COMPARATIVE STUDY OF SELF COMPACTING CONCRETE (SCC) USING RIVER GRAVEL AND CRUSHED STONE AGGREGATES WITH SIMULTANEOUS CEMENT REPLACEMENT BY SRMs

By

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This is to certify that

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Has been accepted towards the partial fulfillment

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ABSTRACT

Self-Compacting Concrete (SCC) has revolutionized construction industry and is being used extensively throughout the world. This study was made to compare the role of river gravel and crushed stone aggregates in Self-compacting concrete (SCC) systems while simultaneously evaluating the feasibility of using local Marble Powder (MP) and Limestone Quarry Dust (LSQD) systems as partial replacement of cement in self-compacting paste and self-compacting concrete (SCC) with a view to manufacture SCC in Pakistan. Limestone Quarry Dust (LSQD) and Marble Powder (MP) were used as secondary raw materials (SRMs) up to 30% replacement of cement in both SCP and SCC systems. The grading and content of both types of coarse aggregates was kept constant. The results indicate that the river gravel and crushed stone aggregates along with secondary raw materials used in this research affect the properties of self-compacting cementitious system (SCCS) in both fresh and hardened state. It was observed that these coarse aggregates and SRMs affect the water demand, super plasticizer demand, flow and strength behaviour of SCCS. At higher replacement levels (more than 10%), SCP systems based on Limestone Quarry Dust (LSQD) had higher water demand as compared to marble powder (MP) based systems and also higher superplasticizer demand for the target flow. In self-compacting concrete formulations, river gravels gave better flowabiltiy indices than crushed stone aggregates while crushed stone aggregates gave better strength results for the tested similar formulations. ***At 10% replacement of cement by LSQD and MP, the optimum results both in terms of flowability and strength were obtained in all the investigated self-compacting cementitious systems***. MP based formulations gave better strengths as compared to LSQD based ones at the same replacement level in Self compacting paste and concrete systems. Self-compacting concrete samples were cast, cured and tested as per EN 196 (4x4x16 cm^3 prisms) and BS EN 12390-1 (4”x4”x4” cubes) with both standards giving comparable results. It is suggested that SCCS samples based on EN 196 should be used for economy and efficiency. After the analysis of results, it can also be stated that river gravel, crushed stone aggregates and both secondary raw materials can be successfully used in making self-compacting concrete systems in Pakistan and pumping may also be used for placements by slight readjustment of SCC formulations.

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ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
C_2S	Di – Calcium Silicate
C_3A	Tri – Calcium Aluminate
C_3S	Tri – Calcium Silicate
C_4AF	Tetra – Calcium Alumino Ferrite
CH	Calcium Hydroxide
CSH	Calcium Silicate Hydrate
HPC	High Performance Concrete
ITZ	Interfacial Transition Zone
MIP	Mercury Intrusion Porosimetry
OPC	Ordinary Portland cement
PCE	Polycarboxylate ether
SCCS	Self-Compacting Cementitious Systems
HP SCCS	High Performance Self Compacting Concrete Systems
HP SCMS	High Performance Self Compacting Mortar Systems
HP SCPS	High Performance Self Compacting Paste Systems
SP	Superplasticizer
SRMs	Secondary Raw Materials
SCMs	Supplementary Cementitious Materials
LSQD	Limestone Quarry Dust

MP	Marble Powder
VMA	Viscosity Modifying Agent
W/C	Water Cement Ratio
W/P	Water Powder Ratio
XRD	X – Ray Diffraction
ESEM	Environmental Scanning Electronic Microscope
WD	Water Demand
SPD	Superplasticizer Demand
IST	Initial Setting Times
FST	Final Setting Times
SSD	Saturated Surface Dry
CS	Crushed Stone
RG	River Gravel

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 General

In early 1980’s, Engineers in Japan were of the opinion that conventional vibrated concrete (CVC) possesses differential compaction and hence differential durability due to the shortage of skilled mechanical vibrator technicians. As durable concrete structures need adequate compaction to remove entrapped air to make concrete dense and homogeneous, it was also the idea that the quality of compaction by mechanical vibration depends on skill of operator, hence the structure possess differential compaction resulting in differential durability. These two factors motivated the invention of self-compacting concrete. It has now gained global acceptance in developed countries particularly due to its inherent distinct advantages and properties over conventional concrete systems. However its use in Pakistan, it is still in inception stage due to lack of research, market support and awareness by engineers and technicians.

1.2 Historical Development of SCC

After 2nd world war, huge construction took place which started showing cracking, spalling and sagging. Therefore, durability of concrete became the main concern in early 1980s. Trained workers are required for sufficient compaction to make durable concrete structures, which were on decline at that time because of strikes for pay raise, manual labour in terms of placing and compacting concrete. Poorly compacted areas in concrete contain voids, so construction industry in Japan was on decline in terms of the quality of construction work. In 1986, Professor Hajime Okamura of the university of Tokyo proposed the use of self-compacting concrete (a concrete that is able to flow under its own weight into every corner of a formwork, while maintaining homogeneity even in the presence of congested reinforcement, and then consolidating without the need for vibrating compaction) as an alternate to the conventional concrete.

Ozawa and Maekawa conducted research at the University of Tokyo to produce self-compacting concrete, encompassing workability of concrete as a major parameter and using already existing materials in market, first model of powder type self-compacting concrete was produced by 1988 in Japan [1]. It performed satisfactorily with regard to drying and hardening shrinkage, heat of hydration, denseness after hardening and other properties and was named “High Performance Concrete.”

Since then, SCC has gone from being a laboratory innovation to practical applications worldwide. The yearly growth in the publishing of numbers of articles covering every features of SCC, for example, from mix design, rheological and physical properties to practical applications, indicates that research is flourishing on this technology.

The ACI 237 describes SCC as “**Highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation**” [2].

There are three basic types of self-compacting concrete systems known encompassing powder type, viscosity modifying agent type and combination type. These types basically differ from each other mainly in the way the segregation resistance is achieved. In powder type self-compacting cementitious system, a lower w/p ratio or higher powder content (cement as well as secondary raw materials) guarantees adequate segregation resistance while the same goal is achieved by viscosity enhancement agent in the viscosity agent type self-compacting cementitious system. The combination type SCC contains high powder content and VMA together. This allows production of a robust self-compacting cementitious system and is believed to have excellent segregation resistance [3]. However, these systems must meet the other special performance requirement i.e. high deformation (flow) in addition to high segregation resistance. This implies that the concrete produced should have low yield stress as well as adequate paste viscosity. Both of these are conflicting necessities to achieve. By means of efficient super plasticizer usage, high deformation is acquired, while segregation resistance is achieved by using any of the earlier mentioned approaches. In this research, the self-compacting paste (SCP) and self-compacting concrete (SCC) systems consists of higher powder content together with super plasticizer. The powders used are cement (Ordinary Portland Cement – ASTM type-I) and secondary raw materials comprising Marble Powder (MP) and Limestone Quarry Dust (LSQD).

The importance of different aspects of self-compacting concrete have been discussed by numerous researchers and have given recommendations to further enhance its performance. There have been many studies conducted out to characterize SCC. These studies were carried out to establish base parameters to accomplish and conform to SCC definition and its structural requirements. The ease presented by SCC qualifies it to be called as high performance concrete (HPC) due to its high flow ability levels in fresh state. The three main properties required for successful SCC mix in fresh state are discussed below [4].

a. **Filling ability** - the concrete fills the formwork easily under its own weight
b. **Passing ability** - the concrete flows through tight spaces, such as congested reinforcement bars, without clogging
c. **Stability** - the concrete does not segregate and remains cohesive.

1.3 Applications of SCC

Since the materializing of first model of SCC in 1988, its use in real structures has slowly increased. The major grounds for the utilization of self-compacting concrete are listed below:

- Tunnels, Pre-stressed concrete making, Transportation systems, Bridge piers, Rafts and High rise buildings.
- Construction of concrete poured on site in confined zones and congested reinforcement, like drilled shafts, columns and earth retaining systems, can be done rapidly by employing SCC.
- This technology can save time, cost, improve quality and durability.
- It eliminates noise resulting from vibrations – notably useful at concrete casting plants.

1.4 Advantages of Self-Compacting Concrete

The advantages of SCC are discussed as follows:

- Enhanced capability of concrete to move into tight spaces and between congested reinforcement without any labour/ vibration.
- Guarantees uniform compaction in the structure- notably in tight spots where compaction from vibrators is tough.
- Reduces construction costs resulting from reduced labour costs and reduced equipment usage.
- Increases construction speed many folds.
- Improves working conditions at site.

- Improves durability and strength of hardened concrete.
- Reduces noise caused by mechanical vibrations.
- Improves surface finish and decreases requirement to patch-up inadequacies in construction like bug holes and honeycombing.

1.5 Research Focus and Objectives

Aggregates are most commonly known to be inert material spread in concrete and are classified as coarse and fine aggregates. Aggregate is cheaper than cement, but their properties have a great influence on the strength, durability, workability, and economy of concrete systems. These various features of aggregates offer the designers and contractors the ease of placement and durability. In this study, river gravels and crushed stone aggregates were used to check their comparative role on different properties of self-compacting concrete.

The paste phase comprises powders (cement, secondary raw materials) and water, thereby, playing a significant role in the overall response of SCCS. The paste phase is the vehicle for transport of aggregate phase and ensures the durable performance of structure life, if selected carefully. Research work on the use of secondary raw materials for SCCS in the world has gained popularity. However in Pakistan, the research work on the subject is still in elementary stages and has led to limited usage of SCCS. The study of paste phase is basic requirement for obtaining desirable properties in self-compacting concrete. Given the importance of self-compacting paste (SCP) systems an additional study was also conducted to assess the effects of secondary raw materials (Limestone Quarry Dust and Marble powder) available locally in Pakistan as cement replacements on SCP systems and then leading to the study of self-compacting concrete systems.

The primary objectives of the research were:

1. To study the response variation of SCC (both in fresh and hardened states) with river gravel and crushed stone aggregates of almost similar size.
2. To study the effects of cement replacement by Limestone Quarry Dust and Marble Powder on the properties of SCC made with different local coarse aggregates to make environmental friendly and green concrete.

1.6 Cement Chemistry

ACI defines Portland cement as "a binding material that sets and hardens by chemical reaction with water and is capable of doing so underwater". Chemical reactions of cement after contact with water will determine the setting and hardening properties of concrete. Heat of hydration of cement as well as its rate play key role in determining concrete strength and durability. On coming in contact with water, hydration of cement starts. Hydration of cement is defined as “dissolution – precipitation process between binder grains and water” [5]. It is a process by which cement powder plus water transform from a fluid suspension to a porous solid within hours and strength gains over days and months [6].It is generally believed that two types of reaction take place in hydration process known as through-solution hydration and solid-state hydration. The earlier involves dissolution of anhydrous compounds to their ionic constituents, formation of hydrates in the solution, and eventual precipitation of hydrates whereas the later deals with the hydration that takes place directly at the surface of the anhydrous cement compounds without the compounds going into solution [7].

Ordinary Portland Cement (OPC) constituents of tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF). Along with these, number of other minerals such as Calcium Sulphates, Calcite, Calcium Oxide, and Magnesium Oxide are usually also present. These constituents react with water to form various hydration products such as main hydration product of C-S-H (Calcium Silicate Hydrate), portlandite ($CaOH_2$), ettringite (C-A-S-H, calcium sulfoaluminate hydrate) and calcium monosulphoaluminate (C_4ASH_{12}) [8]. C_3S is responsible for high early strength of hydrated Portland cement and gains most of its strength in 7days. C_2S is responsible for the later developing strength of Portland cement paste and gains little strength until even 28 days but its final strength is the same as that of C_3S. C_3A exhibits the flash set when hydrated, responsible for initial set after addition of gypsum in small amount (5%) and releases large amount of heat upon hydration. It shows little strength increase after 1day. Increase in amount of C_3A results in faster set. C_4AF behaves like C_3A in which it hydrates rapidly and gains low strength but does not exhibit flash set.

As a result of dissolution/precipitation process a growth of hydration products occurs, Ettringite forms at the earliest and is detectable with 8-9 minutes. It’s a needle shape product and is the result of C_3A phase reaction. It is also known as Calcium Sulfoaluminate Hydrate (C-A-S-H). CH and C-S-H gel are the products which are associated with C_3S phase. Calcium Hydroxide (CH) is a well-defined crystal while Calcium Silicate Hydrate (C-S-H) is a poorly crystalline material.

1.7 Secondary Raw Materials

Concrete is extensively used as construction material in the world for building infrastructure, dams, tunnels and pavements etc. The production of OPC is highly energy intensive operation, source of pollution and main cause of depletion of mineral resources. According to United States Geological Survey minerals commodity summaries, in the year 2014, 4.18 billion ton of Portland cement is produced worldwide [9]. Production of Portland cement is highly energy consuming and environment unfriendly process. This process consumes almost 4 G J of energy per ton of cement powder. Plus, it also releases 0.8-1.3 ton of carbon dioxide per ton of cement produced [7]. Rizwan et al [10] states that, " In an energy hungry world, considerable efforts are being made to find substitutes of cement which are called secondary raw materials (SRM's), supplementary cementitious materials or sometimes waste materials in the literature, a term which is seldom used now because of the fact that these materials can be more costly than cement at times". These SRM's are either pozzolanic or inert powders and are usually used as replacement for cement in SCCS thereby reducing the possible consumption of cement. These may act as fillers because all cement particles may not get hydrated in HPC systems. These SRM's may be by product of various industries or available in natural form having inherent pozzolanic properties and requiring very less or no pyroprocessing before use. Great expenditures on production of cement and pressure from working groups on environment are boosting the increasing use of secondary raw materials as cement replacement.

Cordiero et al [11] reports that SRM's influence the physical as well chemical properties of the concrete to increase its strength. Physical effects incorporate the higher packing density of concrete because SRM particles fill the open spaces present between the cement particles. This property depends on the size, shape and texture and morphology of the SRM particles. They produce chemical changes by producing siliceous and aluminous compounds that are produced as a result of chemical reaction with calcium hydroxide in the presence of water. Calcium hydroxide is produced through cement hydration. Rizwan and Bier [12] reported that three significant effects can be observed by adding mineral admixtures to concrete. These effects include dilution, heterogeneous nucleation and pozzolanic reaction. Heterogeneous nucleation is a physical process but it leads to chemical process which involves the chemical activation of cement hydrates. Rizwan and Bier [12] also stated that addition of SRM to concrete increases the demand for water and super-plasticizer to achieve the required flow parameters because SRM particles absorb water molecules through their internal pores.

Tangpagasit et al [13] reported that during initial 28 days, physical effects of SRM’s dominate and they contribute towards the strength development. However, the chemical reactions or pozzolanic activities contribute towards strength development at later stages. Very small size of SRM’s provides concrete with great advantages as their small particles fit in the cement grains and improves the packing density. Hence, it reduces the bleeding and increases the compressive strength. More dense packing at the aggregate/paste interface produces a thinner transition zone with a denser, more consistent microstructure [14]. Cyr et al [15] reported that an optimum amount of Secondary raw materials should be used to achieve the required properties. Using above this optimal value, benefits of using Secondary raw materials start to diminish. Therefore, it is generally recommended to use 10% replacements of cements contents.

Kronnlof et al [16] reported that small size particles were considered to increase the water demand due to enhancement in surface area. Increase in water demand meant harmful effects to concrete. However, mathematical particle packing theories show that secondary raw materials particles fill the empty spaces present between aggregate particles. Those spaces which are left in between fine particles are filled with water molecules and to some extent air also. But to improve workability excess water is needed which can result in strength loss. So here comes the role of plasticizer and super-plasticizer, which is to disperse the cement particles into spaces within their size ranges. In those mixes where super-plasticizer is not used, SRM particles get flocculated and more water is required to enhance workability. But if super-plasticizers are used, they break the flocculation and hence dense packing is achieved.

In lean concrete, mineral powders should be used to fill the aggregate spacing instead of air or water as far as workability is maintained because high packing density and high compressive is the basic requirement of achieving good quality concrete. While using rock powders, water reduction is considerable in super-plasticizer mixes for lean concrete [16].

It must be remembered that SRMs change the fresh and hardened stage properties of SCC due to dilution, physical filler and chemical pozzolanic effects. Therefore only suitable SRM or a combination (based on experimental data and experience) should be used which closely meets the desired properties in both fresh and hardened states.

Numerous investigations about the influence of filler materials on SCC properties is done. These investigations infer that the advantage of using filler material in self-compacting concrete can be said as enhanced workability with less cement content [17, 18]. Thus, low heat of hydration and less shrinkage cracking can also be attained by this way [17, 18]. Furthermore, decreasing cement content is economical as cement is the most costly part of concrete. Moreover, filler material fill the pores between aggregates and hence impervious concrete can be made resulting in increased durability of concrete [19].

Lothenbach et al [20] reported that the secondary cementitious materials presence affects the quantity and type of hydrates formed in cementitious systems and consequently the volume, the porosity and effectively the durability of such systems. When secondary cementitious materials have alumina, then the C–S–H gel will also include a substantial quantity of this element and when the secondary cementitious materials have magnesium, a hydrotalcite-like phase may emerge.

Lothenbach et al [20] further reported that the secondary cementitious materials' influence on reaction kinetics is complex due to the relationship between the clinker phases and the secondary raw materials. At initial ages "filler" effects governs, causing increased, and occasionally also faster, reaction of the clinker phases, owing to more space comparative to the clinker quantity and prolonged nucleation rates.

The reaction of secondary cementitious materaials (counting silica fume) begins after the first day or so, when the pH of the pore solution increases as a result of sulphate usage and alkalis' release by reaction of the clinker phases, yet the lower Ca/Si ratio C–S–H may adsorb alkalis, resulting to a decrease in reaction rate over time. The secondary raw materials' particle size is obviously important since the reaction occurs on the surface, fine materials react quicker. The composition of the glassy materials similarly plays a part. Higher temperatures greatly quickens the speed of reaction of secondary cementitious materials.

1.8 Pozzolans

The term pozzolan is originated from a village Pozzuolli near napples, Italy from where volcanic ash was extracted. In accordance with ASTM C 125 [21], Pozzolan can be described as “A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide (CH) produced by cement hydration at ordinary temperatures to form compounds possessing cementitious properties”. Pozzolans can be subdivided into natural and by-product materials. Natural Pozzolans have been in use for decades. The naturally occurring materials and their processing is generally limited to crushing, grinding and sieving. Fly ash (FA), silica fume (SF), metakaolin, rice husk ash, ground granulated iron blast furnace slag (GGBFS), wheat straw ash etc. are some most frequently used by-products pozzolans nowadays.

1.9 The Pozzolanic Reaction and its Significance

The reaction between a pozzolan and calcium hydroxide is called the pozzolanic reaction. The pozzolans independently has no or very less cementitious properties, however in the presence of an environment rich in lime such as calcium hydroxide, it gives improved cementitious properties to the later day’s strength (that is greater than 28 days) [22]. The reason for this increase in strength is that silicates reacts with lime (CH) to produce secondary cementitious phases. Chemical composition of the pozzolan effects the development of strength, it means that more the proportion of alumina and silica along with the vitreous phase in the material, the better the pozzolanic reaction and strength. The pozzolanic reaction is slower, with come SRMs like Fly Ash, than reactions involving common Portland cement, delaying the release of heat and the increase in strength. Ordinary Portland cement, on hydration, produces calcium silicate hydrate gel, calcium hydroxide crystals and ettringite whereas in the presence of pozzolans, its amorphous silica component reacts with liberated calcium hydroxide in hydrated cement paste in the presence of water to form another form of calcium silicate hydrate. This interaction leads to the formation of products with cementitious properties of the same type as those formed in the hydration of C-S-H compounds, but with a different nature. These products have a lower CaO/SiO_2 ratio (lower alkalinity) and higher resistance to aggressive environments [7].

Portland cement

$$C_3S + H_2O \xrightarrow{\text{fast}} C - S - H + CH$$

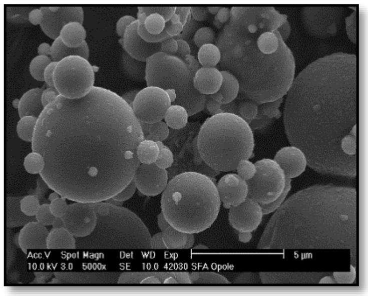
Portland – Pozzolan Cement

$$\text{Pozzolan} + CH + H_2O \xrightarrow{\text{slow}} C - S – H$$

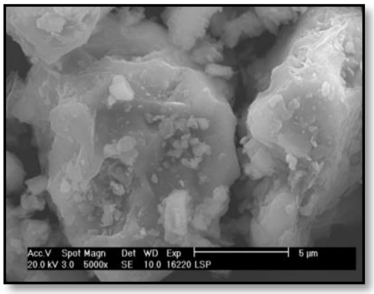
Thus, due to the elimination of free calcium hydroxide, produced during the Portland cement hydration, on reaction with the pozzolan, it has been found that the resistance of concrete against the attacks by sulphate and sea water is increased.

1.10 Need of Using SRMs in Modern Concrete Systems

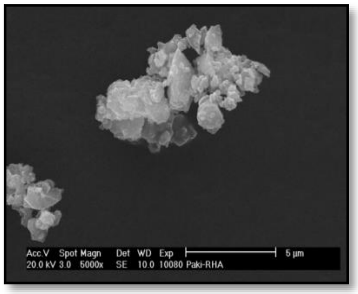
Because only an adequate amount of water is added in HPC/SCC, therefore it is never the idea that all cement particles may get hydrated in modern concrete systems. So it may be thought that in such cases, a part of cement can be replaced by suitable SRM or a combination thereof. The presence of SRMs or their blends usually result in a binary or ternary binder system. It would be very difficult to exactly describe their governing hydration mechanism. The inclusion of SRMs in replacement mode produces dilution (of clinker), physical packing with/without nucleation effect and pozzolanic effects with simultaneous increase or decrease (depending on size, type, composition and morphology of SRM) in the effective w/c ratio of various formulations. Scanning Electron Microscopic Images (SEM) of SRMs used in NICE, NUST are given in Figure 1-1.



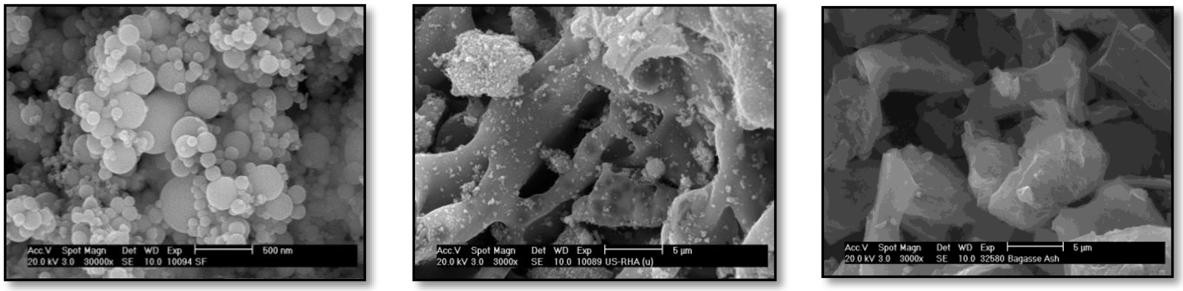
Fly Ash
(Rizwan S. A. 2006)



LSP - Lafarge
(Rizwan S. A. 2006)



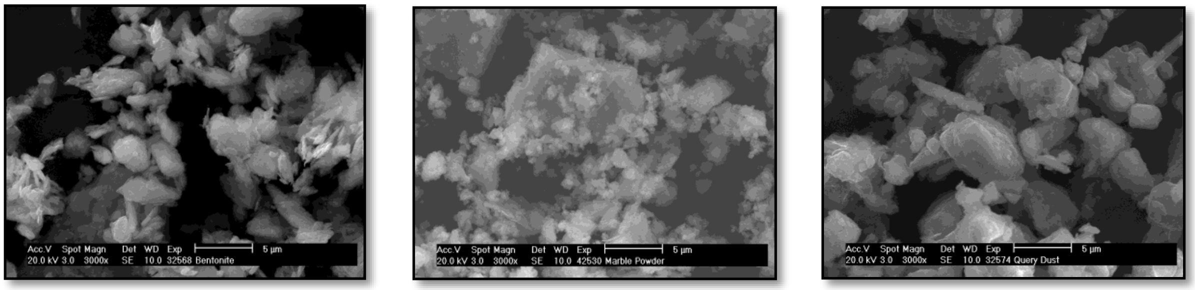
Rice Husk Ash – PAK
(Rizwan S. A. 2006)



Silica Fume
(Rizwan S. A. 2006)

Rice Husk Ash - USA
(Rizwan S. A. 2006)

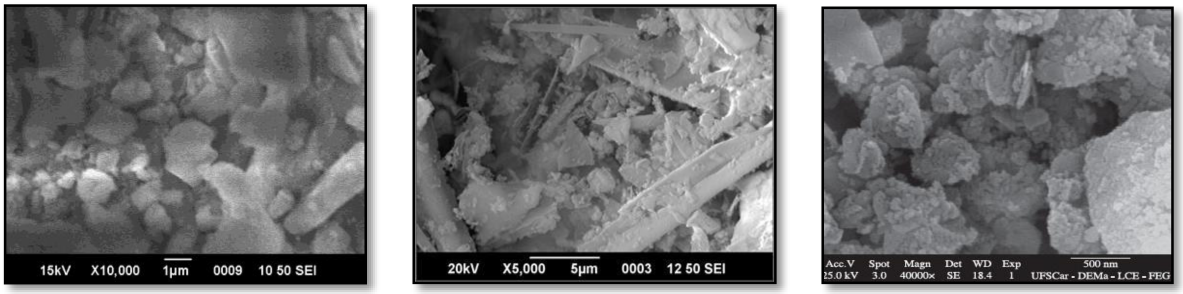
Bagasse Ash
(Bilal Niazi 2010)



Bentonite
(Bilal Niazi 2010)

Marble Powder
(Khurram Javed 2012)

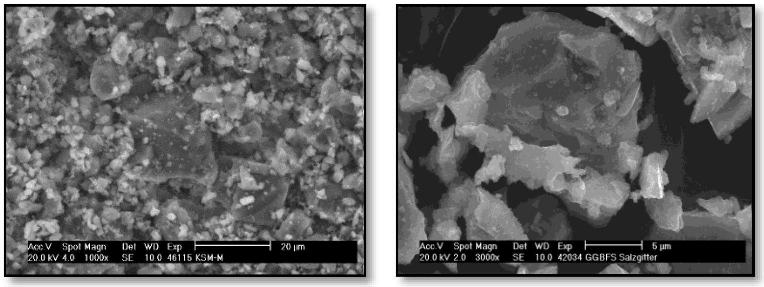
Limestone Quarry Dust
(Adnan Ahsan 2010)



Glass Powder
(Adnan Ahsan 2011)

Wheat Straw Ash (Toori)
(Rao Arslan 2010)

Metakaolin
(Manan 2013)



LSP – Medenbach
(A.A. Chishti 2013)

GGBFS
(Mirza Ayyub 2013)

Figure 1-1: Scanning Electron Microscopic Images Of Commonly Used Secondary Raw Materials (SRMs)

1.10.1 Marble Powder (MP)

Marble has been normally used as a building and construction material since the ancient ages. However, it was mainly used to increase the aesthetics of the buildings. It was used as stone bricks in walls, arches, or as lining slabs in walls, roofs or floors. Marble blocks were cut into smaller pieces for its efficient utilization but it left its wastage at quarry or at the sizing place. This cutting and resizing of marble resulted into millions of tons of marble powder or dust and the sludge generated during cutting is estimated to be between 20% and 30% of the weight of the stone worked [23]. This marble powder waste, if not utilized, can be a source of environmental pollution and economic loss. The marble powder is usually utilized as a resource in several fields, for example ceramic [24], brick [25], building material [26], infiltration [27] and desulphurization processes [28]. In addition, the waste marble dust has been used in the manufacturing of mosaics, mortar, tile, plaster and white cement [29]. Coarse marble wastes were used as aggregate [30] and as filler in asphalt cement [31]. Artificial marble waste was used as a fine aggregate in polymer-modified mortar [32]. Also, marble dust can be used in the production of polymer based composite material [33].It was reported that waste marble sludge can be used to produce clinker [34] and as an additive material in mortar [35]. The waste marble dust is also utilized as an additive in composite cement production [36]. Binici et al. (2007) showed that using up to 15% marble dust as an additive may result in more durable concrete [37].

Valeria et al (2005) reported that Blaine fineness value of marble powder is very high. Its value is about 1.5 m^2/g with 90% of particles passing through 50µm sieves and 50% particles passing through 7 µm. Very small size of marble powder particles increases the surface area of marble powder, so its addition as secondary raw material in mortars and concretes would increase cohesiveness of mix. Numerous studies have been conducted in literature to check the performance of concrete using marble powder or waste marble aggregate especially its use in self-compacting concrete, its application in the mixture of asphaltic concrete and its utilization as an additive in production of cement [38]. Hanifi Binici et al (2007) reported that concrete containing marble powder has higher compressive strength as compared to the lime stone dust concrete having equal water to cement ratio and mix proportion. His research findings also showed that marble powder concrete has lower water permeability than the concrete made using lime stone [37]. Ali Ergun (2011) [39] conducted research to investigate the mechanical properties of the concrete in which he used 5% replacements of cement with diatomite and marble powder in one case. And in another case, he replaced 10% cement with waste marble powder and he found better mechanical properties and compressive strength as compared to the former case. It was also noted that the higher the amount of MP additive, the longer the setting times and the lower the strength of the specimens for all the curing periods [40].

Self-compacting cementitious systems require high water and large amount of cement due to finesses of aggregates. Excess water imparts harmful effects like bleeding, segregation of particles and weak interfaces between granular materials [41]. In SCCS, addition of fine contents makes an important influence on the quality of fresh and hardened concrete. Bedrina et al. [42] in his study on "reuse of local sand in sand concretes" states the importance of marble powder on improving the mechanical and rheological properties. By optimizing the percentage of marble powder in self-compacting concrete that can be in the range of 200kg/m^3, researchers have been able to make more segregation resistant and workable concrete. Jiang and Mei [43] showed that the key to make self-compacting concrete is to use large volumes of fine material. They reported that workability increases by increasing quantity of fines in the mixture. Bhattacharya et al. [44] reported that addition of fine materials and marble powder fillers have resulted in consistent slump flow values. However, these marble powder fillers have increased the slump flow values as compared to other materials. Therefore, by adding powder materials to cement improves the rheological properties of pastes and as a result the workability of the concrete mixture becomes better. Brain (2004) [45] studied the effect of adding marble powder with Portland cement. He stated that it ameliorates the relative content in hydrates as well as microstructure. Marble powder reacts with calcium hydroxide to form calcium silicate hydrate. So volume of binders is increased, which enhances the strength and reduces the permeability.

Topcu et al. [46] states that air content of SCC has increased by using MP in SCC so it can be said that the frost resistance of SCC can also be improved by using MP and increasing air content. Ye et al. [17] have investigated the microstructure of SCC produced with limestone filler. They have observed that the total amount of non-pozzolanic filler material has almost not changed during 28 days of hydration. In the microstructure of SCC with MP as filler material, a good bond between aggregate and cement matrix can be occurred. The well-bonded interfacial zone is a characteristic of higher strength development of the concrete. The high fluidity, workability and the cohesiveness of the fresh SCC were obtained by the addition of admixtures and fine filler. It seems that these materials help a strict contact between organic and inorganic phases [47].

1.10.2 Limestone Quarry Dust (LSQD)

The use of limestone/Limestone Quarry Dust (LSQD) can enhance many aspects of cement-based systems through physical or chemical effects depending upon the origin of rock i.e.: Physical effects are associated with the size of LSQD particles, the smaller ones can enhance the packing density of powder and reduce its interstitial void, thus decreasing required water in the system. Partial replacement of cement by an equal mass of LSQD powder with a specific surface area ranging between 500 and 1000 m^2/kg resulted in an enhancement in fluidity and a reduction of the yield stress of highly flowable mortar [48].

Abu kersh and Fairfield studied the effect of using granite stone as a partial cement replacement on mechanical properties of concrete using 20–50% of granite dust. The experimental test results showed that the use of granite dust at these levels reduces significantly the concrete compressive strength and had little negative effects on concrete tensile strength [49].

Elmoaty et al. [50] used granite dust as a cement replacement or addition from 5.0% up to 15.0%. The test results showed an improvement on concrete compressive strength at 5.0% granite dust as cement replacement and improvement on compressive strength at most levels of granite dust as cement addition. Also, the use of 5.0% granite dust increased the corrosion cracking time and no significant reduction in cracking time was observed at granite dust contents greater than 5.0%. The effect of using granite dust on producing concrete bricks was also studied by Hamza et al. Hamza et al. studied the effect of using 10–40% of granite slurry on compressive strength of concrete bricks. The test results showed that the use of granite dust had a positive effect and the optimum granite content was 10% [51].

Dehwah et al. [52] evaluated the corrosion resistance of self-compacting concrete (SCC) prepared using quarry dust powder (QDP), silica fume (SF) plus QDP or fly ash (FA). He found that the chloride permeability in SCC specimens incorporating QDP or FA was moderate and it was low in the specimens incorporating QDP plus SF.

Kumar et al. [53] used quarry dust as partial replacement of cement and found that 25% of partial replacement is beneficial to concrete without loss of standard strength of cement. In addition to 25% quarry dust as partial replacement of cement as constant, they added metakolin as 2.5%, 5.0%, 7.5%, 10.0%, 12.5% and results were found that quarry dust and metakaolin usage in partial replacement to cement can be done. However, another research work carried out contained an experimental investigation on compressive strength, flexural strength and split tensile strength of concrete made with 2.5% to 20% replacement of cement by quarry dust of less than 75 micron particle size and 7.5% replacement of cement was recommended [54].

Other investigations have shown that partial replacement of cement by an equal mass of LSQD varying from 5% to 20% resulted in an enhancement of the fluidity of high-performance concrete having a W/C ratio ranging between 0.35 and 0.41 [48]. This improvement may be due to the increase in effective W/C obtained by physical filler effect which represents packing of aggregates. Indeed, for given water content, partial replacement of cement by an equal mass of a filler of lower size results in an increase in effective W/C.

1.11 Types of Water Reducing Agents

There are three different groups of chemical agents/materials that can influence the workability of any cement based pastes, mortars or concretes. These include lignosulphates (LS), sulfonated naphthalene and melamine formaldehyde condensates (SNF/ SMF) and polycarboxlate ethers (PCE). These classes are also called first, second and third generation of superplasticizers respectively. The first category of lignosulfonates brings about a water reduction of at least 5% so these are not suitable for HPC and SCC. The second category of superplasticizer brings about a water reduction of 12% at least. In construction technology mostly the sodium, magnesium and calcium salts of lignosulfates are used. The third generation PCE type of SP's were developed in Japan and Germany in the late seventies or early eighties of the last century. But today they have become an essential ingredients of HPC or SCC and are used to bring down the water demand, to regulate setting time and to enhance flow response and workability without causing any bleeding or segregation. Their basic structure is like a "comb- type" molecule. 3rd Generation PCE based SP which work differently from its predecessor the sulfonate based SP, giving cement dispersion by steric stabilisation of grain particles, instead of electrostatic repulsion. The grafting of the polymer on the cement particle surface ensures that the side chains have the possibility to exert repulsion forces, which disperse the particles of the suspension and avoid friction. This form of dispersion is more powerful in its effect and gives improved workability retention to the cementitious mix. They are more effective than LS, SMF and SNF therefore they are called super plasticizers. They provide superb workability to the material in the fresh state, and excellent physical properties in the hardened state.

1.11.1 Superplasticizers

Chemical admixtures represent those materials which can be added to the concrete mixture immediately before or during mixing. The use of chemical admixtures, such as water reducers, retarders, high-range water reducers or superplasticizers (SP), and viscosity-modifying admixtures, is necessary in order to improve some fundamental characteristics of fresh and hardened concrete. They make more efficient use of the large amount of cementitious material in high strength and self-compacting concretes and help to obtain the lowest practical water to cementing materials ratio. Gagne et al [55] reported that Superplasticizers, also known as high-range water-reducers (HRWR), are low molecular-weight, water-soluble polymers designed to reduce water content by 12-30% in concrete mixtures and high slump. The reduction of the water-cement ratio and the creation of a more uniform pore structure mean that the permeability of concrete can be reduced by the use of superplasticizers, along with a general improvement of durability. Rizwan et al, [56] reported that SP are chemical admixtures which increase the workability of cementitious systems at low mixing water contents and are therefore considered to be essential for durability of structures made in HP SCCS. Owing to the availability of superplasticizers or high range water reducing agents (HRWRA), high performance concrete (HPC) and self-compacting concrete were only possible. From literature review it was recommended that use of such HRWR disperses cement grains, reduces water demand and maintains required level of flowability and viscosity.

1.11.2 Mechanism of Action of Superplasticizers

Electron microscopic examinations reveal that in water suspension of cement, large irregular agglomerates of cement particles are formed due to difference in the type of surface charge of various phases of cement. Usually aluminate phases (C_3A and C_4AF) and silicate phases (C_2S and C_3S) show opposite charges with positive charge on aluminate phases. In fresh cement paste

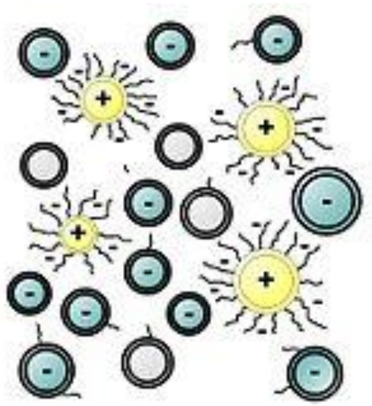


Figure 1-2: Mechanism of Action of Super plasticizers

lacking SP, C_2S and C_3S have a negative zeta potential whereas C_3A and C_4AF have a positive zeta potential. This causes a rapid clotting of the cement grains. The SP polymer molecules bind on the surface sites of cement grains preferentially on aluminate phases and decrease surface potential which become negative for all major phases of cement. The electrostatic repulsive forces are thus created between cement grains. This is the mechanism by which the agglomeration is prevented.

CHAPTER 2: MATERIALS

The following materials were used for this experimental program.

2.1 Cement

Ordinary Portland Cement (OPC), Type I Grade 43 from BEST WAY cement conforming to ASTM C150, was used for the experimental work and stored in accordance with requirements of laboratory research standards to keep it moisture free. The properties of cement used are mentioned in Table A-1 of Annexure-A. XRF analysis of the cement was carried out with a view to determine its chemical composition and results are shown in Table 2-1.

2.2 Fine Aggregate

Natural sand (quarry site at Lawrencepur) was used for making all samples. The sieve analysis was performed in accordance with ASTM C136 [58] and results are mentioned in Table A-4 of Annexure-A while graph is shown in Figure 2-1. The specific gravity and the percentage absorption were determined in accordance with ASTM C128-01 and are mentioned in Table A-2 of Annexure-A.

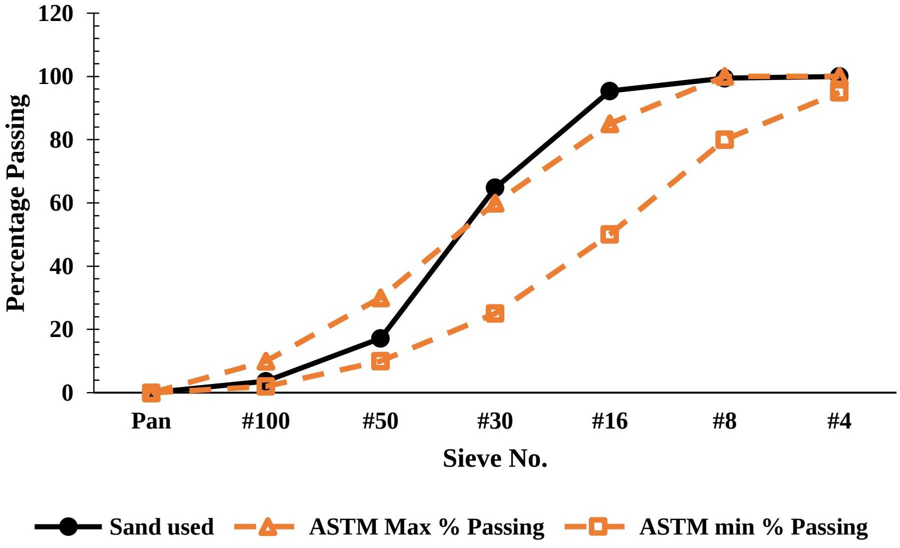


Figure 2-1: ASTM Gradation of used Lawrencepur Sand

2.3 Coarse Aggregate

Coarse aggregates influence each property of self-compacting concrete by affecting the flowing ability, segregation resistance and strength. There are two types of coarse aggregates used in this research, one is crushed limestone sourced from Margalla quarries near Islamabad and have angular shape. While other is river gravel obtained from Swat River bed and they are round in shape. The Crushed stone aggregates of various size fractions were collected and sieve analysis was done in accordance with ASTM C 136 [58]. Then, they were graded within ASTM maximum and minimum limits according to ASTM C33 [59]. The maximum size of coarse aggregates used was 14 mm. Results are mentioned in Table A-5 of Annexure-A while graph is shown in Figure 2-2. The specific gravity and the percentage of water absorption were determined in accordance with ASTM C 127 and are mentioned in Table A-3 of Annexure-A.

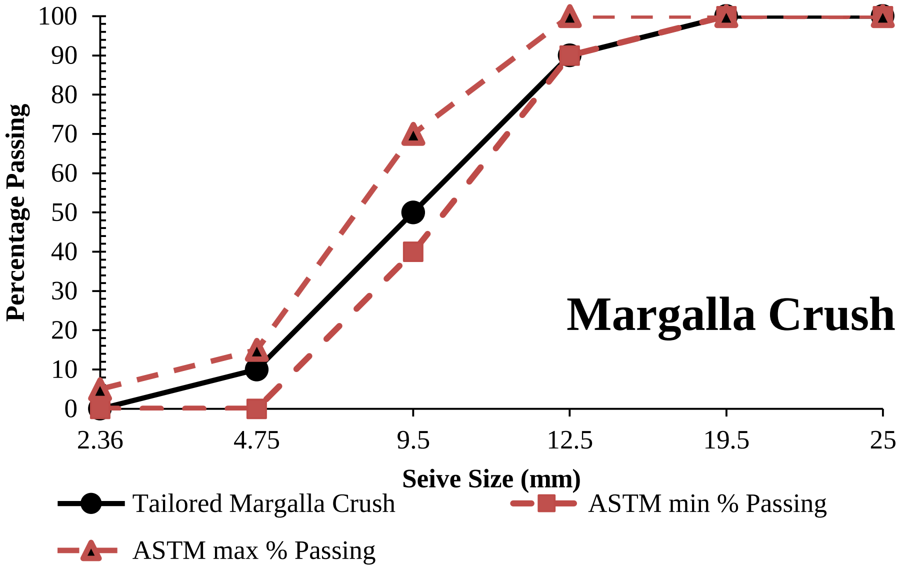


Figure 2-2: Adjusted Gradation of used Crushed Stone Aggregates

River gravel was obtained from Swat River bed and they were round in shape. Their sieve analysis was done in accordance with ASTM C 136 and it was found that their gradation curve did not lie within the ASTM maximum and minimum limits so their size fractions were adjusted to get the gradation within the ASTM limits.

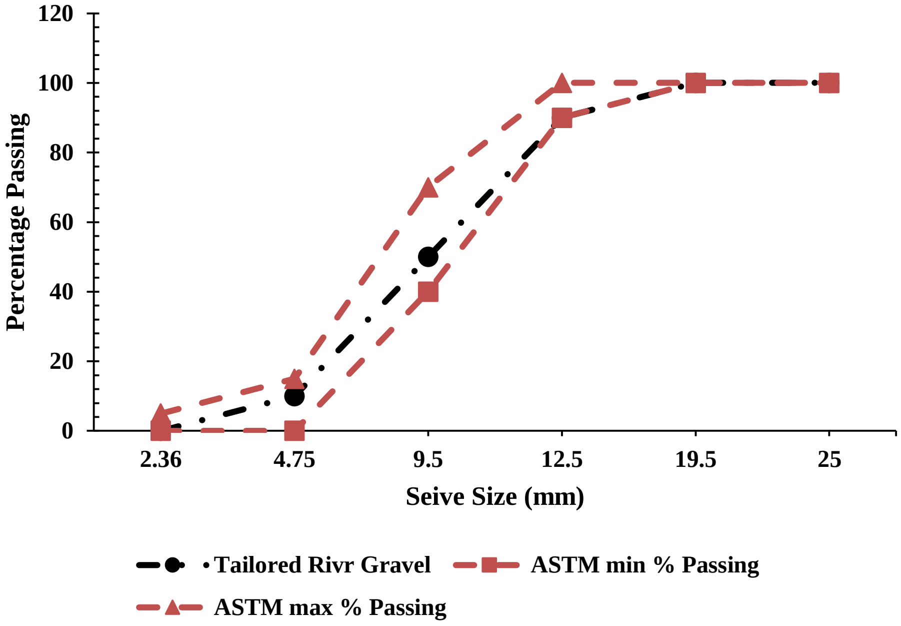


Figure 2-3: Tailored Gradation of used River Gravel

2.4 Secondary Raw Materials (SRMs)

The secondary raw materials used in this research are Limestone Quarry Dust (LSQD) & Marble powder (MP) having particle sizes of 7µm and 6µm respectively.

2.4.1 Marble Powder (MP)

Marble powder (MP) is acquired as a by-product in sawing and shaping of marble. It's generally in pure white colour and free from impurities, MP was obtained in slurry form directly taken from waste deposits of Marble factories. Wet MP was dried in oven for 24 hours at 100ºC before the sample preparation. The high content of CaO confirmed that the original stones were Marble and limestone. The sludge was also tested to identify the absence of organic matter, thus confirming that it could be used in mix, it was used to study its properties and after effects in self-compacting cementitious systems. The results by BET method and chemical analysis (based on XRF analysis) of Marble powder and other powders used is given in Table 2-1.

TABLE 2-1: Chemical Composition & Physical Properties Of Powders Used

Oxides	CEM	LSQD	MP
CaO	68.100	64.348	90.489
SiO_2	15.437	31.504	2.033
Al_2O_3	3.560	-	0.589
Fe_2O_3	4.525	2.604	0.383
MgO	1.929	-	6.233
SO_3	4.215	-	0.100
SrO	0.2421	0.384	0.067
MnO	0.055	-	-
Particle Size (D50)	22.5 µm	7 µm	6 µm
(BET) Specific surface area (m^2/g)	1.07	1.877	3.348

2.4.2 Limestone Quarry Dust

The Limestone Quarry Dust was collected from Margalla hills Islamabad right from the crusher plant containing clay contents. The finished raw material from crushed stone is stone dust along with some larger particles. The material was then reduced to even smaller size by further grinding. The results by BET method and chemical analysis (based on XRF analysis) of the Limestone Quarry Dust and other powders used is given in Table 2-1.

2.5 Particle Size Characterization

The particle-size distribution (PSD) of a powder, or granular material, or particles dispersed in fluid, is a list of values or a mathematical function that defines the relative amount, typically by mass, of particles present according to size. PSD is also known as grain size distribution. Degree of packing is a function of particle size distribution of a mix. The different types of cementitious materials generally have different particle sizes. By mixing appropriate proportions of different materials together, the medium size particles would fill up the gaps between the larger size particles and the smaller size particles would fill up the gaps between the medium size particles and so on. Hence, blending materials of different sizes together could increase the packing density of the cementitious materials and reduce the water demand and SP demand etc.

Both secondary raw materials LSP and MP were first grinded and then sieved, the samples were tested for particle size distribution and results were plotted in MATLAB to find Mass-median-diameter (MMD) or D_{50} (Dv0.5). Median values are defined as the value where half of the population resides above this point, and half resides below this point. The D50 (Dv0.5) is the size in microns that splits the distribution with half above and half below this diameter. The log-normal distribution mass median diameter (MMD), is considered to be the average particle diameter by mass. To ensure accuracy in determination of D50 best fit function of MATLAB was used.

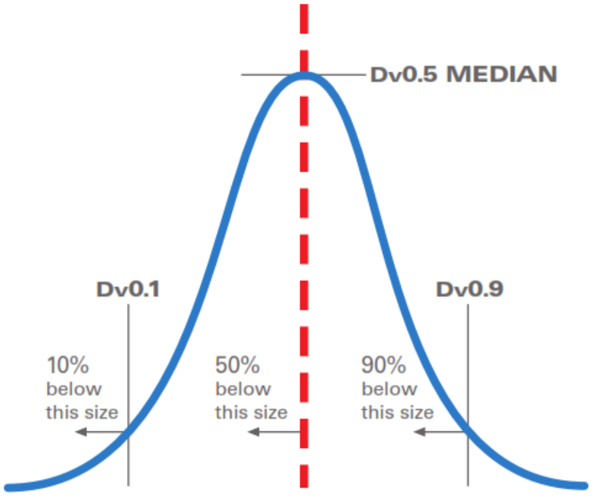


Figure 2-4: Three axis values D10, D50, D90

The average particle size (D_{50}) for LSQD was found to be 7µm and was 6µm for MP. The particle size distribution for LSQD and MP plotted using best fit function of MATLAB are shown in Figure 2-5.

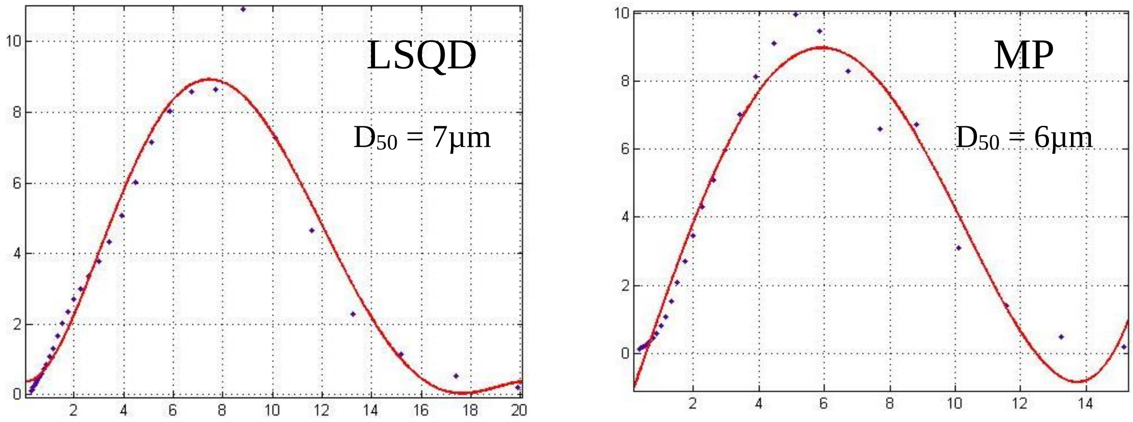


Figure 2-5: Average Particle Size of SRMs

2.6 Chemical Admixtures

Chemical admixtures are an essential component of modern day concreting like high performance concrete (HPC) & self-compacting concrete (SCC) as the fineness of the secondary raw materials SRMs & fine aggregates leads to higher water demand causing detrimental effects such as bleeding, segregation and also causes weak links between grains of the matrix (water voids). To produce a more workable self-flowing concrete with no bleeding nor segregation with a reduced water content of the system, Superplasticizer are introduced in the system.

Powder Melflux® 2651 F, manufactured by BASF Chemical Company Germany was used in this study of SCP system. This was provided by Prof. Dr.-Ing Thomas A. Bier of Technical University, Freiberg Germany to Prof. Dr.-Ing Syed Ali Rizwan under a DAAD sponsored research project.

TABLE 2-2: Technical Data Of Melflux® 2651 F

Physical Form	Powder
Appearance	Yellowish to brownish
Bulk density	300-600 kg/m^3
pH value	6.5-8.5
Dosage recommendation	0.05-1.00% by weight of cementitious material

Melflux® 2651F is a dried powder of modified polycarboxylic ether. It provides excellent early strength development and is based on latest polymer technology and has side chains based on polyethylene glycol.

Liquid type Glenium® 51, manufactured by BASF Chemical Company Pakistan was used in study of SCC. Technical Data of Glenium® 51 is given in Table 2-3.

TABLE 2-3: Technical Data Of Glenium® 51

Physical Form	Viscous Liquid
Appearance	Char light Brown
Relative density	1.1 @ 20ºC
ph Value	6.6
Viscosity	12830 cps @ 20ºC

2.7 Mixing Water

Ordinary tap water was used in all the mixes, and the temperature of water was normally within 19 - 24°C.

CHAPTER 3: EXPERIMENTAL PROGRAM

The tests carried out to find the fresh and hardened properties of self-compacting pastes and concretes are illustrated below.

3.1 Tests on Self Compacting Pastes

3.1.1 Mixing Proportion and Mixing Regime

The basic purpose of the variation in self-compacting paste systems was to understand the change in various fresh and harden properties of different types of self-compacting paste systems containing SRMs. The amount of SRMs replaced was up to 30%. In self-compacting paste systems the total cement replacement with SRMs like LSQD & MP was 5%, 7.5 % 10%, 15 %, 20 %, 25 % and 30 % by weight of cement.

Figure 3-1: 5 litres Hobart Mixer

The materials were then manually dry mixed in the jar for 2 minutes after which they were fed in to the bowl of Hobart mixer [Figure 3-1] and water was added. The mixing was done for 30 seconds at slow speed of 145 rpm. After 30 seconds the mixer was stopped and inner walls of mixer were cleaned, to remove all the agglomerated paste which adhered to the mixer blade and mixing bowl. Thereafter the mixing at slow speed of 145 rpm was again done for 30 seconds after which the mixing was done at 285 rpm for 2 minutes bringing the total mixing time to 3 minutes.

3.1.2 Water Demand and Setting Times

As per the European Guidelines for Self Compacting Concrete, finding water demand of the system is the first stage in self-compacting cementitious system design [57], so water demands of neat cement and formulations comprising cement with secondary raw materials were determined by using the standard Vicat apparatus (Figure 3-2) at 20±1°C as per ASTM C 187 [60] followed by finding their initial and final setting times using same apparatus as per ASTM C 191 [61].

Figure 3-2: Vicat Apparatus

3.1.3 Flow Spread Test

The amount of super plasticizer (Melflux® 2651F- 3rd generation powder type PCE based super plasticizer) required to produce a target spread of 30±1 cm for all paste formulations was obtained by using Hagerman's mini slump cone placed on a plane flat plate. The dimensions of this cone are shown in Figure 3-3. Paste made according to the water demands of the respective formulations is poured into the cone. It is then lifted vertically and the self-compacting paste spreads in a circular manner over the plate. Flow spread is recorded in two orthogonal directions and average value is taken. Trials are made until the total spread is equal to 30±1 cm.

T_{25} cm was measured as recommended [10] on the analogy of Abrams cone (10x20x30 cm) having bottom dia of 20 cm where in a total spread of 50 cm is measured giving a spread/dia ratio of 2.5, which is also same for mini slump cone (Hagerman's cone) if the spread is considered at 25 cm. Therefore, properties of SCC reflected in T_{50} cm time of Abrams cone are the same as those defined by T_{25} cm time of Hagerman's cone for SCP/SCM.

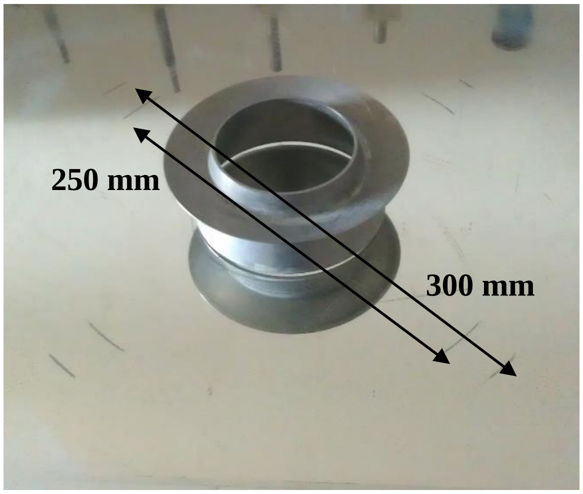


Figure 3-3: T25 cm & T30 cm Markings

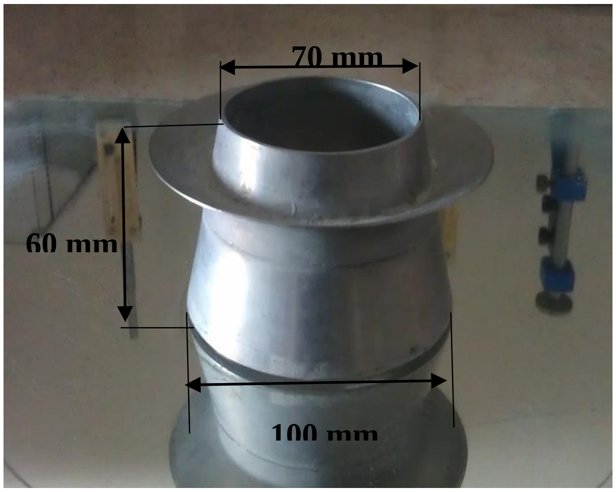


Figure 3-4: Hagerman's mini slump cone 7x7x10 cm^3

3.2 Tests on Concrete Mixes

3.2.1 Mixing Proportion and Mixing Regime

The mixing proportions used in this work of Self-compacting Concrete (SCC) were almost similar to those of literature [10] and are shown as under:

- LSQD and MP replaced cement by 10%, 20% and 30%.
- The ratio of fine to coarse aggregate was 55:45.
- The fine aggregate was of 0-2mm size.
- The coarse aggregates were of 2-8mm and 8-14 mm in equal proportions for a given replacement level.

All materials were placed in concrete mixer pan from SRMs, cement, fine aggregates and then coarse aggregates. These materials were dry mixed for one minute at a speed of 180 rpm, then water, about 70% of the required total water cement ratio, was added to the mix and further mixing was done at 180 rpm for another one minute. The required SP was mixed in the remaining 30% water and was added to the wet mix and further one minute mixing was done at 180 rpm. Then, fast mixing was done for two minutes at a speed of 360 rpm. The total slow mixing time was 3 minutes and fast mixing time was 2 minutes, making a total mixing of 5 minutes.

Figure 3-5: Indigenous local High Performance Concrete Pan Mixer developed at NICE

3.2.2 Tests on SCC's Fresh Properties

(I) Slump flow time

Slump flow test is used to measure the flow-ability and flow rate of self-compacting concrete. It assists us in measuring two flow spread and flow time T50 simultaneously. Flow spread specifies the free deformability without any restrain while flow time shows the rate of deformation within a specified flow stretch.

ASTM C1611 [62] standard offers two cone positioning choices, that is, upright and downside-up. In this experimentation, downside-up position of slump cone was adopted. After the completion of mixing, allow the sample in motionless stance for about 1 minute. By employing damp towel or sponge, dampen the slump cone's interior surface and the base plate's test surface, then put the cone on the 200 mm circle present in the mid of base plate. Fill cone with the sample from the bucket barring any compacting effort, following a little pause (sparsely 30 seconds for cleaning and verification of dampness of test surface), remove the slump cone by lifting vertically upward, so as concrete flows out easily without hindrance of the cone, and set out the timepiece the instant there is disconnection between the cone and base plate. Determine the time when concrete reaches 500 mm diameter (T50) and total spread time. Also determine the final slump flow of concrete when it has halted by measuring in two orthogonal directions. The concrete spread needs to be visually checked carefully for segregation, particularly at the edges. The slump flow apparatus is shown in Figure 3-6.

Figure 3-6: Slump Flow Test for SCC using Abrams Cone of 100x200x300 cm^3 (top end down)

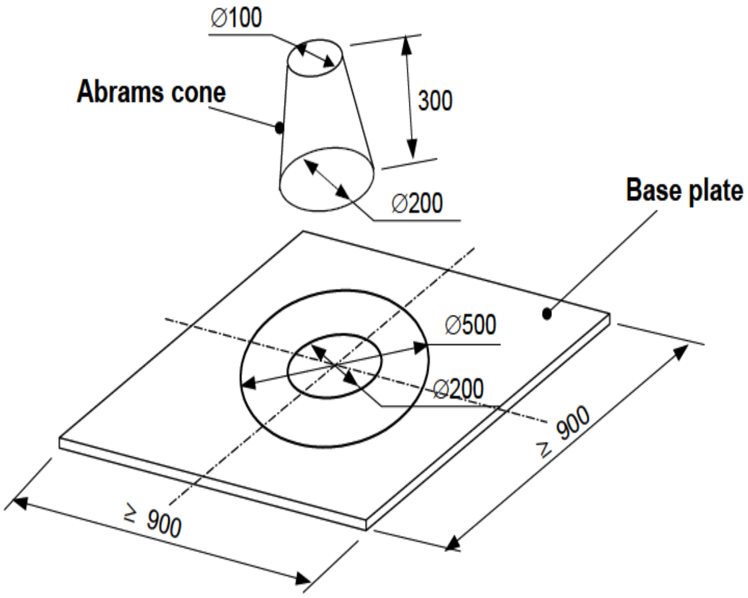


Figure 3-7: Base Plate & Cone Apparatus (Rizwan 2006)

(II) J-Ring flow Test

J Ring test provides the measurement of passing ability of self-compacting concrete. In this test, a ring having steel bars, called J Ring, is placed around the slump flow cone for checking passing ability. This test is described in ASTM C1621 [63]. The contrast among the results of J-Ring flow test and slump flow test provides the blocking which is a measure of passing ability, i.e. lesser the value of blocking better the passing ability and greater the value of blocking littler the passing ability. J-Ring test apparatus is shown in Figure 3-8.

After the completion of mixing, allow the sample in motionless stance for about 1 minute. By employing damp towel or sponge, dampen the slump cone's interior surface and the base plate's test surface, then put the cone on the 200 mm circle present in the mid of base plate. Place J ring above base plate surrounding the slump cone and then fill the cone with the sample from the bucket without any external compaction, following a little pause (sparsely 30 seconds for cleaning and verification of dampness of test surface), remove the slump cone by lifting vertically upward, so as concrete flows out easily without hindrance of the cone, and set out the timepiece the instant there is disconnection between the cone and base plate. Determine the time when concrete reaches 500 mm diameter (T50) and total spread time. The culmination of concrete flow indicates the accomplishment of test.

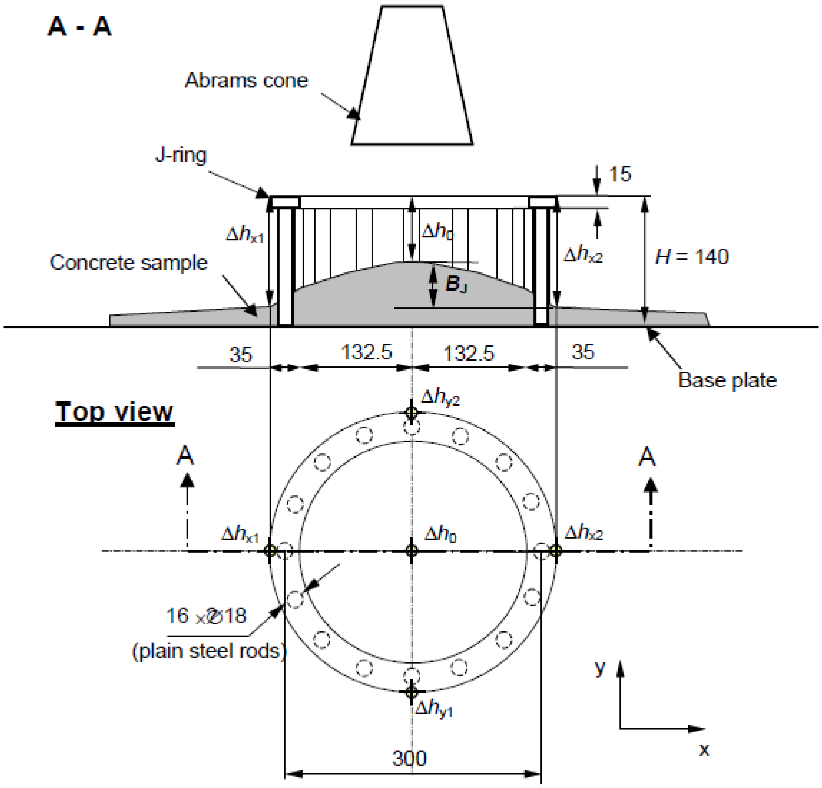


Figure 3-8: Details of J-Ring Apparatus (Rizwan 2006)

(III) V-Funnel Test

V-funnel test provides the measurement of flowability of self-compacting concrete .V-funnel test measures the interval required by concrete sample to pass under the effect of gravity from a small gap in the apparatus as viewed from Figure 3-9. The value given by this test gives an insight on filling ability, passing ability and segregation resistance of concrete.

Position the V-funnel vertically on a hard and level surface. By employing damp towel or sponge, dampen the funnel’s interior surface and eliminate the excess water. Lock the gate and place a bucket beneath the funnel. Wholly fill the funnel with concrete barring any compacting or rodding effort. Strike off any excess concrete from the upper side of the V-funnel. Then after an interval of 10 ± 2 seconds, unfasten the gate. Measure time from unfastening of gate to the sign of viewing the first light from underlying opening. The timer reading thus noted is documented as V-funnel flow time, abbreviated as t_V and expressed to the closest 0.1 second.

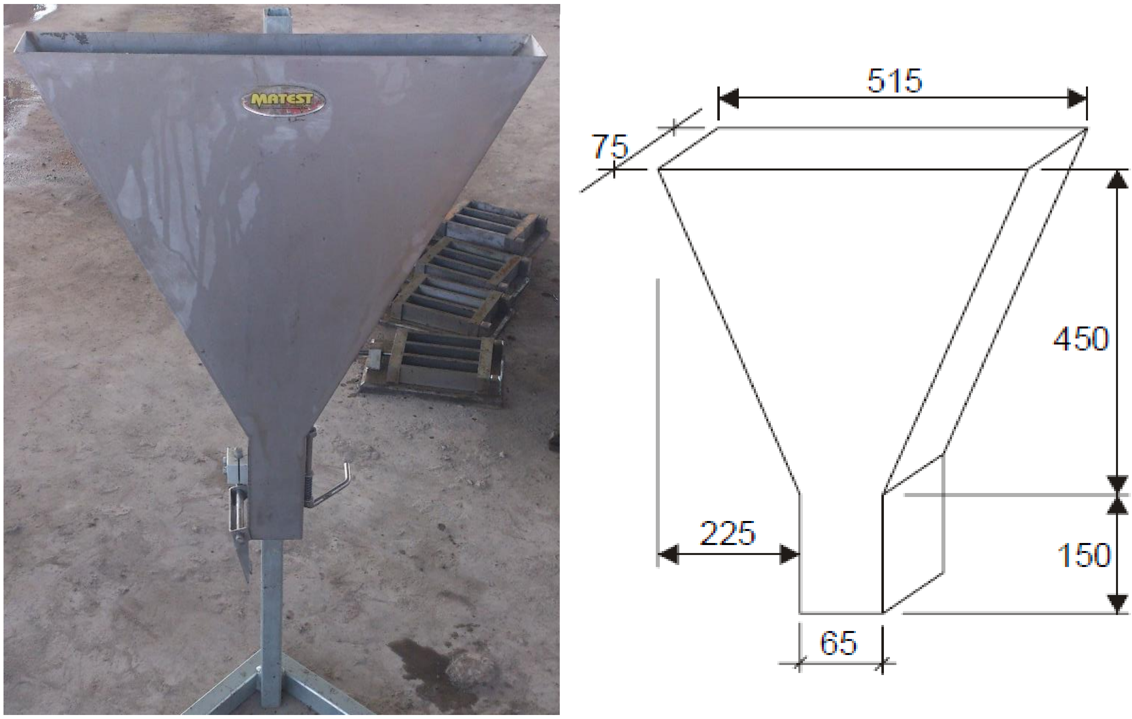


Figure 3-9: V-Funnel for SCC [64]

(IV) L Box Test

L Box test measures passing and filling ability of self-compacting concrete mixes. In this test, the height attained by the fresh concrete mix is determined after its passage through the defined openings between steel bars and movement through a specific span. The passing or blocking behavior of concrete can be concluded through this attained height. L- Box apparatus is shown in Figures 3-10. In this test, two types of gates having 12 mm diameter bars can be utilized. One gate contains 3 bars with 41 mm opening while the other one has 2 bars with 59 mm opening. Position the L-box vertically on a hard and level surface. Close the sliding gate and wholly fill the L-box's vertical part with concrete barring any compacting or rodding effort. Allow the concrete to remain undisturbed in L-box's vertical part for one minute (± 10 seconds). Concrete constituents will adjust themselves in suspension meanwhile. Determine time from fully rising of the sliding gate and concrete flowing from L-box's vertical part and reaching to the points 200 mm, 400 mm and 600 mm in its horizontal part. Also determine the heights H_1, H_2 after concrete flow has ceased.

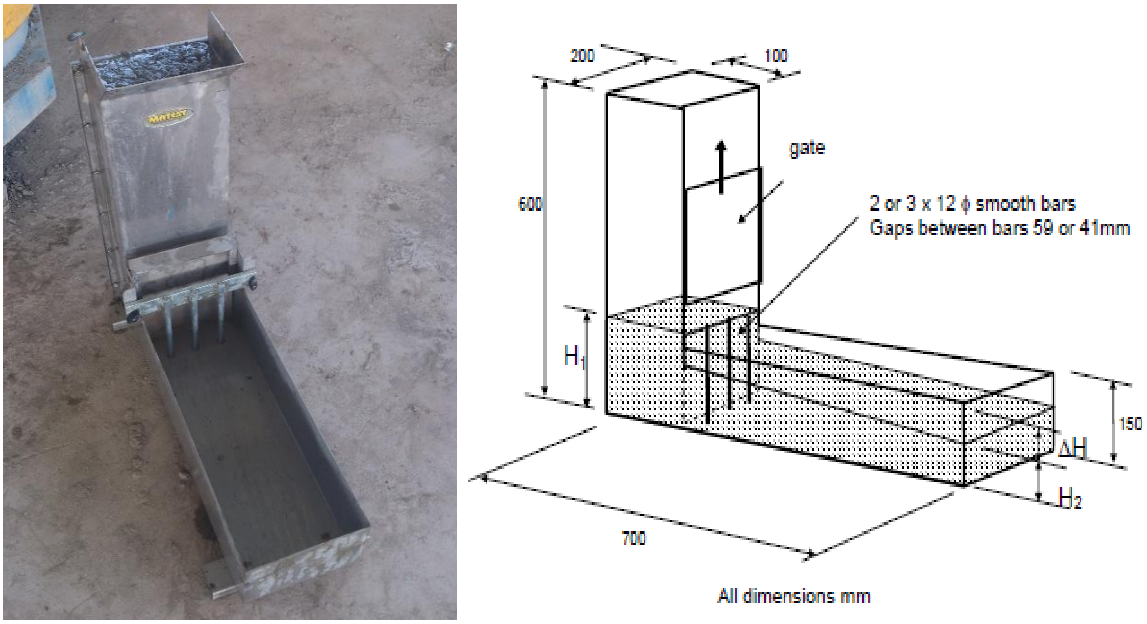


Figure 3-10: L-Box Apparatus for SCC [64]

3.2.3 Flow Test Sequence for Self-Compacting Concrete

After the first mixing of SCC, tests were carried out in the sequence of slump flow test first, followed by V-funnel test, then L-Box test and J-Ring test in last. After every test, concrete was placed inside mixer, and again mixed for 30 seconds. In the end it was remixed again and slump flow was measured again before casting specimens for hardened properties testing.

3.3 Acceptance Criteria for SCC

Typical acceptance criteria for Self-compacting Concrete with a maximum aggregate size up to 20 mm are shown in Table 3-1.

TABLE 3-1: Acceptance Criteria For Scc Flow [64]

	Method	Unit	Typical range of values	
			Minimum	Maximum
1	Slump flow by Abrams cone	Mm	650	800
2	T50 cm slump flow	Sec	2	5
3	J-ring	Mm	0	10
4	V-funnel	Sec	6	12
6	L box	H_2/H_1	0.8	1.0

Particular attention should always be taken to make certain that there is no possibility of segregation of the mix because, currently, there is no simple and reliable test that provides information on the resistance to segregation of SCC in all practical situations.

3.4 Casting & Curing

The casting, curing and testing was carried out as per EN 196-1 of 1994. After the tests for fresh properties were completed, the concrete was cast into moulds at least three samples of each formulation. The formulations were poured in to the prisms of 40x40x160 mm size (EN 196-1) for self-compacting paste whereas prisms of 40x40x160 mm size and cubes of 4”x4” were cast for self-compacting concrete (BS EN 12390-1). In total 320 prisms were cast for paste systems with CEM I and varying amounts of LSQD and MP replacements in laboratory at a temperature of 20±2 ºC and relative humidity of 40±5%. For SCC, 126 prisms and cubes were cast at a temperature of 25±2 ºC and relative humidity of 35±5%. The cast samples are shown in Figure 3-11 and 3-12.

Figure 3-11: 4x4x16 cm^3 Prisms for SCP and SCC (EN 196-1)

Figure 3-12: 4x4x4 $inch^3$ Cubes for Self-compacting Concrete (BS EN 12390-1)

The samples were placed in sealed plastic bags for 24 hours at room temperature to ensure minimum moisture loss due to temperature changes. Then these samples were demoulded, weighed and placed underwater in a closed tank till the age of testing i.e. 7 days till 56 days. Samples were tested in SSD conditions.

3.5 Strength Evaluation

In case of self-compacting pastes (SCP), the flexural strength was the average of 3 prisms (Figure 3-10) whose resulting six parts were further tested for compressive strength. The specimen prisms had dimensions of 4x4x16cm^3 while compression test samples were of the cross-section of 40x40 mm^2. For self-compacting concrete (SCC) the 4x4x4 $inch^3$ mould cubes (BS EN 12390-1) were tested along with the prism moulds of 4x4x16 cm^3 (EN 196-1) which were tested for flexural & compressive strengths as shown in Figure 3-14. For this research specified ages were 1, 7, 14, 28 and 56 days. Demoulded samples are shown in Figure 3-13 and Figure 3-14.

Figure 3-13: Demoulded Prisms (EN 196-1)

Figure 3-14: Demoulded Cube (BS EN 12390-1)

The specimens were tested in SSD condition after weighing them for water absorption test.

Figure 3-15: Flexure & Compression Testing Assembly for Prisms using Controls 500 kN Compression Testing Machine

Figure 3-16: Compression Testing Assembly for Cubes using Controls 500 kN Compresstion Testing Machine at NICE Structures Lab

3.6 Calorimetry

F-CAL 8000 Field Calorimeter (Figure 3-17) obtained by NICE through an international

Figure 3-17: F-CAL 8000 Field Calorimeter

research project sponsored by DAAD was used for this investigation. Calorimetry is the technique used to measure the hydration kinetics of a cement based system with time. Better monitoring of concrete heat flow leads to an improved understanding of characteristics of concrete materials and mix proportions. With calorimetry, forecasting of setting time and required curing regime, prediction of strength gain, evaluation of thermal cracking risk and identification of materials incompatibility etc. can be made. 48 hours conduction Calorimetry on the self-compacting pastes formulations with super plasticizer and secondary raw materials was done. The samples were taken from the dry mixes of formulations prepared for other tests e.g. strength / flow tests etc and the Calorimetry was performed in parallel to these tests. For SCP systems the calorimetry was done with 5%, 10%, 15% LSQD to understand the effects of varying amounts on heat of hydration of cement pastes. 10% replacement give optimum strengths and flow time in all the systems so formulations with 10% cement replacements with LSQD, MP were tested.

3.7 Mercury Intrusion Porosimetry

The microstructure in terms of pore sizes distribution reported in this study was performed using Pascal 140 and 440 mercury intrusion porosimetry, shown in Figure 3-18, at Technical

Figure 3-18: Mercury Intrusion Porosimeter at TU Freiberg Germany Pascal 140 (Right) and Pascal 440 (Left)

University Freiberg, Germany by a fellow research worker under a DAAD sponsored by a research of Professor Dr.-Ing. Syed Ali Rizwan and Professor Dr.-Ing Thomas A. Bier. The small samples of about 5-10 mm size were prepared from the previously cast prisms for flexure and compression tests. The hydration process was stopped by dipping the samples in Acetone for about 10 hours followed by iso-propanol dipping. Then, these were subjected to a controlled incremental pressure till 400 MPa. All the measurements of pressure, volume of mercury intruded into sample and radii of pores etc. were recorded by Pascal 440 Porosimeter.

CHAPTER 4: RESULTS AND DISCUSSIONS

The results acquired from experiments are presented along with discussion in this chapter. The influence of local Marble Powder (MP) and Limestone Quarry Dust (LSQD) as partial replacement of cement in self-compacting paste (SCP) systems and self-compacting concrete (SCC) systems is investigated along with the role of river gravel and crushed stone aggregates in Self-compacting concrete (SCC) systems. Furthermore, fresh and hardened properties encompassing workability parameters and compressive strength development are also presented.

4.1 Self-Compacting Paste Systems

4.1.1 Water Demand (WD) of SCP Systems

Water demand of the self-compacting paste system was found based on the water cement ratio. It can be seen in Figure 4-1 that water demand of the paste system is increased with the addition of secondary raw materials. Greater the amount of SRMs, greater is the water demand of the system. As secondary raw materials used have smaller particle size than cement, so an increase in specific surface area of the grains results in higher water demand to wet the whole surface area. Thus, more is the specific surface area, the higher is the water demand of the self-compacting cementitious system. However, Marble Powder replacement shows lower, at equal percent addition, water demand as compared to the Limestone Quarry Dust replacement. The water demand for equal percent of addition of MP is lower than those of corresponding LSQD addition, one reason for LSQD can be said that as CaO is the main component as it comprises about 64 percent of the total LSQD mass as seen in Table 2-1, and CaO is the main component of Limestone, and Limestone when used as partial cement replacement seems to absorb water in its porous surface pits and therefore shows increase in water demand which may be due to higher internal porosity or bigger pores with connectivity. Second reason can be said that it contains dust particles, about 31 percent crystalline SiO_2 and alumina is also present which indicates possibly fine clay particles, so it absorbs more water resulting in higher water demand of the system. Whereas MP being metamorphic rock, formed from metamorphism of limestone rocks, is less porous than parent rock and hence reduced water demand of systems. Additionally, MP, having particle size of about 6 microns which is less than that of LSQD (particle size of 7 microns), leads to better packing and hence reduced water demand of the system.

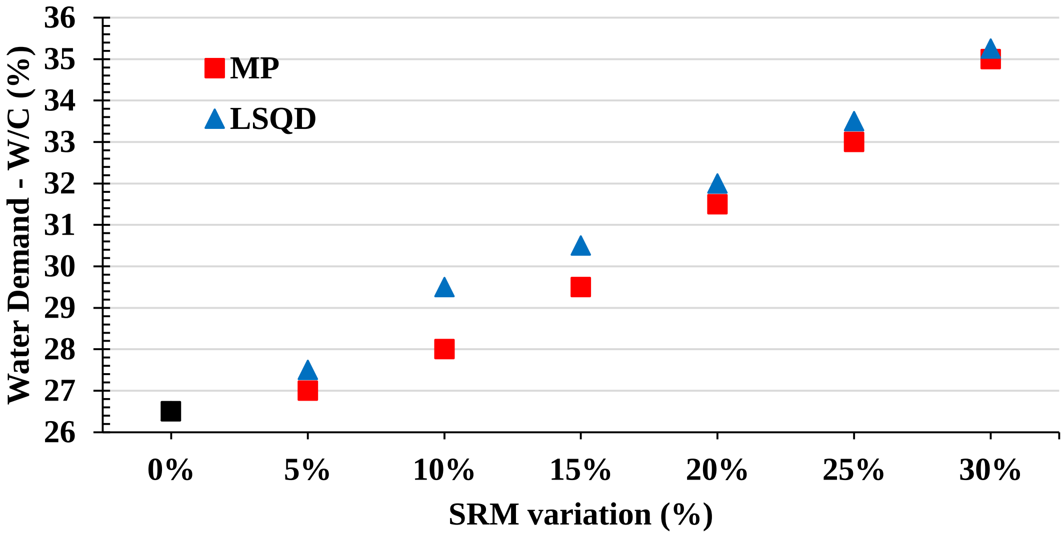


Figure 4-1: Water Demands of the Self-Compacting Paste Systems

4.1.2 Setting Times of SCP Systems

Figure 4-2 and Figure 4-3 are showing the initial setting time and final setting time of the cement paste as well as the paste systems incorporating Marble Powder and Limestone Quarry Dust as secondary raw materials respectively. It can be seen that initial and final setting times of Marble Powder and Limestone Quarry Dust incorporated pastes is less as compared to cement only paste while Marble Powder incorporated pastes are showing even less setting times than Limestone Quarry dust incorporated ones.

As LSQD contains limestone and in literature, the influence of limestone filler on cement hydration is in most cases considered to be limited due to the rate of the reactions. Several authors mention that the setting kinetic is improved, the dormant period is reduced and the hydration process within the first hours is accelerated [65,66]. Similarly, Marble Powder is also influencing the hydration kinetics, the filler particles promote sites of heterogeneous nucleation to precipitate more or less crystallized hydrates, and in this way accelerate the hydration [67]. This is due to higher $CaCO_3$ content reflected in terms of CaO, both MP and LSQD are based on

$CaCO_3$ and due to higher lime content in MP, setting is accelerated. Because, a higher CaO content indicates more nucleation sites for the preferential precipitation of hydration products. So, with the increase in amount of cement replacement by MP a more significant decrease in initial and final setting time can be observed resulting in reduced dormant period and higher peak of hydration as seen from calorimetry results shown in Figure 4-11.

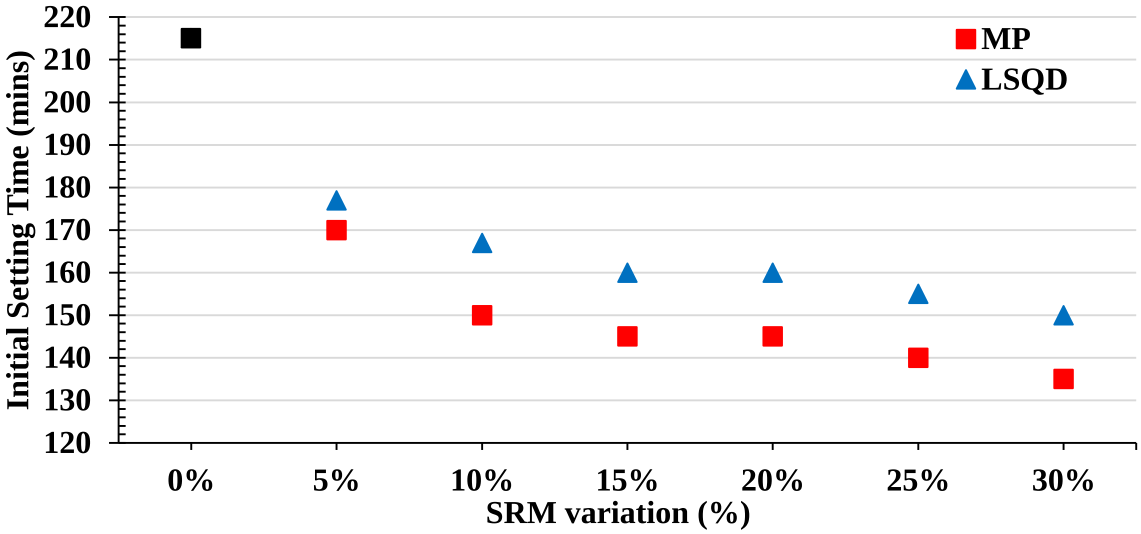


Figure 4-2: Initial Setting Times of Self-Compacting Paste Systems using MP and LSQD

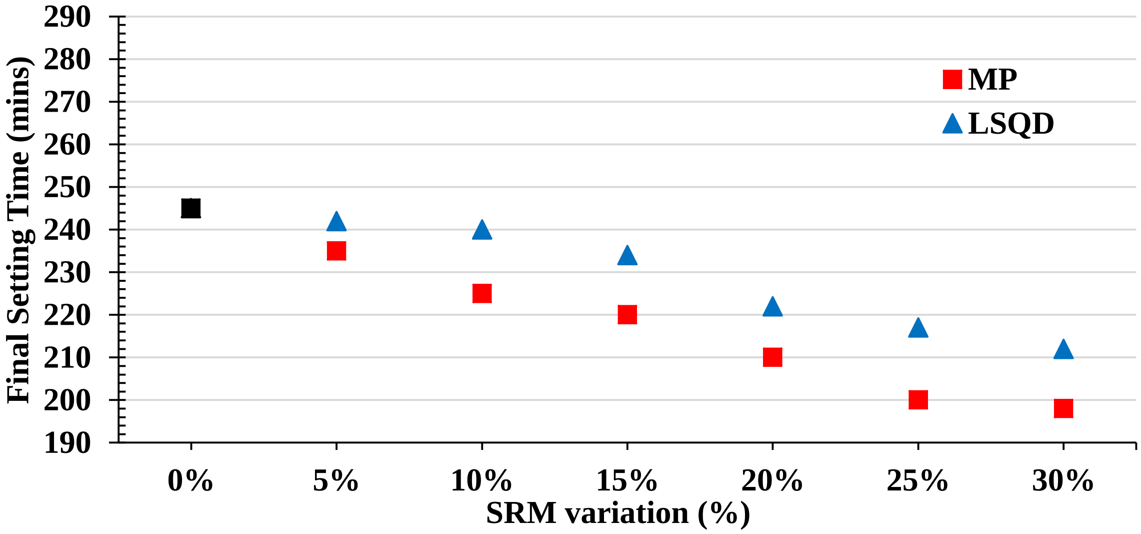


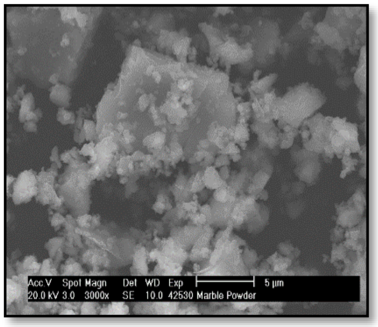
Figure 4-3: Final Setting Times of Self-Compacting Paste Systems using MP and LSQD

4.1.3 Flow Spread Test of SCP Systems

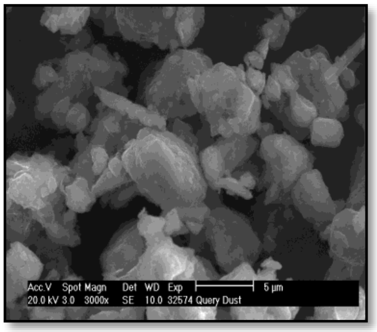
Figure 4-4 shows the super plasticizer (Melflux® 2651-F) requirement of the control self-compacting paste system (with cement only) and those with SRMs (MP and LSQD). This was obtained using Hagerman's mini slump cone. Super plasticizer requirement of control SCP systems (with cement only) is less as compared to SRMs incorporated self-compacting pastes. It can be seen that at same replacement level super plasticizer demand of MP is less as compared to LSQD and super plasticizer demand is increasing with increase in the replacement levels.

LSQD contains more than 64 percent CaO and limestone seems to adsorb super plasticizer in their bottle necks or porous surface pits making it inaccessible to the solution for dispersion purposes which confirms the higher super plasticizer demand of LSQD (24.49% porosity) than MP which has less porosity (19.99%) as shown in Table 4-1. LSQD contains dust particles, about 31 percent crystalline SiO_2, so it requires more super plasticizer for target flow of 30 cm.

Additionally, shape of particle also plays an important role for SP contents. So, irregular shape small sized LS particles and clay content in LSQD both require higher SP content. While MP particles are smoother than LSQD particles. So, there are two irregular components in LSQD while MP contains only one, thus resulting in higher SP content of MP than LSQD.



MarblePowder (Khurram Javed 2012)



Limestone Quarry Dust (Adnan Ahsan 2010)

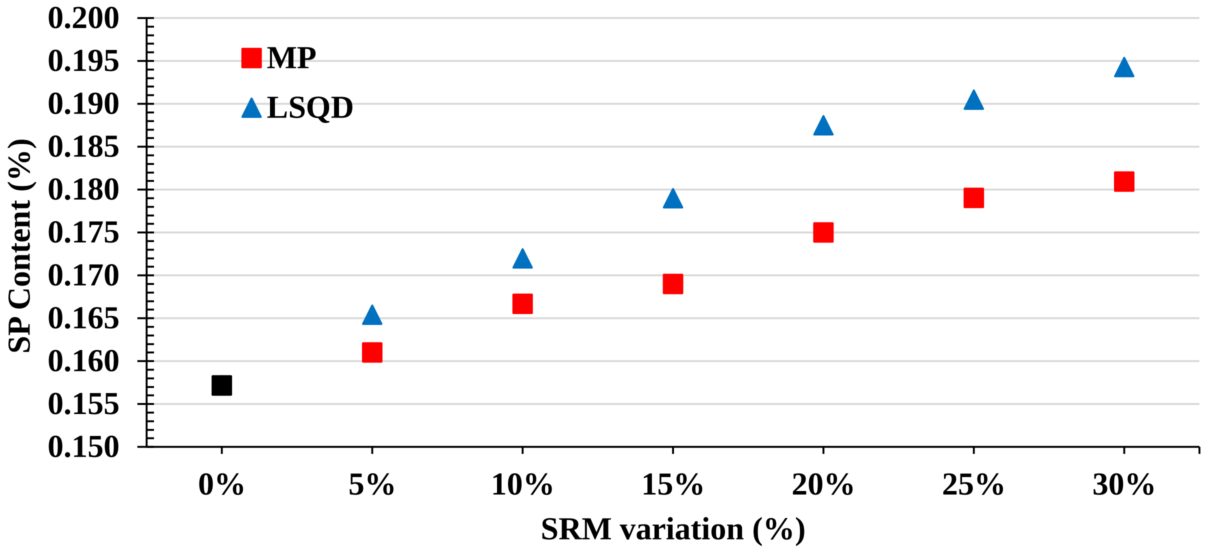


Figure 4-4: Super Plasticizer demand of the Self-Compacting Paste Systems using MP and LSQD

Figure 4-5 and figure 4-6 are showing the flow time for a spread of 25 cm and 30 cm for cement and varying amounts of MP and LSQD as cement replacements, measured by Hagerman’s mini slump cone. T-25 cm and T-30 cm time of cement are 2.14 and 12.90 respectively.

MP being very small in size offering a large surface area has the ability for consuming more water showed highest values for T30 cm time indicating a higher value of yield stress and higher viscosity as well. MP showed more slump flow times as compared to LSQD which can be attributed towards better packing, more rough texture and interlocking of the of the particles.

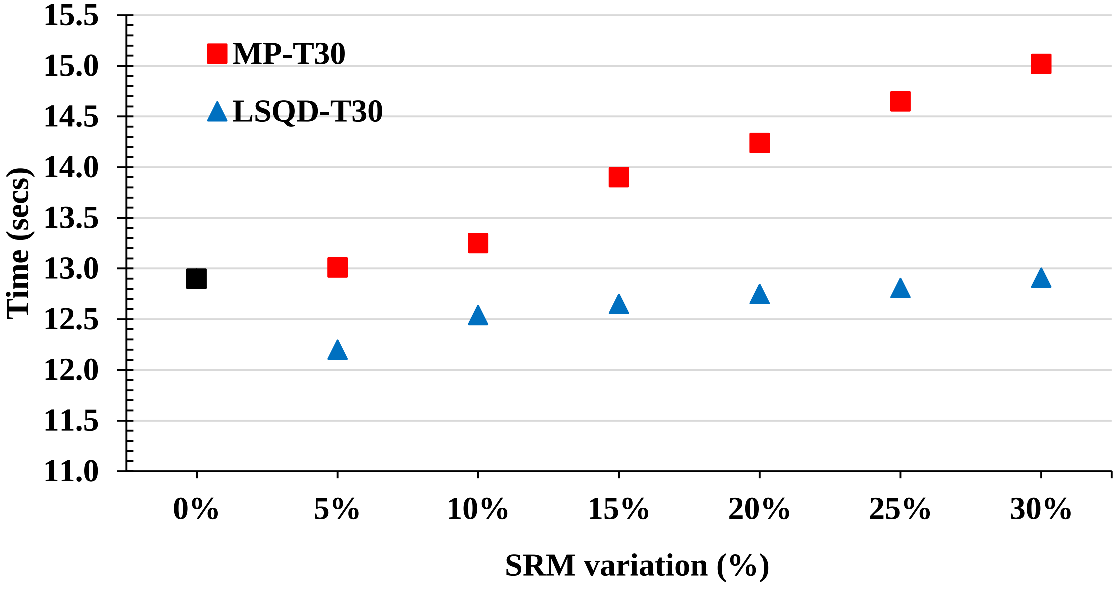


Figure 4-5: T-30 cm Flow Times of Self-Compacting Paste Systems

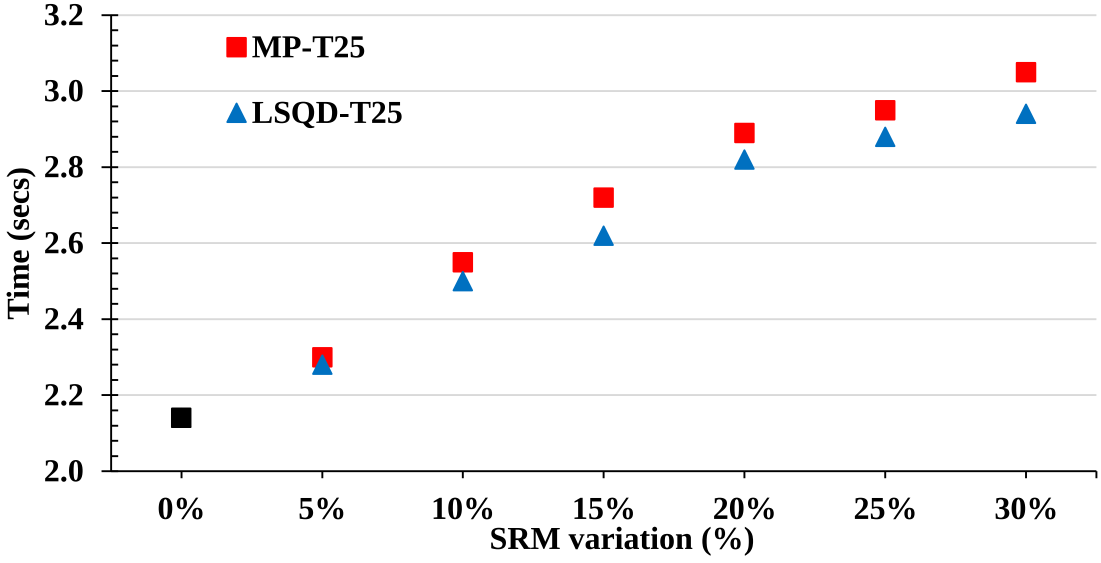


Figure 4-6: T-25 cm Flow Times of Self-Compacting Paste Systems

4.1.4 Strength Evaluation of SCP Systems

Figures 4-7 and 4-9 show the compressive strengths and Figures 4-8 and 4-10 show the flexural strengths of 4x4x16 cm^3 prisms containing SCP systems with cement only and varying amount of MP and LSQD as SRMs for 1,3,7,14,28 and 56 days respectively. It is observed here that 1, 3, 7 and 14 days compressive strength of marble powder containing systems is more as compared to only cement containing samples while LSQD formulations have less strength than cement only samples. It is also observed that MP containing formulations have more strength as compared to LSQD containing samples.

It can be seen that the total porosity as well as the volume intruded by mercury of LSQD based formulations is more than that of MP based ones and cement only samples. This shows that strengths of LSQD based formulations is less as compared to Cement and MP based SCP formulations.

Marble Powder produces the best nucleation sites, MP with 10% cement replacement shows the highest heat of hydration (Figure 4-11). Here physical packing effect and the nucleation sites are dominant at earlier ages which accelerates the hydration as it is clear from this figure 4-6 while dilution effect is dominant at later ages where neat cement based formulations give more strength. MIP conducted at 7 Days (Figure 4-12) confirms the higher 7 days strength as the amount of mercury intruded in MP is quiet low as compared to LSQD replaced formulations and control cement ones. The porosity for MP was 19.99 % whereas it was 24.49 % for LSQD and 25.33 % for control cement formulation at the same age. This indicates denser and less porous pore structure for MP replaced formulations and hence more strength as compared to the LSQD and control cement ones. While LSQD is decreasing strength at all replacement levels. Using LSQD from 0 to 30 percent as cement replacement in SCP system, the compressive strength drops at all ages. This is due to higher average pore radius and threshold diameters.

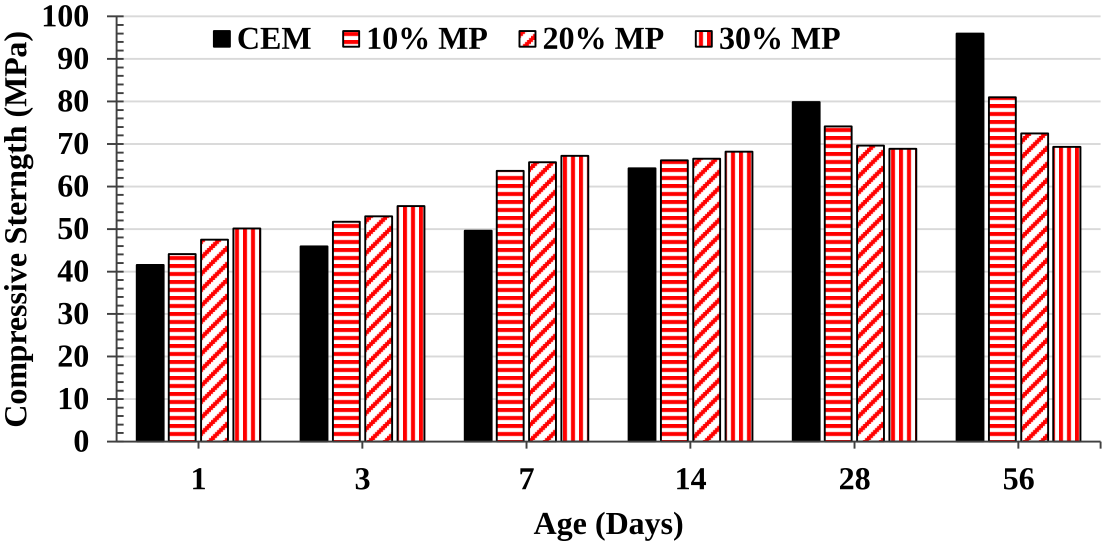


Figure 4-7: Compressive Strength of Self-Compacting Paste Systems by Varying MP content

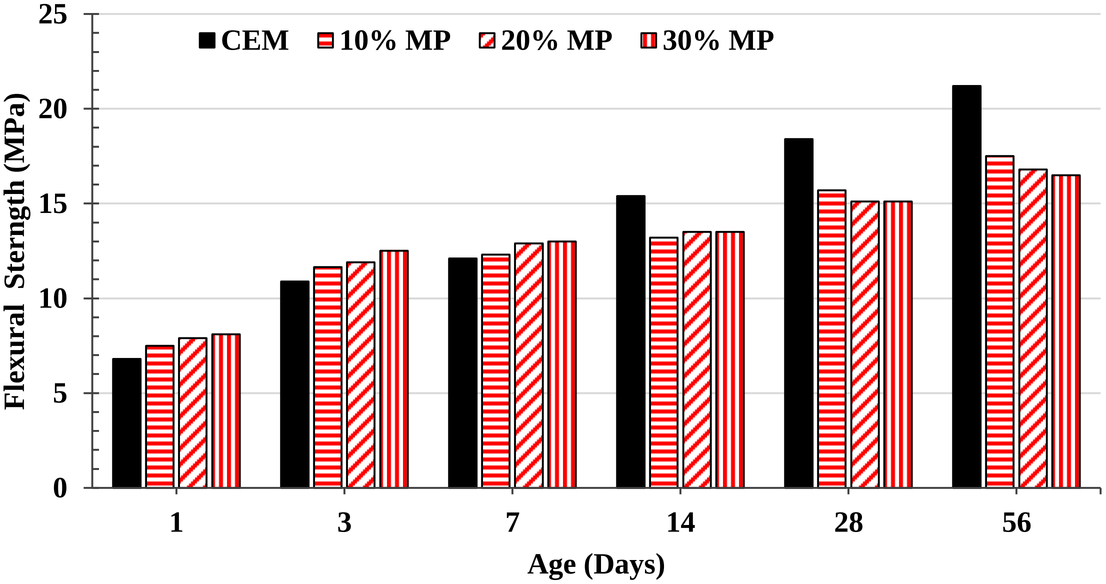


Figure 4-8: Flexural Strength of Self-Compacting Paste Systems by Varying MP content

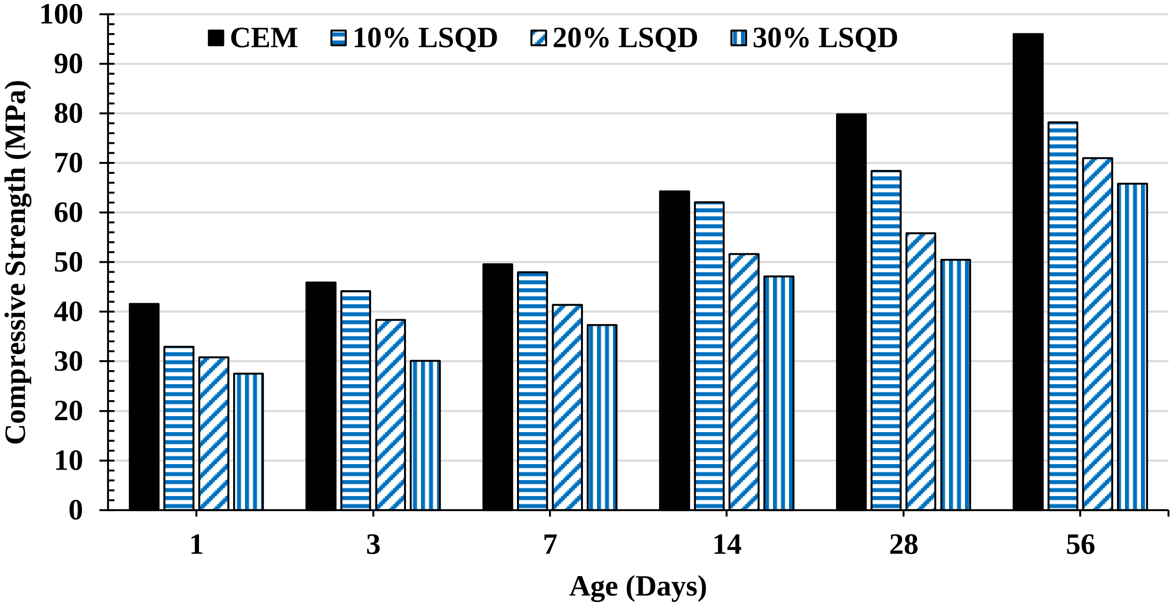


Figure 4-9: Compressive Strength of Self-Compacting Paste Systems by Varying LSQD content

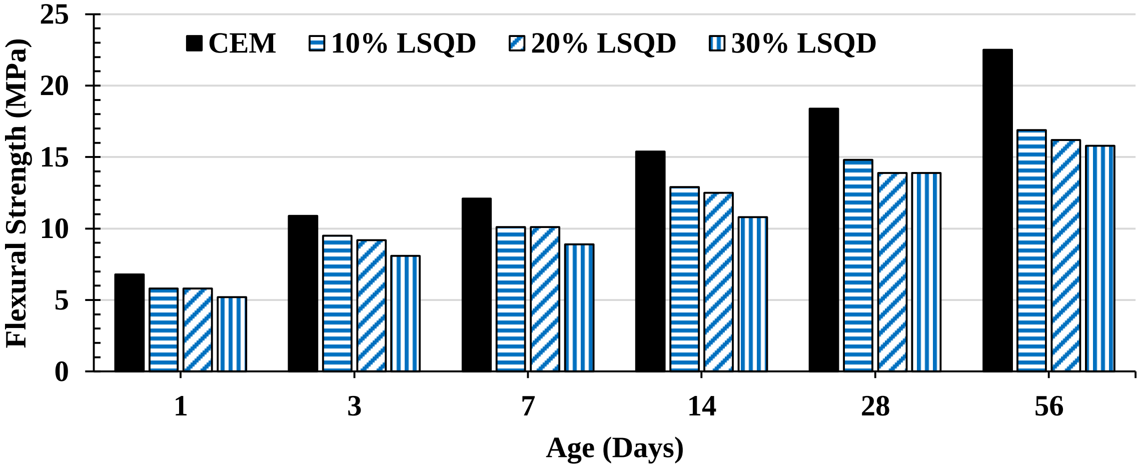


Figure 4-10: Flexural Strength of Self-Compacting Paste Systems by Varying LSQD content

4.1.5 Calorimetry of Self Compacting Paste Systems

The calorimetric study was done on paste systems containing cement only sample and secondary raw materials (SRMs) encompassing marble powder and Limestone Quarry Dust in 10 % cement replacement. The graph shown in Figure 4-11 shows the early setting times and high early strengths of marble powder containing samples as compared to cement only samples and limestone Quarry Dust based samples while late setting times and low early strengths of Limestone Quarry Dust containing samples.

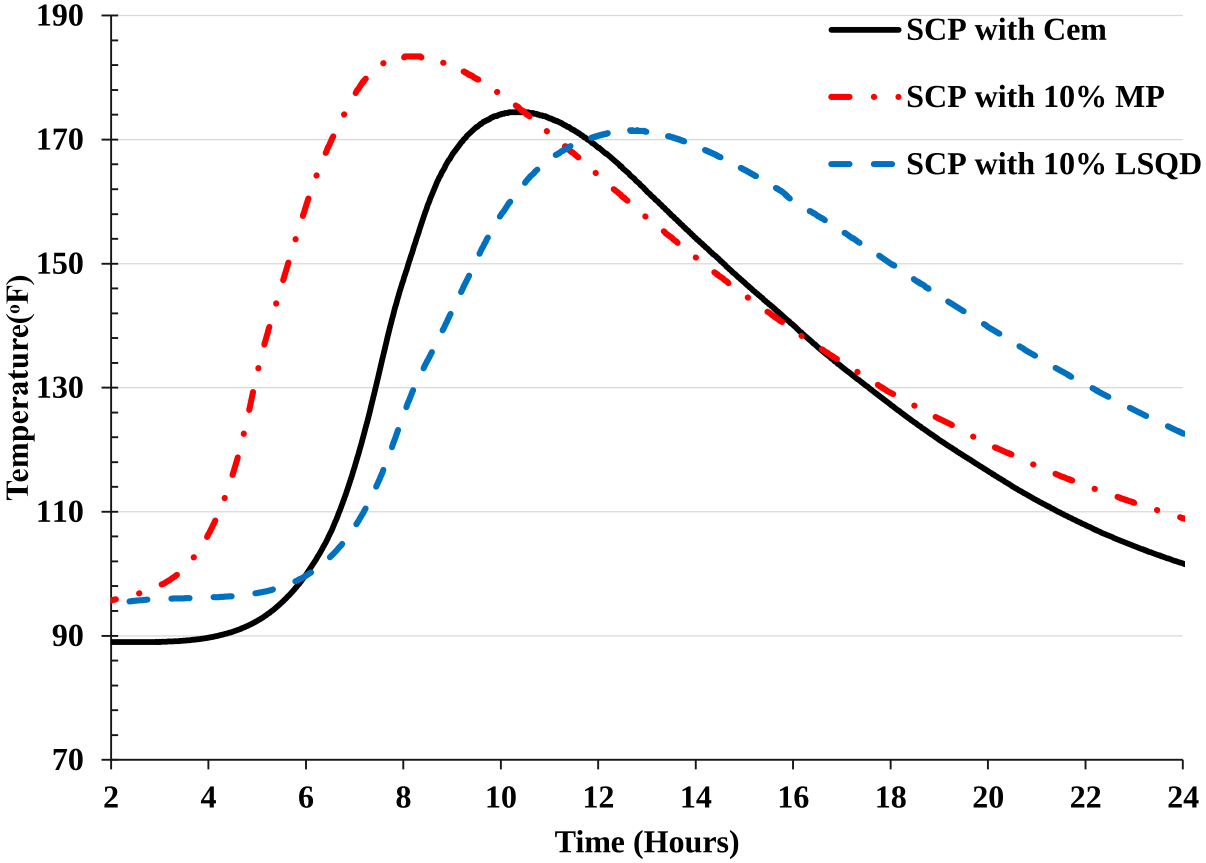


Figure 4-11: Calorimetry of Self-compacting paste systems

4.1.6 MIP of Self-Compacting Paste Systems

The MIP study was done on self-compacting paste systems containing cement only sample and secondary raw materials (SRMs) encompassing marble powder and Limestone Quarry Dust in 10 % cement replacement at the age of 7 days.

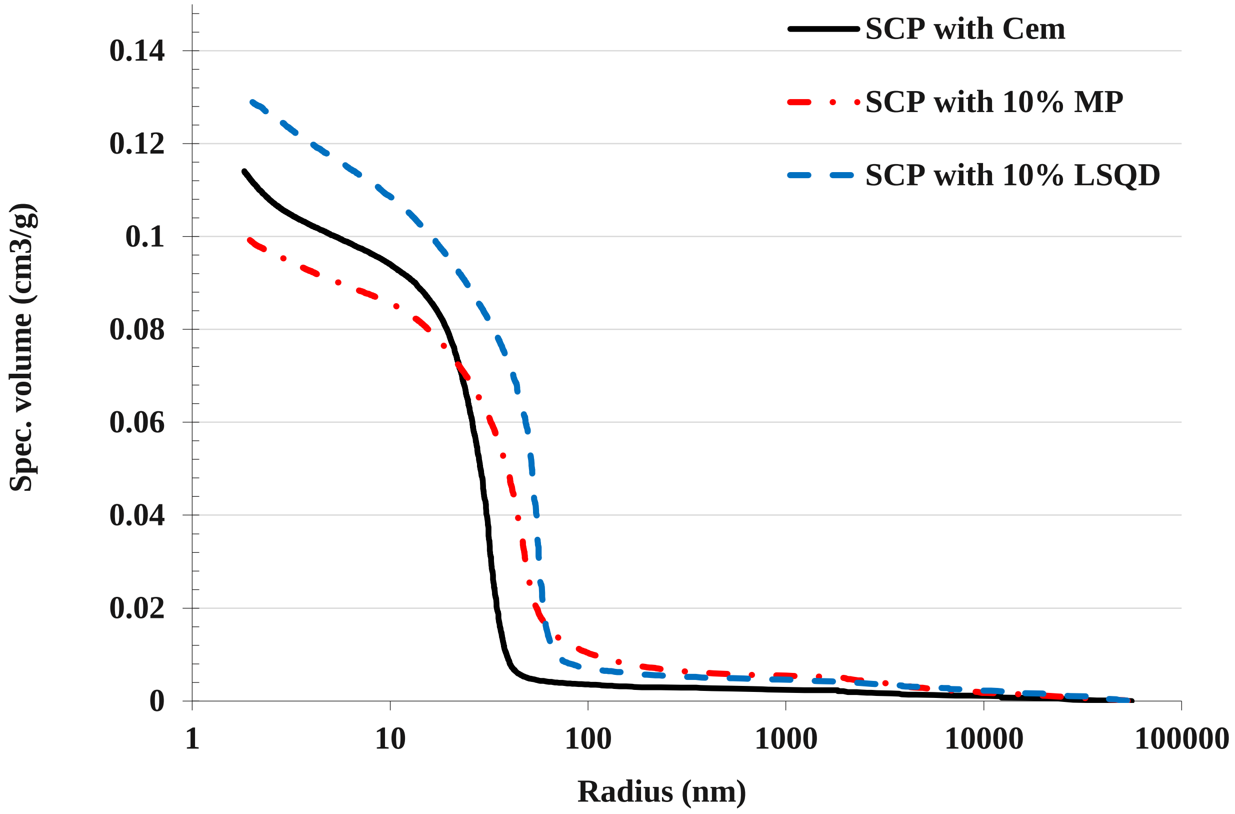


Figure 4-12: A typical Cumulative MIP curve of Self-Compacting Paste systems at 7 days

TABLE 4-1: MIP Data of SCP Systems Made at Respective Water Demands Based on Control Cement along with 10% MP and 10% LSQD Replaced Samples at 7 Days

	Cement	MP	LSQD
Average Pore Radius (Nanometer)	29.787	44.329	54.322
Total Porosity (%)	25.331	19.993	24.498
Bulk Density (g/cm^3)	2.220	1.998	1.876
Threshold Diameter (Nm)	43.5	60.15	77.5

4.1.7 Shrinkage of Self-Compacting Paste Systems

Figure 4-13 shows the shrinkage of the control self-compacting paste system (with cement only) and those with SRMs (MP and LSQD) as cement replacement. MP shows initial shrinkage up to an age of around 8 hours and thereafter they start showing reduction in shrinkage due to creation of ettringite and CaOH. Higher is the replacement level by MP and LSQD in SCP system, greater is the expansion. Similarly, SCP using LSQD for cement replacement show considerable expansion at around 20 to 30 percent replacement.

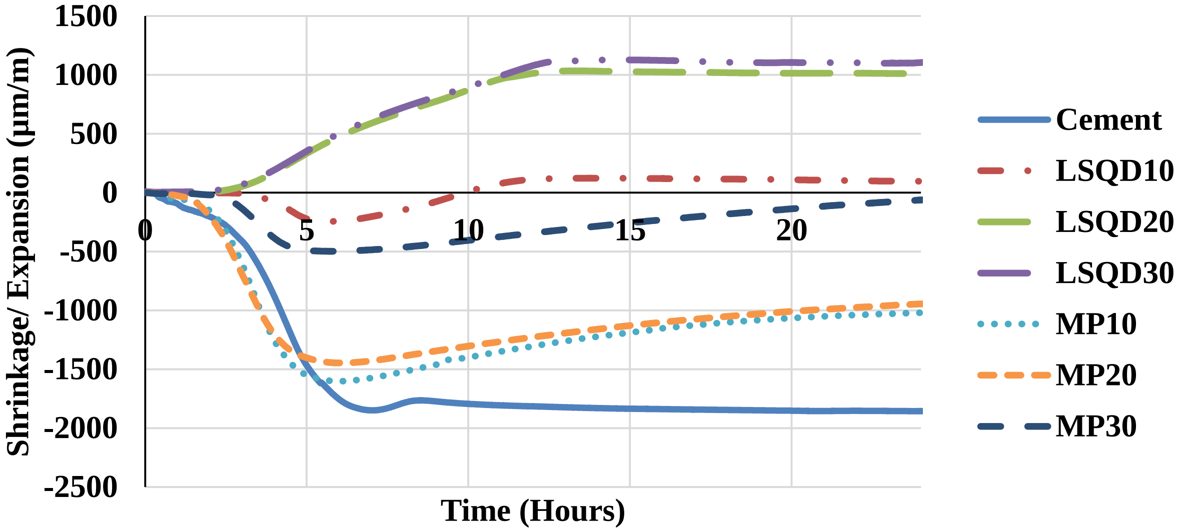


Figure 4-13: Shrinkage of Self-Compacting Paste systems

4.2 Self-Compacting Concrete Systems

4.2.1 Cone Flow Test of SCC Systems

Figure 4-14 shows the super plasticizer (Glenium® 51) requirement of the cement only concrete and SRMs (MP and LSQD) incorporated concretes along with concretes made from crushed stone aggregates (indicated by CS) and river gravel (indicated by RG) in addition to the above mentioned powders. Test was obtained using slump cone for a target flow of 70±1 cm. It can be observed that Super plasticizer requirement of cement only concretes is less as compared to SRMs incorporated concretes. It can be seen that SP requirement of MP and LSQD is increasing with increase in the replacement levels. While SP demand of MP incorporated concretes is less as compared to LSQD ones. Furthermore, concretes containing crushed stone aggregates require more SP as compared to river gravel ones.

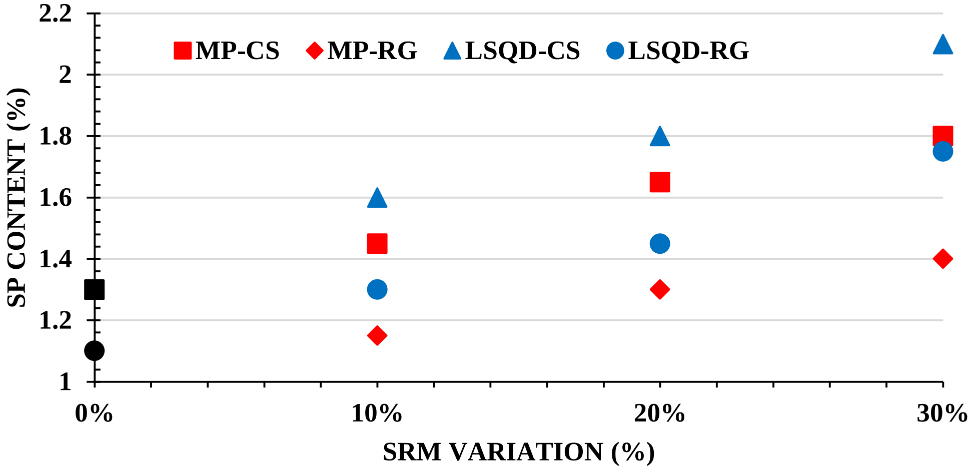


Figure 4-14: Super Plasticizer (Glenium® 51) demand of Self-Compacting Concrete Systems

It is clearly observed from above results that shape and texture of aggregate affects the properties of fresh concrete. Concrete is more workable when smooth and rounded aggregates are used instead of rough, angular or elongated aggregates. River gravel being round in shape and having smooth surface offered little friction and hence provided good workability and low super plasticizer content values as seen from the hatched lines showing river gravel aggregates in concrete. While on the other hand, when concretes were prepared with crushed stone aggregates, which being rough and angular provided friction and inter particles locking effect and hence less workability as seen from higher super plasticizer content values of the Figure 4-14.

Figure 4-15 shows the flow times for 50 cm and 70 cm of the cement only concrete and SRMs (MP and LSQD) incorporated concretes along with concretes made from crushed stone aggregates (indicated by CS) and river gravel (indicated by RG) in addition to the above stated powders. Test was carried out using slump cone. It can be seen that T50 cm and T70 cm times of MP and LSQD are increasing with increase in the replacement levels. While difference between T50 cm and T70 cm times of MP incorporated concretes and LSQD ones is negligible. It can also be observed that T50 cm and T70 cm times of crushed stone aggregates is more as compared to river gravels one. River gravel being round in shape and having smooth surface offered little friction and hence provided good workability and low T50 cm and T70 cm values while concretes prepared with crushed stone aggregates, which being rough and angular provided friction and inter particles locking effect and hence less workability as seen from higher T50 cm and T70 cm values as seen from Figure 4-15.

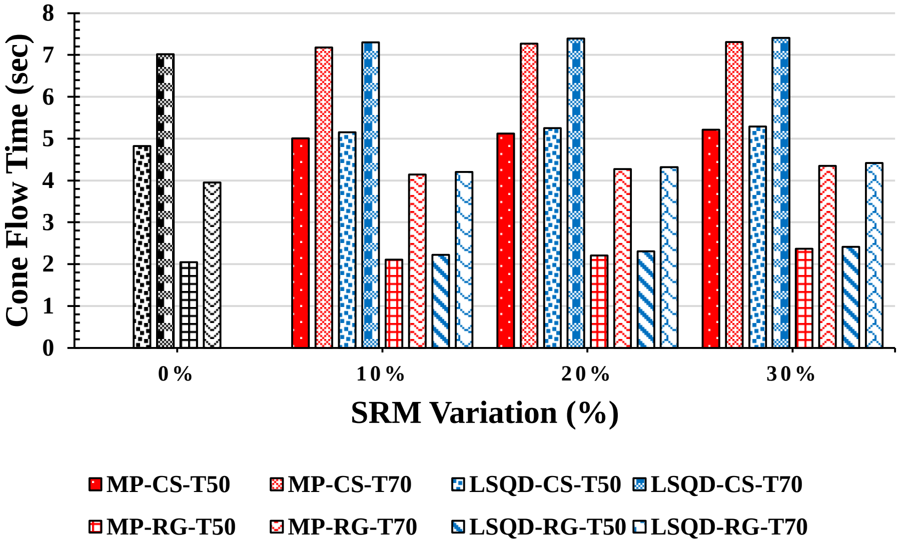


Figure 4-15: T50 cm and T70 cm flow times of Self-Compacting Concrete Systems

4.2.2 V-Funnel Flow Test of SCC Systems

Figure 4-16 shows the V-funnel times of the cement only concrete and those with SRMs (MP and LSQD) along with concretes made from crushed stone aggregates (indicated by CS) and river gravel (indicated by RG) in addition to the above mentioned powders. It can be seen that V-funnel times of MP and LSQD are increasing with increase in the replacement levels. While difference between V-funnel times of MP incorporated concretes and LSQD ones is negligible. It can also be observed that V-funnel times of crushed stone aggregates is more as compared to river gravels one. The reason is same as rough and angular crushed stone aggregates surface provides more friction due to the inter particles locking as compared to the smooth and round river gravels.

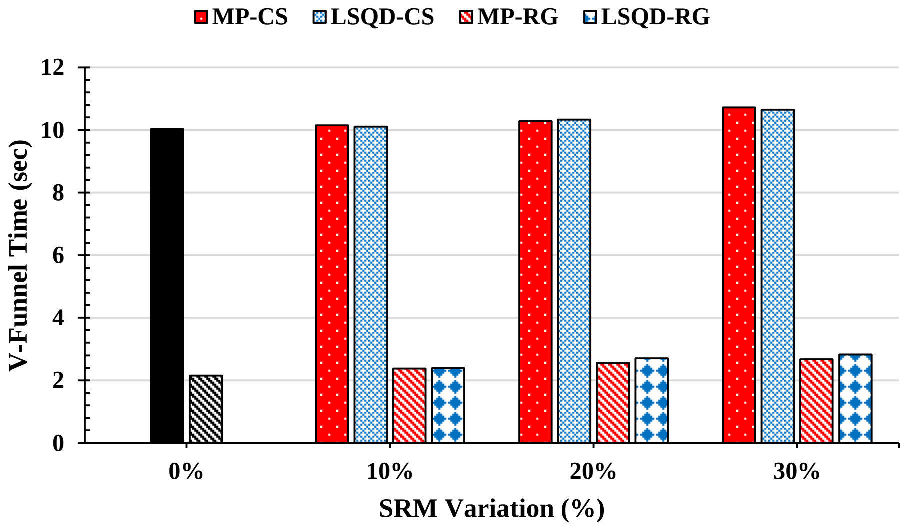


Figure 4-16: V-Funnel times of Self-Compacting Concrete Systems

Slump flow T_{50} cm time and V-funnel relation is shown in Figure 4-17 for river gravel containing concretes. V-funnel indicates viscosity and slump flow T-50 cm time seems to be predominantly indicating viscosity.

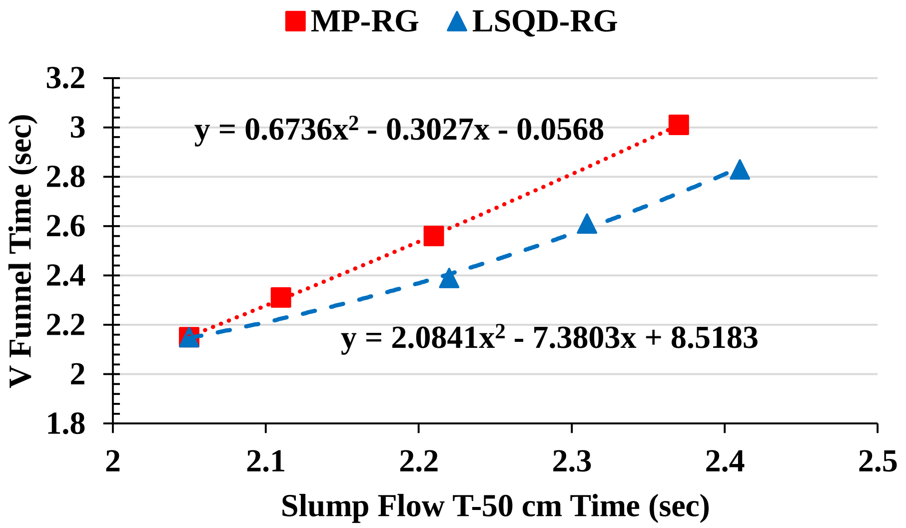


Figure 4-17: Trend of Slump Flow T50 and V-Funnel flow times of SCCS containing River Gravel along with SRM variation

4.2.3 J-Ring Flow Test of SCC Systems

Figure 4-18 shows the J-Ring T50 cm flow times of the cement only concrete and those with SRMs (MP and LSQD) along with concretes made from crushed stone aggregates (indicated by CS) and river gravel (indicated by RG) in addition to the above mentioned powders. It can be seen that J-Ring T50 cm flow times of MP and LSQD are increasing with increase in the replacement levels. While J-Ring T50 cm flow times of MP incorporated concretes and LSQD ones is negligible. It can also be observed J-Ring T50 cm flow times of crushed stone aggregates is more as compared to river gravels one as rough and angular crushed stone aggregates surface provides more friction due to the inter particles locking as compared to the smooth and round river gravels.

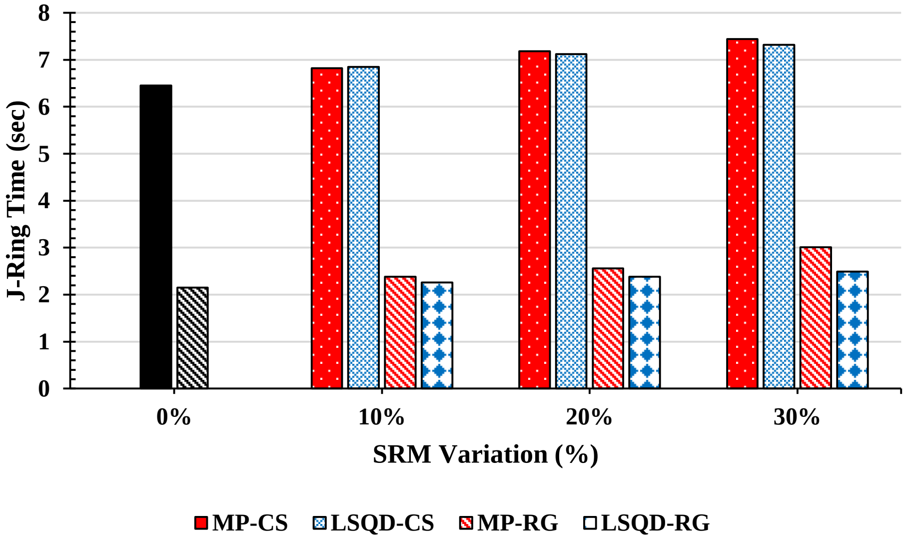


Figure 4-18: J-Ring T50 cm time of Self-Compacting Concrete Systems

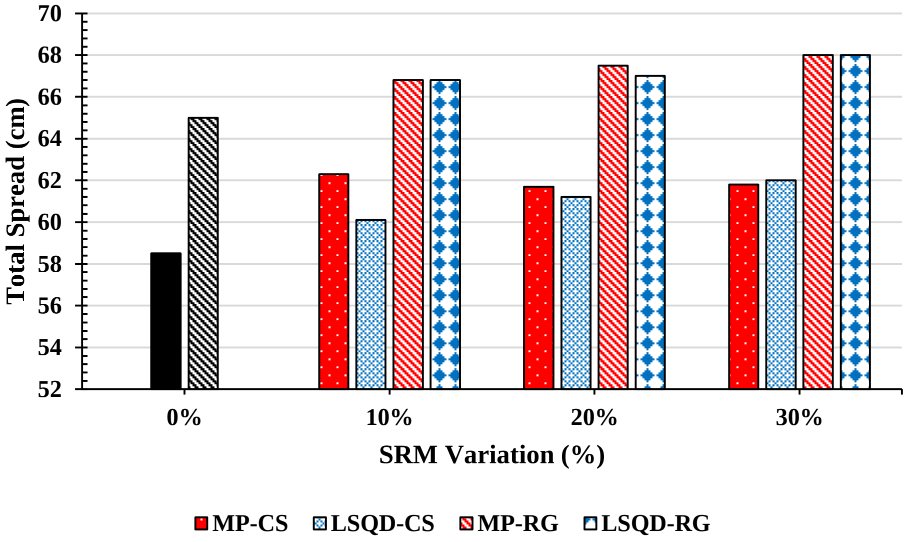


Figure 4-19: J-Ring Total Spread of Self-Compacting Concrete Systems

Slump flow T_{50} cm time and J-Ring T-50 time relation is shown in Figure 4-20 for river gravel containing concretes.

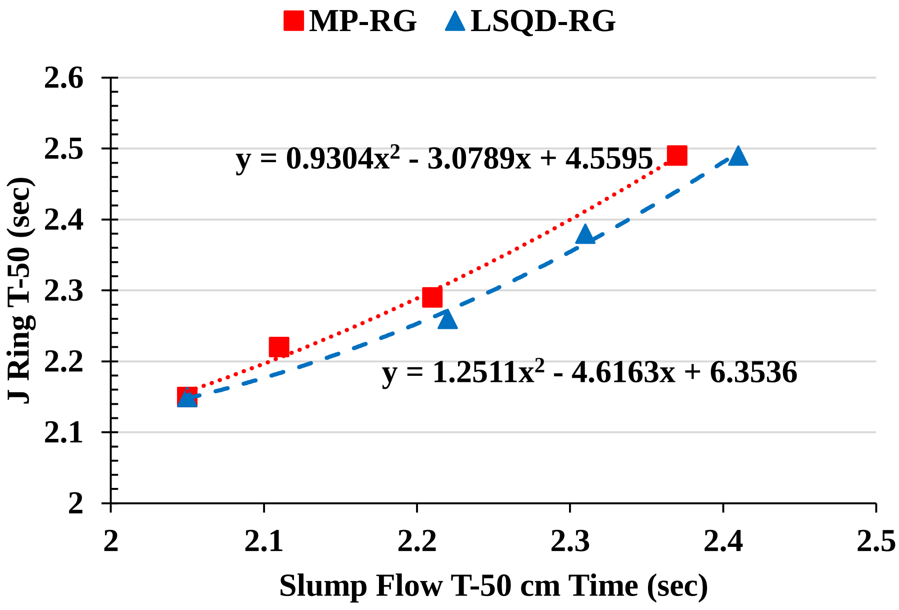


Figure 4-20: Trend of Slump Flow T50 cm and J-Ring T-5o cm times of SCCS containing River Gravel along with SRM variation

4.2.4 Strength Evaluation of SCC Systems

BS EN 12390-1 was used to evaluate the compressive strength of 4”x4”x4” SCC cubes while EN 196 was used for evaluating compressive and flexural strength of SCC prisms. Figure 4-21 to Figure 4-23 shows the self-compacting concretes containing cement and MP (as cement replacement) while Figure 4-24 to Figure 4-26 shows the self-compacting concretes containing cement and LSQD (as cement replacement) along with aggregates comprising crushed stone aggregates and river gravel. It can be seen that MP and LSQD containing concretes compressive strengths are decreasing with increase in the replacement levels. While compressive strengths of MP incorporated concretes is about 10 to 15% more as compared to LSQD ones based on the same replacement level. It can also be observed that compressive strengths of crushed stone aggregates is about 12% more as compared to river gravels one. Aggregate surface texture is one of the most important factors that affect matrix–aggregate bond strength, with rougher aggregates having superior bonds. Bond development depends on two things, exposed surface of aggregates and friction between aggregates. Thus, when concretes were prepared with crushed stone aggregates, their rough surface texture and angular shape gives more exposed surface area for bonding and enhanced mechanical interlocking, thus resulting in increased concrete strength and toughness. While, gravel aggregates having round and smooth surface of particles, gives less exposed surface area for bonding and less friction between aggregate particles, resulting in lower bonding strength with the matrix with main failure mechanism included extensive debonding.

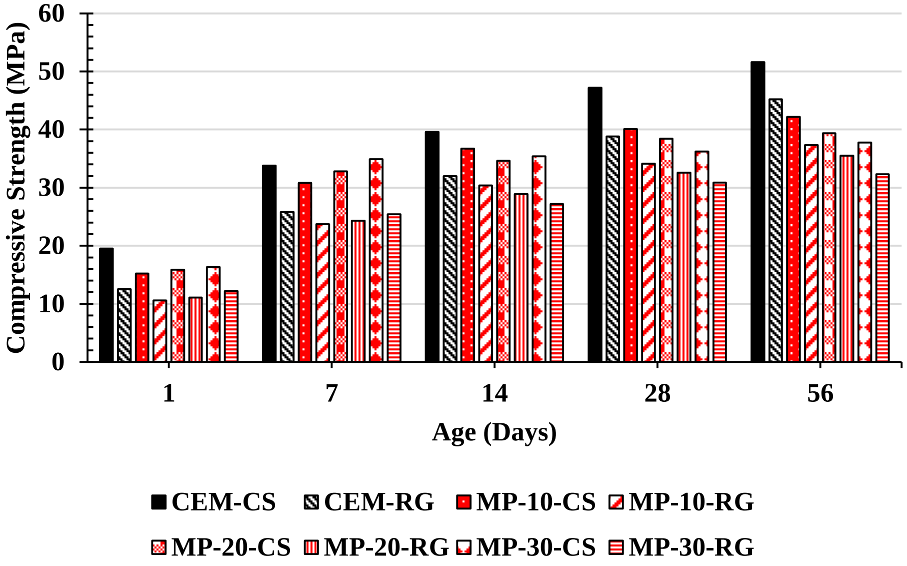


Figure 4-21: Compressive Strength of Self-Compacting Concrete Cubes by varying MP content

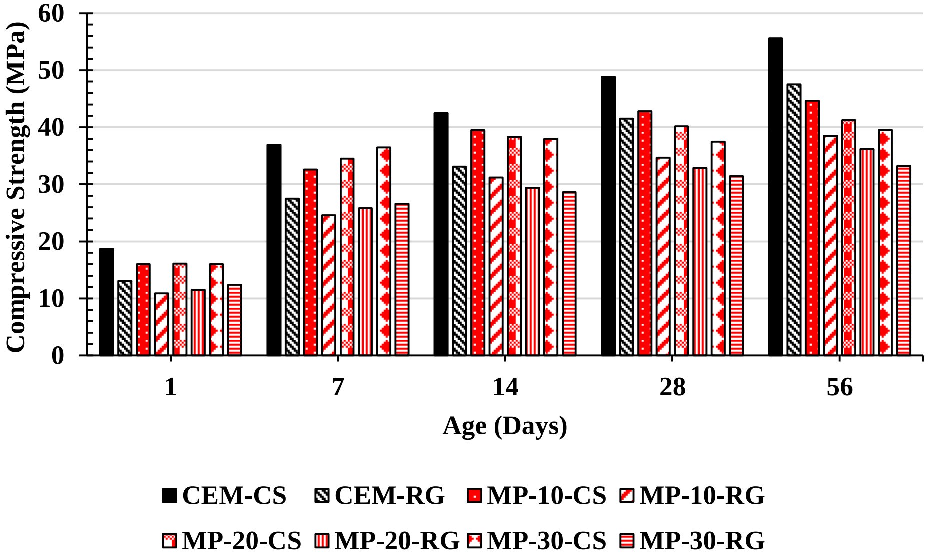


Figure 4-22: Compressive Strength of Self-Compacting Concrete Prisms by varying MP content

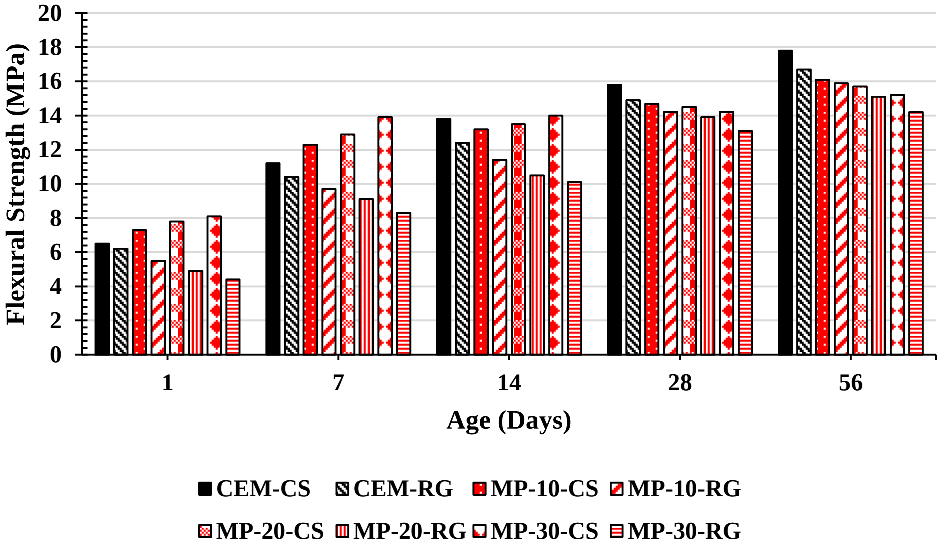


Figure 4-23: Flexural Strength of Self-Compacting Concrete Prisms by varying MP content

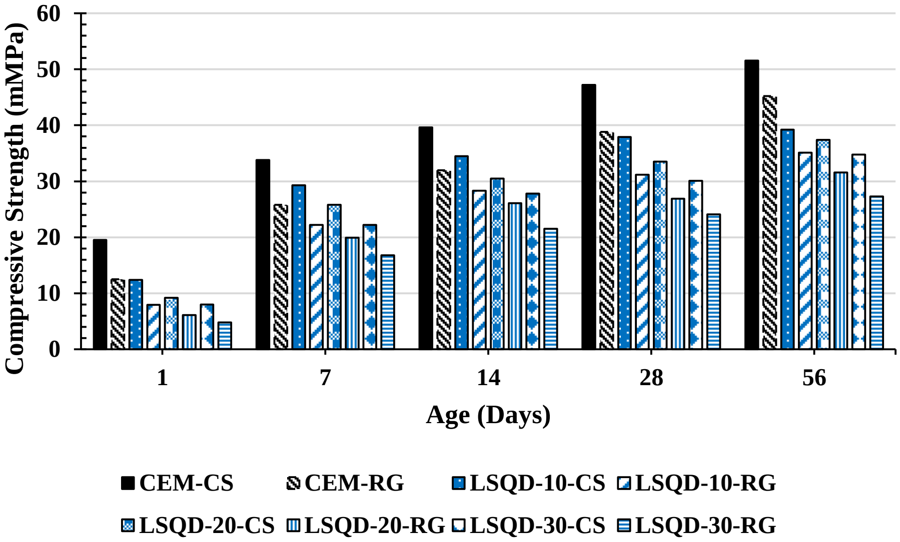


Figure 4-24: Compressive Strength of Self-Compacting Concrete Cubes by varying LSQD content

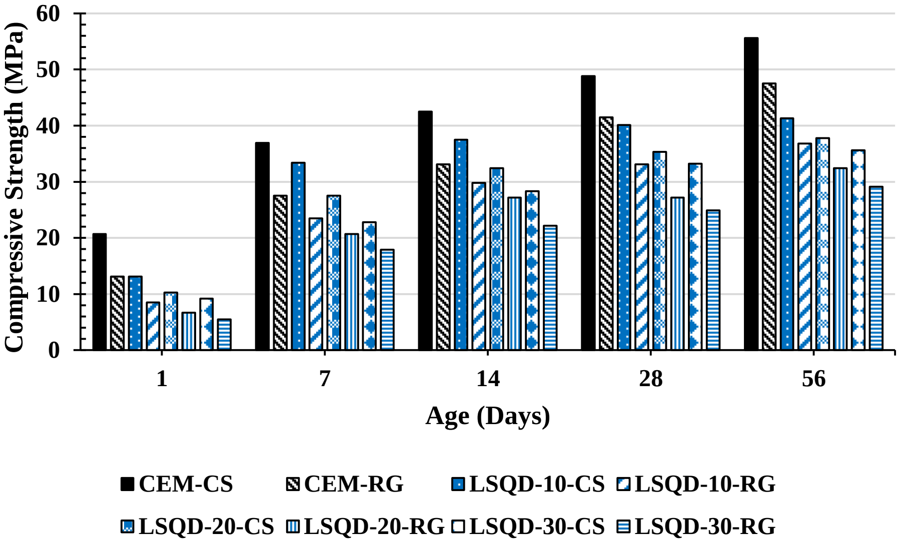


Figure 4-25: Compressive Strength of Self-Compacting Concrete Prisms by varying LSQD content

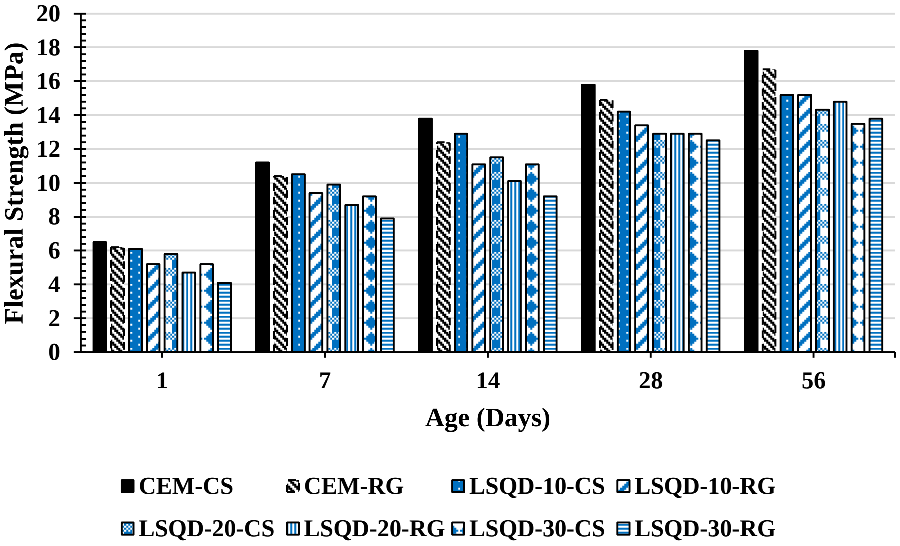


Figure 4-26: Flexural Strength of Self-Compacting Concrete Prisms by varying LSQD content

CHAPTER 5: CONCLUSIONS

Following are the salient conclusions extracted from the report:

1. 10% replacement of cement by any SRM gives optimum results in self-compacting paste and concrete systems.
2. MP showed reduced water demand along with higher slump flow times in both SCP and SCC systems as compared to LSQD.
3. LSQD when incorporated as SRM in SCPS gives lower strength than the control system at all ages and at all replacement levels.
4. In SCP systems, MP incorporated formulations are showing more strengths up to 14 days as compared to control systems and LSQD incorporated ones.
5. MP containing formulations give 10% more strength at all ages investigated as compared to LSQD containing ones based on replacement level in both SCP and SCC systems.
6. Control cement systems have final strength more as compared to both MP and LSQD containing ones at from 28 days onwards in case of SCP systems.
7. In SCC systems, neat cement containing formulations have more strength at all ages as compared to the SRMs (MP and LSQD) containing ones.
8. MP seems to be better local SRM than LSQD.
9. Self-compacting concrete systems containing river gravels give better flow indices than crushed stone aggregate ones.
10. Self-compacting concrete systems containing crushed stone aggregates have 12 to 14 percent higher strengths than the systems with river gravels of the similar grading.2

CHAPTER 6: RECOMMENDATIONS

1. River gravel may be preferred to crushed stone aggregates in making SCC based on the strength and workability results.
2. Different combinations of crushed stone aggregates and river gravels should be used to o optimize fresh and hardened properties of SCC.
3. Further investigations on other locally available coarse aggregates and secondary raw materials should be carried out in self-compacting concrete system so that high performance concrete with low cost can be produced locally and will also contribute towards an environment friendly construction.
4. Advanced testing facilities for concrete materials should be setup in Pakistan for the advancement of local research.
5. Relation between response of SCP and SCC systems should be established in similar parameters.

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Annexure-A

Materials

TABLE A-1: Properties of BEST WAY Cement

Tests	**Test Results**	**Specifications**
Specific Gravity	3.10	ASTM C 188
Standard Consistency	26.5	ASTM C 187
Initial Setting Times	215 min at 21 ºC	ASTM C 191
Final Setting Times	245 min at 21 ºC	ASTM C 191

TABLE A-2: Properties of Used Lawrencepur Sand

Tests	**Test Results**	**Specifications**
Bulk Specific Gravity (Natural)	2.97	ASTM C 128
Bulk Specific Gravity (SSD)	2.89	ASTM C 128
Absorption Capacity	1.42 %	ASTM C 128
Fineness Modulus (Natural)	2.19	ASTM C 33
Fineness Modulus (Altered)	2.61	ASTM C 33
Gradation	Figure.3-3	ASTM C 136

TABLE A-3: Properties of Crushed Stone Aggregates

Tests	**Test Results**	**Specifications**
Bulk Specific Gravity (Natural)	2.78	ASTM C 127
Bulk Specific Gravity (OD)	2.76	ASTM C 127
Bulk Specific Gravity (SSD)	2.78	ASTM C 127
Absorption Capacity	0.30%	ASTM C 127
Gradation	Figure.3-3	ASTM C 136

TABLE A-4: Properties of Used River Gravels

Tests	**Test Results**	**Specifications**
Apparent Specific Gravity	2.92	ASTM C 127
Bulk Specific Gravity (OD)	2.89	ASTM C 127
Bulk Specific Gravity (SSD)	2.91	ASTM C 127
Absorption Capacity	0.27%	ASTM C 127
Gradation	Figure.3-3	ASTM C 136

TABLE A-5: ASTM Gradation of Used Sand

Sieve Number	Sieve size (mm)	Weight retained	Percentage retained	Cumulative Percentage Retained	Percentage passing	ASTM min Percentage passing	ASTM max Percentage passing
#4	4.75	0	0	0	100	95	100
#8	2.36	5.5	0.55	0.55	99.45	80	100
#16	1.18	40.5	4.05	4.60	95.4	50	85
#30	0.6	305.5	30.59	35.19	64.81	25	60
#50	0.3	475.5	47.60	82.79	17.21	10	30
#100	0.15	135.5	13.57	96.36	3.64	2	10
Pan	-	36.35	3.64	100	0	0	0
Total weight retained		998.9	F.M	2.19	-	-	-

TABLE A-6: ASTM Gradation of Coarse Aggregate

Sieve Number	Sieve Size (mm)	Weight Retained (gm)	Percentage Retained	Cumulative Percentage Retained	Percentage Passing	ASTM minimum Passing	ASTM maximum Passing
# 8	2.36	100	10.00	100.00	0.00	0.00	5.00
# 4	4.75	400	40.00	90.00	10.00	0.00	15.00
$^{3}/_{8}$ inch	9.5	400	40.00	50.00	50.00	40.00	70.00
$^{1}/_{2}$ inch	12.5	100	10.00	10.00	90.00	90.00	100.00
$^{3}/_{4}$ inch	19.5	0	0.00	0.00	100.00	100.00	100.00
1 inch	25	0	0.00	0.00	100.00	100.00	100.00
Total weight Retained		1000	100.00	-	-	-	-

Annexure-B

Self-Compacting Paste System (SCPS)

TABLE B-1: Water Demand and Setting Times of Self-Compacting Paste Systems

SRM Variation	LSQD			MP		
	WD	**IST**	**FST**	**WD**	**IST**	**FST**
0%	26.5	215	245	26.5	215	245
5%	27.5	177	242	27	170	235
10%	29.5	167	240	28	150	225
15%	30.5	160	234	29.5	145	220
20%	32	160	222	31.5	145	210
25%	33.5	155	217	33	140	200
30%	35.25	150	212	35	135	198

TABLE B-2: SP Content and Flow Times of Self-Compacting Paste Systems

SRM Variation	LSQD			MP		
	SP	**T25 cm**	**T30 cm**	**SP**	**T25 cm**	**T30 cm**
0%	0.157	2.14	12.90	0.157	2.14	12.90
5%	0.165	2.28	12.20	0.161	2.30	13.01
10%	0.172	2.50	12.54	0.167	2.55	13.25
15%	0.179	2.62	12.65	0.166	2.72	13.90
20%	0.188	2.82	12.75	0.175	2.89	14.24
25%	0.190	2.88	12.81	0.179	2.95	14.65
30%	0.194	2.94	12.91	0.175	3.05	15.02

TABLE B-3: Compressive Strength of Self-Compacting Paste Systems by Varying MP Content Using 4x4x16 cm^3 Prisms (EN 196-1)

SRM Variation	DAYS					
	1	**3**	**7**	**14**	**28**	**56**
0%	41.55	45.88	49.57	64.26	79.84	96
5%	46	49.12	56.53	57.56	66.63	71.1
10%	44.12	51.68	63.7	66.13	74.11	81
15%	45.73	52.67	64.3	65.33	68.4	73.6
20%	47.5	53.01	65.7	66.53	69.6	72.5
25%	48.32	54.33	66.8	67.2	68.32	70.32
30%	50.1	55.38	67.20	68.21	68.9	69.35

TABLE B-4: Flexural Strength of Self-Compacting Paste Systems by Varying MP Content Using 4x4x16 cm^3 Prisms (EN 196-1)

SRM Variation	DAYS					
	1	3	7	14	28	56
0%	6.8	10.88	12.1	15.4	18.4	21.2
5%	7	11	12.3	13.2	15.7	18.2
10%	7.5	11.65	12.3	13.2	15.7	17.5
15%	7.5	11.82	12.9	13.5	15.9	17.5
20%	7.9	11.9	12.9	13.5	15.1	16.8
25%	8	12.5	13	13.5	15.1	16.8
30%	8.1	12.5	13	13.5	15.1	16.5

TABLE B-5: Compressive Strength of Self-Compacting Paste Systems by Varying LSQD Content Using 4x4x16 cm^3 Prisms (EN 196-1)

SRM Variation	DAYS					
	1	3	7	14	28	56
0%	41.55	45.88	49.57	64.26	79.84	96
5%	38.68	47.2	62.37	67.8	71.46	78.4
10%	32.95	44.12	47.93	62.1	68.4	78.2
15%	31.87	42.02	44.7	54.3	60.5	74.32
20%	30.79	38.33	41.4	51.6	55.8	70.98
25%	28.9	37.24	38.9	48.5	53.21	68.2
30%	27.5	30.1	37.32	47.1	50.5	65.8

TABLE B-6: Flexural Strength of Self-Compacting Paste Systems by Varying LSQD Content Using 4x4x16 cm^3 Prisms (EN 196-1)

SRM Variation	DAYS					
	1	3	7	14	28	56
0%	6.8	10.88	12.1	15.4	18.4	22.5
5%	6.5	10.2	10.5	12.9	15.2	18.8
10%	5.8	9.5	10.1	12.9	14.8	16.9
15%	5.8	9.2	10.1	12.5	14.8	16.9
20%	5.8	9.2	10.1	12.5	13.9	16.2
25%	5.2	8.1	8.9	10.8	13.9	16.2
30%	5.2	8.1	8.9	10.8	13.9	15.8

Annexure-C

Self-Compacting Concrete Systems (SCCS)

TABLE C-1: SP Content & Slump Flow Times of Self-Compacting Concrete Systems Using Crushed Stone Aggregates

SRM Variation	**LSQD**			**MP**		
	SP	**T50 cm (sec)**	**T70 cm (sec)**	**SP**	**T50 cm (sec)**	**T70 cm (sec)**
0%	1.3	4.82	7.02	1.3	4.82	7.02
10%	1.6	5.15	7.3	1.45	5.01	7.18
20%	1.8	5.25	7.39	1.65	5.12	7.27
30%	2.1	5.29	7.41	1.8	5.21	7.31

TABLE C-2: SP Content & Slump Flow Times of Self-Compacting Concrete Systems Using River Gravels

SRM Variation	**LSQD**			**MP**		
	SP	**T50 cm (sec)**	**T70 cm (sec)**	**SP**	**T50 cm (sec)**	**T70 cm (sec)**
0%	1.1	2.05	3.95	1.1	2.05	3.95
10%	1.3	2.22	4.2	1.15	2.11	4.14
20%	1.45	2.31	4.32	1.3	2.21	4.27
30%	1.75	2.41	4.42	1.4	2.37	4.35

TABLE C-3: Fresh Properties of Fresh SCC Mixes

SCC Mix	**Slump Time T50 in s**	**V- Funnel Time in s**	**L-Box Time in s/ h2/h1**	**J-Rimg T50 in s/ spread in cm**
CEM-CS	4.82	10.03	7.01/0.9	6.45/58.5
MP-10-CS	5.01	10.15	7.32/0.94	6.82/62.3
MP-20-CS	5.12	10.28	7.49/0.89	7.18/61.7
MP-30-CS	5.21	10.72	7.55/0.87	7.44/61.8
LSQD-10-CS	5.15	10.11	7.35/0.89	6.85/60.1
LSQD-20-CS	5.25	10.33	7.54/0.93	7.12/61.2
LSQD-30-CS	5.29	10.65	7.69/0.96	7.32/62
CEM-RG	2.05	2.15	3.17/0.85	2.15/65
MP-10-RG	2.11	2.38	3.21/0.91	2.38/66.8
MP-20-RG	2.21	2.56	3.33/0.88	2.56/67.5
MP-30-RG	2.37	2.67	3.42/0.87	3.01/68
LSQD-10-RG	2.22	2.26	3.17/0.90	2.26/66.8
LSQD-20-RG	2.31	2.38	3.32/0.88	2.38/67
LSQD-30-RG	2.41	2.49	3.44/0.90	2.49/68

TABLE C-4: Compressive Strength of Self-Compacting Concrete Cubes by Using Crushed Stone Aggregates and Varying LSQD Content

SRM Variation	Compressive strength of 4x4x4 inch^3 SCC Cubes (BS EN 12390-1) (MPa)				
	1	7	14	28	56
CEM only	19.5	33.8	39.6	47.2	51.58
10%	12.4	29.3	34.5	37.9	39.2
20%	9.2	25.8	30.5	33.5	37.39
30%	8	22.2	27.8	30.1	34.75

TABLE C-5: Compressive Strength of Self-Compacting Concrete Cubes by Using River Gravels and Varying LSQD Content

SRM Variation	Compressive strength of 4x4x4 inch^3 SCC Cubes (BS EN 12390-1) (MPa)				
	1	7	14	28	56
CEM only	12.5	25.8	32	38.8	45.2
10%	7.9	22.2	28.3	31.2	35.1
20%	6.1	19.9	26.1	26.9	31.6
30%	4.8	16.8	21.5	24.1	27.3

TABLE C-6: Compressive Strength of Self-Compacting Concrete Prisms by Using Crushed Stone Aggregates and Varying LSQD Content

SRM Variation	Compressive strength of 4x4x16 cm^3 SCC Prisms (EN 196-1) (MPa)				
	1	7	14	28	56
CEM only	20.7	36.9	42.5	48.8	55.58
10%	13.1	33.4	37.5	40.1	41.3
20%	10.3	27.5	32.4	35.3	37.8
30%	9.2	22.8	28.3	33.2	35.64

TABLE C-7: Compressive Strength of Self-Compacting Concrete Prisms by Using River Gravels and Varying LSQD Content

SRM Variation	Compressive strength of 4x4x16 cm^3 SCC Prisms (EN 196-1) (MPa)				
	1	7	14	28	56
CEM only	13.1	27.5	33.1	41.5	47.5
10%	8.5	23.5	29.8	33.1	36.8
20%	6.7	20.7	27.2	27.2	32.4
30%	5.5	17.9	22.2	24.9	29.1

TABLE C-8: Flexural Strength of Self-Compacting Concrete Prisms by Using Crushed Stone Aggregates and Varying LSQD Content

SRM Variation	Compressive strength of 4x4x16 cm^3 SCC Prisms (EN 196-1) (MPa)				
	1	7	14	28	56
CEM only	6.5	11.2	13.8	15.8	17.8
10%	6.1	10.5	12.9	14.2	15.2
20%	5.8	9.9	11.5	12.9	14.32
30%	5.2	9.2	11.1	12.9	13.5

TABLE C-9: Flexural Strength of Self-Compacting Concrete Prisms by Using River Gravels and Varying LSQD Content

SRM Variation	Compressive strength of 4x4x16 cm^3 SCC Prisms (EN 196-1) (MPa)				
	1	7	14	28	56
CEM only	6.2	10.4	12.4	14.9	16.7
10%	5.2	9.4	11.1	13.4	15.2
20%	4.7	8.7	10.1	12.9	14.8
30%	4.1	7.9	9.2	12.5	13.8

TABLE C-10: Compressive Strength of Self-Compacting Concrete Cubes by Using Crushed Stone Aggregates and Varying MP Content

SRM Variation	Compressive strength of 4x4x4 $inch^3$ SCC Cubes (BS EN 12390-1) (MPa)				
	1	7	14	28	56
CEM only	19.5	33.8	39.6	47.2	51.58
10%	15.2	30.8	36.7	40.1	42.2
20%	15.9	32.8	34.6	38.4	39.39
30%	16.3	34.9	35.4	36.2	37.75

TABLE C-11: Compressive Strength of Self-Compacting Concrete Cubes by Using River Gravels and Varying MP Content

SRM Variation	Compressive strength of 4x4x4 $inch^3$ SCC Cubes (BS EN 12390-1) (MPa)				
	1	7	14	28	56
CEM only	12.5	25.8	32	38.8	45.2
10%	10.6	23.7	30.4	34.1	37.3
20%	11.1	24.3	28.9	32.6	35.5
30%	12.2	25.4	27.2	30.9	32.3

TABLE C-12: Compressive Strength of Self-Compacting Concrete Prisms by Using Crushed Stone Aggregates and Varying MP Content

SRM Variation	Compressive strength of 4x4x16 cm^3 SCC Prisms (EN 196-1) (MPa)				
	1	7	14	28	56
CEM only	18.7	36.9	42.5	48.8	55.58
10%	16	32.6	39.5	42.8	44.65
20%	16.1	34.5	38.3	40.2	41.22
30%	16	36.5	38	37.5	39.54

TABLE C-13: Compressive Strength of Self-Compacting Concrete Prisms by Using River Gravels and Varying MP Content

SRM Variation	Compressive strength of 4x4x16 cm^3 SCC Prisms (EN 196-1) (MPa)				
	1	7	14	28	56
CEM only	13.1	27.5	33.1	41.5	47.5
10%	10.9	24.6	31.2	34.7	38.5
20%	11.5	25.8	29.4	32.9	36.2
30%	12.4	26.6	28.6	31.4	33.2

TABLE C-14: Flexural Strength of Self-Compacting Concrete Prisms by Using Crushed Stone Aggregates and Varying MP Content

SRM Variation	Compressive strength of 4x4x16 cm^3 SCC Prisms (EN 196-1) (MPa)				
	1	7	14	28	56
CEM only	6.5	11.2	13.8	15.8	17.8
10%	7.3	12.3	13.2	14.7	16.1
20%	7.8	12.9	13.5	14.5	15.7
30%	8.1	13.9	14	14.2	15.2

TABLE C-15: Flexural Strength of Self-Compacting Concrete Prisms by Using River Gravels and Varying MP Content

SRM Variation	Compressive strength of 4x4x16 cm^3 SCC Prisms (EN 196-1) (MPa)				
	1	7	14	28	56
CEM only	6.2	10.4	12.4	14.9	16.7
10%	5.5	9.7	11.4	14.2	15.9
20%	4.9	9.1	10.5	13.9	15.1
30%	4.4	8.3	10.1	13.1	14.2

TABLE C-16: Mix Ingredients of SCC Formulations

Replacement %		**CEM**	**MP**			**LSQD**		
		0%	**10%**	**20%**	**30%**	**10%**	**20%**	**30%**
Cement (kg/m^3)		517	465	413	361	465	413	361
SRMs (kg/m^3)		0	52	104	156	52	104	156
Sand (kg/m^3)	**0/2 mm**	904	904	904	904	904	904	904
Coarse Aggregate (RG/CS) (kg/m^3)	**2/8 mm**	375	375	375	375	375	375	375
	8/16mm	375	375	375	375	375	375	375
w/c = 0.4 (kg/m^3)		206.4	186	165.2	144.4	186	165.2	144.4
SP (kg/m^3)	**%**	1.3	1.45	1.65	1.8	1.6	1.8	2.1
	Weight	6.708	6.7425	6.8145	6.498	7.44	7.434	7.581
VEA (kg/m^3)		x	x	x	x	x	X	x
Total (kg/m^3)		2384.41	2365.19	2344.67	2323.7	2366.04	2345.43	2325.08

TABLE C-17: Typical Range of SCC Mix Composition [68]

Constituent	**Typical range by mass (Kg/m^3)**	**Typical range by volume (litres/m^3)**
Powder	380 – 600	
Paste		300 – 380
Water	150 – 210	150 – 210
Coarse aggregate	750 – 1000	270 – 360
Fine Aggregate (sand)	Content balances the volume of the other constituents, typically 48-55% of total aggregate weight	
Water/Powder ratio by vol.		0.85 – 1.10