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SELF-COMPACTING CONCRETE -A USEFUL TECHNOLOGY

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ABSTRACT

A study on high performance (HP) self-compacting concrete (SCC) is reported. It contains basic information on such systems, their manufacture and applications. The objective of the paper is to introduce this wonderful technology of the decade to the engineers in Pakistan. This technology finds special applications in cases of congested reinforced sections, rafts, highly reinforced columns, bridge piers, tunnel linings, placements and underwater repairs. These are some of the situations where ordinary vibrated concrete can not be effectively utilized. Considering the current pace of research on SCC in the advanced countries it is likely that SCC would replace conventional vibrated concrete in the near future altogether.

Unlike most of the published research based on laboratory results only, the information provided in this paper is based on the experience gained in the laboratory, studies made at concrete manufacturing plant and then at the underground placements made in a local tunnel of a teaching and research mine. SCC was pumped therein with a total horizontal (above and below ground level) and vertical distances of 150 meters each. It is interesting to note that a similar SCC formulation gives different response in laboratory, at plant and then at sites due to differences in mixing regimes, plasticizer activation degree, environmental factors, incorrect estimation of aggregate surface moisture and its correction at plants, time factor involved in the transportation and onsite waiting and the pumping process of SCC. The results suggest that a thorough understanding of all aspects of this technology is essential for successful SCC production and placements. It is hoped that this single article would provide adequate information on all relevant issues of a durable HP SCC.

Keywords High performance concrete, self compacting concrete, superplasticizer, viscosity enhancing agents, flow, microstructure, shrinkage and secondary raw materials.

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INTRODUCTION

Despite its wide spread use now in the developed countries, it has been difficult to define high-performance concrete (HPC) in a unified way and no simple and consensus definition exits to date. American Concrete Institute (ACI) defines HPC as the concrete that meets special performance and uniformity requirements that may not always be obtained using conventional ingredients, normal mixing procedures and typical curing practices [1] and these requirements may include enhancement of ease of placement without segregation, long term mechanical properties, early age strength, toughness, volume stability and life in severe environments. Several researchers have defined HPC in their own way. In this study, like many others, the term HP is used in terms of ease of placement without segregation and is therefore applicable to SCC as well [2,3,4,5].

The vibrated concrete produces differential compaction and hence differential durability. This aspect coupled with shortage of skilled workmen and noisy nature of vibrated concrete were the factors which forced Japanese to think about a concrete that flows by itself without segregation, does not need vibration for full compaction and is environment friendly due to the absence of noise. It was Prof. Okamura and his team from Tokyo university Japan who was able to conceive and produce a powder type of flowing concrete, in early nineties of the previous century. This was called self-compacting concrete (SCC). With the continued research, special flow tests and equipment were designed and specifications were written after detailed testing of this innovative building material which has also been very much liked by the architects due to its excellent surface finish. The main requirements of SCC are very high flow or slump spreads and very high segregation resistance, the two properties which are often contradictory in nature. In the literature, SCC has been classified as powder type, viscosity agent type and the combination type each differing in the way segregation resistance is achieved. Combination type of SCC uses a moderate powder content and a reasonable quantity of viscosity agent and is considered more robust for structural applications was chosen for local placements in the tunnel.

Upto 1940, the maximum concrete strength at constructions sites was of the order of 20 MPa which had risen to 40 MPa by 1970 and now more than 100 MPA has been used in structures [6,7,8,9,10].This quantum jump in attainable strength was possible only due to the superplasticizers (SP) which were simultaneously developed in Germany and Japan in late 80’s of the previous century. The utilization of high performance concrete (HPC) and self-compacting concrete (SCC) has been possible only due to SP availability. In general when such high strengths with sufficient workability are desired, the maximum size of aggregates should be around 10-12 mm though aggregate size in 12-20 mm range has also been used with water cement ratio in the range of 0.3-0.40[9]. Use of SP, sufficient powder and continuous aggregate gradings are the other main ingredients of any HPC or SCC. Continuous grading improves particle packing and hence reduces the voids. Lesser voids would require lesser paste and hence lesser water to fill them and to produce a given level of workability. Less paste also means savings on cement and reduced shrinkage. An improved aggregate packing is indicated when the shape of grading curve starts approximating to a straight line. If the binder phase is also packed, the resulting voids are reduced to a great extent and high performance and self-compacting concretes can be made with improved microstructure resulting in enhanced durability. Unfortunately in most of the developing countries SPs are considered to be only the workability enhancing agents and their main role on the structural durability is seldom recognized by the structural engineers.

In addition to SP, secondary raw materials (SRM) or secondary cementitious materials including lime stone powder (LSP), fly-ash (FA), rice-husk ash (RHA), ground granulated blast furnace slag(GGBFS) or silica fume (SF) are also used.The selection of a typical powder is largely based on required qualities of concrete in both fresh and hardened state. The role of SRMs is to improve packing and hence reduce the water demand of the system. They also replace a part of cement in mortars and concretes resulting in economy, less heat of hydration and hence lower shrinkage. In ready mixed concrete constituents, cement is the most expensive, energy intensive and environment unfriendly material. The less energy intensive SRMs being sought are the easily available industrial by-products requiring a little or no pyro-processing and having inherent or latent cementitious properties. Low calcium fly-ash and blast furnace slag have been in the market for a long time whereas high-calcium fly ash, condensed silica fume, and rice husk ash are relatively new. Use of Fly Ash in concrete is increasing. High cost of cement and pressure from environmental lobbyists are encouraging the use of SRMs to replace cement in concrete. Role of SRMs on SCC performance would be explained in the following text.

FILLERS FOR SCC

Materials less than 0.125 mm(125 microns) are called powders or fillers and include SF, Fly-ash, ground lime stone(LSP) etc. The fillers should have at least 75% material passing through 0.063 mm sieve for better stability.

Various fillers have been employed in the research reported in the literature including lime stone powder (LSP), fly-ash (FA) and ground granulated blast furnace slag (GGBFS). These fillers modify the rheological properties of SCC in fresh state and in the hardened state. When high volumes of lime stone filler are added to SCC mix, the required self-compacting properties are achieved at a lower water/ (cement +filler) ratio. Twenty eight days compressive strength is also increased due to filler effect resulting in improved fine-particle packing [11] with LSP particles acting as sites for the nucleation for CH and CSH reaction products. It is reported that the replacement of large volumes of cement by limestone filler (on the order of 100 kg/m^3) is shown to reduce the cement content needed to achieve a given slump flow, viscosity, and compressive strength at early age. The increase in limestone filler content can reduce the HRWRA demand necessary to secure a given deformability. For a given dosage of HRWRA, the loss in slump flow is shown to decrease with the increase in lime stone filler in mixtures containing 360 kg/m^3 of cement with the opposite trend observed for concrete with 290 kg/m^3 of cement [12]. It has been observed in the laboratory by the authors that calcium carbonate based LSP decreases WD and setting times while dolomite based LSP decreases lesser WD than calcium carbonate based LSP and has no significant effect of setting. The $CaCO_3$ content in LSP was 92.3 % by mass. The authors while making a comparative study on the use of different fillers like LSP, FA and FA combinations with SF and RHA found that the use of lime stone filler in self-compacting systems requires the greatest amount of SP for a target flow, gives the least strength, highest linear shrinkage and also has higher maximum pore size [13].This was due to rough and porous nature of LSP , ascertained by SEM and MIP studies, which could retain SP in their bottle necks making it inaccessible to the solution for dispersion purposes. One study suggests that lime stone filler used in SCC does not contribute to strength gain in SCC and is mainly used to increase paste volume without generating excessive heat [14]. It appears that it could be of dolomite based LSP because calcium carbonate based LSP shortens the setting time and would therefore generate more heat than dolomite based LSP or other fillers. It also said therein that SCC columns would have greater ductility but 10% lower strength than similar normal vibrated concrete. It is probably due to higher paste content in SCC columns which reduces the modulus in comparison to aggregates it replaces. After a formulation has been arrived at in the light of literature [15], the first step is to carry out the flow tests and these are described now. FA has also been extensively used in making SCC. Low calcium ASTM class F FA generally reduces the water demand, SP content for a target flow, reduces heat of hydration due to delayed setting due to unburnt carbon. SF and RHA can be used with FA by about 20% of its mass to improve flow and strength properties. SPs are essential for flow and durability but the information about them is not easily available except the suppliers brochure. Therefore in the following text the necessary information is being provided.

MECHANISM OF ACTION OF SUPERPLASTICIZERS

There are four main clinker phases of cement namely C_2S, C_3S, C_3A and C_4AF and it is reasonable to think that the chemical compounds of these SP's get grafted on them. In a fresh cement paste without SP, C_2S and C_3S have a negative zeta-potential while C_3A and C_4AF have a positive zeta-potential. This leads to a faster coagulation of the cement grains.

Cement particles act like a colloid in suspension containing SP. Each colloid carries a "like electrical charge". Particle charge can be controlled by modifying the suspending liquid characteristics. Modifications include changing pH of liquid or changing the ionic species in solution. Another more direct technique is to use surface active agents (SP) which directly adsorb to the surface of colloid and change its characteristics. Calcium aluminate content (C_3A &C_4AF) along with cement fineness effects the fluidity in addition to C_3A/ CaSO4 ratio Deflocculation test as described in [16] is able to predict more accurately, the minimum active dosage of an admixture to retain fluidity. A simpler hydrometer tests is also proposed to assess the relative effectiveness of the plasticizing admixtures[17].The literature also cites that lower alkali content along with lower C_3A+C_4AF and higher SO_3 contents give higher fluidity[18]. These are the conditions suiting the SP to remain in the solution. Some studies on sulfonated polymers of naphthalene, melamine and styrene show that the polymer which is least adsorbed(with highest molecular weight) gives highest negative zeta potential and higher dispersing capacity[19].However, this is not true for PCEs' which have lower zeta potential than SNF and SMF type of super-plasticizers. The addition method (time of addition) of traditional superplasticizers is an important factor determining workability of SMF and SNF type superplasticizers. To obtain high workability, their addition should be delayed and optimum time is the beginning of dormant period. However with PCE's the time of addition is less important to obtain higher workability [20]. The enhanced effect of superplasticizer when added a few minutes after the mixing water, can be explained in a simple way. When SP is added along with the mixing water the SP is rigidly attached in substantial amounts by C_3A-gypsum mixture leaving only small amounts for the dispersion of silicate phases. By late addition, the SP is adsorbed to a lesser extent and there will be enough SP left in the solution to promote dispersion of silicate phases and to lower the viscosity of the system.

Double Layer Model

A "double layer" model explains the electrical repulsion mechanism and helps understand the definition of Zeta potential. A colloid (negative ion, co-ion) will be surrounded by positive ions(counter ions) in the solution. The attraction from negative ion forces some of the positive ions to stick to its surface around colloid. This layer of counter ions is called "stern-layer". Additional positive ions are still attracted by the negative colloid, but with a small equilibrating force, and are now repelled by the stern layer counter ions and by other counter ions which are trying to approach the colloid.. Figure 1 presents the double-layer model. The double layer is formed to neutralize the charged colloid and in turn causes an electrokinetic potential between the surface of the colloid and any point in the mass of a suspending liquid. This is called surface potential and is in milli-volts. The electrical potential at the junction of stern and diffuse layer is called "zeta-potential" and is related to the mobility of the particle. Zeta-potential can be quantified by tracking the colloid particles through a microscope as they migrate in a voltage field.

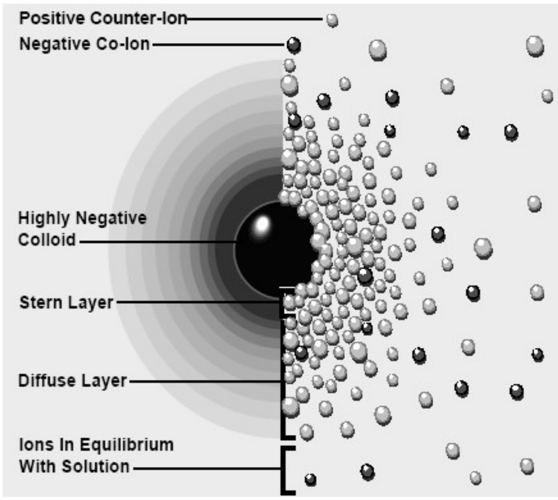

Fig. 1 Double layer Model of SP mechanism of action.

This dynamic equilibrium results in the formation of a "diffuse layer" of counter ions over-lapping the stern-layer. Diffuse layer is followed by a layer of ions which are in equilibrium with solution. In a similar but opposite fashion, there is a lack of negative ions in the neighborhood of the surface because they are repelled by the negative colloid. The concentration of co-ions gradually increases with the distance as repulsive forces of colloid are screened out by the positive ions until equilibrium is again reached. The diffuse layer can be visualized as a charged atmosphere surrounding the colloid. The stern layer and diffuse layers are called double-layer.

Van der Waals attraction is the result of additive forces between the individual molecules in each colloid. Subtracting attractive curve from the repulsive curve, the net interaction curve is obtained. In order to maximize the repulsion to get dispersion, the colloids should be kept at a minimum prescribed distance, by over coming Van der Waals " attraction". This may be done by adding surface active agents like SP.

Due to addition of SP, the surface potential of all cement phases becomes negative and they start repelling each other. PCEs adsorb more selectively to C_3A and C_4AF than to C_2S and C_3S. That's why PCEs need a smaller dosage to achieve the same reduction in water content. In addition long polyether side chains lead to a steric repulsive effect between the cement particles and increase the workability. Longer main and side chains lead to better dispersing and water reduction effect while having a small effect on setting times.

Polymeric (Steric) Forces

When a polymer layer is present at the surface of particles (either adsorbed or chemically grafted), a repulsion force can be created when the layers on two neighboring particles overlap. This happens whenever the polymer molecules would rather become more compact as the two layers are squeezed together. Polymeric repulsion occurs only when polymeric stabilizer layers overlap. The thickness of these layers is often of the order of 10 nm. In contrast electrostatic double layers can be much thicker if the ion concentration of the medium is low and polymer repulsion potential is quite steep.

SHAPE AND GRADING OF AGGREGATES

In general the aggregate shape requirements for both normal concrete and SCC are the same stating that no more than 15 % of aggregates could be elongated. According to DIN EN 933-4 an aggregate is considered elongated if the ratio of length to the maximum thickness is more than 3.0.

Fig. 11 The shape of 8-16 mm size of coarse aggregates used in SCC

These elongated aggregates can cause increased internal friction, voids and also pipe blockings at times. Such blockages are also caused by bleeding, high coarse/fine aggregate ratio, and using pipes with different wear [21]. A high elongated aggregate content also needs a higher paste volume for SCC conveyance because paste is the vehicle for the aggregates.

Fig 11 shows the shape of 8-16 mm size coarse aggregates used in SCC. According to above mentioned DIN standard, it was evaluated and was found a border line case with 15% elongated aggregates.

CALCULATION OF WATER DEMAND OF SCC SYSTEMS

The calculation of a system's water demand is often the first required SCC design step [22], therefore a simple procedure should be devised for its evaluation. Complicated procedures using sophisticated equipments [23-24] have been reported in the literature for determining the water demand (WD) of the system. For production of durable SCC mixtures it is important that the water content of the mixture does not exceed the water demand of the system by a big margin. The importance of making SCCS at a mixing water content close to system's WD has already been mentioned. The total WD of a SCC system is the sum of individual water demands of the powder and the aggregate components. The WD of the powder can be determined by mixing cement in the selected mass proportions and test with Vicat needle. For determining the water demand of various size fractions of coarse and fine aggregates simple procedures outlined in ASTM C 127 and 128 can be followed. The results can then be added to get the systems WD as shown in table 5.4.

Example

The following amounts of materials were in a typical SCC formulation. Water demand of 1 m³ of SCC was calculated as given in table 1.

Table 1: Calculation of the water demand for 1 m³ SCC-mixture

Material	Amount in SCC mixture (kg/m³)	WD of material (% of mass)	WD (kg/m³)
Cement : fly ash (1 : 0.387 by mass)	(380 +147) 527	27.5	145
Aggregate size 0/2 mm	824	1.73	14.25
Aggregate size 2/8 mm	412	0.933	3.84
Aggregate size 8/16 mm	412	1.06	4.37
Total system's WD			167.5
Mixing water (w/c=0.45)			171
Difference			3.5

ASSESSMENT OF SCC IN FRESH STATE

The architectural Institute of Japan established standard specifications for SCC in 1997 as well as guidelines which made use of SCC very common. Three basic criteria are required to achieve self-compaction: high deformability, high passing ability and high resistance to segregation. To secure good deformability, it is important to reduce the friction among solid particles during flow. Aggregate interparticle contact can decrease by reducing the aggregate content and increasing the paste volume to maintain high passing ability among closely spaced obstacles. Adequate cohesiveness can be achieved by incorporating viscosity-enhancing agent (VEA) along with HRWRA to control bleeding, segregation and surface settlement. Another way to enhance the cohesion of SCC is to reduce free water content, increase the volume of fines and cement paste or both. Fine materials and fillers with greater surface area than cement can reduce free water content. The incorporation of VEA in the presence of HRWRA requires greater HRWRA content for a given flow level due to reduction of free-water resulting from the long chain polymer molecules of VMA that absorb and fix part of the mixing water, hence increasing the viscosity of the mixture. The dynamic and static stabilities of SCC are also the main functional requirement for adequate production and use. The dynamic stability prescribes the resistance to segregation during transport and placement while the later refers to the resistance of the fresh concrete to segregation and bleeding once the concrete is cast into place and until onset of hardening. The dynamic stability is assessed by V-funnel flow time, J-ring, L-box, U-Box and pressure bleed tests. For static stability the determination of surface settlement, aggregate segregation and monitoring the in place changes of electrical conductivity are done. The SCC technology is based on adding or partially replacing cement with fine materials like fly-ash, blast furnace slag and SF without modifying the water content. This process changes the rheological behavior of concrete. In order to achieve a balance between flowability and stability, the particles<150μm should be between 520-560 Kg/m^3. High powder content improves thecohesiveness. SCC offers environmental, social and economic advantages in addition to offering better performances than normal concrete due to increased cementitious materials content and denser ITZ, (Interfacial transition zone between aggregates and pastes) ,faster construction, noise elimination and placements without skilled labor. HRWRA lowers mostly the yield value but results in a limited drop of viscosity making it possible to have highly flowable concrete without significant reductions in viscosity/cohesiveness.

Reduction in water-powder (w/p) ratio results in reduction of deformability of cement paste while an increase in w/p secures high deformability but can reduce cohesiveness of paste and mortar necessitating a balance in w/p ratio to enhance deformability without substantial reduction in cohesiveness. Inter-particle friction increases when the concrete spreads through restricted spacing due to greater collisions between various solid particles. This increases viscosity thus requiring greater shear stress to maintain a given capacity and deformation speed.

It is also essential to reduce the coarse aggregate and sand volumes and instead increase the paste volume to enhance deformability. Continuously graded cementitious materials and fillers can also reduce inter-particle friction.

Self-compacting concrete offers a rapid rate of concrete placement, with faster construction times and ease of flow around congested reinforcement. The fluidity and segregation resistance of SCC ensures a high level of homogeneity, minimal concrete voids and uniform concrete strength, providing the potential for a superior level of finish and durability to the structure. SCC is often produced with low water-cement ratio to provide high early strength, earlier demoulding and faster use of elements and structures.

The elimination of vibrating equipment improves the environment on and near construction and precast sites where concrete is being placed thus reducing the exposure of workers to noise and vibration.

The improved construction practice and performance, combined with the health and safety benefits, make SCC a very attractive solution for both precast concrete and civil engineering construction.

The reduction in aggregate content necessitates the use of a higher volume of cement that increases cost and temperature during hydration. Therefore SCC often contains high-volume replacements of fly-ash, blast furnace slag, lime stone filler, or stone dust to enhance fluidity and cohesiveness and also limit temperature due to hydration. The combined use of HRWRA and VEA can insure both high deformability and adequate stability required for high filling capacity, good bond with reinforcement and uniformity of in-situ mechanical properties.

Viscosity Agents

Commonly used VEA in concrete include cellulose derivatives and polysacchrides of microbial sources-in particular welan gum that improve the capacity of the paste to suspend solid particles.

Mixes containing VEA exhibit shear thinning behavior whereby the apparent viscosity decreases with the increasing shear rate. Once in place shear rate decreases and the apparent viscosity increases resulting in greater stability. It has been reported that SCC mixtures entrap less air than thoroughly vibrated control concrete having identical volumes of water and cementitious materials. Moreover statistically insignificant differences have been observed between the in situ $f_c^/$ values of both types of concrete[25].Viscosity modifying admixture (VMA) not only increases the viscosity but also provides mixture robustness and overcomes effects due to poor aggregate shape and grading[26].At a concrete plant even a limited failure in the aggregate humidity estimation will typically generate 10-20 L excess dose of water per m^3 of concrete causing bleeding and segregation in the absence of viscosity agent[27]. The cracking performance and behavior under load suggested that in general cast in place compressive strengths of SCC were closer to standard cube strengths than those of ordinary concrete and at service load level and the crack width was wider with greater depth for ordinary concrete beams than for SCC beams[28]. Based on a study encompassing 70 SCC formulations with w/cm ratio in 0.35-0.42, performance based specifications have been formulated for structural applications of SCC [29]. Such SCC's should have a settlement rate of 0.16%/h at 30 minutes corresponding to a maximum 0.5% maximum settlement. Fillers for SCC are very important and brief information on such powders is given in the next article.

FLOW TESTS FOR SCC

SCC was originally pioneered in Japan and therefore specified flow tests for SCC were basically designed there and are markedly different from those of normal concrete. These tests are now universally performed tests on SCC.

Slump Spread

It has been suggested [26,30] that slump spread in the range of 500-700 mm is usual for SCC. Flow time (T-50 cm) upto 6 seconds is considered good for SCC. However higher time can also be obtained in case of very cohesive mixes. Flow time generally increases with increase in FA content at the same w/cm [26]. As per authors findings reported elsewhere, flow time was found to be a function of particle shape of powders and it can be further improved by using a small quantity of SF (say 20% by FA mass) in FA[26].This would also improve setting, strength and microstructure. For a target flow level pozzolanic powder addition in pastes and mortars increases the water demand and hence SP has to be added and its amount depends upon the particle characteristics. The strength of HP SCP and SCM is increased with such pozzolanic powders and microstructure is refined and the shrinkage also increases [31-33]. Fig 2 shows SEM of FA particles and fig 3 shows general arrangement of the slump test for SCC. It shows the base of Abrams cone to be in touch with steel plate. However as per German literature the Abrams cone is placed on the narrow end down with the obvious advantage of not requiring an additional person to firmly hold the cone while SCC is being put in. Both the versions of slump tests (with narrow end up or down give almost the same slump value). The process involves filling the cone gently and then lifting it and noting the time when spread reaches the 500 mm Φ mark. If cone is lifted correctly and the platform is level, the spread would be a true circle. The total spread when the flow stops is also recorded. This test is simple to perform and an experienced practitioner can obtain lots of information about a typical SCC mix. The total spread gives an idea about the yield while T 50 cm time can be indicative of viscosity. Moreover visual inspection of any water at the rim of spread can be an indication of bleeding while uniform dispersion of particles and especially the uniform presence of coarse aggregate particles in the entire spread and particularly near the extreme periphery gives an idea about segregation resistance and viscosity of the mix.

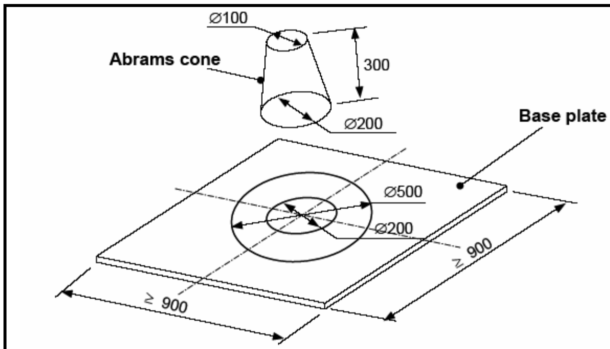

Fig. 3. Slump Test and T500 measurement arrangement

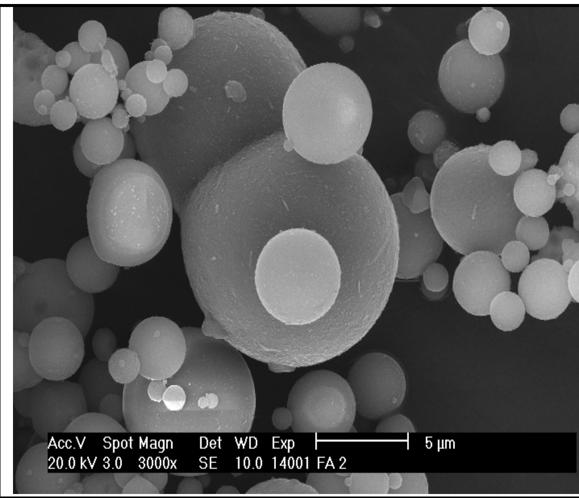

Fig. 2. SEM Pictures of FA particles

L-box Test

Figs 4 and 5 give the general arrangement of the L-Box test. The vertical part of the box is filled with about 12.7 L of concrete and is left for rest for 1 minute [34] as per Canadian practice but German practice does not necessarily call for this 1 minute wait. The gate separating the vertical and horizontal compartments is then lifted and the concrete flows out through closely spaced reinforcing bars at the bottom. The gap and size of the bars depends on the maximum size of the coarse aggregate. The time for the leading edge of concrete to reach the end of 600 mm long horizontal section is noted. The height of concrete remaining in the vertical section (h_1) and that at the leading edge (h_2) is evaluated. Various sources set h_2/h_1 ratio but values between 0.8-1.0 are generally recommended [34]. This test can detect both blocking and stability of SCC mixes.

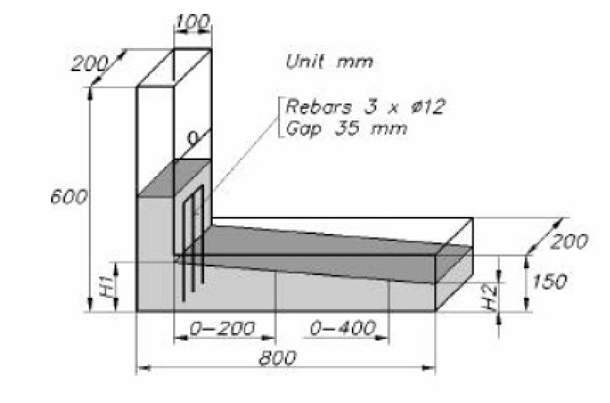

Fig. 4 General arrangement of L-Box Test.

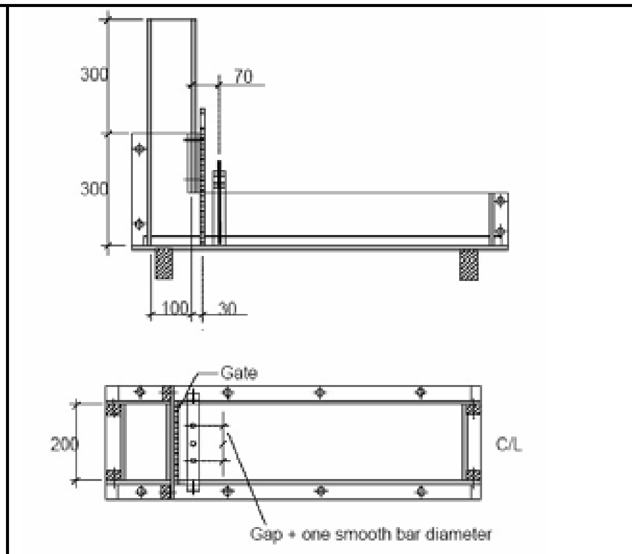

Fig 5 Elevation and Sectional View of L-Box test arrangement

V-Funnel Time

Fig. 6 gives the general arrangement of the apparatus. Various dimensions and specially those at the bottom are used but mostly the opening size is 65x75 mm at the bottom. The funnel requires about 10 L concrete and is filled gently.

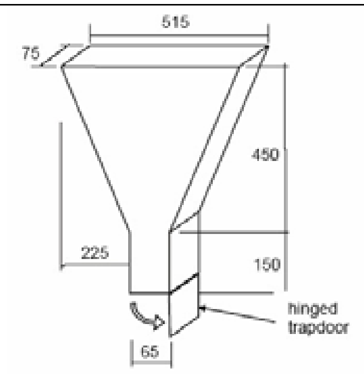

Fig 6 General arrangement of V-Funnel test.

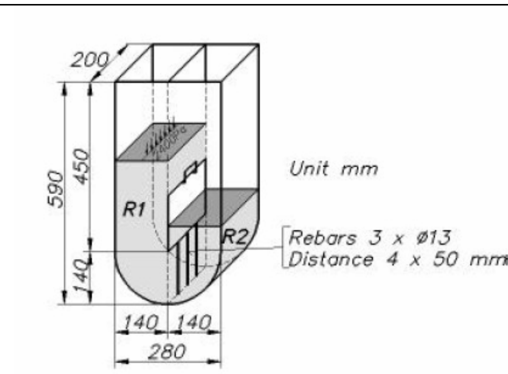

Fig 7 General arrangement of U-Box Tests

The bottom gate is opened either immediately or after 1 minute (German and Canadian practice respectively) and the time required for the concrete to flow through the opening is measured.

The flow is considered to be stopped when light is seen through the opening bottom when looking from the funnel top.

This test is used to evaluate the ability of the aggregate particles and mortar to flow through a continuously reducing section without segregation and blocking. The funnel time between 6-12 seconds is generally desired for SCC [34]. V-funnel time generally decreases with increase in w/cm ratio and also with the increase of fly-ash content for a given w/cm ratio [26].

U-Box Test

Fig. 7 gives the general arrangement of the apparatus. This test is used to evaluate the narrow opening passing ability of SCC under a particular head of fresh concrete. One minute after filling the vertical compartment with concrete, the bottom gate is removed to allow concrete to flow into another rising compartment through closely spaced reinforcements. After the flow stops, the height of concrete in rising compartment is measured from the bottom of the apparatus to the top surface. This filling height represents the passing ability and non-blocking behavior of SCC. A maximum of this value is 338 mm [34]. The time required to complete the flow in the rising compartment is also noted and it represents the rate of deformability of the concrete. JSCE recommendations stipulate that a SCC concrete sample should have a minimum filling height of 300 mm while the Europeans guidelines propose to measure the difference of height in both the compartments. The closer this difference is to zero, the better the flow and passing ability of the concrete, however, this difference should not exceed 30 mm [34].Literature also specifies the ranges of values for different tests as applicable to SCC as structural concrete [29].

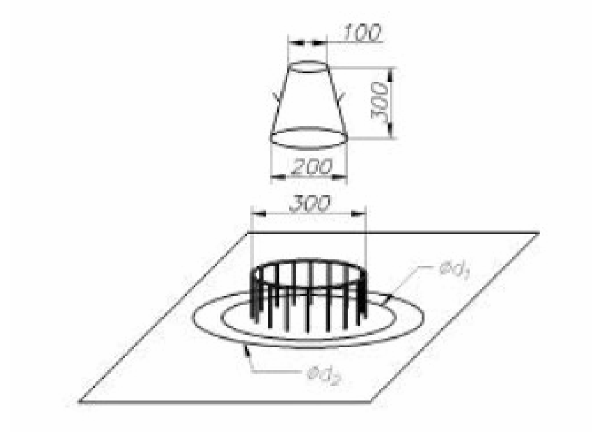

Fig 8. General arrangement of Blocking ring test.

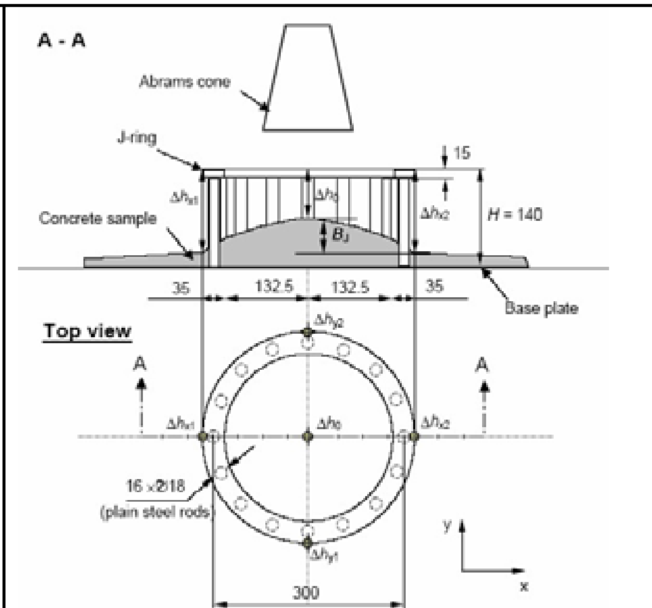

Fig. 9 Details of blocking ring apparatus.

Blocking Ring (J-Ring) Test

Figures 8 and 9 give the general arrangement of the apparatus and its details. At the base of the slump cone, a concentric ring can be used to assess the passing ability of concrete through closely spaced obstacles. The measurement is carried out as the mean diameter of the concrete spread when the flow stops. The gaps between reinforcing obstacle bars depend on the maximum size of the coarse aggregate.

The J-Ring can be used in conjunction with the slump flow to evaluate the passing ability and the amount of spread loss when concrete is made to flow through obstacle reinforcing bars simulating the actual placing conditions. The difference between the slump spread and J-Ring spread should not be more than 50 mm (German guidelines) or 10 mm by European guidelines [34]. It has been experienced that when the shape of coarse aggregate is rather elongated, it is extremely difficult to satisfy the requirements laid down in the European Guidelines; however, German requirements for this test look reasonable as these seem to take care of the variation in shape of coarse aggregate as well.

Fig 10 Air Content Meter

The SCC sample is gently put into the container (bottom half of the air content meter) approximately upto top by leaving a gap of around 1-2 mm between top of the concrete and the top of bottom half. There should be no aggregate particle or paste at the rim junction of top and bottom of the apparatus to provide an air-tight connection between the two halves of the apparatus. After filling, the apparatus is rotated and wobbled without impact so as to release any air. Then water is sprayed into as shown. After that red stoppers are put down and air is pumped by using brown top lever. Correction is done by using top black button (right) and tabbing the glass plate till the needle reads zero. Then green measurement button (left) is pushed and air content is displayed.

Air Content

Fig 10 shows the air content meter used in the investigation. The air content in concrete is an important criterion**.** Sometimes a higher air content in SCC may be desired to increase the freeze-thaw resistance, however, an air content of around 2-3% remains entrapped in normal SCC mix depending upon the dosage of SP and VEA and type of powders being used.**.** Due to various admixtures used, its amount can vary and has to be checked against the design value. In case of discrepancy the mix may be revised. Generally an air content of around 2% in non-air entrained SCC can be considered OK. Air content is also important w.r.t pumping procedure. With higher air content induced due to admixtures or other ingredients, the yield stress can increase with a corresponding accompanying plastic viscosity can decrease [35].

EXPERIMENTAL

Materials

Many cement types were used by the authors including CEM I(C I) and CEM II/A-LL 32.5R (C II) and hard coal fly-ashes (SRM) were used in various SCC formulations. Table 2 gives the properties of powders used.

Table 2: Properties of Powders used

Powder	Particle Size (μm)	BET Area (m^2/g)	Density (g/cc)	SiO_2	Fe_2O_3	MgO	CaO	Al_2O_3	Na_2O	K_2O	LOI %	SO_3
CI 32.5R	23.7	0.858	3.135	20.29	2.26	1.71	62.45	5.41	0.83	0.72	1.87	3.25
CI 42.5R	18.9	0.81	3.168	18.92	2.27	1.72	63.16	5.09	1.48	1.35	2.34	3.48
CII	16.90	1.353	3.11	18.74	2.23	1.38	58.9	4.78	1.25	1.01	7.09	3.20
FA1	26.59	1.65	2.31	51.44	5.55	2.51	4.03	26.13	1.23	2.63	2.71	-

The Bogue's potential parameters of CEM II/A-LL 32.5R are C_2 S= 19.56, C_3 S= 51.18, C_3 A= 10.5 and C_4 AF= 6.87. These parameters for the other two cements can be easily calculated.

Siliceous sand (0-2 mm) and natural gravel (2-8 mm and 8-16 mm) was used for the SCC-mixes. Figure 12 shows the grading curves of sand and of total aggregates.

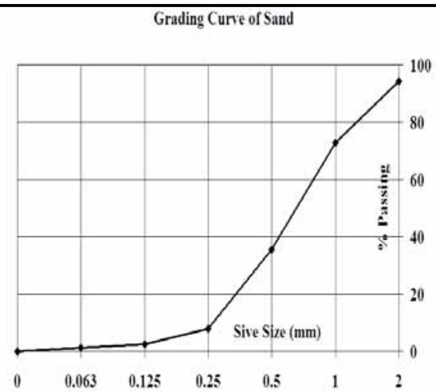

Figure 12 (a): Grading curves of sand (0-2 mm)-

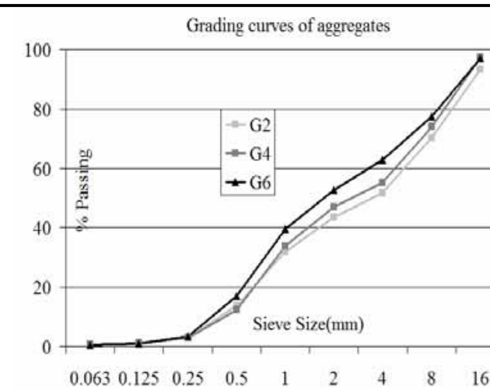

Figure 12 (b) Grading of total aggregate used for SCC. Contents of fractions (0-2 : 2-8 : 8-16 mm):G1 (39:33:28), G2 (45:27:28), G4 (50:25:25),G6 (5:22.5:22.5),

The grading curves of aggregates used in this research work with a maximum aggregate size of 16 mm falls within the limits of German standards DIN EN 206-1 and DIN 1045-2 [25]. A random sample of 8/16 mm fraction of aggregates when tested for % elongated material according to DIN EN 933-4 showed about 15 % of such material.

MIXING PROCEDURE

The mixing sequence consisted of:

- Mixing of dry constituents for 30 seconds
- Then adding water, superplasticizers and viscosity agent at the same time.
- Mixing the ingredients for another 90 seconds. In the laboratory, mix was kept undisturbed for 7 minutes and then 1 minute of final vibration was given for SP activation. For each tests in fresh state after slump spread, the mix was again given 5 seconds mixing. At plant after 2 minutes, the concrete was poured in the truck and was continuously agitated slowly. After 9 minutes it was given 1 minute of fast truck mixing before starting flow tests at plants. At site same sequence was observed before pumping SCC in the tunnel.

This may not be the most efficient mixing regime but it had to be adjusted to the stringent plant mixing procedures which normally do not allow the use of optimal mixing procedures as recommended elsewhere [22].

SCC FLOW TESTING

In the fresh state the tests including slump spread (cone standing on narrow end), V-funnel time, L-box and J-ring (blocking ring) were carried out in sequence. After that air content was tested. The average time spent on completing the flow tests was around 20 minutes for a three men party. The sample was mixed again for 5 seconds before starting another test after slump test. Figure 13 shows the relation between the admixtures ratio (plasticizer: stabilizer; P/S) and V-funnel time of SCC formulations with CEM II (For powder and aggregate content see table 5.4 and for grading details see Fig. 5.10(b).The target slump spreads for G4 and G2 formulations were 66±1 and 70±1 cm respectively.

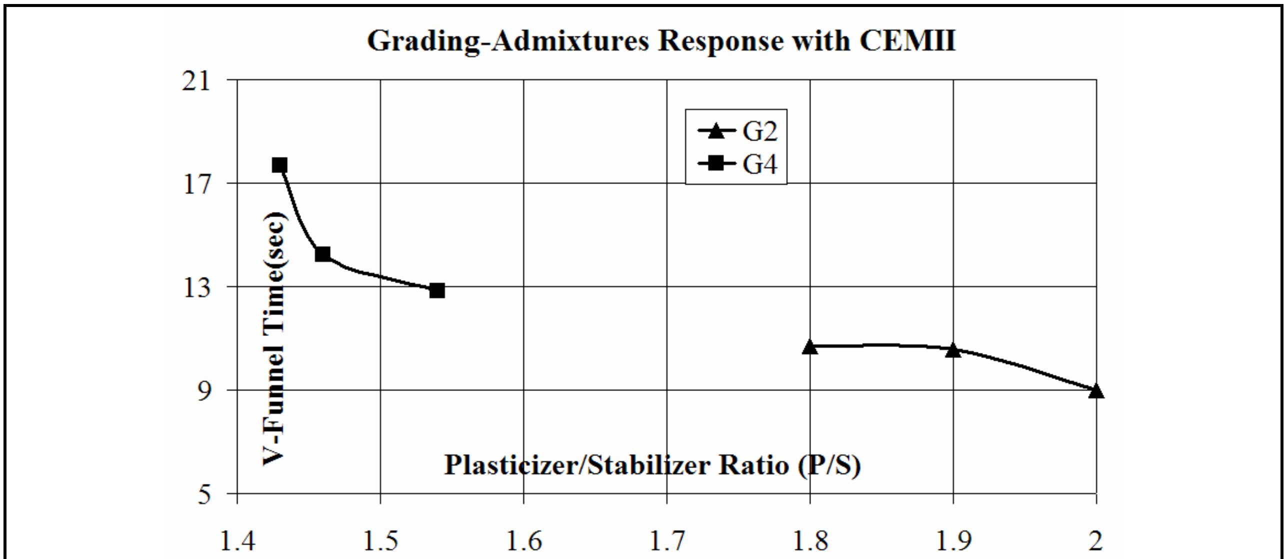

Figure 13: V-funnel time and P/S relation for two aggregate gradings with CEM II

The mixing regime in the laboratory was the same as that used at plant. It may not be very efficient though especially the activation of the activation of superplasticizers may not be achieved in a total two minutes of mixing time because of low shear rates of the laboratory mixer and smaller SCC sample volume (50 litres). It is therefore suggested that slump should be taken after the activation of the superplasticizers otherwise the slump test values (T50 cm and spread) will be incorrect and its comparison with J-ring may not be accurate. This can be done to leave the mixed material in the pan upto seven more minutes and then mixing for 1 minute more. Alternatively the total mixing time can be increased fro addressing the issue. Although a final consistence adjustment with water is allowed [22], however laboratory observation showed that even a very small water addition after the addition of admixtures can reduce the mix cohesion and/or could be misinterpreted and may therefore be avoided. Table 3 and 4 show quantities of SCC mixes designed for the stated spreads.

Table 3: SCC mix ingredients

Mix. No\ constituents	1	2	3	4	5	6	7	8	9	10	11
Cement-kg/m^3	C132.5R,380	C132.5R-380	CII-380	CII-380	CII-380	CII-380	CII-380	CII-380	CI-330	CI-330	CII-380
Water-kg/m^3	168	171	171	171	171	171	171	171	148.5	148.5	171
FA kg/m^3	147	147	147	147	147	147	147	147	197	197	147
Sand 0-2 mm kg/m^3	635	635	635	732	732	732	813	898	919	919	893
Aggregate-2/8 mm kg/m^3	538	538	538	439	439	439	406	366	376	376	366
Aggregate-8/16mm kg/m^3	456	456	455	455	455	455	406	366	376	376	366
SP (% cement mass), kg/m^3	1.3,4.94	1.8,6.84	1.8,6.8	1.8,6.84	1.9,7.22	1.9,7.22	2,7.6	2.6,9.88	3.4,11.22	4.2,13.86	2.8,10.9
VEA (% cement mass), kg/m^3	0.64,2.4	0.89,3.4	0.95,3.6	0.95,3.6	1.05,4	1,3.8	1.3,4.94	1.2,4.56	1.3,4.28	1.3,4.28	1.4,5.32
Grading	G1	G1	G1	G2	G2	G2	G4	G6	G6	G6	G6
W/c	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
w/cm	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.28	0.28	0.32

Table 4: SCC mix ingredients (contd)

Mix.No\ constituents	12	13	14	15	16	17	18	19	20	21	22
Cement-kg/m^3	C1-330	C1-330	CII-340	C1-300	C1-330	C1-300	C11/BM,340	C11/BM, 350	C1-300	C1-300	C11-340
Water-kg/m^3	165	188	153	171	185	171	153	157	171	171	160
FA kg/m^3	197	197	187	227	197	227	187	177-2	227	227	187
Sand 0-2 mm kg/m^3	896	793	830	887	789	795	829	819	795	795	815
Aggregate-2/8 mm kg/m^3	366	397	415	362	394	398	414	414	397	398	408
Aggregate-8/16mm kg/m^3	366	397	415	362	394	398	414	414	397	398	408
SP (% cement mass), kg/m^3	3.1,10.3	2.65,8.76	1.91,6.46	2.5,7.5	2.5,8.3	2.4,7.2	2.4,8.15	2.4,8.4	2.3,7.2	2.45,7.35	2.2,7.47
VEA (% cement mass), kg/m^3	1.3,4.3	1.35,4.5	1.5,5.1	1,3	1,3.3	1.2,3.6	0.9,3	0.9,3.15	1.25,3.76	1.12,3.36	1.1,3.75
Grading	G6	G4	G4	G6	G4	G4	G4	G4	G4	G4	G4
w/c	0.5	0.57	0.45	0.57	0.57	0.57	0.45	0.45	0.57	0.57	0.47
w/cm	0.31	0.35	0.29	0.32	0.35	0.32	0.29	0.29	0.32	0.32	0.3

FLOW RESPONSE

The flow response of each SCC mix was noted by slump spread, V-funnel time, L-box, J-ring test and air content test in the sequence. All these tests required 20 minutes for a three men party. The SCC mixes were designed for two slump spread ranges, 65-68 cm and 69-72 cm. Table 5 gives flow response of 65-68 cm slump spread mixes while Table 6 gives the flow response of 69-72 cm slump spread.

Table: 5 Flow properties of mixes designed for slump spread of 65-68 cm

Grading	G4	G6			G4	G6	G4
Mix number	7	8	11	12	13	15	19
T50,s Spread,cm	8.5 65	7 68	6 67	9.3 68	6.4 67	8.1 68	8.5 68
Funnel, Time, s	12.8	10.3	15.8	14.6	9.2	12.2	15
L-box T60,s-h2/h1	11 0.93	8.37 0.98	13.4 0.92	14 0.96	7.18 0.98	12.3 0.96	15.9 0.97
J-ring T50, spread. cm	14.8 60	12.3 63	13.3 66.5	20 62.5	8.91 66	16.7 63.4	13.4 66
Air %	2.7	2.9	2.6	2.8	1.9	2.5	2.2

Table 6: Flow properties of mixes designed for slump spread of 69-72 cm

Mix	1	2	3	4	5	6	14	17	18	20	21	22
T50,s Spread, cm	6 71	5.5 71	5.6 69	7 70	8 69	7 71	11.5 69	5.8 72	9.2 71	6.7 70.5	6.3 71	9.3 70
Funnel, Time, s	18	12.4	11.6	9	10.7	10.6	18.8	11.8	18.5	10.1	10.3	15.4
L-box T60,s- h2/h1	9 1	9.6 1	6.2 0.96	7 1	7 1	9.2 1	17.5 0.92	12.6 0.96	19.6 0.9	11.4 0.96	9.7 0.93	14.1 0.93
J-ring T50, spread, cm	12 63	7.7 71	8.7 68	10 69	11.5 66.5	11.8 68.5	19.6 63	13.6 63.5	17.9 67.5	11 68.5	12 67	18.1 66.5
Air %	1.0	1.8	1.5	1.7	2.1	1.9	2.5	1.6	2.1	2.1	1.9	2.5

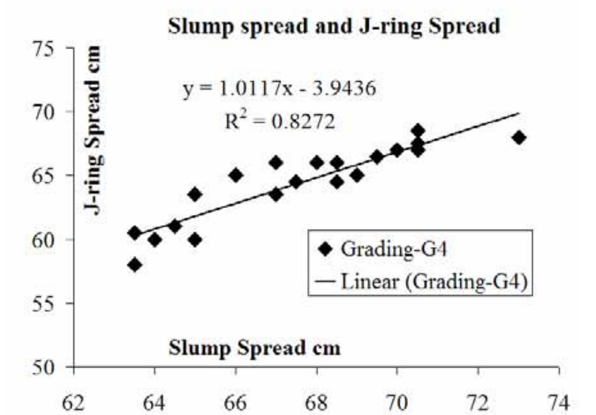

Fig. 14 shows the slump spread and J-ring spread of SCC mixes pertaining to G4 grading. It can be seen that relationship is fairly good except that J-ring values are less than corresponding slump spreads due to obvious blocking effect of the ring.

Figure 14: Slump and J-ring slump spreads relation for G4 grading.

STRENGTH RESPONSE

After casting, the specimens were placed in plastic containers at 20°C and 90%+ relative humidity. Those were demoulded after 24 hours and then put in water till the age of testing. According to German specifications, concrete has to be taken out of water after 7 days and then air cured at 67% relative humidity at 20°C. How ever as the effect of curing in various relative humidity ranges was also studied, 28 days strength of water cured samples can be reduced by about 14% to get the strength according to German standards. Table 7 shows the 28 days SCC compressive strength of 10 cm cubes. The differences and the reasons in the flow and strength response of SCC mixes cast in the laboratory, at plant and then at placement site in tunnel by pumping are given elsewhere [15].

Table 7: 28 day compressive strength of some SCC mixes.

Mix Number	Compressive Strength, MPa
9	80
10	75
11	68
12	70
13	66
15	65
16	68
17	70
18	74
20	68
21	68
22	63

Figure 15 gives the relationship of w/c ratio and compressive strength of G6 mixes while figure 16 explains the effect of relative humidity (at constant temperature of 20°C) on the compressive strength of a typical SCC mix.

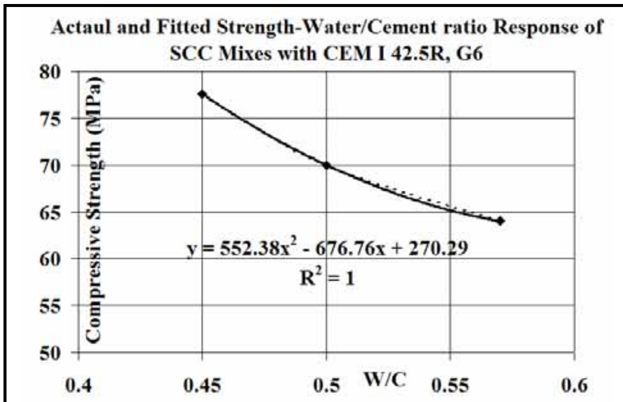

Fig. 15 28 days w/c-strength relation for G6 grading.

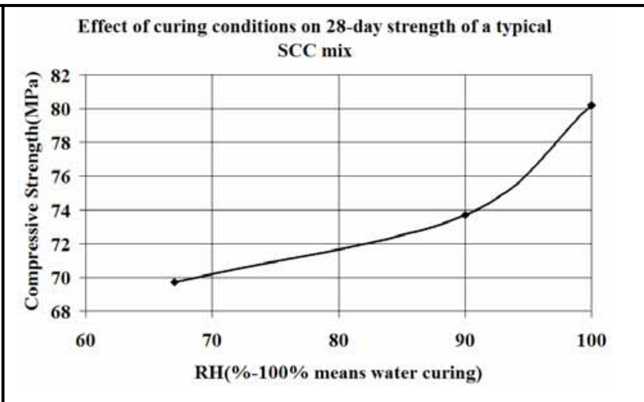

Fig 16 Effect of relative humidity(at 20°C) on the compressive strength of SCC.

MICROSTRUCTURE

Various methods of microstructural investigations can be used depending on what is being looked after. Environmental scanning electron microscopy (ESEM) is being increasing used in the studies of microstructure along with x-ray diffraction (XRD) and thermal analysis (Thermogravimetry –TG and differential scanning calorimetry- DSC).

In a reinforced concrete structure the forces are transferred to steel from concrete through bond. Between the paste and aggregate of concrete there exists an area called interfacial transition zone (ITZ) of about 30-50 microns whose properties are different from the surrounding mortar. Moreover in this ITZ some water may collect encouraging the growth of weak $Ca(OH)_2$ crystals(CH) . Therefore in this entire assemblage, ITZ becomes the weakest link. Material engineers are trying to improve the quality of this ITZ by incorporating such SRM (SF, RHA, FA) which react with CH and hence improve the microstructure. A typical microstructure is shown below.

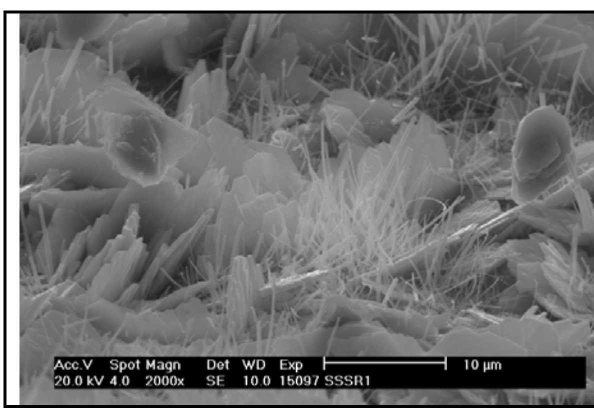

Fig 17: A microstructure of a typical HP SCM system using LSP with CEM I at the age of 28 days is shown. Hydration products (thin needles) and calcium hydroxide crystals (flaky and plate like) are clearly seen. The microstructure growth generally takes place in the pores for a continuously graded and packed formulation.

SECONDARY RAW MATERIALS (SRM) FOR SCC IN PAKISTAN

A physical survey was carried out to know the availability of SRMs for making SCC in Pakistan. Fly-ash is available in a small quantity from the thermal power plants in private sector but it may not be economically exploited. The lime stone flour, obtained during crushing of Margallah rocks for making coarse aggregates, is available and can be used very effectively. For the time being it is adding to environmental problems. Ground granulated blast furnace slag can also be an option. Rice husk ash can be made locally and can be used along with LSP for the improvement of resulting SCC concrete. The authors are busy in making tests on locally available SRMs and results will be published in near future.

CONCLUSIONS

1. A simple procedure of calculation of water demand of SCC mixes has been developed and used .All HP/SCC mixes must be at a mixing water content equaling that corresponding to the demand of the system for economy and durability.
2. The shape of coarse aggregate is very important for the flow response of SCC. Elongated coarse aggregates create larger voids in the mix and therefore require higher paste contents for meeting flow targets. Such aggregates can produce pipe- blocking during pumping if mix is inadequately designed.
3. Mixing regime is very important for making HPC/SCC. The time and sequence of addition of chemical admixtures were also very important**.**
4. Use of FA reduces cement and hence early shrinkage which is a very big consideration in HPC/SCC. Its spherical particle shape is useful for flow through congested sections.
5. In the laboratory, the flow measurements should be taken only after the activation of superplasticizer.
6. Increasing SP/VEA ratio increases flow. The flow starts at a typical SP/VEA ratio for a given SCC formulation and further increases do not improve the flow very significantly.
7. SCC mixes were designed for 60 MPA and all mixes had higher strengths by a reasonable margin.
8. The reasons for the response differences of a similar formulation when tested in laboratory, at plant and then at site are attributed to batch size differences, inadequate estimation of aggregate surface moisture, transportation time and waiting at site. Pumping also changes flow response.
9. This technology can be effectively used by the engineers in Pakistan.

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