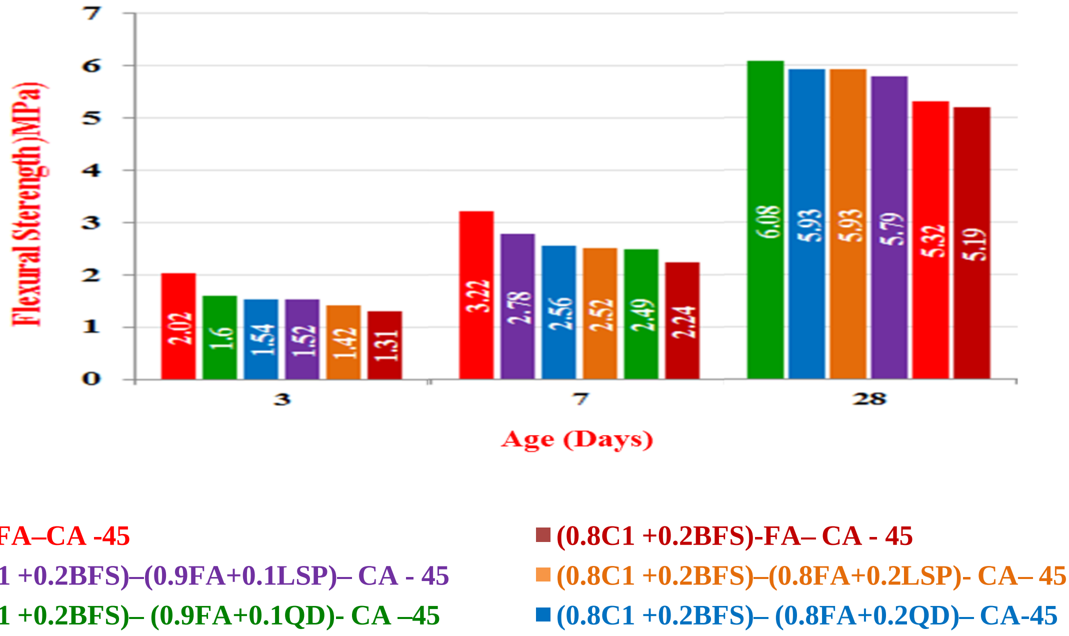


Fig 4.26 : Flexural Strength of SCC Formulations

4.3.3 GGBF Slag Activation by Alkali in SCC Mix

GGBF slag is an economical, effective and readily available SRMs. Contrary to SCP formulations; activation of GGBF Slag in SCC mix is quite late which increases formwork expenditures thus making this cheap and readily available SRM uneconomical. After consulting literature and discussion [14,41], Ca $(OH)_2$ has been selected to offset delayed setting and increase early strength in order to remove formwork.

4.3.3.1 Effect of Alkali Activation on Formwork Removal Time of SCC Mixes

An effort was made to address this issue while using Ca $(OH)_2$ to activate GGBF Slag in early time frame in order to have initial strength and ultimately remove formwork. For this purpose three different contents (5, 10 & 20) % by weight of cement was added in ((0.8C1 +0.2BFS)-FA–CA - 45) formulation. Results are shown in Fig 4.27.

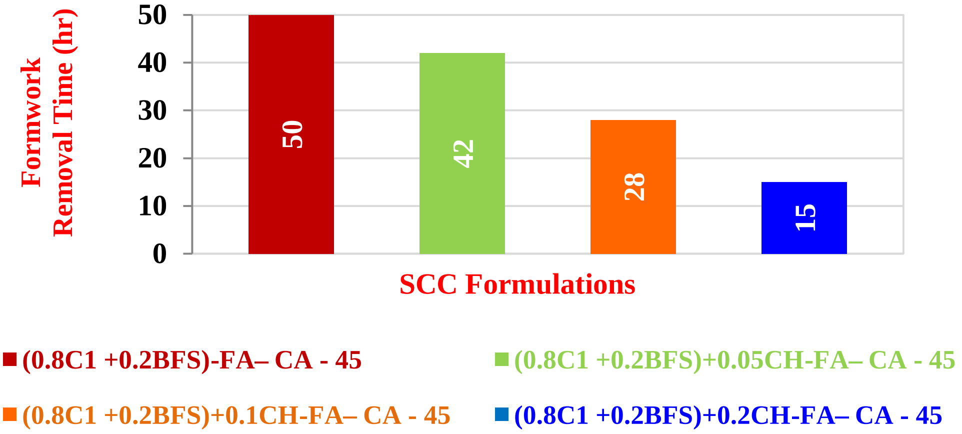


Fig 4.27: Effect of Ca $(OH)_2$ on Formwork Removal Time

4.3.3.2 Effect of Added Alkali on Compressive Strength

Use of Ca $(OH)_2$ is effective as it has addressed the issue formw faork removal time. It has not only increased initial strength but also did not reduce later age strength to an extent. Results are shown in Fig 4.28.

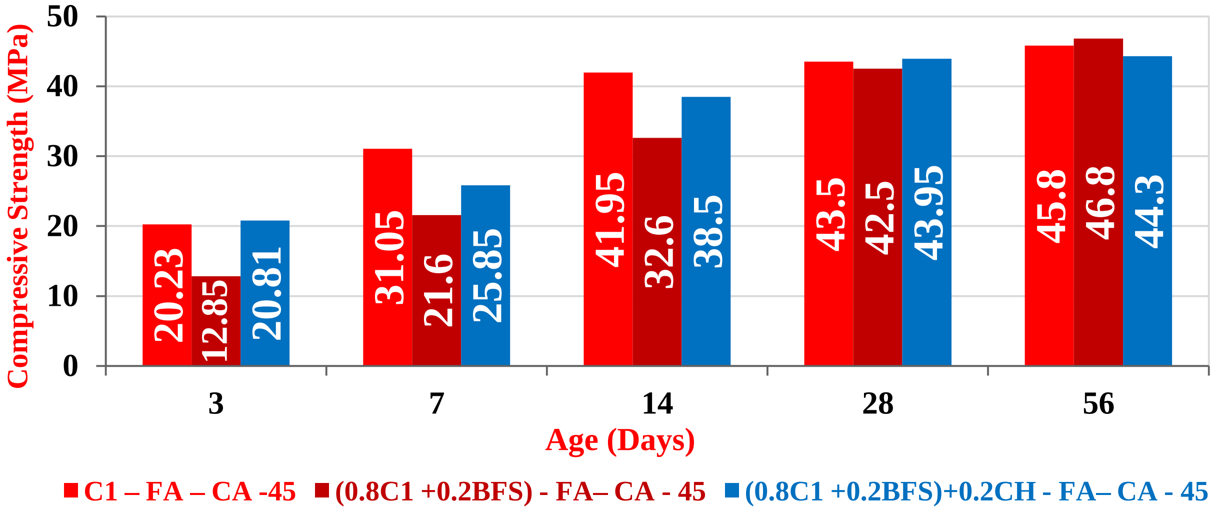


Fig 4.28: Effect of Ca $(OH)_2$ on Compressive Strength on SCC Mixes Containing GGBF Slag

4.3.3.3 Effect of Alkali Activation on Hydration Kinetics

Fig 4.29 represents effect of Ca $(OH)_2$ on hydration kinetics on SCC mix using GGBF Slag. It is clearly evident that how dormant period is reduced from 60 hrs to less than a day which is very near to (C1 – FA – CA -45) formulation. It not only affects other properties of SCC both in fresh and hardened state positively but also brings economy by timely removal of formwork.

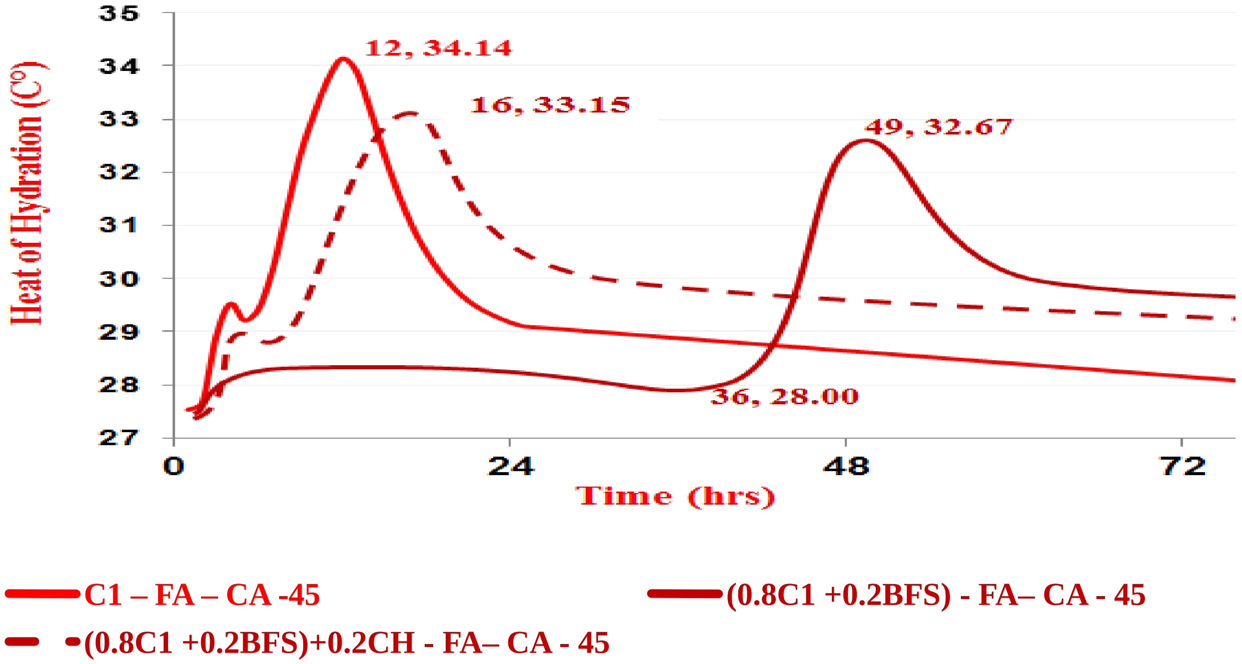


Fig 4.29: Effect of $Ca(OH)_2$ on Hydration Kinetics for SCC Formulations using GGBF Slag

CHAPTER 5 – DISCUSSION

5.1 Characterization of SRMs

In this chapter, an effort has been made to discuss experimental results in the light of influencing parameters of SRMs like particle shape, size and surface morphology. These parameters not only effect fresh and but also hardened properties of SCCS by altering flow, strength, calorimetry and microstructure etc.

5.1.1 Size & Surface Area of SRMs Particles

Particle size of SRMs has a vital role in SCCS matrix as it not only generates filler (physical) effects but can also perform nucleation and growth (N+G) being smaller in size and pozzolanic effects (both physical & chemical). With decrease in particle size, specific surface area increases which tends to increase SP as well as WD because more quantity will be required for grafting. Parallel phenomena of packing will also take place which will reduce porosity and hence decrease WD. However former phenomena will dominate.

SRM particles of two orders less than the cement particle will pack binder phases effectively thus reducing porosity in SCCS [1]. “Surface Area Analysis” (SAA) along with Particle Size Analysis (PSA) was done at SCME, (NUST) (results are attached as Annexure D). Average Particle Size (D-50) was then determined by engineering software “MATLAB” in which “Gaussian Exponential Curvature” was selected. A procedure has been developed in consultation with Statistics expert [36] to arrive at average particle size (D-50) using data of PSA as under:

- Open m-file in MATLAB. (Clear previous data if any)
- Write x=[ ];then copy 1st column from excel sheet and paste with in brackets as x=[paste here];
- Similarly write multiple columns as y1= [ ]; y2= [ ]; y3= [ ]; and paste column 2, 3, 4…. as required from excel sheet into values into y1, y2 & y3 respectively.
- Use Curve Fitting (CF) tools to draw the desired curve. Write CF tool and save” m file”.
- Run code by clicking green arrow on m-file top tool row. New page will open (curve fitting tool). Click data
- Select x & y data as X-1, Y-1 etc.
- Click “Create Data Set” and close current window.
- Click fitting from CF Tool window a new window will open, click new fit, select type of fit, click apply fit and close the fitting window.
- In curve fitting tool window, click tools and apply grid, or zoom in or zoom out. Adjust horizontal and vertical axes by axes limit control. Finally save curve fit graph by clicking file button.

- Print to Figure option a new Figure page will open, save this Figure into “bitmap” or “tiff” file.

D-50 curves obtained from the software have been shown in Fig 5.1 (a-d). Results of D-50, BET & Pore Volume have been summarized in table 5.1.

Table 5.1: Characterization of Powders Particles (Results of experiments done at SCME)

Powders	D-50 (µm) By Gaussian Curve	BET (m^2/g)	Pore Volume (cm^3/g)
Cement	19.5	1.07	-
LSP	9.5	1.8775	0.000862
QD	8.25	4.2429	0.001963
GGBF Slag	14.5	-	-

Water quenched GGBF Slag was brought from Pakistan Steel Mills Karachi. Contrary to literature, minimum available size was 2mm. Since no standard facility to grind SRMs to the required size i.e. below 10 (µm) is available at NICE (NUST), unconventional methods were adopted from local market after a lot of effort. GGBF Slag could be milled up to 14.5 (µm) and LSP (9.5µm) & QD (8.25 µm). All were lesser in size than cement particle 20 (µm).

Table 5.1 indicates that BET surface area and pore volume of QD is more than LSP which implies that WD & SP demand of QD would be more than LSP as additional liquid is required to wet more surface area and to absorb in extra pore volume in QD. A parallel phenomenon of “Packing” is also likely to be there due to smaller particle size of SRMs than cement. This may result into reduction of WD in SCCS.

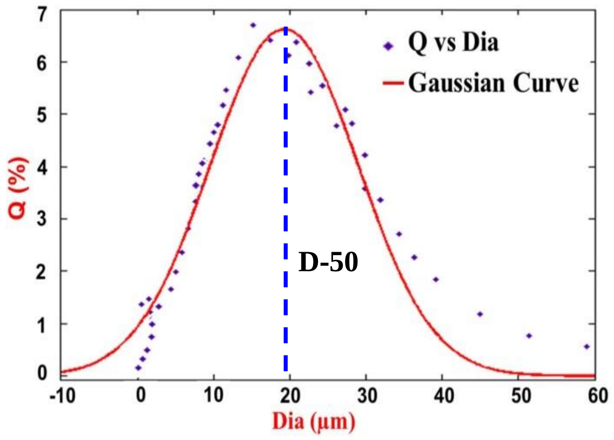


Fig 5.1 (a): D-50 of Cement Particles by Gaussian Curve.

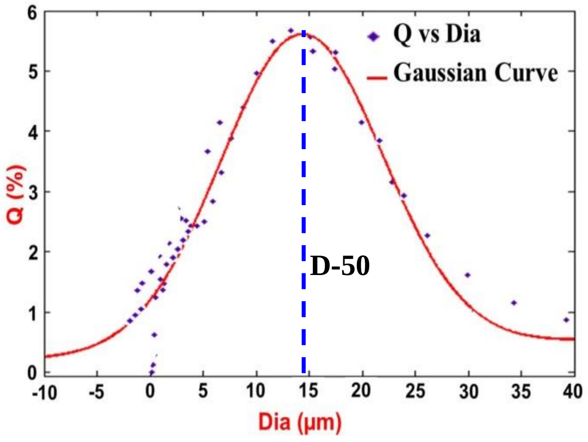


Fig 5.1 (b): D-50 of GGBF Slag Particles by Gaussian Curve.

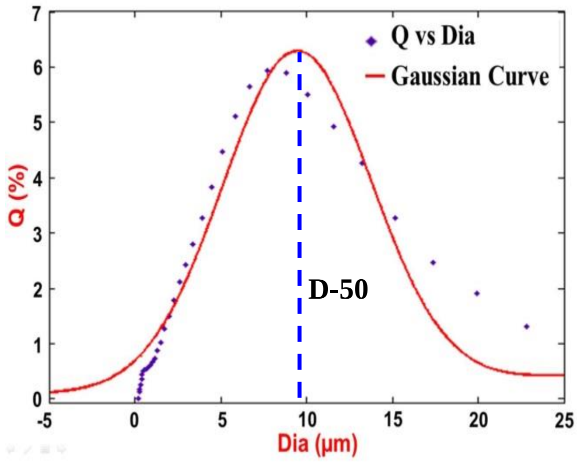


Fig 5.1 (c): D-50 of LSP Particles by Gaussian Curve.

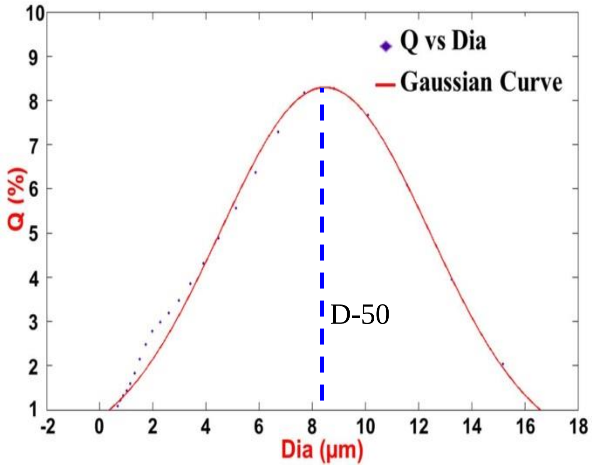


Fig 5.1 (d): D-50 of QD Particles by Gaussian Curve.

5.1.2 Particle Shape and Surface Texture

Particle shape of SRMs affects flow properties of SCCS in terms of SP demands in fresh state and mechanical properties like flexural or compressive strength and microstructure of concrete in hardened state. It is evident from SEM images of powdered SRMs in Fig 4.1(a) to 4.1(d) that:

- LSP particles are flaky, highly abrasive and rough with irregular surface texture and angular edges offering more resistance to flow thereby need more SP to overcome resistance to flow. Patches can also be seen in SEM images resulting into internal porosity which can absorb SP thus increasing SP demand.
- QD particles are almost similar to LSP particles with an addition of some glassy surfaces of silicon deposited by clay / dust during natural course of action. SEM images support the evidence of XRF analysis of LSP & QD (XRF analysis results at Annexure C are attached). SEM images of GGBF Slag indicate that particles are glassy having smooth surface thus require less water and SP.
- Particles of cement also seem to be rough and angular in shape.

5.1.3 Composition of SRMs

5.1.3.1 Suitability of GGBF Slag.

After going through previous literature [11] available, following checks have been applied to determine the suitability of GGBF Slag,

- **Check 1** Contents of CaO(30-50)% CaO 43.45% - OK
- **Check 2** $(CaO + MgO + SiO_2) \geq$ 66 % by mass
  $= (43.45+5.32+31.57)$ $= 80.34\ \% > 66$ - OK
- **Check 3** Mass Ratio $(CaO + MgO) / SiO_2 > 1$
  $(43.45 + 5.32) / 31.57 = 1.54 > 1$ - OK

- **Check 4** Contents of SiO_2 (28 – 40) 31.57% - OK
- **Check 5** Contents of Al_2O_3 (8 to 24)% 12.17% - OK
- **Check 6** Contents of MgO (1-8)% 5.32% - OK
- **Check 7** Co-efficient of quality – MgO= $K \leq 10$

K = $(CaO + MgO + Al_2O_3) / (SIO_2 + TiO_2)$

= (43.45+5.32+12.17) / (31.57+0.85)

= $1.88 \leq 10$ - OK

GGBF Slag obtained from PSM Karachi satisfies all the checks there by suitable for research purpose.

- **Modulus of activity.**

M_a = $Al_2 O_3 / SiO_2$ = 12.17 / 31.57

= **0.385** < 0.4 - OK

- **Modulus of basicity.**

Mb = $(CaO + MgO + Al_2 O_3) / (SIO_2 + TiO_2)$

Mb = (43.45 + 5.32+12.17) / (31.57+0.85)

= 1.88> 1 **(Basic Slag)** - OK

- **Reactivity index** = $(CaO + MgO) / (SiO_2)$

= (43.45 + 5.32) / 31.57

= 1.55 > 1 - OK

- **Lime / Silica** = CaO / SiO_2

= 43.45 / 31.57

= 1.37 < 1.4 - OK

5.1.3.2 Comparison of Chemical Compositions of Various SRMs

Chemical composition of various SRMs used under research was extracted from elemental analysis done at IESE (NUST). It is summarized in Table 5.2.

Following deductions can be inferred which will be testified in results of various tests in coming paragraphs:-

- CaO effects dormant period and gives an accelerating affect in the solution during early ages. These are highest in LSP (97.64%), reduced in QD (70.30%) and are even less than 50 % in GGBF Slag. This dictates order of activation with reference to CaO as LSP, QD & GGBF Slag respectively.
- SiO_2 contents are absent in LSP and significantly present in QD (23.18%). Probably these have been added in QD from environmental pollution in the form of dust. Being crystalline in nature, SiO_2 will not contribute towards pozzolanic activity.

- Alkali contents (Na_2O & K_2O) enhance workability and decrease strength [37]. Absence of alkali contents will make LSP formulation stiff with comparatively higher strengths. Presence of K_2O (1.19%) in QD will positively affect workability of the formulations.

Table 5.2: Comparison of Chemical Composition of Powders

Major Elements	SRMs			
	Cement	LSP	QD	GGBF Slag
CaO	65	97.64	70.31	48.43
SiO_2	17.15	Not detected	23.17	27.5
Al_2O_3	5.6	"	Not detected	7.6
Fe_2O_3	3.21	1.72	4.35	1.66
MgO	1.74	Not detected	Not detected	5.27
K_2O	1.19	"	1.19	0.6
Na_2O	1.86	"	Not detected	Not detected
SO_3	2.66	"	"	2.03
Particle Size (µm)	19.5	9.5	8.25	14.5
Density (g/cc)	3.181	2.75	2.6963	2.930

5.2 Tests of Self-Consolidated Paste (SCP) Systems

SCP has been categorized into two formulations. One with binary binder i.e. CS formulations of SCP systems and the other is ternary binders is “SCP formulations having blends of powders (GGBF Slag & LSP / QD)”. In this article, individual trends of both formulations will be discussed along with the probable logics behind.

5.2.1 Water Demand of SCP Formulations

Mixing water contents should be very close to WD of the system to minimize SP contents required for the target flow in order to have economy and durability [1]. In CS formulations of SCP systems, GGBF Slag is added in various contents ranging from 5 to 20 %, WD tends to decrease. It is probably due to smooth surface of GGBF Slag. Phenomena of specific surface area are also there but not dominant. Trends are shown in Fig 5.2 (a).

In SCP formulations having blends of powders (GGBF Slag with LSP / QD), variation of particle sizes of cement and SRMs result into better packing in the matrix which drops WD of the system. GGBF Slag tends to decrease WD due to its surface texture but LSP particles with shape, size & surface texture as shown in SEMs & some internal porosity reported elsewhere [1] tend to increase WD. Shape, surface morphology and reported internal porosity of LSP & QD dominate. Resultantly WD of SCP formulations having blends of powders increases than controlled formulation (0.9C1 + 0.1BFS – WD). Increase in LSP & QD contents from 10 to 20% improves packing which drops WD due to more availability of effective water as shown in Fig 5.2 (b).

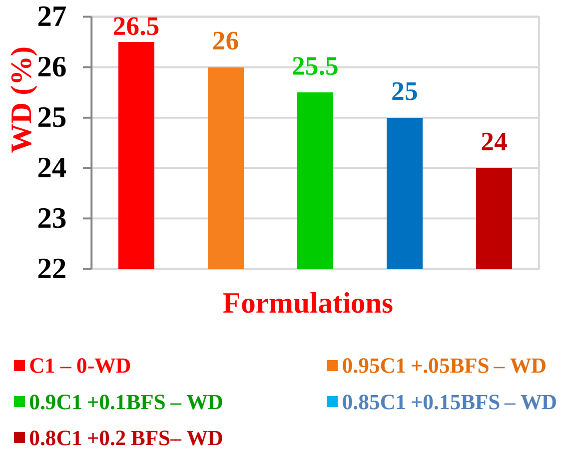


Fig 5.2 (a): WD of CS Formulations – SCP Systems

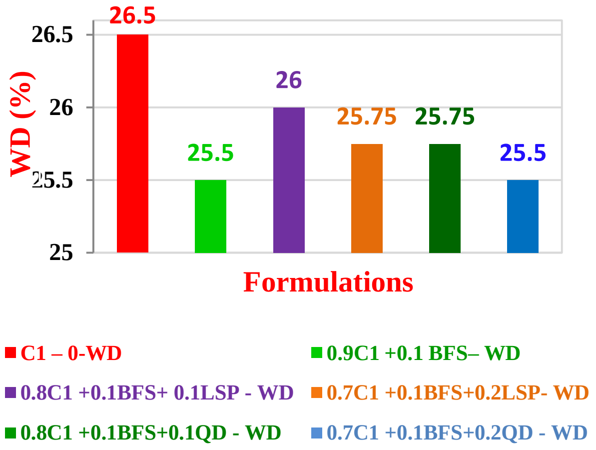


Fig 5.2 (b): WD – SCP Formulations having Blends of Powders

5.2.2 Setting Times (ST) of SCP Formulations

Setting time (ST) gives an idea of open time for placement of SCCS. ST when related with calorimetric curve gives a good comprehension regarding hydration kinetics related to SCCS. In CS formulations, IST & FST increase due to dilution effect, delayed hydration & lower CaO contents (45-48 %) in GGBF Slag.

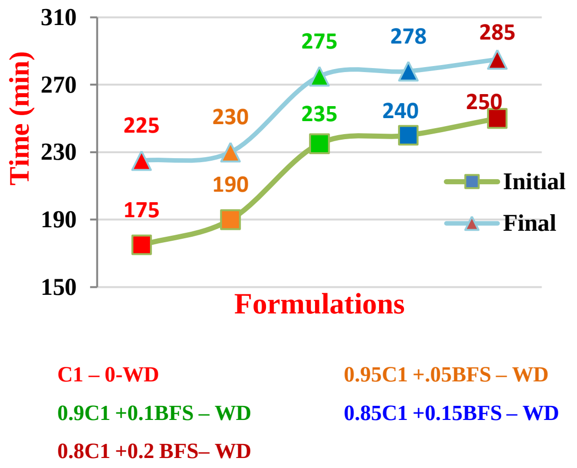


Fig 5.3 (a): Setting Time of CS Formulations – SCP Systems

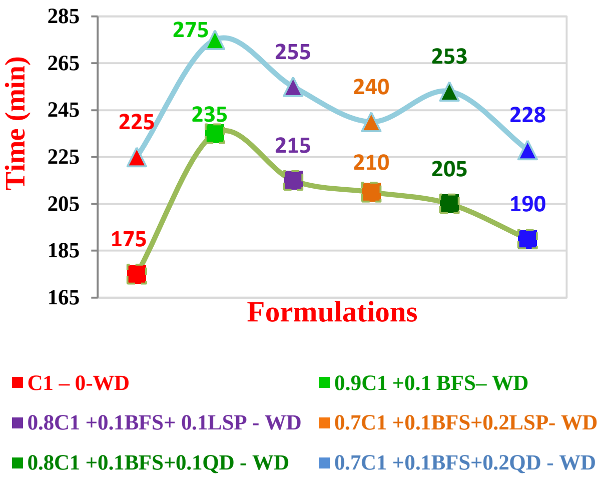


Fig 5.3 (b): Setting Time – SCP Formulations having Blends of Powders

In SCP formulations having blends of powders (GGBF Slag with LSP/QD), ST results are interesting and comprehension is as under:-

- GGBF slag tends to retard due to the reasons explained above and increases dormant period.
- LSP being rich in CaO contents (97%) & QD (71%) will effect on ST. pH value of the SCP formulation will also tend to improve due to presence of (OH^{-}) ions in LSP / QD which had otherwise been controlled by GGBF Slag. [38]

- ➢ Particle size of LSP & QD is half than cement thus more surface area will generate (N+G) effect hence acceleration will be there.
- ➢ Increased effective water due to packing will also contribute towards hydration thus ST will be reduced.
- ➢ A drop in IST & FST is clearly visible when LSP & QD contents are increased from 10 to 20 % obviously due to the reasons discussed above.
- ➢ Relation between ST and dormant period will be established in article (5.2.4).

5.2.3 Flow of SCP Systems

SP plays a vital role in augmenting flow properties of SCCS. Size, shape, morphology, internal porosity and degree of pozzolanic activity of SRMs influence SP demand to a greater extent. In order to minimize SP demand, water contents must be equal to WD of the system. It will ensure economy as well as durability [1]. In CS formulations of SCP systems, with the increase of GGBF Slag contents, SP contents dropped as evident from Fig 5.4 (a). Although GGBF Slag being finer than cement integrates more surface area and tends to increase WD & SP demand in these SCP formulations. But its surface morphology & better packing increase effective water and decrease both the demands. These mechanisms go side by side & later dominate and drop both SP demand & WD. In SCP formulations having blends of powders (GGBF Slag with LSP/QD), generally a trend of increase in SP demand is reported. Size, shape, surface morphology, variation in WD and packing phenomena of GGBF Slag, LSP & QD classically explains this trend. QD having more BET area & pore volume than LSP (Table 5.1) further increase SP demand. Effect of SiO_2 in QD on WD & SP demand can’t be neglected [39].

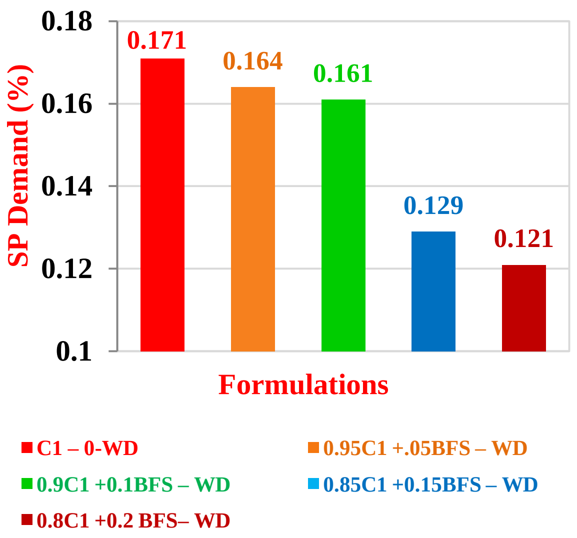


Fig 5.4 (a): SP Demand of CS Formulations – SCP Systems

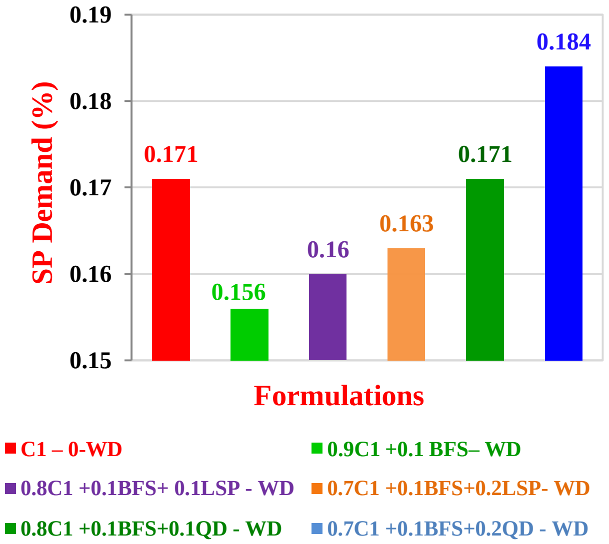


Fig 5.4 (b): SP Demand of SCP Formulations having Blends of Powders

Flow Times & Spread (D max) may be considered a function of plastic viscosity and yield stress (stress required to start the flow) of SCCS. Yield stress determines the stress above which the material becomes a fluid. Plastic viscosity is a measure of how easily the material will flow, once the yield stress is overcome. Physical interpretation of this factor is that yield stress is the stress needed to be applied to a material to initiate flow. Yield stress term is a manifestation of friction between solid particles while the plastic viscosity term results from viscous dissipation due to the movement of water in the sheared material. Idea of T-25 is quite interesting but its relationship with plastic viscosity & yield stress is still not very clear. However, researchers relate it both with viscosity & yield stress Fig 5.5 (a) [1]. Effort has also been made to discuss these parameters in "Flow Windows" to draw useful inferences. Smaller flow times & more spread indicate lesser internal friction offered during flow by powder particles and translates into higher deformation & lower yield stress and vice versa.

Flow windows have been developed using relationship between **T-30 & spread** of SCP formulations in terms of viscosity and yield stresses. (C1 – 0-WD) & (0.95C1 + .05BFS – WD) formulations have lower viscosity and lower yield stresses. This can be related with higher SP contents at WD which reduces viscosity and make the formulations more workable thus results into lower yield stresses. In other CS formulations lesser SP contents corresponds to more viscosity and lesser workability thus stiff paste will have relatively higher yield stresses as shown in Fig 5.5(a).

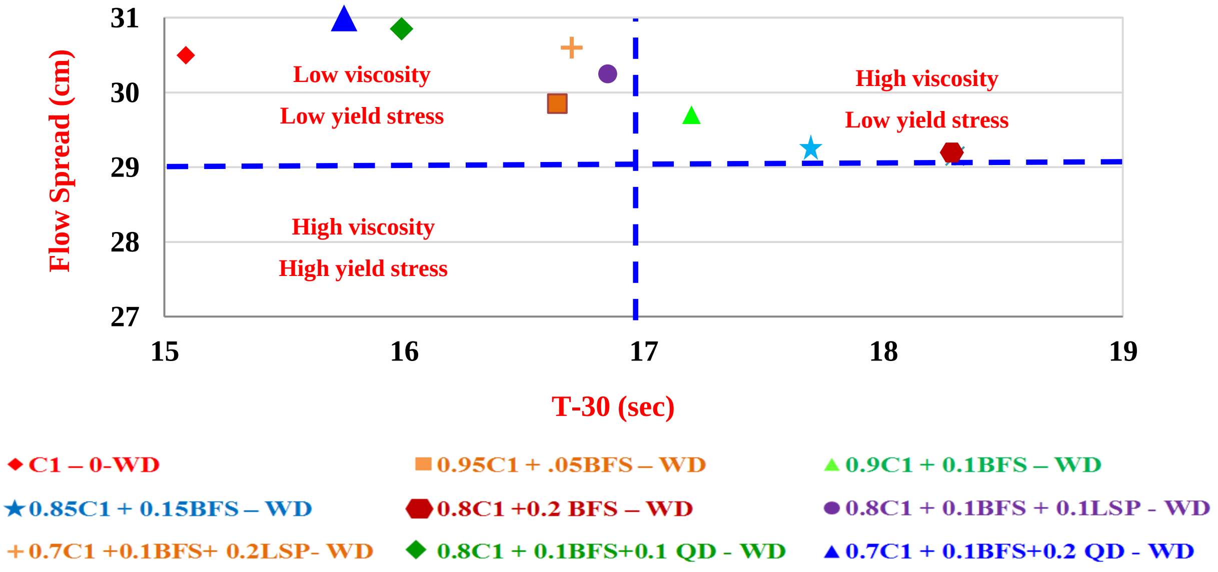


Fig 5.5(a): Relationship Between Time (T-30) & Flow Spread (SCP Formulations)

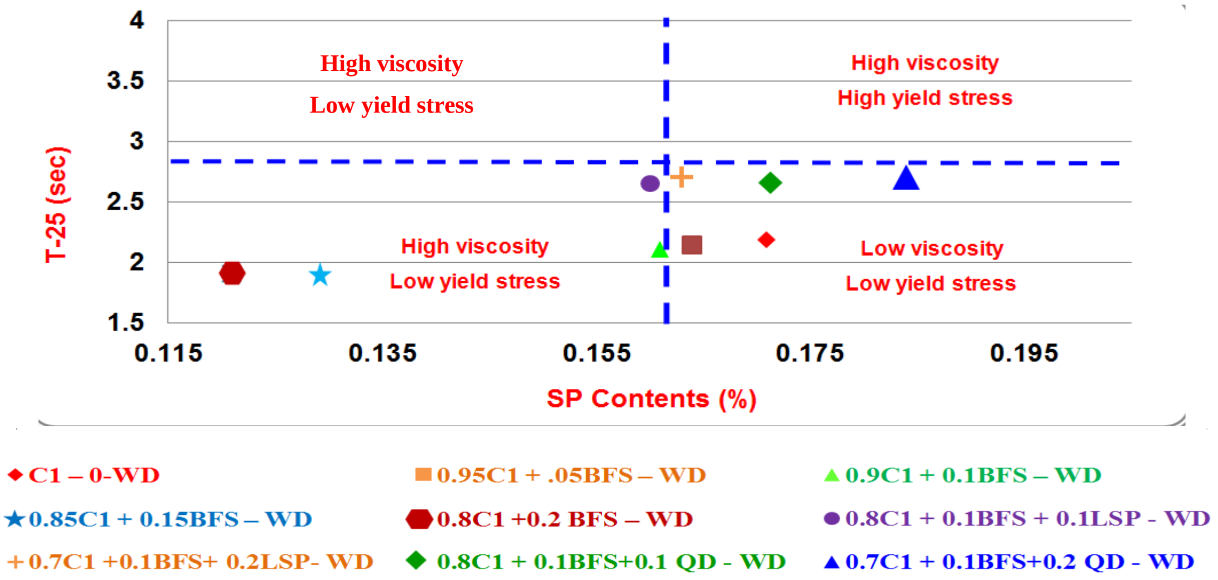


Fig 5.5(b): Relationship Between Time (T-25) & SP Contents (SCP Formulations)

SCP formulations having blends of GGBF Slag with LSP / QD have lower viscosity & low yield stresses. It can be associated with higher SP contents which make these formulations less viscous & more workable thus leading towards lower yield stresses. Flow windows of T 25 & SP contents support previous inferences drawn shown in Fig 5.5(b) with a slight variation of (0.8C1 + 0.1BFS + 0.1LSP - WD) which is a boarder case and is within acceptable limits. Relationship between T-25 & T-30 for both the categories of SCP formulations has been established in Fig 5.5 (c). Results in the flow window support relationships of both the flow windows at Fig 5.5 (a&b).

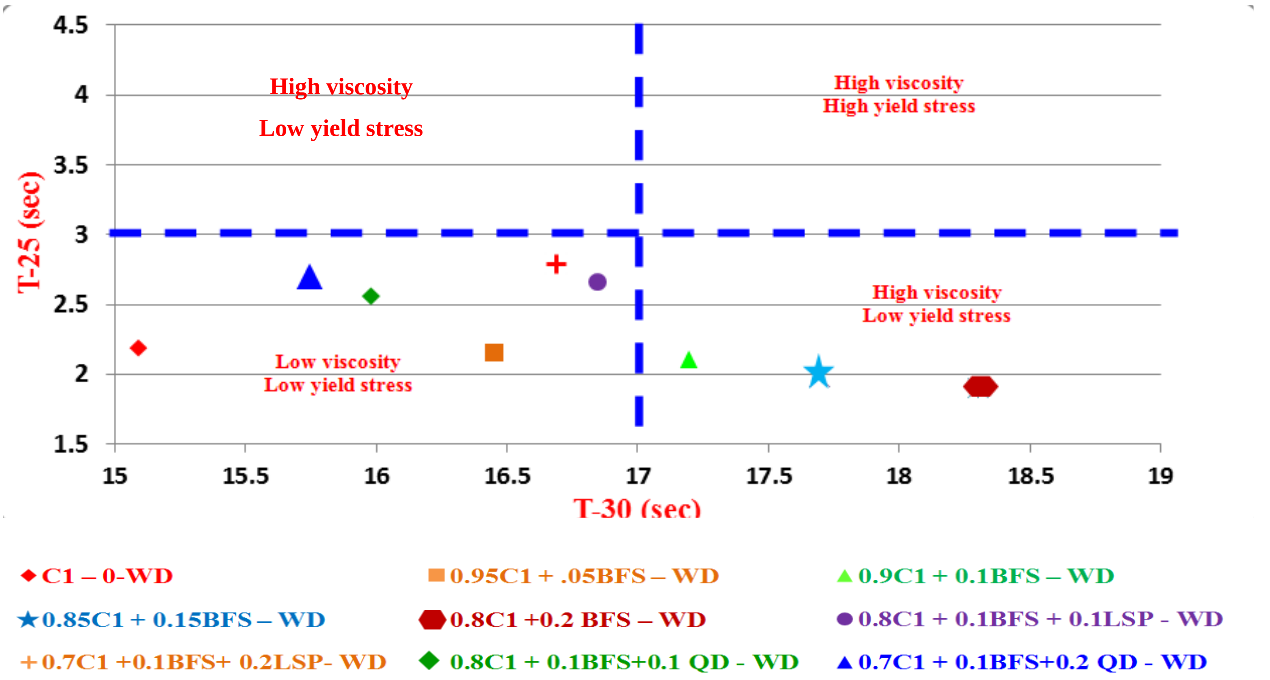


Fig 5.5(c): Relationship Between T-25 & T30 - SCP Systems

5.2.4 Hydration Kinetics of SCP Formulations

Calorimetric examinations were done on SCP formulations to investigate hydration kinetics. Higher the cement contents hydrated, higher will be exothermic reaction and more will be the heat liberated. Water contents & pozzolanic nature of partially replaced powders (SRMs) are vital for hydration kinetics which can influence workability, setting behaviour, rate of strength gain and pore refinement; hence affect the early age behaviour as well as long term performance of concrete.

In CS Formulation of SCP Systems, hydration of aluminate (C_3A) phases was very rapid and could not be reflected in calorimetric curve due to its rapidity. However hydration C_3S phases is shown graphically in which large amount of heat was released shown by exothermic signal on calorimeter F Cal 8000.

- First peak shown in Fig 4.14(a) within an hour which is due to initial temperature difference between the formulation and the eqpt.
- In initial reaction stage, large amount of heat was released followed by a significant drop. This can be attributed to consumption of Ca^{++}& OH^{-} ions in the solutions until a balance is achieved [10].
- Dormant period of each formulation is shown in Fig 4.14(a) which varies slightly depending upon contents of GGBF Slag. Dormant period may either be attributed to "Metastable Barrier Hypothesis" or "Slow Dissolution Step Hypothesis" [10]. This period gives open time to place mix before setting.
- Rise in pH value due to Ca^{++} & OH^{-} ions terminated dormant period. This was followed by a rise in heat release known as acceleration stage. This is mainly attributed to Nucleation & Growth (N + G) of hydrates [10].
- Deceleration stage can be due to lack of water & space, consumption of small cement particles leaving large size particles to react [10].

For (C1 – 0-WD) formulation heat of hydration is the highest while dormant period is shortest. Effect of GGBF Slag as partial replacement of cement is quite interesting. It decreases heat of hydration and increases the dormant period as shown in Fig 4.14 (a). In (0.8C1 + 0.1BFS + 0.1LSP - WD) & (0.7C1 +0.1BFS+ 0.2LSP- WD) formulations, there is a slight increase in heat of hydrations and drop in dormant period than controlled formulations (0.9C1 + 0.1BFS – WD) as shown in Fig 4.14 (b) which may be attributed to high CaO contents which probably alter pH value and break metastable barrier along with (N + G) effect. In (0.8C1 + 0.1BFS+0.1 QD – WD) & (0.7C1 + 0.1BFS+0.2 QD - WD) formulations, there is further rise in heat of hydration & drop in dormant period even than LSP. This may be attributed to presence of CaO and finer QD (8.25μm) which enhance (N+G) effect.

5.2.5 Strength of Self-Consolidating Paste Formulations

Compressive & flexural strengths of SCP formulations are graphically represented in Figs 4.12 & 4.13 respectively. In CS formulations of SCP systems at all contents of GGBF Slag, both compressive & flexural strengths decrease at early age due to delayed activation of GGBF Slag and dilution of cement. After 7 days, Ca $(OH)_2$ produced as result of hydration of C_3S activate GGBF Slag thus pozzolanic activity is enhanced at later ages, increase in degree of pozzolanic activity of Slag contributes towards CSH gel which gives strength to the microstructure. Recovery trend is clearly visible in Fig 4.12(a) and maximum increase in compressive & flexural strength for (0.8C1 +0.2 BFS – WD) at 56 days is 15.5% & 17.2% respectively as compared to controlled formulation (C1 – 0-WD). In SCP formulations having blends of powders (GGBF Slag & LSP/QD), early strength of all these formulations specially (0.8C1 + 0.1BFS + 0.1LSP - WD) & (0.8C1 + 0.1BFS+ 0.1QD - WD) is more than controlled formulation (0.9C1 + 0.1BFS – WD). In spite of dilution of cement by ternary binders, this increase in strength is due to integration of surfaces by finer SRMs generating (N+G) effect [1]. At 7 days, compressive strength of controlled formulation (0.9C1 + 0.1BFS – WD) is more than all SCP blends formulation due to dilution of cement yet effect of free silica in QD is visible in terms of increase in strength in (0.8C1 + 0.1BFS+0.1QD - WD) formulation. At 28 days, compressive of controlled formulation (0.9C1 + 0.1BFS – WD) is highest due to overriding activation to GGBF Slag. Early flexural strength of formulations having LSP as ternary binder is more than the formulations with QD while at later ages (28 days), results are opposite. It is possibly due to high CaO contents of LSP which have accelerated hydration of cement [1] while free silica in QD becomes effective at later ages [10,39].

It is concluded that suitable binary and ternary binder or their combinations increase flow, strength and durability due to their shape and pore-refinement effect [1] respectively Particle size along with texture and surface morphology of SRMs are of utmost importance in relation to the strength development.

5.3 Tests on Self-Consolidating Concrete

In SCC formulations, W/C, VEA contents & coarse aggregate contents have been kept constant while flow properties, strengths and hydration kinetics have been investigated, keeping percentage of SRMs variable as a partial replace of cement & fine aggregates along with SP contents. Various recipes have been prepared in line with [1] and quantification of these recipes has been tabulated as under:-

Table 5.3: Mix Ingredients of SCC Formulations

Ser	Constituents	Units	Formulations						Remarks
			(C1 – FA – CA -45)	(0.8C1 +0.2BFS) - FA– CA - 45	(0.8C1 +0.2BFS) – (0.9FA +0.1LSP)– CA - 45	(0.8C1 +0.2BFS) – (0.8FA +0.2LSP)- CA – 45	(0.8C1 +0.2BFS) – (0.9FA +0.1QD)- CA –45	(0.8C1 +0.2BFS) – (0.8FA + 0.2QD)– CA-45	
1.	Cement	Kg/m^3	527	422	422	422	422	422	
2.	GGBF Slag	Kg/m^3	-	105	105	105	105	105	SRM for cement replacement
3.	Fine aggregate	Kg/m^3	889	889	803	726	803	726	
4.	LSP / QD	%	-	-	10	20	10	20	SRM for replacement of fine aggregate
		Kg/m^3	-	-	89	178	89	178	
5.	Coarse aggregate (2-9 mm)	Kg/m^3	494	494	494	494	494	494	CA -1
6.	Coarse aggregate (9-19 mm)	Kg/m^3	247	247	247	247	247	247	CA -2
7.	Water contents	Kg/m^3	237	190	190	190	190	190	0.45C
8.	SP	% (Cem)	1.49	1.21	1.40	1.87	1.85	2.28	By weight of cement
		Kg/m^3	19.33	12.67	14.67	19.62	19.63	23.85	
9.	VEA	% (Cem)	0.6	0.6	0.6	0.6	0.6	0.6	By weight of cement
		Kg/m^3	6.3	6.3	6.3	6.3	6.3	6.3	
10.	W / C	Ratio	0.45	0.45	0.45	0.45	0.45	0.45	-

5.3.1 Flow Tests.

5.3.1.1 Super Plasticizer (SP) Demand

Replacement of fine aggregates with LSP & QD in both the categories (pure cement & binder replacement with GGBF Slag) of SCC formulation results into increase in SP demand. It is reportedly more in pure cement formulations. This is probably due to shape & surface morphology of SRMs both being used as partial replacement of binders & fine aggregates. SP contents of (C1 – FA – CA - 45) SCC formulation are 1.49% which drop to 1.21% in ((0.8C1 +0.2BFS) - FA– CA – 45) formulation & is lowest amongst all SCC Formulations. It may be due to shape & surface morphology of GGBF Slag. When fine aggregates are replaced with 10 & 20% LSP in the controlled formulation ((0.8C1 +0.2BFS) - FA– CA – 45), SP demand increases to 1.4% & 1.87% respectively. Same trends are visible while using QD as partial replacement of fine aggregates. SP contents are maximum (2.28%) for (0.8C1 +0.2BFS) – (0.8FA + 0.2QD) – CA-45 which can be related with high BET surface area and pore volume as given in Table 5.1. Thus requiring more SP for grafting. These results support following inferences of SRMs characterization:-

- LSP particles are rough, highly abrasive, flaky, angular and spongy patches with high internal porosity. Absence of alkalis in LSP make ((0.8C1 +0.2BFS) – (0.9FA +0.1LSP) – CA - 45) & ((0.8C1 +0.2BFS) – (0.8FA +0.2LSP) - CA– 45) formulations tiff (less workable) and increases SP demand at constant water contents. [44]
- QD particles with alkalis K_2O increase workability. However more BET surface area & pore volume require more SP for grafting.
- W/C is 0.45, constant for SCC formulations. Addition of LSP & QD (10 & 20%), need more water to make surface of particles wet but due to constant water contents, more SP will be required.
- D-50 of LSP & QD is approximately 9.5 & 8.25 (μm) which is far less than fine aggregates (0-2) mm as well as GGBF Slag 14.5 (μm) and cement so LSP provides more specific surface area in the matrix.

5.3.1.2 Slump Flow & J Ring Tests – SCC

Efforts have been made to analyze slump flow and J Ring tests individually and then draw a comparison amongst each other. Time of “J Ring” is always more & spread is always less than “Slump Flow test”.

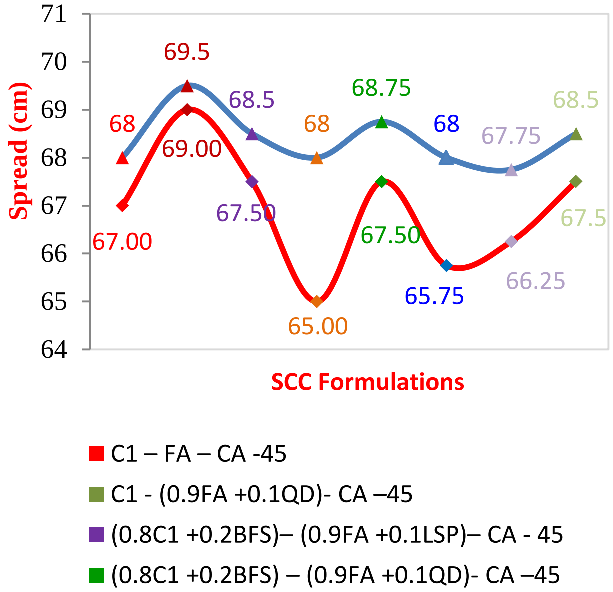
5.3.1.2.1 T-50 cm (Time at 50 cm)

T-50 cm is an indicator of viscosity. In J Ring, T-50 cm of SCC formulations under investigation, are more in comparison with Slump Flow test due to presence of intermittent resistance in the form of 12 rods of J Ring. However, trends are quite similar as shown in Fig 5.7(a).

- T-50 cm is more in pure cement formulations due to shape & surface morphology of LSP & QD than the formulations having blends of powders GGBF Slag as binder replacement. Flow time is maximum for C1 – (0.9FA +0.1LSP)– CA – 45 formulations due to same effect mentioned above.
- SP contents of (0.8C1 +0.2BFS) - FA– CA - 45) are less than (C1 – FA – CA - 45) yet T-50 drops from 5.35 sec to 4.2 sec, probably due to glassy surface texture

of GGBF Slag that reduces internal flow resistance into the matrix, hence flow time is reduced.

- In SCC formulations (0.8C1 +0.2BFS) – (0.9FA +0.1LSP) – CA – 45 & (0.8C1 +0.2BFS) – (0.8FA +0.2LSP) - CA – 45) there is a mix trend. Shape and surface texture of LSP particles will increase flow resistance but more SP contents (1.4 to 1.87) % tend to reduce the friction during flow. These mechanisms run side by side and former takes over. Hence flow times & T-50 cm increases shown in Fig 5.6 (a).



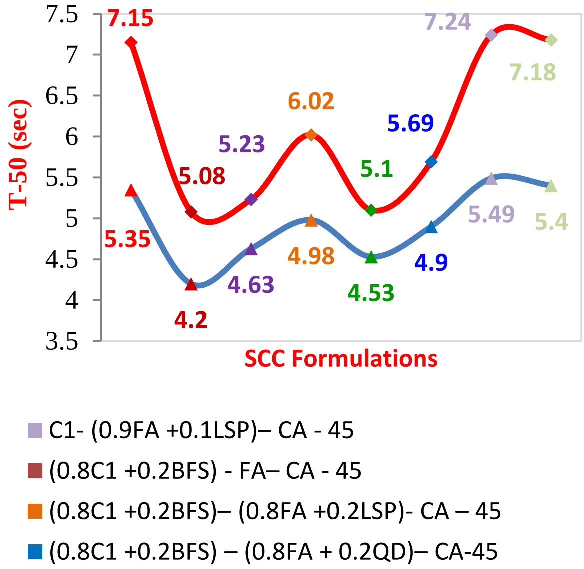


Fig 5.6 (a) : Comparison of T-50 of Slump Flow & J Ring Test.

Fig 5.6 (b): Comparison of Spread (D Max) of Slump Flow & J Ring Test.

- In SCC formulations (0.8C1 +0.2BFS) – (0.9FA +0.1QD) – CA – 45 & (0.8C1 +0.2BFS) – (0.8FA +0.2QD) – CA – 45) trends are similar to LSP formulations. However presence of silicon contents in QD, tend to decrease internal friction during flow. Presence of K_2O (Table 5.2) also enhances workability hence T50 cm is even lesser than SCC formulations with LSP contents.

5.3.1.2.2 Flow of Self-Consolidating Concrete (D Max).

Slump spread represents yield stress. It increases in (0.8C1 +0.2BFS)-FA-CA-45) formulation as compared to (C1 – FA – CA -45) due to less WD of GGBF Slag thus ensuring more availability of effective water at constant W/C. Moreover GGBF Slag reduces internal friction into the matrix, thereby reducing yield stress of the mix and slump spread increases from 68 to 69.5 cm. Micro sized LSP / QD being finer than cement improve packing thus ensuring more availability of effective water at constant W/C contributing towards better flow. Contrary to this, shape & surface texture of these particles stiffens the mix increase yield stresses in (0.8C1 +0.2BFS) – (0.9FA

+0.1LSP) – CA – 45 & (0.8C1 +0.2BFS) – (0.8FA +0.2LSP)- CA – 45) formulations. Later phenomena is more effective and spread decreases than (0.8C1 +0.2BFS) - FA– CA – 45) formulation. Difference between LSP & QD is the presence of smooth clay & alkali contents in QD improves workability [40] which reduces flow resistance and spread of (0.8C1 +0.2BFS) – (0.9FA +0.1QD)– CA – 45) & (0.8C1 +0.2BFS) – (0.8FA +0.2QD)- CA – 45) formulations. Trends are shown in Fig 5.7 (b) which supports trends of T-50 cm in Fig 5.7 (a). J Ring spread in all formulations is less than slump flow due to intermittent obstruction of 12 rods of J Ring. Trends of spread and T-50 of both the tests have the relation of inversely proportion as evident in Fig 5.6 (a & b).

5.3.1.3 V Funnel Test

V funnel time is related to passing ability, filling ability and segregation resistance. It is an indicative of viscosity [1] like T-50 cm in Slump Flow test. It is maximum for C1 - (0.9FA +0.1LSP)– CA - 45 formulation due to shape & surface morphology of LSP. Presence of K_2O in QD improves work ability & hence reduces V funnel time as reported in C1 - (0.9FA +0.1QD)– CA – 45 formulation. V funnel time drastically decreases in (0.8C1 +0.2BFS) - FA– CA – 45) formulation as compared to (C1 – FA – CA -45). It may be due to GGBF Slag which ensures availability of more effective water at constant W/C and less flow resistance into the matrix by its smooth surface texture thus reducing V funnel time from 6.25 sec to 3.18 sec (highest & lowest V-Funnel time is SCC formulations under research). Packing of micro sized LSP enhances flow but rough abrasive, angular & flaky particles offer resistance in passing ability from the aperture of V Funnel. Thus V Funnel time of (0.8C1 +0.2BFS) – (0.9FA +0.1LSP) – CA – 45 & (0.8C1 +0.2BFS) – (0.8FA +0.2LSP) - CA – 45) formulations increases. In case of QD, above described reasons are applicable but presence of smooth clay with alkalis K_2O in QD improve workability which decreases V funnel time. Increase in LSP & QD contents from 10 to 20% increase the flow resistance, thus V Funnel Time increases.

5.3.1.4 L Box Test

L Box test measures passing & filling ability of SCC mixes. Result of L-Box Test supports flow time of slump flow, J-Ring and V Funnel test therefore flow times of C1 - (0.9FA +0.1LSP)– CA - 45 formulation are maximum. T-200 drops in (0.8C1 +0.2BFS) - FA– CA – 45) formulation as compared to (C1 – FA – CA -45) due to availability of more effective water contributed by smooth surface of GGBF Slag at constant W/C ratio. Same trend can be seen in T-400 & T-600. In other SCC formulations having blends of GGBF Slag with LSP / QD, these flow times tend to increase than controlled formulation (0.8C1 +0.2BFS) - FA– CA – 45) which supplement previous results of flow test and SRMs characterization. Considering concrete height ratio (H_2/H_1), if the ratio is near unity the mix will be high deformable. The values of blocking ratio (near unity) indicate that all mixes under research are highly deformable. Blocking ratio has a close relationship with flow time. (C1 – FA – CA -45) formulations has lowest blocking ratio, its flow times (T200, T400 & T600) are highest as reflected in Fig 5.7. (0.8C1 +0.2BFS) - FA– CA – 45) formulation has highest (very close to unity) its flow times are lowest. (0.8C1 +0.2BFS) - FA– CA –45) formulation is more deformable than (C1 – FA – CA - 45) formulation. Similarly (0.8C1 + 0.2BFS) – (0.9FA + 0.1LSP) – CA – 45 & (0.8C1 + 0.2BFS) – (0.8FA + 0.2LSP) - CA – 45) formulations are less deformable than (0.8C1 +0.2BFS) - FA– CA - 45) formulation due to absence of alkalis & shape and surface texture of LSP. In (0.8C1 + 0.2BFS) – (0.9FA + 0.1QD) - CA –45 & (0.8C1 + 0.2BFS) – (0.8FA + 0.2QD) – CA - 45) formulations deformability more LSP due to presence of smooth clay particles and presence of alkalis [37]. Hence results of SCC flow tests supplements one another as well as deductions of SRMs characterization.

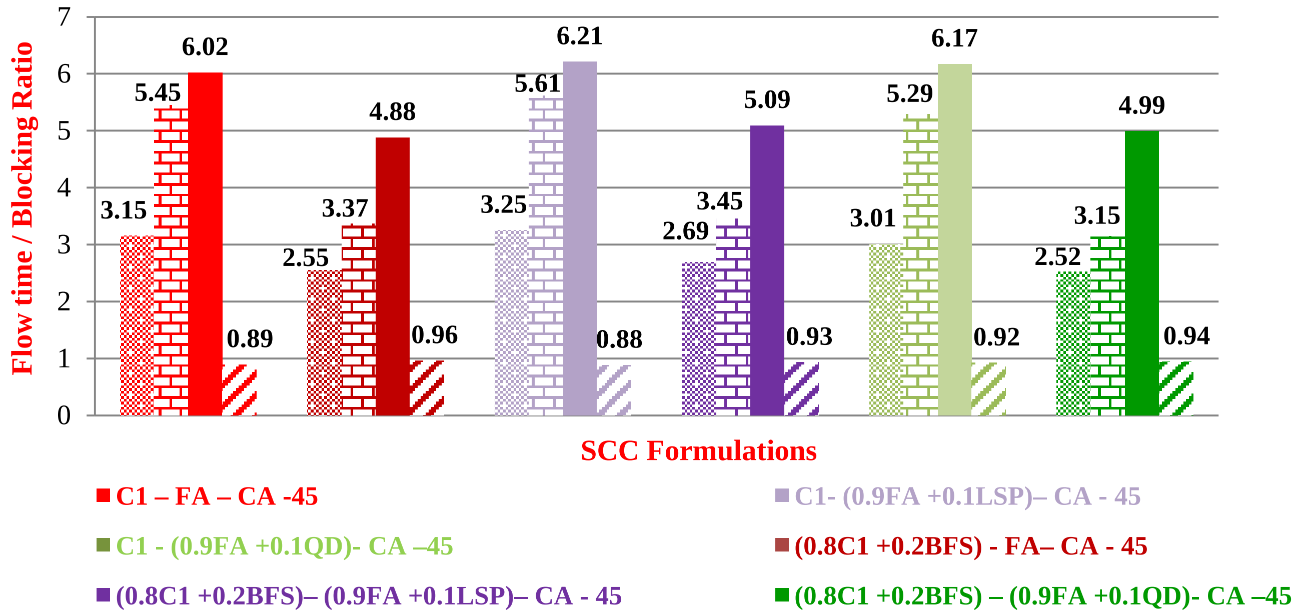


Fig 5.7: Relationship between Flow Times & Blocking Ratio (H_2 / H_1) – SCC Formulations

5.3.1.5 Relationship between Flow Properties

Flow time & total spread may be considered a function of plastic viscosity and yield stress (Stress required to start the flow) of SCCS. Powders under research ranged in size (8-20) µm. These powders ensure more availability of effective water by improving inter particle packing of concrete matrix at constant W/C ratio when used as replacement of cement and / or fine aggregate. Thus workability is enhanced which decreases yield stresses thereby flow ability & passing ability are improved. Surface morphology of these powders also effect on workability.

V Funned time & T-50 are function of viscosity [1]. Fig 5.8 (a) represents relationship between V funnel time & T-50 of Slump Flow test. Comparing (C1 – FA – CA -45) & (0.8C1 +0.2BFS) - FA– CA - 45) formulations, V funnel time & T 50 of former are more although its SP contents are higher. It is due to better packing of GGBF Slag in (0.8C1 +0.2BFS) - FA– CA - 45) which ensures more availability of effective water at constant W/C ratio. It increases workability and reduces V funnel time & T-50. So (C1 – FA – CA -45) formulation is comparatively stiff with higher yield stresses & higher viscosity. In other SCC formulations having blends of powders, their shape & surface morphology played a vital role along with inter particle adjustment. Therefore V funnel time &T-50 of (0.8C1 +0.2BFS) - FA– CA - 45) are lowest due to smooth surface of GGBF Slag while those of (0.8C1 +0.2BFS) – (0.8FA +0.2LSP)- CA – 45) formulations are the highest owing to rough, highly abrasive particles of LSP with spongy patches as shown in SEM at Fig 4.1 [1].

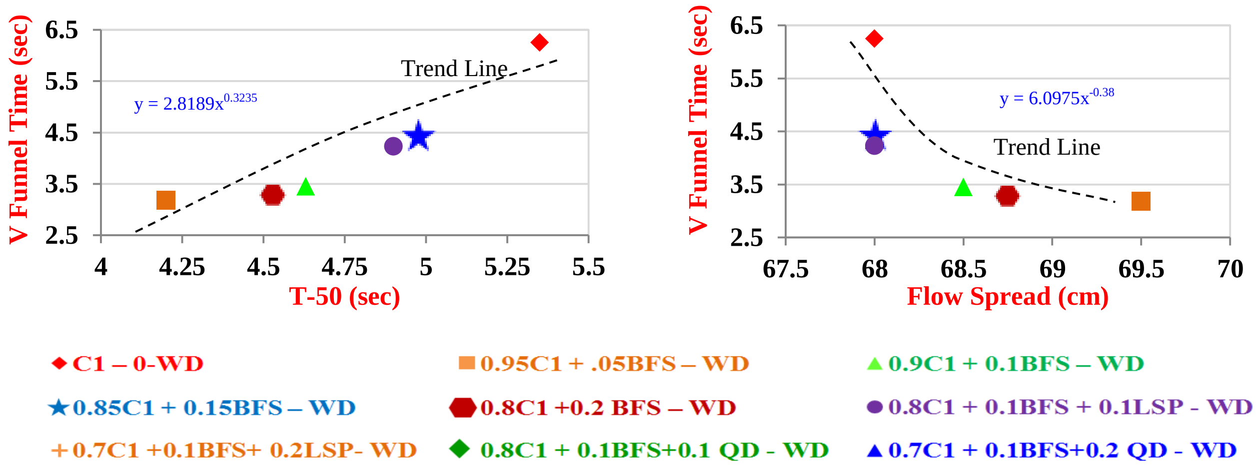


Fig 5.8 (a): V Funnel Time vs T-50 (Slump Flow Test)

Fig: 5.8 (b): V Funnel Time vs Flow Spread (Slump Flow Test)

Fig 5.8 (b) relates viscosity with yield stress. It represents relationship between V funnels time & flow spread. Comparing SCC formulations having blends of powders, (0.8C1 +0.2BFS) - FA– CA - 45) formulation has largest spread & lowest V funnels time while (0.8C1 +0.2BFS) – (0.8FA +0.2LSP) - CA – 45 & (0.8C1 +0.2BFS) – (0.8FA +0.2QD) - CA – 45) have least spread & maximum V funnels time. Similarly (0.8C1 +0.2BFS) - FA– CA - 45) formulation has more spread & less V funnel time than (C1 – FA – CA -45). This relation verifies results & discussion of Fig 5.10(a).

Fig 5.8 (c) shows relation between spread &T-50. T-50 is the more for (C1 – FA – CA -45) than (0.8C1 +0.2BFS) - FA– CA - 45) formulation. This is supported by spread results. In other SCC formulations having blends of powders, (0.8C1 +0.2BFS) - FA– CA - 45) has largest spread & lowest T-50 while (0.8C1 +0.2BFS) – (0.8FA +0.2LSP) - CA – 45 & (0.8C1 +0.2BFS) – (0.8FA +0.2QD) - CA – 45) have least spread & maximum T-50. It is concluded from these results that shape, size, surface morphology and inter particle packing of SRMs play a vital role in improving flow behavior of SCC.

In Fig 5.8 (d) relation between slump spread and concrete height ratios of L Box test has been established Results of slump spread and H_2/H_1 ratio totally support above discussion where (0.8C1

+0.2BFS) - FA– CA - 45) formulation has largest spread and (H_2/H_1) ratio. Fig 5.8 (e) represents relationship between Flow Times (T-50 & T max) of SCC Formulations. (C1 – FA – CA -45) formulation has high yield stress & viscosity, whereas, on other formulations are relatively less viscos with low yield stress.

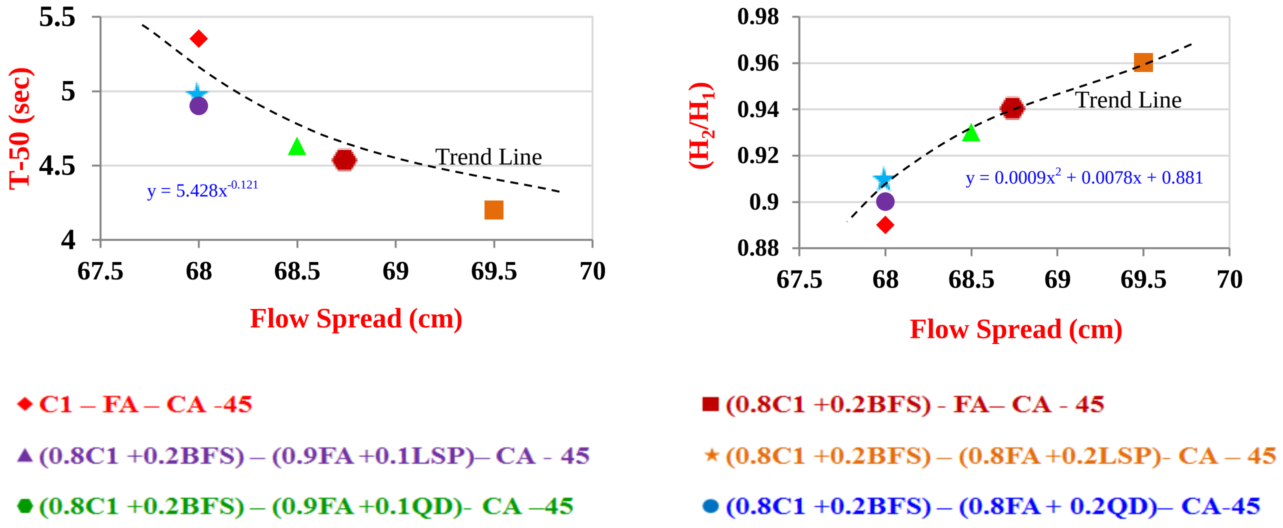


Fig 5.8 (c):T-50 vs Flow Spread (Slump Flow Test)

Fig 5.8 (d): Blocking Ratio (H_2/H_1) vs Spread (Slump Flow)

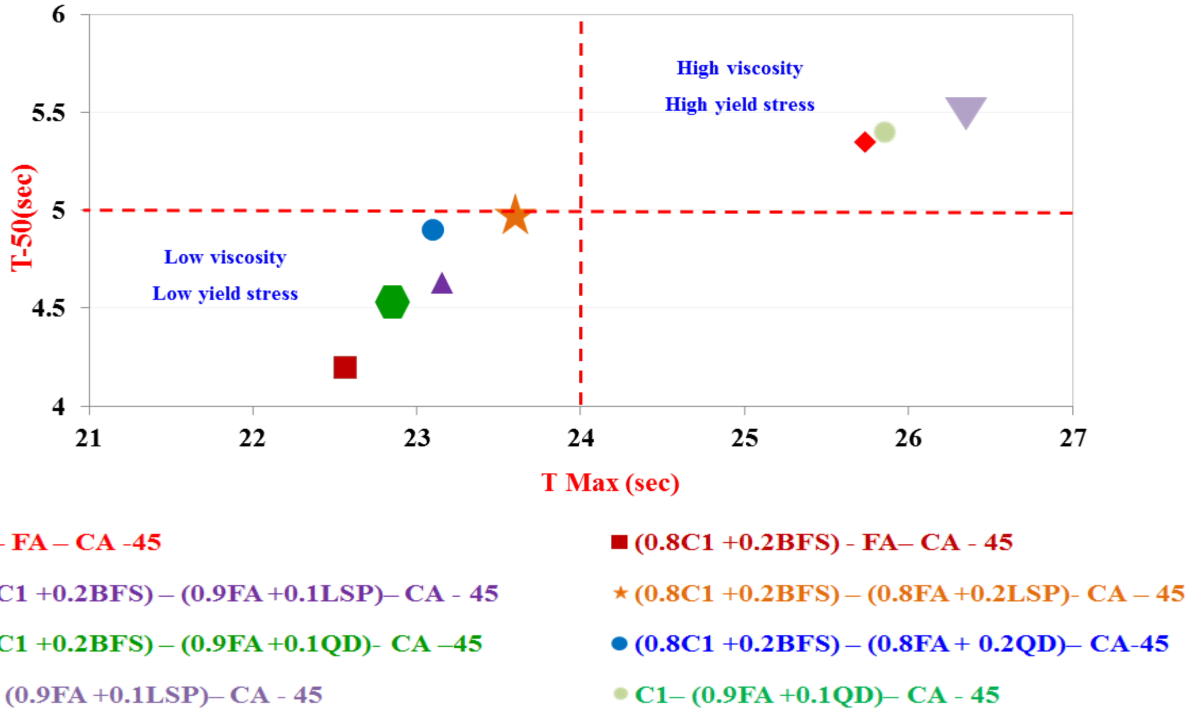


Fig 5.8 (e): Relationship between T-50 & T-70 (max) of SCC Formulations

5.3.2 Study of Hydration Kinetics of SCC Mix

Hydration kinetics of various SCC formulations is shown in Fig 4.24. Dormant period of controlled mix (C1 – FA – CA - 45) was quite less. In (0.8C1 + 0.2BFS) - FA– CA - 45) formulation, dormant period prolonged tremendously to 36 hours than (C1 – FA – CA - 45) formulation. It may be due to dilution of cement [1] & delayed activation of GGBF Slag. Moreover, average particle size (D-50) of GGBF Slag is around 15µm instead of 5-7µm. It may result into delayed pozzolanic activity and hence strength as reflected in strength tests. In other SCC formulation, accelerating effect by LSP & QD through integration of areas / sites for nucleation and growth (N+G), is visible where dormant period reduced (26 to 22) hours which is still too much as it will increases formwork removal time and cost. Seeding with Ca $(OH)_2$ in (0.8C1 +0.2BFS) - FA– CA - 45) formulation proved to be an effective idea to get desired results in order to reduce dormant period near controlled formulation [14]. Ca $(OH)_2$ provided (OH) ions desired for high pH value in the solution in order to offset delayed activation of GGBF Slag. Effects of seeding of GGBF Slag will be discussed in coming article.

5.3.3 Air Content Test

SRMs particles being smaller then cement particles generate batter packing, resulting into reduced are contents which is clearly evident from Fig 5.9. In (C1 – FA – CA - 45) formulation air contents are maximum i.e., (3%). In (0.8C1 +0.2BFS) - FA– CA - 45), GGBF Slag having an average particle size (D-50) of 14.5 (µm) gives better packing and reduces air contents to 2.7%. In (0.8C1 + 0.2BFS) – (0.9FA + 0.1LSP)– CA – 45 & (0.8C1 + 0.2BFS) – (0.8FA +0.2LSP) - CA – 45) formulations, air contents further drops to 2.5% & 2% due to better packing by smaller particles of LSP with D-50 of 9.5 (µm) providing a range of various sizes and facilitate inter particle packing. In (0.8C1 + 0.2BFS) – (0.9FA + 0.1QD) - CA – 45 & (0.8C1 + 0.2BFS) – (0.8FA + 0.2QD) – CA-45) formulations, QD has D-50 of 8.25 (µm), it drops air contents to 2.3% & 1.9% respectively. At 20% replacement of fine aggregates with micro meter particles of LSP / QD, reduction of air content is more owing to better inter particle packing in the matrix. It can be inferred that blends of SRMs give a better packing and reduced air contents in SCC mixes. Moreover, concept of replacing fine aggregate with SRMs is also useful to reduce air contents in SCC mixes. Relation of air contents with compressive strength will be discussed in next article.

5.3.4 Compressive Strength - SCC Mixes

Replacement of fine aggregates with LSP & QD in both the categories (pure cement & binder replacement with GGBF Slag) of SCC formulation results into increase in compressive strength both at early & later ages. 1 day strength of pure cement formulations was measureable due to formation of initial skeleton whereas in other SCC formulations having binder replacement, samples were not ready even after 48 hours for de-moulding. It is due to relatively coarser particle size of GGBF Slag & its delayed activation which had controlled pH value in the solution.

Comparing (C1 – FA – CA - 45) & (0.8C1 + 0.2BFS) - FA– CA – 45) formulations, early age drop in compressive strength is (36.5 %) shown in Table 5.4 which is quite significant. Similar trends are reported in both the categories SCC formulations where fine aggregates have been replaced (10%) with LSP & QD at 10 %. At later age, recovery trend is prominent, where compressive strength is increasing than (C1 – FA – CA - 45) formulation (-2.3 % at 28 & + 3.5% at 56 days). Initial trend of (0.8C1 + 0.2BFS) - FA– CA – 45) formulation is due to dilution of cement & delayed activation of GGBF Slag which drops pH value in the solution. At later ages, pozzolanic activity of GGBF Slag gets accelerated which not only recovers but contribute in compressive strength as given in table 5.4. Increase in compressive strength is also supported by air contents of these formulations.

Table 5.4: Trends of Compressive Strength – SCC Formulations with Partial Replacements of Binders & Fine Aggregates

Formulations	**Age (Days)**	
	3	**28**
C1 – FA – CA -45 --- (1)	20.23	43.50
C1- (0.9FA +0.1LSP)– CA – 45 ---- (2)	22.70	48.12
C1 - (0.9FA +0.1QD)- CA –45 ---- (3)	23.15	50.13
(0.8C1 +0.2BFS) - FA– CA – 45 ----(4)	12.85	42.50
(0.8C1 +0.2BFS) – (0.9FA +0.1LSP)– CA – 45 ---(5)	14.85	47.45
(0.8C1 +0.2BFS) – (0.9FA +0.1QD)- CA –45 ---(6)	15.85	49.75
%age variation in strength (1 & 4)	**-36.48**	**-2.30**
%age variation in strength (2 & 5)	**-34.58**	**-1.39**
%age variation in strength (3 & 6)	**-31.5**	**-0.75**

Comparing ((0.8C1 +0.2BFS) – (0.9FA +0.1LSP) – CA – 45) & (0.8C1 +0.2BFS) – (0.8FA +0.2LSP) – CA - 45) with controlled formulation (0.8C1 +0.2BFS) - FA– CA – 45), tendency of increase in compressive strength both at early & later ages is seen. However, this increase in compressive strength is more for formulation having 10 % LSP contents than 20%. Integration of nucleation sites by LSP (9.5µm) is much more than fine aggregates (0 - 2mm) which have facilitated (N+G) in the matrix. Moreover (97.64%) contents of CaO in LSP increase cement hydration and hence compressive strength. Decrease in air contents also contribute to compressive strength. 10% contents of LSP give optimum packing; beyond which space for hydration products reduces consequently compressive strength is reduced. So replacement of fine aggregates with LSP (10% contents) is contributing towards compressive strength both at initial (15%) and later ages (20%). While increasing LSP contents to 20%, effect on compressive strength is relatively less.

Table 5.5: Trends of Compressive Strength - (0.8C1 + 0.2BFS) - FA– CA – 45), (0.8C1 + 0.2BFS) – (0.9FA + 0.1LSP) – CA – 45) & (0.8C1 + 0.2BFS) – (0.8FA + 0.2LSP) - CA – 45)

Formulations	**Age (Days)**	
	3	**28**
(0.8C1 +0.2BFS) - FA– CA – 45 --- (4)	12.85	42.50
(0.8C1 +0.2BFS) – (0.9FA +0.1LSP)– CA – 45 --- (5)	14.85	47.45
(0.8C1 +0.2BFS) – (0.8FA +0.2LSP)- CA – 45 --- (7)	14.35	48.35
%age variation in strength (4 & 5)	**+ 15.6%**	**+ 11.6%**
%age variation in strength (4 & 7)	**+ 11.67%**	**+ 13.76%**

Comparing (0.8C1 + 0.2BFS) – (0.9FA + 0.1QD) – CA – 45 & (0.8C1 +0.2 BFS) – (0.8FA + 0.2 QD) – CA - 45) with (0.8C1 + 0.2BFS) - FA– CA – 45), trends are almost similar to LSP formulations. The trend has been tabulated in Table 5.6. QD particle (8.25 (µm), far smaller than fine aggregates incorporate additional nucleation sites where hydration products grow thus generate (N+G) effect. 10% contents of QD gave optimum packing beyond which space for hydration products reduced subsequently compressive strength at 20% contents of QD is dropped. So replacement of fine aggregates with QD (10% contents) is contributing towards compressive strength both at initial (23.35%) and later ages (15.73%) like LSP.

Table 5.6: Trends of Compressive Strength - (0.8C1 + 0.2BFS) - FA– CA – 45), (0.8C1 + 0.2BFS) – (0.9FA + 0.1QD) – CA – 45) & (0.8C1 + 0.2BFS) – (0.8FA + 0.2QD) - CA – 45)

Formulations	**Age (Days)**	
	3	**28**
(0.8C1 +0.2BFS) - FA– CA – 45 --- (4)	12.85	42.50
(0.8C1 +0.2BFS) – (0.9FA +0.1QD)– CA – 45 --- (6)	15.85	49.75
(0.8C1 +0.2BFS) – (0.8FA +0.2QD)- CA – 45 --- (8)	15.15	48.4
%age variation in strength (4 & 6)	**+ 23.35%**	**+ 17.06%**
%age variation in strength (4 & 8)	**+ 15.49%**	**+ 12.43%**

Amongst the comparison of (0.8C1 + 0.2BFS) – (0.9FA + 0.1LSP) – CA – 45) & (0.8C1 + 0.2BFS) – (0.9FA + 0.1QD) - CA – 45) formulations, former have less compressive strength.

Table 5.7: Statistical Analysis of Compressive Strength – SCC Formulations containing various contents of GGBF Slag, LSP & QD

Formulations	**Age (Days)**	
	3	**28**
(0.8C1 +0.2BFS) – (0.9FA +0.1LSP)– CA – 45 ---(5)	14.85	47.45
(0.8C1 +0.2BFS) – (0.8FA +0.2LSP)- CA – 45 --- (7)	14.35	48.35
(0.8C1 +0.2BFS) – (0.9FA +0.1QD)- CA –45 ---(6)	15.85	49.75
(0.8C1 +0.2BFS) – (0.8FA + 0.2QD)– CA-45 ---(8)	15.15	48.4
%age variation in strength (5 & 7)	**- 3.37%**	**+ 1.90%**
%age variation in strength (5 & 6)	**+ 6.73%**	**+ 4.85%**
%age variation in strength (5 & 8)	**- 4.42%**	**- 2.71%**
%age variation in strength (6 & 8)	**- 4.42%**	**- 2.71%**

(6.73%) at initial days while more (3.38%) at later age. This may be due to presence of SiO_2 contents in QD which has accelerated initial strength. Similar trend was observed in (0.8C1 +0.2BFS) – (0.8FA +0.2LSP) – CA – 45) & (0.8C1 + 0.2BFS) – (0.8FA + 0.2QD) - CA –45) but with lesser values probably due to the reason discussed above.

Replacement of fine aggregates with micro sized LSP & QD has resulted into increase in compressive strength both at initial and later ages. This increase can be linked with integration of nucleation sites by micro sized LSP & QD. Moreover their composition with CaO & SiO_2 has contributed towards CSH gel which is very much desirable .Increasing the contents beyond 10% do not optimize the results. Therefore, selection of contents of SRMs must be given due weight age in order to optimize compressive strength.

5.3.5 Flexural Strength - SCC Mixes

At early ages flexural strength of GGBF Slag formulations is less than (C1 – FA – CA - 45). This can be related with delayed activation of GGBF Slag along with dilution of cement. Later on, a recovery trend can be seen and at 28 days, it becomes comparable with (C1 – FA – CA - 45). At later ages, it is even more than (C1 – FA – CA - 45). This increase in flexural strength can be associated with pozzolanic activity of GGBF Slag. In case of ratio of compressive to flexural strength, at early ages, it is around 10±. At 7 days, increase in flexural strength is more so, ratio tends to decrease and ratio is slightly above 9.5. At later ages, the same trend continues and ratio further drops as shown in Table 4 of Annexure B.

In (C1 – FA – CA -45) formulation, partial replacement of cement with GGBF Slag (20%) lessens significantly, flexural strength (35.29%) & (30.43%) at age of 3 & 7 days respectively.

At 14 days drop is still substantial. This can be related with delayed activation of GGBF Slag. Beyond 28 days, a recovery trend due to pozzolanic activity of GGBF Slag can be observed where flexural strength is increasing than (C1 – FA – CA - 45) formulation (2.18 % at 56). Ratio of compressive to flexural strength ranges 9-9.5 as shown in Table 4 of Annexure B. So replacement of cement with GGBF Slag is economical as well as contributing towards flexural strength at later ages.

(0.8C1 + 0.2BFS) - FA– CA – 45), (0.8C1 + 0.2BFS) – (0.9FA + 0.1LSP) – CA – 45) & (0.8C1 + 0.2BFS) – (0.8FA + 0.2LSP) – CA - 45). In (0.8C1 + 0.2BFS) - FA– CA – 45) formulation, partial replacement of fine aggregates with 10 & 20% LSP has been carried out and its effect on flexural strength has been observed**.** A trend of rise in flexural strength for both the contents of LSP can be seen at all ages. However, this escalation is more for at 10 % LSP contents than 20%.

5.4 GGBF Slag Activation by Alkali in SCC Mix

Use of GGBF Slag in SCC mixes increases dormant period and formwork removal time. Thus making this cheap and readily available SRM in developing countries like Pakistan, uneconomical due to increase expenditures of formwork.

5.4.1 Effect of GGBF Slag Activation on Formwork Removal Time

This experiment was done with an intention to find the solution of delayed activation of GGBF Slag faced during experimental stage. Previous literatures were thoroughly consulted [14,41] and an effort was made to improve pH Value of the solution SCC mix by seeding with $Ca(OH)_2$ at (5,10,20) % in (0.8C1 +0.2BFS) - FA– CA - 45) SCC formulation. Formwork removal time dropped to 42 hrs on addition of 5% $Ca(OH)_2$ thus decreasing 16% removal time. It further drops to 28 hrs at 10% contents & 15 hrs at 20% contents of $Ca(OH)_2$ as shown in Table 5.10. So, there is a drop in time (46 to 70%) respectively. It probably due to OH^- ions provided by $Ca(OH)_2$ to increase pH value up to desired level in order to activate GGBF Slag in early time frame. Reduction of formwork removal time to 70% is a saving of millions of dollars in multinational projects.

5.4.2 Effect of Slag Activation on Compressive Strength

Delayed activation and low pozzolanic activity at initial age may be attributed to average particle size (D-50) of GGBF Slag which was around 15µm instead of 5-7 µm. Effect of $Ca(OH)_2$ on early age in (0.8C1 + 0.2BFS) + 0.2CH - FA– CA - 45) formulation is encouraging at the cost of later age strength. In initial 3 days, compressive strength is increased by 62% which is remarkable and this effect is nearly over at 28 days, and at 56 days, compressive strength is lesser than ((0.8C1 +0.2BFS) - FA– CA – 45) Formulation by 5.5%. Based on study of previous literature [41], initial boost in compressive strength can be explained by proposed hypothesis.

“According to Metastable Barrier Hypothesis, a threshold pH value is desired to overcome the dormant period. In SCC mixes containing GGBF Slag, delayed activation of Slag further increases dormant period and formation of initial skeleton is further delayed. To achieve this threshold pH value, seeding of Ca $(OH)_2$ is used. Ca $(OH)_2$ contributes with Ca^{++}& $(OH)^{-}$ ions in the solution and uplifts pH to the threshold level and offsets the delayed activation of slag and ultimately gives boost to initial age compressive strength”.

5.4.3 Effect of Slag Activation on Hydration Kinetics

In Fig 5.11 represents effect of $Ca(OH)_2$ on hydration kinetics on SCC mix containing GGBF slag in comparison with (C1 – FA – CA -45). (C1 – FA – CA -45) peak is at 13 hrs. In (0.8C1 +0.2BFS) - FA– CA - 45) formulation peak extends to almost 50 hrs. There is almost an increase of 36 hrs required for development of sufficient early strength. In (0.8C1 +0.2BFS) +0.2CH - FA– CA - 45), peak occurs at 16 hrs. This behavior supports above proposed hypothesis that Ca $(OH)_2$ provides $(OH)^{-}$ ions and increase pH value upto desired level which helps in activation of GGBF Slag and provide sufficient early strength in first 24 hrs.

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the research work, following conclusions can be drawn:-

- Micro sized Secondary Raw Materials used in this research (Ground Granulated Blast Furnace Slag, Lime Stone Powder & Quarry Dust) show physical & chemical effects (Nucleation + Growth) in Self Compacting Cementitious Systems by seeding additional surfaces in order to improve their microstructure thus enhance compressive & flexural strength. (Tables No 5 & 6 of Annexure A & Tables No 2 & 3 of Annexure B)
- Chemical composition of Lime Stone Powder and Quarry Dust is also vital in improving strength & flow behavior of Self Compacting Cementitious Systems. High contents of Calcium Oxide positively contributed towards compressive & flexural strengths. (Figures 4.25 & 4.26).
- Use of Ground Granulated Blast Furnace Slag as partial replacement of cement not only improved flow behaviour, retarded setting, reduced water / Super Plasticizer's demand, improved microstructures and enhanced later age strength 17% in Self Consolidating Paste systems and 23% in Self-Consolidating Concrete formulations but also proved environment friendly (Figure 4.12, 4.13, 4.25 & 4.26).
- In Self Consolidating Concrete formulations, relatively large average particle size (15µm) of Ground Granulated Blast Furnace Slag, resulted into delayed activation and low initial pozzolanic activity which extended dormant period to 49 hours thus increases of formwork cost. Slag activation by alkali $Ca(OH)_2$, proved effective in this aspect. At 20% contents of $Ca(OH)_2$, dormant period was reduced by more than 300% thus making it economical for Self Consolidating Concrete. (Figure 4.29)
- Partial replacement of fine aggregates with Lime Stone Powder & Quarry Dust has been proved brilliant. It improved passing ability & flow ability, reduced air contents (Table 1 of Annexure B), improved microstructure & durability thus enhanced compressive strength upto 23% initially & upto 20% during later ages which is quite significant. Similar trends are seen for flexural strength. (Figures 4.25 & 4.26).
- Lime Stone Powder being rough, highly abrasive, irregular surface texture, flaky & angular with patches effected flow properties, increased Super Plasticizer's demand maximum upto 7%, attempted to balance out retarding effect of Ground Granulated Blast Furnace Slag improved microstructure by (Nucleation + Growth) and increased strength and alter hydration kinetics.

Research supplements previous work on these secondary raw materials by concluding that their shape, size along with surface morphology / texture and chemical composition has noteworthy effect on Water and SP demand, flow comportment, refinement of microstructure, development of strength and durability. The new idea of partial replacement of fine aggregates with Lime Stone Powder and Quarry Dust proved effective due to its contribution both in fresh and hardened state of Self-Consolidating Concrete.

6.2 Recommendations

- Partial replacement of fine aggregates with LSP & QD for pure cement formulation i.e. (C1 – FA – CA – 45) be carried out to compare the results with SSC formulations of current research.
- Response of SCC formulations under study be investigated while increasing GGBF Slag contents (as partial replacement of cement) from 20 to 30 & 40 % in order to relate the results with current data of SCC formulations.
- Under study SCC formulations should be investigated while replacing GGBF Slag with Fly Ash & Baggasse Ash or LSP.
- Due to paucity of time, use of $Ca(OH)_2$ as slag activator was limited to ((0.8C1 + 0.2BFS) - FA– CA - 45) SCC formulations only. Effect of $Ca(OH)_2$ on other formulations of current research be also examined.
- Standard milling facility be provided at structural lab (NICE) for superior research work.
- Powder of GGBF Slag be obtained by thermal shock by immersing molten slag into chilled water / liquid nitrogen for research work.

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ANNEXURE – A

SCP FORMULATIONS

Table 1: WD, Setting Times & Flow Properties of SCP (CS Formulations)

Formulations	WD (%)	SP (%)	IST (Min)	FST (Min)	Time 25 (Sec)	Time 30 (Sec)	Spread (cm)
C1 – 0-WD	26.5	0.171	175	225	2.18	15.09	30.5
0.95C1 +.05BFS – WD	26	0.164	190	230	2.14	16.46	29.85
0.9C1 +0.1BFS – WD	25.5	0.161	235	275	2.10	17.2	29.70
0.85C1 +0.15BFS – WD	25	0.129	240	278	1.98	17.7	29.25
0.8C1 +0.2 BFS– WD	24	0.121	250	285	1.90	18.3	29.15

Table 2: WD, Setting Times & Flow Properties of SCP Formulations having Blends of Powders

Formulations	WD (%)	SP (%)	IST (Min)	FST (Min)	Time 25 (Sec)	Time 30 (Sec)	Spread (cm)
C1 – 0-WD	26.5	0.171	175	225	2.18	15.09	30.5
0.9C1 +0.1BFS – WD	25.5	0.156	235	275	2.10	17.22	29.70
0.8C1 +0.1BFS+ 0.1LSP - WD	26	0.160	215	255	2.65	16.85	30.25
0.7C1 +0.1BFS+0.2LSP- WD	25.75	0.163	210	240	2.78	16.69	30.6
0.8C1 +0.1BFS+0.1QD - WD	25.75	0.171	205	253	2.56	15.98	30.85
0.7C1 +0.1BFS+0.2QD - WD	25.50	0.184	190	228	2.70	15.75	31

Table 3: Compressive Strengths of CS Formulations in SCP Systems

Formulations	Age (Days)					
	1	3	7	14	28	56
C1 – 0-WD	37.06	46.83	56.72	66.65	74.56	78.13
0.95C1 +.05BFS – WD	31.47	46.07	56.23	69.83	80.50	86.15
0.9C1 +0.1BFS – WD	28.70	40.70	55.60	71.70	82.15	88.19
0.85C1 +0.15BFS – WD	25.29	41.90	55.03	67.70	80.33	89.55
0.8C1 +0.2 BFS– WD	20.08	25.13	31.25	60.75	82.30	90.23

Table 4: Compressive Strengths (MPa) of SCP Formulations having Blends of Powders

Formulations	Age (Days)				
	1	3	7	14	28
C1 – 0-WD	37.06	46.83	56.72	66.65	74.56
0.9C1 +0.1BFS – WD	28.70	40.70	55.60	71.70	82.15
0.8C1 +0.1BFS+ 0.1LSP – WD	30.33	36.10	52.19	64.69	76.27
0.7C1 +0.1BFS+0.2LSP- WD	28.95	34.84	49.93	67.28	75.32
0.8C1 +0.1BFS+0.1QD – WD	32.30	37.50	52.78	65.63	76.86
0.7C1 +0.1BFS+0.2QD – WD	29.03	35.55	51.48	67.99	75.47

Table 5: Flexural Strengths (MPa) of CS Formulations in SCP Systems

Formulations	Age (Days)					
	1	3	7	14	28	56
C1 – 0-WD	6.94	10.92	11.99	13.03	14.01	14.53
0.95C1 +.05BFS – WD	6.43	10.20	11.82	13.70	15.16	16.24
0.9C1 +0.1BFS – WD	6.10	9.73	11.50	13.87	15.44	16.62
0.85C1 +0.15BFS – WD	5.45	9.45	12.38	13.67	15.05	16.76
0.8C1 +0.2 BFS– WD	5.05	7.01	8.48	12.80	15.65	17.03

Table 6: Flexural Strengths (MPa) of SCP Formulations having Blends of Powders

Formulations	Age (Days)				
	1	3	7	14	28
C1 – 0-WD	6.94	10.92	11.99	13.03	14.01
0.9C1 +0.1BFS – WD	6.10	9.73	11.50	13.87	15.44
0.8C1 +0.1BFS+ 0.1LSP – WD	5.60	8.56	11.15	12.66	14.06
0.7C1 +0.1BFS+0.2LSP- WD	5.33	8.36	10.89	12.43	14.17
0.8C1 +0.1BFS+0.1QD – WD	5.62	8.71	11.62	12.87	14.65
0.7C1 +0.1BFS+0.2QD – WD	5.39	8.43	11.36	12.64	14.36

ANNEXURE – B

SCC FORMULATIONS

Table 1: Flow Properties of SCC Formulations

Formulations	SP Contents (%)	Slump Flow			V Funnel Time (sec)	L Box				J Ring		Air Contents (%)
		T-50 (sec)	T max (sec)	Spread (cm)		T-200 (sec)	T-400 (sec)	T-600 (sec)	Blocking Ratio	T-50 cm (sec)	Spread (cm)	
C1 – FA–CA -45	1.49	5.35	25.73	68	6.25	3.15	5.45	6.02	0.89	7.15	67	3
(0.8C1 +0.2BFS)-FA– CA – 45	1.21	4.20	22.56	69.5	3.18	2.55	3.37	4.88	0.96	5.08	69	2.7
(0.8C1 +0.2BFS)–(0.9FA+0.1LSP)– CA-45	1.40	4.63	23.15	68.5	3.45	2.69	3.45	5.09	0.93	5.23	67.5	2.5
(0.8C1 +0.2BFS)–(0.8FA+0.2LSP)- CA–45	1.87	4.98	23.60	68	4.43	2.79	3.62	5.26	0.91	6.02	65	2.2
(0.8C1 +0.2BFS)–(0.9FA+0.1QD)- CA-45	1.85	4.53	22.85	68.75	3.28	2.52	3.15	4.99	0.94	5.1	67.5	2.3
(0.8C1 +0.2BFS)–(0.8FA+0.2QD)– CA-45	2.28	4.90	23.10	68	4.23	2.72	3.26	4.94	0.90	5.69	65.75	1.9
C1– (0.9FA+0.1LSP)– CA-45	1.62	5.49	26.35	67.75	7.09	3.25	5.61	6.21	0.88	7.24	66.25	-
C1– (0.9FA+0.1QD)– CA-45	1.93	5.40	25.85	68.5	6.58	3.01	5.29	6.17	0.92	7.18	67.5	-

Table 2: Compressive Strength (MPa) of SCC Formulations

Formulations	Age (Days)			
	3	7	14	28
C1 – FA–CA -45	20.23	31.05	41.95	43.50
(0.8C1 +0.2BFS)-FA– CA - 45	12.85	21.60	32.60	42.50
(0.8C1 +0.2BFS)–(0.9FA+0.1LSP)– CA - 45	14.85	26.80	35.30	47.45
(0.8C1 +0.2BFS)–(0.8FA+0.2LSP)- CA– 45	14.35	24.07	36.95	48.35
(0.8C1 +0.2BFS)– (0.9FA+0.1QD)- CA –45	15.85	24.00	39.10	49.75
(0.8C1 +0.2BFS)– (0.8FA+0.2QD)– CA-45	15.15	24.73	37.20	48.40
C1– (0.9FA+0.1LSP)– CA-45	22.70	33.18	44.08	48.12
C1– (0.9FA+0.1QD)– CA-45	23.15	33.51	44.28	50.13

Table 3: Flexural Strengths (MPa) of SCC Formulations

Formulations	Age (Days)			
	3	7	14	28
C1 – FA–CA -45	2.02	3.22	4.61	5.32
(0.8C1 +0.2BFS)-FA– CA - 45	1.31	2.24	3.59	5.19
(0.8C1 +0.2BFS)–(0.9FA+0.1LSP)– CA - 45	1.52	2.78	3.88	5.79
(0.8C1 +0.2BFS)–(0.8FA+0.2LSP)- CA– 45	1.42	2.52	4.06	5.93
(0.8C1 +0.2BFS)– (0.9FA+0.1QD)- CA –45	1.60	2.49	4.30	6.08
(0.8C1 +0.2BFS)– (0.8FA+0.2QD)– CA-45	1.54	2.56	4.09	5.93

Table 4: Comparison of Compressive & Flexural Strengths of SCC Formulations

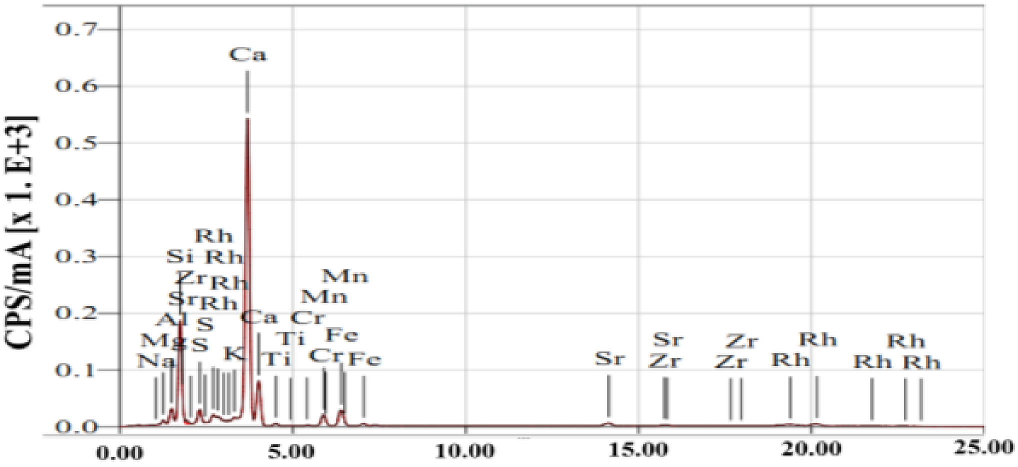
Formulations	Age (Days)								
	3			7			28		
	Flex	Comp	Ratio	Flex	Comp	Ratio	Flex	Comp	Ratio
C1 – FA – CA -45	2.02	20.23	10.00	3.22	31.05	9.64	5.32	43.5	8.18
(0.8C1 +0.2BFS) - FA– CA - 45	1.31	12.85	9.82	2.24	21.60	9.58	5.19	42.5	8.14
(0.8C1 +0.2BFS) – (0.9FA +0.1LSP)– CA - 45	1.52	14.85	9.78	2.78	26.80	9.73	5.79	47.45	8.20
(0.8C1 +0.2BFS) – (0.8FA +0.2LSP) - CA – 45	1.42	14.35	10.11	2.52	24.07	9.50	5.93	48.35	8.15
(0.8C1 +0.2BFS) – (0.9FA +0.1QD) - CA –45	1.60	15.85	9.94	2.49	24.00	9.60	6.08	49.75	8.10
(0.8C1 +0.2BFS) – (0.8FA + 0.2QD)– CA-45	1.54	15.15	9.84	2.56	24.73	9.55	5.93	48.4	8.16

Table 5: Effect of Ca $(OH)_2$ on Compressive Strength (MPa) of (0.8C1 +0.2BFS) - FA– CA – 45) Formulation

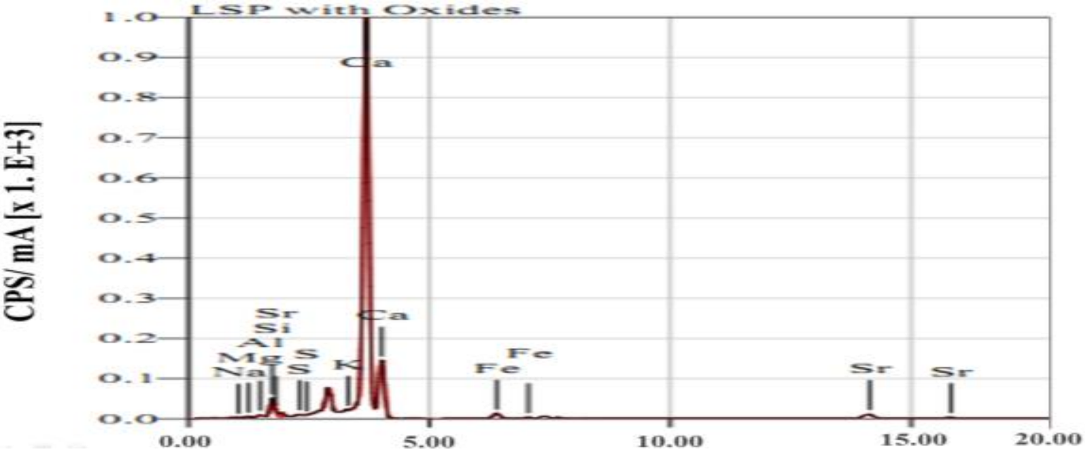
Formulations	Age (Days)				
	3	7	14	28	56
C1 – FA–CA -45	20.23	31.05	41.95	43.5	45.8
(0.8C1 +0.2BFS)-FA– CA - 45	12.85	21.6	32.6	42.5	46.8
(0.8C1 +0.2BFS)+0.2CH-FA– CA - 45	20.81	25.85	38.5	43.95	44.3

ANNEXURE – C
XRF ANALYSIS

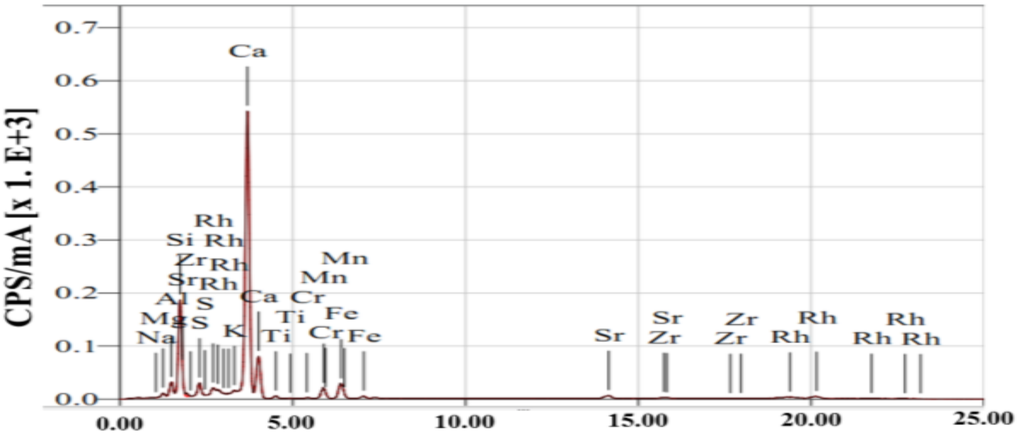
GGBF SLAG ELEMENTAL ANALYSIS WITH OXIDES



LSP ELEMENTAL ANALYSIS WITH OXIDES

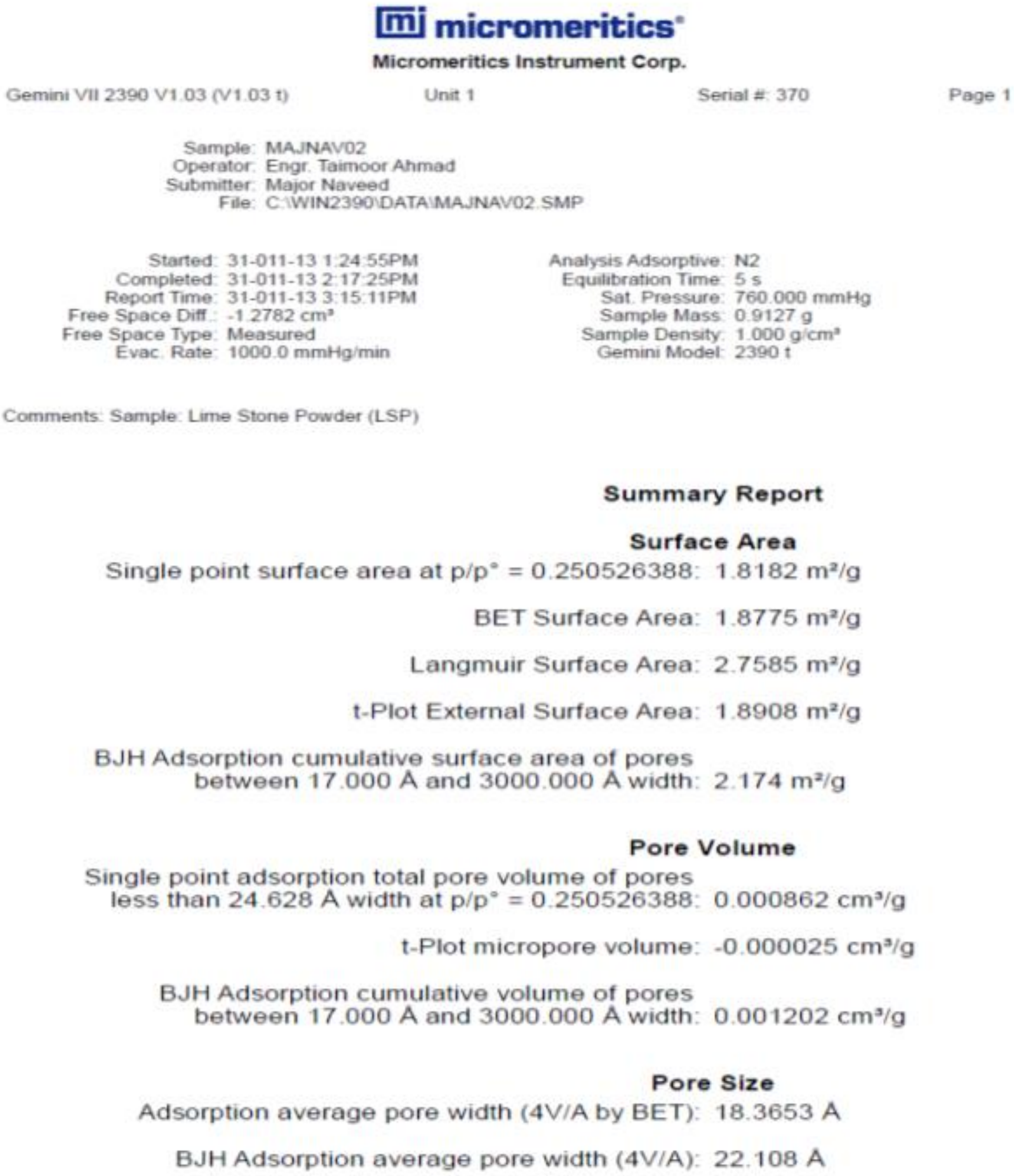


QD ELEMENTAL ANALYSIS WITH OXIDES



ANNEXURE – D
SURFACE AREA ANALYSIS (SAA)

SURFACE AREAS OF LSP BY MICROMETRICS ANALYSIS AT SCME, NUST



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Micromeritics Instrument Corp.

Gemini VII 2390 V1.03 (V1.03 t)   Unit 1   Serial #: 370   Page 1

Sample: MAJNAV02
Operator: Engr. Taimoor Ahmad
Submitter: Major Naveed
File: C:\WIN2390\DATA\MAJNAV02.SMP

Started: 31-011-13 1:24:55PM
Completed: 31-011-13 2:17:25PM
Report Time: 31-011-13 3:15:11PM
Free Space Diff.: -1.2782 cm^3
Free Space Type: Measured
Evac. Rate: 1000.0 mmHg/min

Analysis Adsorptive: N2
Equilibration Time: 5 s
Sat. Pressure: 760.000 mmHg
Sample Mass: 0.9127 g
Sample Density: 1.000 g/cm^3
Gemini Model: 2390 t

Comments: Sample: Lime Stone Powder (LSP)

Summary Report

Surface Area

Single point surface area at p/p° = 0.250526388: 1.8182 m^2/g

BET Surface Area: 1.8775 m^2/g

Langmuir Surface Area: 2.7585 m^2/g

t-Plot External Surface Area: 1.8908 m^2/g

BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å width: 2.174 m^2/g

Pore Volume

Single point adsorption total pore volume of pores less than 24.628 Å width at p/p° = 0.250526388: 0.000862 cm^3/g

t-Plot micropore volume: -0.000025 cm^3/g

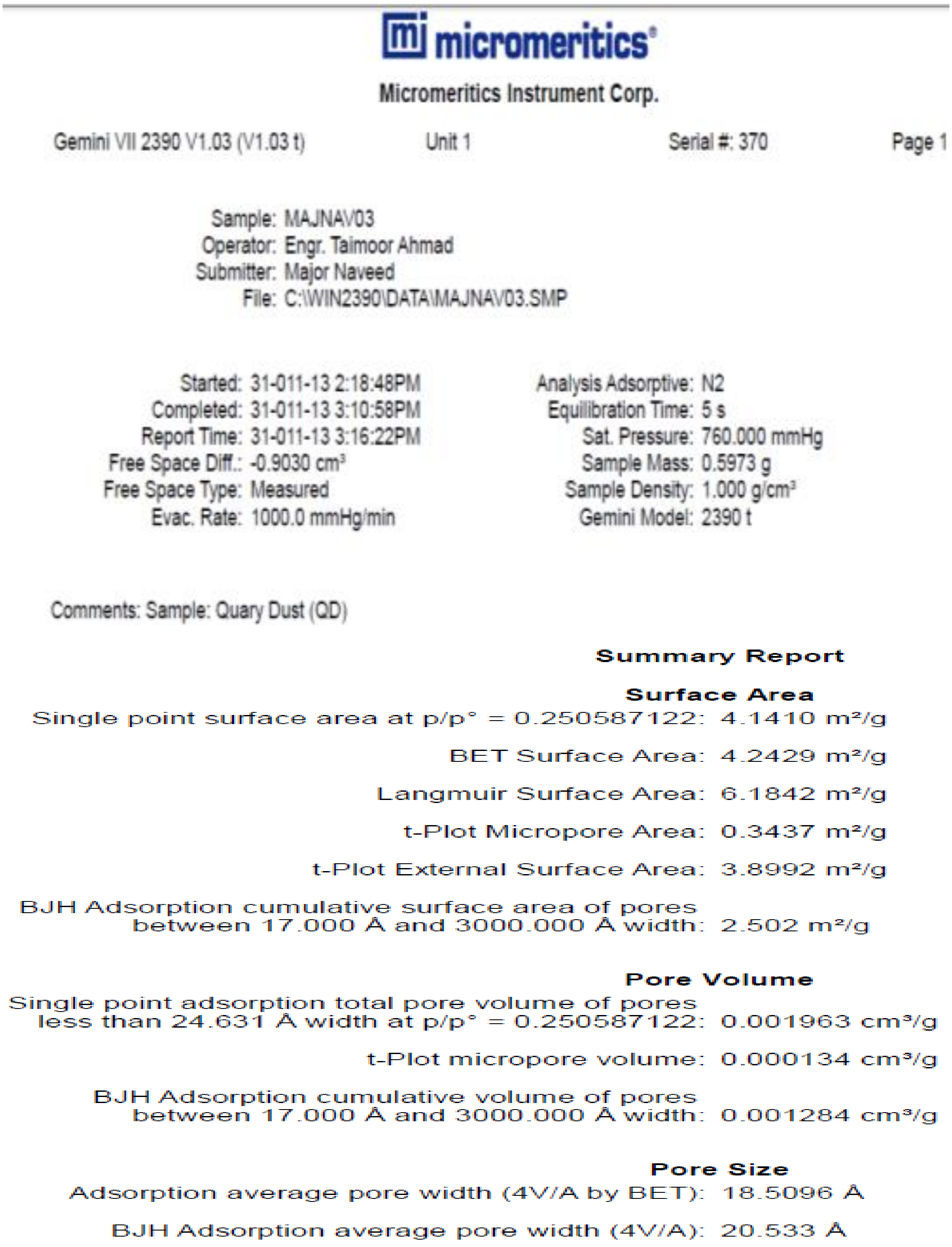
BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å width: 0.001202 cm^3/g

Pore Size

Adsorption average pore width (4V/A by BET): 18.3653 Å

BJH Adsorption average pore width (4V/A): 22.108 Å

SURFACE AREAS OF QD BY MICROMETRICS ANALYSIS AT SCME, NUST



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Micromeritics Instrument Corp.

Gemini VII 2390 V1.03 (V1.03 t) Unit 1 Serial #: 370 Page 1

Sample: MAJNAV03
Operator: Engr. Taimoor Ahmad
Submitter: Major Naveed
File: C:\WIN2390\DATA\MAJNAV03.SMP

Started: 31-011-13 2:18:48PM
Completed: 31-011-13 3:10:58PM
Report Time: 31-011-13 3:16:22PM
Free Space Diff.: -0.9030 cm^3
Free Space Type: Measured
Evac. Rate: 1000.0 mmHg/min

Analysis Adsorptive: N2
Equilibration Time: 5 s
Sat. Pressure: 760.000 mmHg
Sample Mass: 0.5973 g
Sample Density: 1.000 g/cm^3
Gemini Model: 2390 t

Comments: Sample: Quary Dust (QD)

Summary Report

Surface Area

Single point surface area at p/p° = 0.250587122: 4.1410 m^2/g

BET Surface Area: 4.2429 m^2/g

Langmuir Surface Area: 6.1842 m^2/g

t-Plot Micropore Area: 0.3437 m^2/g

t-Plot External Surface Area: 3.8992 m^2/g

BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å width: 2.502 m^2/g

Pore Volume

Single point adsorption total pore volume of pores less than 24.631 Å width at p/p° = 0.250587122: 0.001963 cm^3/g

t-Plot micropore volume: 0.000134 cm^3/g

BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å width: 0.001284 cm^3/g

Pore Size

Adsorption average pore width (4V/A by BET): 18.5096 Å

BJH Adsorption average pore width (4V/A): 20.533 Å