Computers and Concrete, *Vol. 22, No. 2 (2018) 183-196*
DOI: https://doi.org/10.12989/cac.2018.22.2.183

Experimental study on rheology, strength and durability properties of high strength self-compacting concrete

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(Received December 9, 2017, Revised June 3, 2018, Accepted June 10, 2018)

Abstract. The rheological behaviour of high strength self compacting concrete (HS-SCC) studied through an experimental investigation is presented in this paper. The effect of variation in supplementary cementitious materials (SCM) vis-à-vis four different types of processed crushed sand as fine aggregates is studied. Apart from the ordinary Portland cement (OPC), the SCMs such as fly ash (FA), ground granulated blast furnace slag (GGBS) ultrafine slag (UFS) and micro-silica (MS) are used in different percentages keeping the mix -paste volume and flow of concrete, constant. The combinations of rheology, strength and durability are equally important for selection of mixes in respect of high-rise building constructions. These combinations are referred to as the rheo-strength and rheo-durability which is scientifically linked to performance based rating. The findings show that the fineness of the sands and types of SCM affects the rheo-strength and rheo-durability performance of HS-SCC. The high amount of fines often seen in fine aggregates contributes to the higher yield stress. Further, the mixes with processed sand is found to offer better rheology as compared to that of mixes made using unwashed crushed sand, washed plaster sand, washed fine natural sand. The micro silica and ultra-fine slag conjunction with washed crushed sand can be a good solution for high rise construction in terms of rheo-strength and rheo-durability performance.

Keywords: rheo-strength; rheo-durability; high strength self-compacting concrete; supplementary cementitious materials (SCM); unwashed crushed sand; crushed washed sand; fine crushed washed sand; fine natural washed sand

1. Introduction

Advancement in concrete technology has been generally based on the strength of concrete. However, nowadays it is widely accepted that strength of concrete alone does not suffice; the environmental condition to which concrete is exposed over its entire life is equally important. Therefore, both- strength and durability, are required to be considered explicitly at the design stage. Many concrete technologist and researchers have been working on improvement of concrete over the years and invented many new materials and innovative concepts such as Self-Compacting Concrete (SCC), High Performance Concrete (HPC), High Strength Concrete (HSC), etc. High-strength and High-performance concretes are being widely used nowadays throughout the world. It is necessary to reduce the water/binder ratio and increase the binder content for producing such type of concrete. Universally, Self-Compacting Concrete is defined as a category of high performance concrete having an excellent deformability in the fresh state and high resistance to segregation; and can be placed and compacted under its self-weight without resorting to application of vibration.

Development of self-compacting concrete (SCC) is one of the significant development in concrete technology whereas on the other hand, high strength concrete is the most desirable structural component for many civil engineering structures. The combination of high strength with self-compacting property offers potential benefits to the construction industry. The high strength self-compacting concrete (HS-SCC) would give flexibility to the structural designers for developing high rise structures and reducing dimensions of the structural element. Pursuant to this, the development of HS-SCC is the main desire of the researchers in the field of concrete technology. The production of such type of concrete does not require special cement or cementitious materials. Fly ash, silica fume, or slags often used in the production of high-strength concrete can be used for HS-SCC. The replacement of supplementary cementitious materials (SCM) has got significant effect on the performance of concrete mixtures in terms of the improvement of flow property, reduced segregation potential and increase in the later age strength; and improved durability.

The rheological or flow properties of concrete in general and of HS-SCC in particular are important because many factors such as ease of placement, consolidation, durability, and strength depend on the flow properties. The rheology of concrete exhibits a complex behavior, both- in fresh and hardened state. The flow of concrete is very complicated because of the complex suspension of particles therein. The particles of coarse aggregates are dispersed in mortar and within the mortar, particles of fine aggregates are dispersed in the cement paste; and further, within cement paste, the cement particles are dispersed in water. Owing to this, the rheological behavior of fresh concrete cannot be described

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http://www.techno-press.org/?journal=cac&subpage=8
ISSN: 1598-8198 (Print), 1598-818X (Online)

using *Newtonian* viscosity function which is the simplest equation for describing the flow behavior of liquids. Generally, the flow behavior of concrete approximates that of a *Bingham* fluid. Therefore, at least two parameters, yield stress and viscosity, are necessary to characterize the flow. Major challenge in high-rise construction is pumping of the concrete vertically at higher elevation. Various combination of mixes will help to achieve the placement target. The behaviour of concrete changes under pressure. Hence, simulation of pumping trial can be of tremendous help to fine tune the mix and avoid future challenges. This underscores the importance of strength and durability in concrete in respect of any high-rise structures.

2. Literature review

Many researchers (Ozawa *et al.* 1989, Okamura *et al.* 1995, Bartos and Marrs 1999, Khayat 1999, Maekawa *et al.* 1999) carried out the research that led to the development of the self-compacting concrete. However, during initial days, the more emphasis of research was in the context of the strength. Recently, the focus has shifted towards the studies on the rheological behavior of self-compacting concrete. Some of the works involved on the effect of supplementary cementitious materials (SCM), fine aggregates, chemical admixtures on the rheology of SCC. Some of the prominent studies in this context are reviewed in this section.

Tattersall and Banfill (1983) had proposed scientific term “rheology” to define the flow behaviour of SCC it can be measured with a concrete rheometer. Ferraris (1999) described that the flow behavior of SCC is complex and approximates that with *Bingham* fluid. These researchers opined that once the stress passes the yield value, the flow of the mixture occurs with velocity proportional to plastic viscosity. Donza *et al.* (2002) reported the increase in the use of crushed aggregates for SCC and stated that the ‘SCC requires higher contents of fine aggregates as compared to that in normal traditional concrete’. Mindess *et al.* (2003) presented a broad overview of the factors affecting the workability and rheology of SCC and enlisted several factors such as water content of the mix, mix proportions, aggregate properties, time, temperature, cement type, and admixtures etc. Ponikiewski (2011), Ponikiewski and Katzer (2017) proposed the definition self-compacting concrete by at least two parameters, namely- yield stress and a plastic viscosity.

Many researchers studied the effect of type of fine and coarse aggregates in regard with mix quality, performance and pumpability of the concrete. Wills *et al*. (1967) pointed out that significance of the shape of the fine aggregate on the requirement of water requirement for concrete. Hudson (1999) pointed out that the effect of the shape of fine aggregate is much prominent on the quality of concrete and workability than the effect of the shape of coarse aggregate. Daniel *et al.* (2006) pointed out the considerable effect of grading of fine aggregates on the workability than that of grading of coarse aggregates. Ahmad and Mahmood (2008) found workability of concrete with crushed sand on lesser side than the concrete prepared using natural sand. Celik (1996), Banfill (1994) expressed the possibility of increase in risk of segregation mentioned in case of too coarse aggregates. Celik *et al.* (1996), Bederrina *et al*. (2013) emphasized on the clean, hard and strong fine aggregates which are free from the absorbed chemicals and other fine materials for producing good concrete and reducing its deterioration rather than the cost consideration and availability in the local vicinity. Donza *et al.* (2002) suggested the adverse effects of particle shape on the workability and stated that water demand can be reduced by using a super plasticizer. Kwan *et al.* (2010) underscored the importance of better packing density on workability, pumpability and segregation of cementitious materials by resorting to the optimization of particle size distribution of fine aggregates.

Supplementary cementitious materials (SCM) are used to increase the strength and improve durability and flowability of concrete. Ground granulated blast furnace slag (GGBS), fly ash (FA) and microsilica (MS) are some of the typical SCMs used for achieving these properties. Some of the investigators carried out their research in this context. Rudzinski *et al*. (1984) reported freshly mixed cementitious materials are generally more workable when fly ash is applied. This is attributed to the spherical particles and smooth surface texture of the fly ash which can act as small ball bearings to reduce interparticle friction. Nehdi *et al.* (1998) reported that these minerals significantly affect rheology of cementitious materials in the fresh state, which is directly related with developing strength, durability and engineering properties of hardened structures. Vengala *et al.* (2003) reported an increase in the 28days’ compressive strength of the SCC by around 38% with the use of fine fly ash when volume of paste was between 0.43 and 0.45. Li *et al. (*2004) showed that the particle size distribution, density and particle morphologies of fly ash are the major factors affecting their fluidity. Kim *et al.* (2012) pointed out general decrease in yield stress with the replacement of some of the cement with fly ash and opined further such replacement may either increase or decrease the viscosity depending on the properties of the SCM and its interaction with the cement. Bauchkar and Chore (2014) investigated the effect of natural sand and SCM on the rheological properties of self-compacting concrete (SCC) in which the grade of concrete was HS-SCC having paste volume 42%. Ravindra rajah *et al.* (2003) showed that fine and coarse aggregates could be partially replaced with fly ash in producing high-strength self-compacting concrete with sufficient flow property and low segregation potential without affecting the early age strength.

Tattersall (1991) reported that the ground granulated blast furnace slag (GGBS) on rheology strongly depends on cement contents and type of slag. Hooten *et al.* (1993) investigated the influence of silica fume when replaced with cement on physical properties and resistance to sulphate attack, freezing and thawing, and alkali-silica reactivity. According to few researchers (Cry *et al*. 2000, Ferraris *et al.* 2001), In the high performance concretes these SCMs are used for developing special performances such as self-compacting properties and self-leveling of concrete, long-time workable concrete, low heat of hydration and high strength development concrete, high durability concrete, etc. Vikan and Justnes (2007) reported that the silica fume or micro silica can improve rheology, when used at low replacement rate (2 to 3%), alters the rheology at higher replacement /content. The addition of 2 to 3% micro-silica or silica fume by mass of cement can be used as a pumping aid for concrete. Boukendakdji *et al.* (2009) pointed out that the addition of GGBS as partial replacement of cement (15%) in concrete can improve the workability of self-compacting concrete up to 20%w.r.t. concrete made up of OPC.

Further, some of the researchers (Tattersall and Banfill 1983, Ramchandran 1992, Neubauer *et al.* 1998, Jayasree and Gettu 2008, Aydin *et al.* 2009, Plank 2009, Kwan and Ng 2009) studied the effect of chemical admixtures on the rheology of self-compacting concrete. It was found that the super-plasticizers can significantly improve the workability of concrete, reduce the water demand and enhance the strength of cementitious construction materials. Due to dispersion effect, the fluidity of the paste is increased whereby yield stress and plastic viscosity is reduced. Vasusmitha *et al.* (2013) revealed that due to intrinsic low porosity, SCC usually has high performance properties in terms of mechanical behaviour and durability. Ahmed *et al.* (2016) described a new term ‘High Strength-Self Compacting Concrete (HS-SCC)’ used for concrete mixture which possesses high workability, high strength, High density and low permeability. The high-performance concrete has denser microstructure with low inherent porosity and permeability because of lower water cement ratio and use of mineral admixture in concrete. Bilodeau *et al.* (1992) measured water and chloride permeability of concretes having 55 to 60% cement replacement with various sources of fly ash and reported that both the parameters in respect of fly ash concretes were comparable to that for silica fume concrete.

3. Significance of the present work

Plenty of studies have explored the effect of SCM and chemical admixtures along with different types of aggregates on the rheological behavior of SCC. However, the studies with respect to the selection process of HS-SCC mixes for high-rise building construction based on combination of rheology, strength and durability performance has hardly been reported. Pursuant to this, effect of the characteristics of supplementary cementitious materials on fresh and hardened properties of HS-SCC such as rheology, strength and durability is studied in the present investigation. The combination of rheology, strength and durability is uniquely defined by author as the *Rheo-strength* and *Rheo-durability* based on performance matrix is presented in this study. The study includes the evaluation of influence of fly ash, ground granulated blast furnace slag, ultrafine slag and micro silica on the workability, rheology and durability of HS-SCC. The industry trends for various replacement ratio of supplementary cementitious materials are 30% PFA, 50% GGBS, 7.5% MS or 7.5% UFS, which is considered as benchmark for experiments. However, the rheo-durability properties, especially the water permeability (WP), Water absorption (WA) and rapid chloride permeability (RCPT) of hardened concrete containing the sands of various fineness combined with rheo-strength have not been solely explored yet. Increased use of HS-SCC demands augmented knowledge of the properties such as rheo-strength and rheo-durability for successful application in high rise building constructions.

Table 1 Chemical compositions of the cementitious materials used in the study

Material	Unit	PFA	GGBS	MS	UFS	OPC
Blaine fineness	(m^2/kg)	345	390	-	-	328
BET Surface Area	(m^2/kg)	-	-	22000	4968	-
Compressive strength as % of cement	(%)	84.2	92	156	-	100
Lime reactivity	MPa.	5.6	-	8.5	-	-
Autoclave expansion	(%)	0.06	-	NA	13.5	0.059
Sp. gravity	(%)	2.3	2.86	2.2	NA	3.14
Loss on ignition (LOI)	(%)	1.2	0.37	2.6	2.9	2.81
Silica (SiO2)	(%)	60.72	33.72	92.3	1.9	20.68
Iron oxide (Fe2O3)	(%)	5.32	0.64	0.06	26.8	4.76
Alumina (Al2O3)	(%)	27.5	18.22	0.62	2	5.54
SiO_2+Al_2O_3+Fe_2O_3	(%)	93.54	52.58	93.88	21.9	30.98
Calcium oxide (CaO)	(%)	1.42	34.51	0.3	50.7	61.39
Magnesium oxide (MgO)	(%)	0.48	11.22	0.3	31.5	1.07
Total Sulphur (SO_3)	(%)	0.21	0.22	0.05	1	2.5
Alkalies (Na_2O+K_2O)	(%)	1.71	0.53	0.6	-	0.38
Chloride	(%)	0.36	0.001	0.001	-	0.055
Retained on 45 microns	(%)	15	1.55	0.2	-	10.66

4. Experimental method

4.1 Materials

An ordinary Portland cement (ASTM-Type-I) conforming to the requirement of OPC 53, was used. Four types of supplementary cementitious materials, namely- fly ash(PFA), ground granulated blast furnace slag (GGBS), micro silica (MS) and ultrafine slag (UFS), were also used in binary blends. The physical and chemical properties of OPC, PFA, GGBS, MS and UFS as obtained through systematic laboratory investigations carried out at the Research and Development center of Counto Microfine Products Pvt. Ltd. (Goa), are summarized in Table 1.

Further, the details of the particle size distribution analysis (PSD) of OPC, PFA, GGBS, MS and UFS, as obtained through systematic laboratory investigations carried out at the Research and Development center of Counto Microfine Products Pvt. Ltd., Goa, are summarized in Table 2.

The crushed basalt aggregates of size 10 mm and 20 mm wereused as the coarse aggregates (CA). Similarly, four different types of sands,such as washed crushed sand (WS), unwashed crushed sand (CRF), washed crushed plaster sand (PS) and fine natural sand(NS), were selected for this study as the fine aggregates. The physical properties (dry sieve analysis) of the aggregates obtainedthroughsystematic laboratory investigations carried out at the Research and

Table 2 Particle size distribution for SCM

Details	PSD in μm					Sp. Gravity	Blaine m^2/kg
	D 10	D 50	D 90	D 95	D 100		
OPC	4.07	21.38	61.96	79.06	181.97	3.08	313
GGBS	4.07	16.71	40.74	48.93	79.433	2.92	371
Fly ash	6.78	32.65	83.42	103.15	181.97	2.14	249
Micro silica	3.54	24.90	50.46	58.07	91.20	2.05	-
Ultrafine slag	2.12	4.60	9.06	10.57	17.38	2.82	897

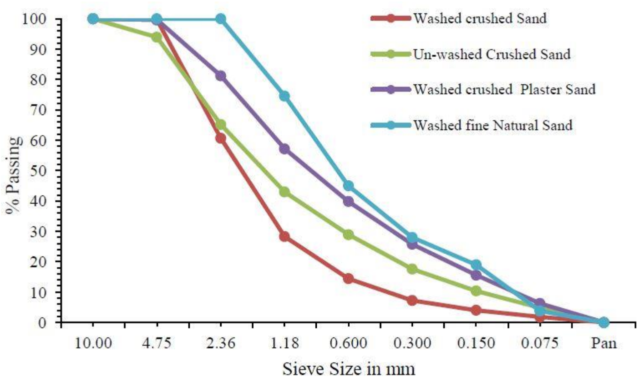


Fig. 1 Grading curves of different fine aggregates

Table 3 Physical properties of coarse and fine aggregates used in the study

	20 mm	10 mm	Washed Crushed Sand	Un-washed Crushed Sand	Washed Crushed Plaster Sand	Washed Fine Natural Sand
IS Sieve Size (mm)	% Passing					
20	97.4	100				
10.00	2.9	82.6	100	100	100	100
4.75	1.1	3.4	99.64	93.93	99.7	100
2.36	1.1	2.8	60.70	65.18	81.2	100
1.18	0	0	28.28	42.97	57.2	74.54
0.600	0	0	14.43	28.91	39.8	45.00
0.300	0	0	7.24	17.57	25.7	28.00
0.150	0	0	4.00	10.38	15.6	19.00
0.075	0	0	1.80	4.79	6.3	3.80
Pan	0	0	0.00	0.00	0.0	0.00
F.M. =	6.94	5.6	3.14	3.59	4.19	4.67
Specific Gravity	2.82	2.8	2.73	2.68	2.72	2.5
Water Absorption	1.50%	1.80%	2.97%	3%	2.78%	0.5
Silt Content (by vol.) %	0.50%	0.50%	6%	12.50%	5%	1%

Development center of BASF India Ltd., Navi Mumbai, are given in Table 3 and Fig. 1.

A specially formulated Poly-carboxylate Ether based MasterGlenium SKY 8855, a high range water reducer with in-built retarder, was used in this study. The physical properties of MasterGlenium SKY 8855, presented in Table 4, were evaluated using state of the art instrumentation available at the Research and Development center of BASF India Ltd., Navi Mumbai.

Table 4 Physical properties of Master Glenium SKY 8855

Aspect	Light brown liquid
Relative Density	1.05 ± 0.01 at 25℃
pH	>6
Chloride ion content	< 0.2%

Fig. 2 ICAR Rheometer set up and testing

4.2 Test procedures

The HS-SCC contains the ordinary Portland cement (OPC) and other supplementary cementitious materials (SCM) such as fly ash (PFA) 30%, ground granulated blast furnace slag (GGBS)50%, and micro silica 7.5%; and Ultrafine slag (UFS) 7.5%. These supplementary cementitious materials were replaced by various percentages, maintaining volume of the mix paste (45%), w/b ratio 0.27 and constant flow of concrete (700+/-30 mm). The mixtures were mixed in batches of 40 liters using a Pan mixer. Mixing efficiency, type of mixer, sequence of mixing, ambient temperature, etc. are the factors affecting the rheology of HS-SCC during its production. Therefore, these factors were not changed throughout the study. The mixing materials were kept at temperature of 30±2℃ (approximately) before mixing. Following the end of mixing, mixtures had approximately constant temperatures of 33±2℃. The mixing procedure for concrete mixtures consisted of homogenizing the fine and coarse aggregate for 1 minute and introducing 25% of the mixing water. Following a rest period of 1 minute to allow the saturation of the aggregates, binder and 50% of water were added. After two minutes of mixing, the HRWR diluted with the remaining water was introduced gradually over two minutes while the mixer was turned on. Following two minutes of rest, the concrete was mixed for three additional minutes.

The concrete was discharged directly from the pan mixer into the ICAR Rheometer container.Simultaneously sample was also withdrawn for other engineering fresh properties such as flow, *V*-funnel, *L* box, *U* box etc. Two types of tests were performed in ICAR rheometer. The first one was a stress growth test in which the vane was rotated at a constant slow speed of 0.025 rev/sec. The initial increase of torque was measured as a function of time. The maximum torque measured during the test was used to calculate the static yield stress. The other type of test was a flow- curve test to determine the dynamic yield stress and the plastic viscosity. The set-up of the ICAR rheometer, flow table, *V*-funnel used for the testing is shown in Figs. 2-3.

(a) *V*-Funnel

(b) Slump Flow

Fig. 3 *V*-funnel, flow table, ICAR Rheometer used for the testing

The slump cone was lifted and three measurements were made corresponding to the time for the concrete to spread to a horizontal diameter of 500 mm (T_{500}), the final horizontal spread diameter; and the visual stability index (VSI). The VSI ratings were determined based on the definition as given by Wallevik (2008). Other than slump-flow test, all the mixes satisfied VSI 1 requirements. The *V*-funnel test (Fig. 3(a)) was performed as per EFNARC (2005) standards.

In order to determine thecompressive strength and durability, 420 cubes of size 150×150×150 mm for twenty mixes were cast. The cube specimens were tested for compressive strength at the age of 7 days, 28 days and 56 days. Subsequently, the tests for water absorption (BS 1881-Part 122), water permeability (DIN 1048-5) and rapid chloride permeability (ASTM C 1202) in respect of each mix were conducted at the edge of 28 days as per relevant standard.

4.3 High strength self-compacting concrete mix details

In the present work, twenty different mixes of high strengths self-compacting concrete (HS-SCC) were designed, the concrete mix proportions being calculated in accordance with the norms laid inIS-10262and. These mix proportions are shown in Table 5. It was also ensured that all the HS-SCCs mixes satisfied the regulations given by EFNARC (2005) guidelines. The fresh properties of the SCCs were determined by slump flow, T_{500}, *V*-funnel and *L*-Box blocking ratio.

5. Results and discussion

The various rheological properties of fresh high strength self-compacting concrete (HS-SCC) with different cementitious materials and contents thereof are presented in Table 6. From the various test results obtained in view of the workability of fresh HS-SCC concrete are reported in Table 6. The slump flow is found to be constant 700+/-30 mm for all mixes. This indicates the good deformability of the fresh concrete and no influence of flow variation on other parameters. The effect of the mineral admixtures on the properties such as flow, *V*-funnel and T_{500} values is

Table 5 Mix proportions for laboratory trials and results of fresh properties

Mix Details	OPC	PFA	GGBS	MS	UFS	CA	WS	CRF	PS	NS
WS-SCC-OP	650	0	0	0	0	591	1075	0	0	0
CRF -SCC - OP	650	0	0	0	0	962	0	701	0	0
PS -SCC- OP	650	0	0	0	0	1148	0	0	531	0
NS -SCC- OP	650	0	0	0	0	1148	0	0	0	506
WS-SCC-PFA	455	195	0	0	0	569	1035	0	0	0
CRF -SCC - PFA	455	195	0	0	0	926	0	674	0	0
PS -SCC- PFA	455	195	0	0	0	1105	0	0	511	0
NS -SCC- PFA	455	195	0	0	0	1105	0	0	0	487
WS-SCC-GGBS	325	0	325	0	0	582	1059	0	0	0
CRF -SCC - GGBS	325	0	325	0	0	948	0	691	0	0
PS -SCC- GGBS	325	0	325	0	0	1131	0	0	524	0
NS -SCC- GGBS	325	0	325	0	0	1131	0	0	0	499
WS-SCC-MS	601	0	0	49	0	584	1063	0	0	0
CRF -SCC - MS	601	0	0	49	0	952	0	693	0	0
PS -SCC- MS	601	0	0	49	0	1135	0	0	525	0
NS -SCC- MS	601	0	0	49	0	1135	0	0	0	500
WS-SCC-UFS	601	0	0	0	49	589	1072	0	0	0
CRF -SCC - UFS	601	0	0	0	49	959	0	699	0	0
PS -SCC- UFS	601	0	0	0	49	1144	0	0	530	0
NS -SCC- UFS	601	0	0	0	49	1144	0	0	0	504

(OP-100 % OPC, PFA-30% fly ash, GGBS -50% GGBS, MS -7.5% Microsilica, UFS-7.5% Ultra fine slag, washed crushed sand -WS, unwashed crushed sand - CRF, washed crushed plaster sand - PS and washed fine natural sand -NS)

Table 6 Results of fresh and harden properties

	Description	MG SKY 8855 (%)	Flow (mm)	T_{500} (sec.)	V funnel (sec.)	L-Box	Yield Stress (τ) (Pa)	Viscosity (μ) (Pa. s)	3 Days (N/mm^2)	7 Days (N/mm^2)	28 Days (N/mm^2)	90 Days (N/mm^2)
OPC -100% OPC	WS-SCC-OP	0.54	700	2.09	9.19	0.92	37.10	31.30	55.8	72.0	96.3	101.5
	CRF -SCC - OP	0.60	710	2.97	11.22	0.94	52.40	49.40	57.9	70.3	89.0	105.2
	PS -SCC- OP	0.50	720	2.97	11.50	0.95	67.10	56.40	56.8	71.4	92.1	103.3
	NS -SCC- OP	0.53	710	3.03	13.00	0.94	72.00	66.80	56.4	76.0	86.2	102.5
PFA - 30% FA	WS-SCC-PFA	0.33	700	2.04	5.97	0.88	38.00	42.20	32.6	53.9	64.9	81.4
	CRF -SCC - PFA	0.45	700	1.91	10.10	0.9	55.90	57.70	32.7	53.9	65.8	81.7
	PS -SCC- PFA	0.35	700	2.66	12.50	0.9	76.20	78.80	34.1	55.7	73.4	85.1
	NS -SCC- PFA	0.43	700	4.12	14.38	0.9	105.4	111.90	29.2	56.3	63.0	73.0
GGBS - 50 % GGBS	WS-SCC-GGBS	0.34	700	3.56	10.32	0.9	47.10	67.10	26.8	51.8	69.3	76.4
	CRF -SCC-GGBS	0.52	700	3.17	11.60	0.9	73.40	81.90	24.5	52.9	67.3	70.1
	PS -SCC- GGBS	0.42	710	3.62	12.56	0.92	208.20	147.60	28.9	58.3	72.7	82.5
	NS -SCC- GGBS	0.46	720	4.12	23.50	0.95	224.50	213.00	24.7	57.8	69.7	70.5
MS- 7.5% MS	WS-SCC-MS	0.80	680	2.78	7.34	0.9	85.80	39.60	57.4	75.1	104.5	112.5
	CRF -SCC - MS	1.10	690	3.00	7.41	0.9	100.50	41.00	52.6	69.6	94.8	100.3
	PS -SCC- MS	1.05	680	3.12	7.89	0.91	210.30	50.10	61.1	80.7	110.5	114.5
	NS -SCC- MS	1.00	60	2.80	8.36	0.88	247.30	59.00	62.9	80.3	105.4	109.6
UFS- 7.5% UFS	WS-SCC-UFS	0.62	670	2.66	7.91	0.9	78.80	40.50	61.7	78.5	101.0	106.2
	CRF -SCC - UFS	0.77	680	2.62	8.00	0.9	86.90	43.30	62.5	70.7	97.2	97.4
	PS -SCC- UFS	0.70	680	3.00	8.80	0.9	90.90	44.00	60.4	82.4	109.2	107.9
	NS -SCC- UFS	0.64	670	3.00	12.85	0.9	101.40	46.50	70.7	82.0	103.0	106.4

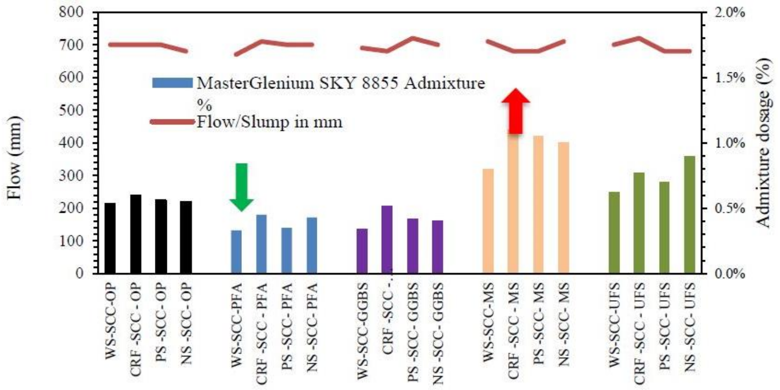


Fig. 4 Effect of fine aggregates on admixture dosage requirement for similar flow

observed to be significant in terms of its nature.

The effects of the various cementitious materials used in the present investigation such as fly ash, ground granulated blast furnace slag, ultrafine slag, micro-silica on the rheological behavior of HS-SCC are discussed below.

5.1 Effect of cementitious material and replacement ratio on dosage of superplasticizer

Though the paste volume of HS-SCC mixes is constant, the physical properties of fine aggregates influence the rheology of concrete. As per material properties and gradation report (Table 3), the NS, PS and CRF are finer than WS which results into more cohesive and densely packed concrete mix. Moreover, the washing of sand from 75 micron gives an idea of silt content.In respect of CRF, the 15% material is found to pass 75 micron which is nothing but silt and clay. They adsorb water and admixture which is resulted in the higher dosage of admixture.

The influence of cementitious materials and replacement thereof on the dosage of admixture for similar workability in HS-SCC mixes is shown in Table 6 and indicated in Fig. 4**.** It is observed that for similar initial flow, the HS-SCC mixes with crushed unwashed sand are found to require higher dosage of admixture (MasterGlenium SKY 8855) than that in the mixes with other three types of sand. The mixes with crushed sand is found to require approximately 10% higher dosage of admixture than that in the mixes with washed crushed sand, for similar flow value. An increase in fines in crushed unwashed sand can reduce both- the initial workability and the workability retention performance of a high-range water reducer (HRWR). The higher dosages of HRWR than the normal dosage is required due to the presence of large amounts of micro-fine particles (less than

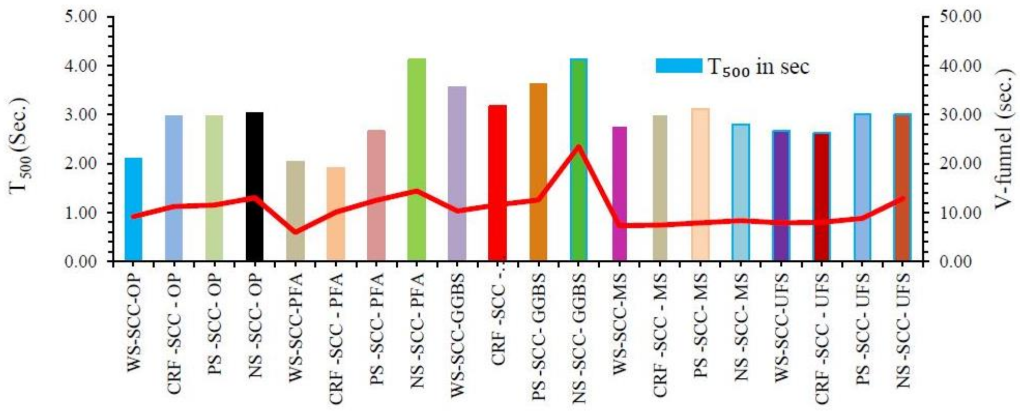


Fig. 5 The influence of different types of fine aggregates on *V*-funnel, T_{500} time for similar workability in different cementitious SCC mixes

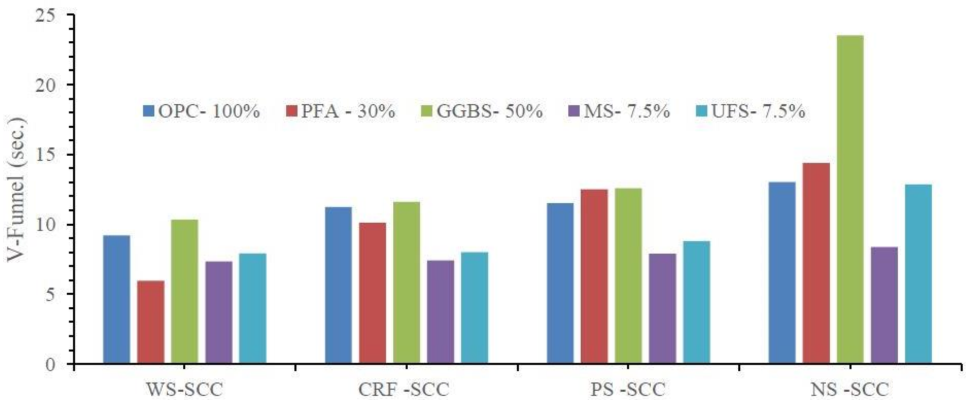


Fig. 6 Correlation of *V*-funnel values for different mixes

~75 μ).

At the construction site this can be interpreted as an addition of water to the concrete mixture to maintain the workability which can result in the higher dosage of admixture for maintaining *w/b* value and achieving the desired workability and workability retention. From these results, it can be inferred that the proper control of the aggregate source and an understanding of the variance in fines is necessary to ensure good quality control of HS-SCC concrete at the site. In typical observation, the unwashed crushed sand also leads to decrease in the dosage of admixture. This indicates washing and processing of sand helps in reducing the demand of water and admixture for similar workability. The processing or washing of fine aggregates generally removes silt and clay that contributes in drastic increase in demand of water and admixture for similar flow properties.

The fineness of fly ash and GGBS is lesser than that of Microsilica. The addition of fly ash and GGBS decreases the demand of admixture while that of micro silica, increases the demand for similar workability in all the five sets of mixes, i.e., the mixes with OPC, Fly ash, GGBS, Microsilica andultrafine slag.An increase in the dosage of super-plasticizer to obtain similar flow in microsilica mix is attributed to the fineness of MS.

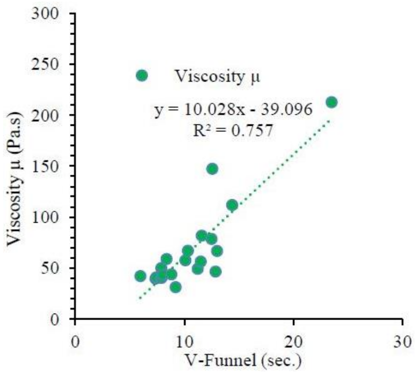
5.2 Effect of the types of cementitious material and sand on T_{500} and V-funnel

The influence of different types of fine aggregates on V-funnel and T_{500} time for similar workability in different cementitious SCC mixes for same water to binder ratio and paste volume is compared in Fig. 5. The effect of the supplementary cementitious materials on the flow, *V*-funnel and T_{500} is remarkable in terms of its nature.

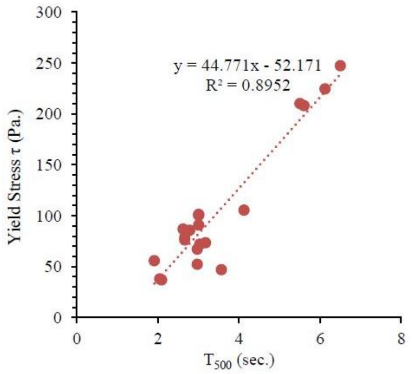
It is seen from Fig. 5 that the washed sand significantly reduces T_{500} and *V*-funnel time values despite the influence of cementitious materials. The primary reason for the results in increase in T_{500} and *V*-funnel values in plaster and fine natural sand is the fineness of sand. The shape of fine aggregates is found to have less influence on T_{500} and *V*-funnel than fineness. Hence, despite spherical shape, T_{500} and *V*-funnel values are found to increase in the fine natural sand. The GGBS and Fly ash are found to more sensitive to changes in the fine aggregates when compared with OPC, MS and UFS.

The statistical analysis presented in Fig. 6 shows that *V*-funnel value is highly influenced by type of SCM and the type of fine aggregate used irrespective of the same *w/b* ratio, paste volume, flow properties etc. The fine aggregate in particular is found to have more influence on the *V*-funnel results. In a typical observation, the unwashed crushed sand leads to decrease in the results of *V*-Funnel and T_{500} when compared with other three types of sand.

5.3 Significance of the relationship between traditional test method and rheology data.



(a)



(b)

Fig. 7 Relation between viscosity, *V*-funnel, yield stress and T_{500}

Few researchers (Roussel 2006, Bouziani *et al*. 2013, Bauchkar *et al.* 2014, Zhu *et al.* 2017) demonstrated linear relationships between both *V*-funnel vs viscosity and Slump flow vs yield stress. Along similar lines, the statistical modeling is also carried out using multiple linear regression to establish a relation between the *V*-funnel versus plastic viscosity and T_{500}versus Yield stress for HS-SCC (Fig. 7).

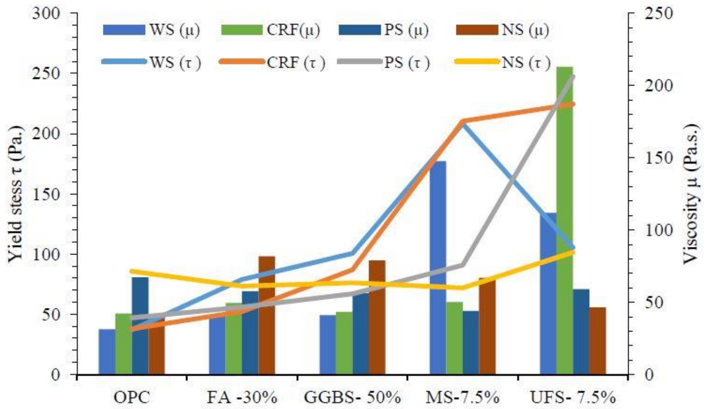
The results indicate that the T_{500} time is a unique function of the yield stress and *V*-funnel, respectively, with the viscosity; but rather a more complex function of both. The 500-mm spread time is proved to be more closely connected with the yield stress than that with the viscosity; especially, at high viscosity whereas on the other hand, the *V*-funnel time is more dependent on the viscosity. Consequently, the following relationships are established between T_{500} and yield stress; and V-Funnel and viscosity for the HS-SCC mixes.

$$\text{Yield Stress} = 44.771\ (T_{500}, \text{sec}) - 52.17 \tag{1}$$

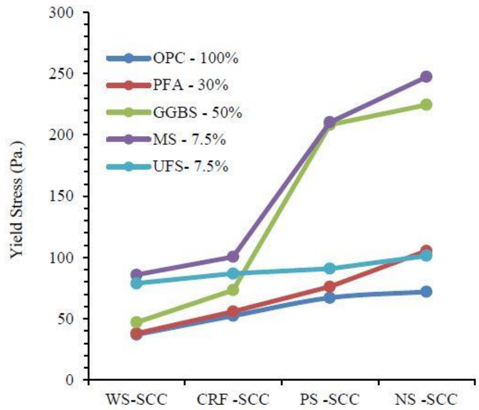
$$\text{Viscosity} = 10.028\ (V\text{-funnel, Sec}) - 39.096 \tag{2}$$

5.4 Effect of types of supplementary cementitious materials and sand on rheology

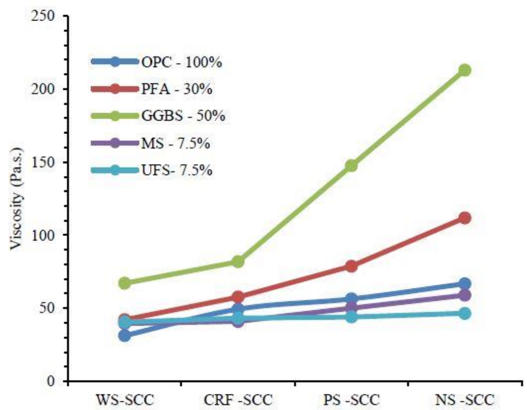
The results reported in Table 6 with respect to changes in SCM and the properties of fine aggregates are indicated graphically in Fig. 8 to show the rheological behaviour of the mixes.



(a)



(b)



(c)

Fig. 8 Variation of yield stress and viscosity due to changes in fine aggregates

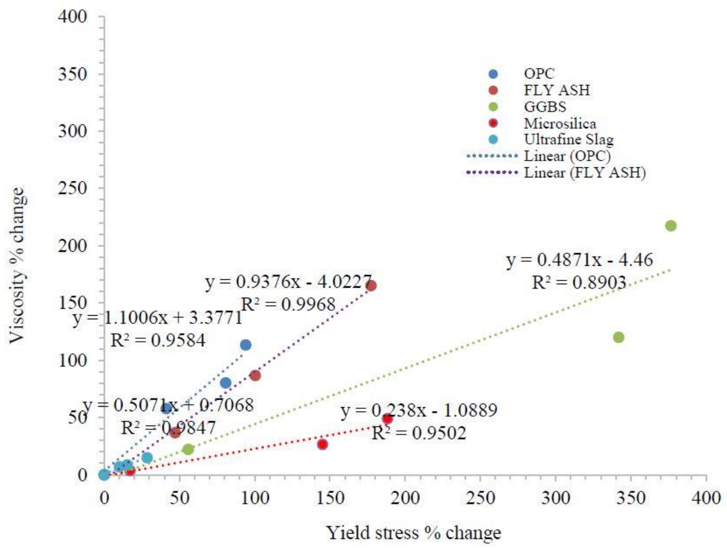


Fig. 9 Effect of fineness of sand on the yield stress and viscosity w.r.t. washed crushed sand

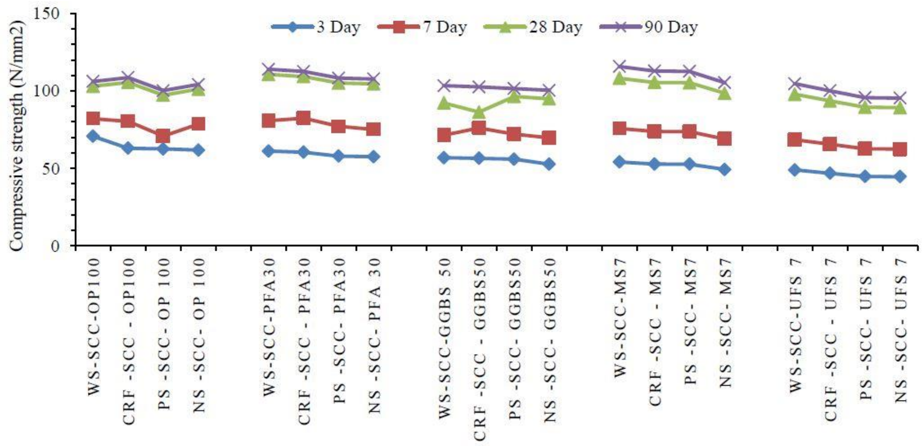


Fig. 10 Effect of sand and various cementitious materials on compressive strength

From Fig. 8, it is seen that the behaviour between the plastic viscosity and the yield stress is by and large same for all the types of fine aggregates, i.e., sand. That means when there is an increase in one of these parameters, the other also increases. The results also show that the properties and amount of the fine aggregate have a strong influence on the rheology. The large amount of fines often found in the fine aggregates primarily increases the yield stress of the HS-SCC. The amount of fines also contributes to the plastic viscosity which is attributed to the increased interparticle friction. The results clearly show that the particle size of the fine aggregates strongly contributes to the plastic viscosity. A decrease in plastic viscosity and yield stress is observed in respect of WS mixesas compared to that in CRF, PS and NS mixes. This tendency seems to be physical parameters of the type of fine aggregate used in mixes.

The effect of fineness of sand w.r.t. that of washed crushed sand on rheology of the HS-SCC mixes is indicated in Fig. 9.

In this experiment, HS-SCC content paste volume more than 45% is incorporated to meet all the requirements pf EFNARC (2005). Hence, rheology of HS-SCC is highly dependent on the type of SCM and fine aggregates used. From Fig. 9, it is found that the yield stress and plastic viscosity increases with the specific surface area of the fine aggregates and the type of SCM used in the mixes. The results also suggest that the shape, fineness along with the percentage replacement of the supplementary cementitious materials also influences the plastic viscosity of HS-SCC. The change in the viscosity of the HS-SCC mixes with elongated shape GGBS fines is on higher side than the corresponding fly ash with spherical shaped fines.

On the contrary, when ultrafine slag was added, yield stress and viscosity were decreased compared to microsilica based HS-SCC (Fig. 9). In simple words, the mortar mixes were getting more fluid and workable when ultrafine slag was added. There seems to be a significant difference between the micosilica and ultrafine slag in its effect on rheology. According to these results the ultrafine slag is a promising addition to reduce the effect of ultrafine SCM on the rheology of HS-SCC. Further, it is also observed that the fineness of fine aggregate and shape and fineness of SCM significantly control yield stress and viscosity of HS-SCC, GGBS mix with finer fine aggregates shown maximum yield stress and viscosity.

The work underscores the higher yield stress and plastic viscosity often in concrete containing higher fineness in fine aggregate. The GGBS is required to be used with utmost care in HS-SCC concrete; especially, when the quality of sand is finer in nature.

5.5 Effect of fine aggregates on development of strength

The compressive strength of the HS-SCC mixes obtained in respect of four different types of sands for 3 days, 7days, 28 days and 90 days' curing period corresponding to various proportions of SCM is already reported in Table 6. The effect of types sand and various cementitious materials used in the study on the compressive strength is shown in Fig. 10.

It is observed from Fig. 10 that the washed sand based mixes shows slightly better strength as compared to that in unwashed crushed sand, washed plaster sand and washed fine natural sand mixes. It may be noted that the fineness of the sands affects the strength to some extent. The mixes with replacement of OPC by GGBS mix show lower strength gain whereas that by fly ash, ultrafine slag and Micro silica, enhancement in the strength. This means that the addition of SCM helps in long term strength gain. It is also seen that the strength in respect of ultrafine slag is lesser corresponding to 90 days as compared with that in MS. This could be attributed to the slow reaction of UFS materials with OPC, mainly due to the difference of silica content and fineness value.

5.6 Effect of fine aggregate on durability

The effect of different types of sands in different SCM mixes on various durability parameters is indicated in Fig. 11 (a)-(c). It is seen that the washed sand based mixes show slightly better durability results as compared to that in unwashed crushed sand mixes. This shows that the washing of crushed sand helps to improve the durability of HS-SCC. It may be noted that the fineness of the sands positively improves the water permeability (WP), water absorption (WA) and rapid chloride penetration (RCPT) values, mainly due to dense packing of mix voids. The mixes with SCM replacement of MS and UFS is found to improve WA, WP and RCPT results as compared to that in OPC, FA and GGBS mixes.

5.6.1 Rheo-strength and rheo-durability properties of High strength self-compacting concrete

The properties of HS-SCC such as rheology, strength and durability are important for the selection of the mixes for high-rise construction. Unique performance based rating systems helps to draw an excellent baseline 'report card' for selection of the mixes for high-rise construction. They are useful for evaluating the performance of various fresh and hardened concrete properties and to set the meaningful targets for designing HS-SCC mixes as per the specifications or target requirements. This method replaces guesswork with a scientific methodology to establish targets, evaluate and selection of mix. Over the time, it helps to consistently improve the mixes by shifting specification parameters to better performing levels.

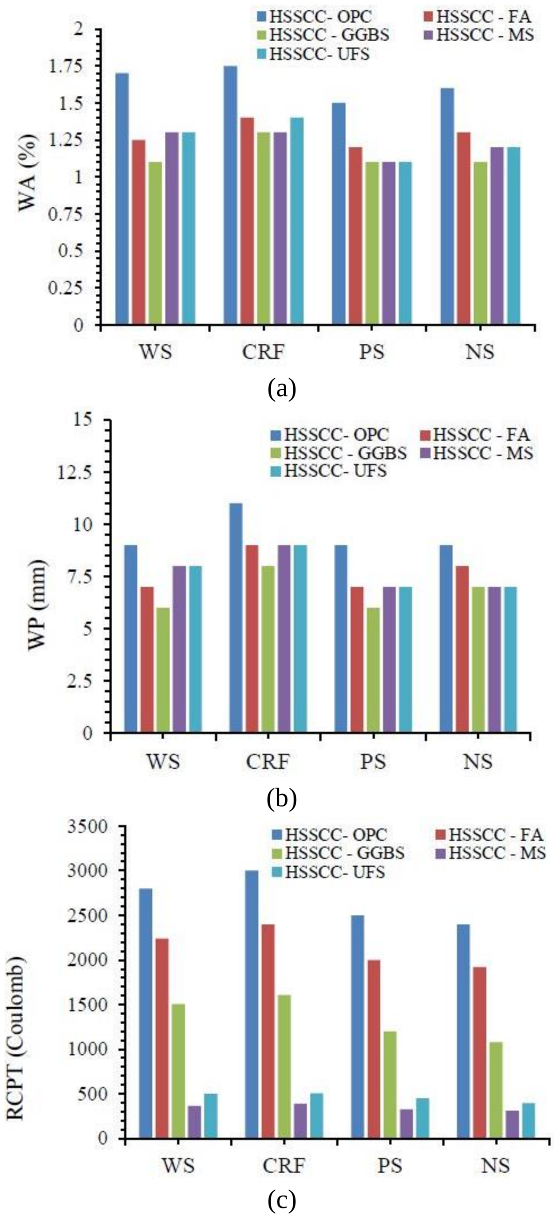
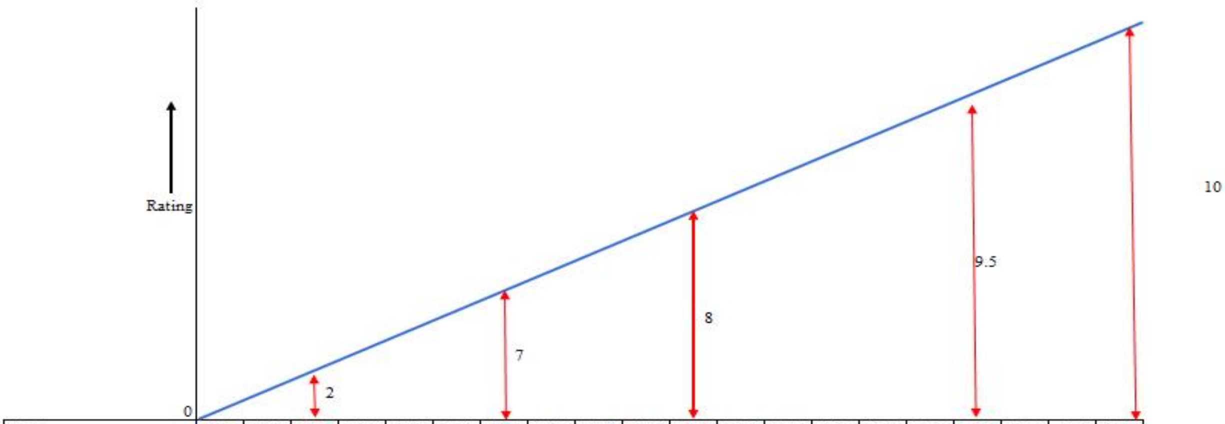


Fig. 11 Effect of different types of sands in different SCM mixes on various durability parameters

In this study, a regression based statistical method is used. This method is transparent, widely accepted and easy to adopt for multipurpose rating system in different areas. This approach is used for the first time in this study and compares the whole rheological, strength and durability parameters of the HS-SCC mixes under consideration with a benchmark mix of similar characteristics, and derive a score based on its performance results. A four-step statistical methodology described below is used as a way around this problem.

i. Yield stress results
ii. Viscosity results
iii. Compressive Strength
iv. Durability parameter (WA, WP and RCPT)

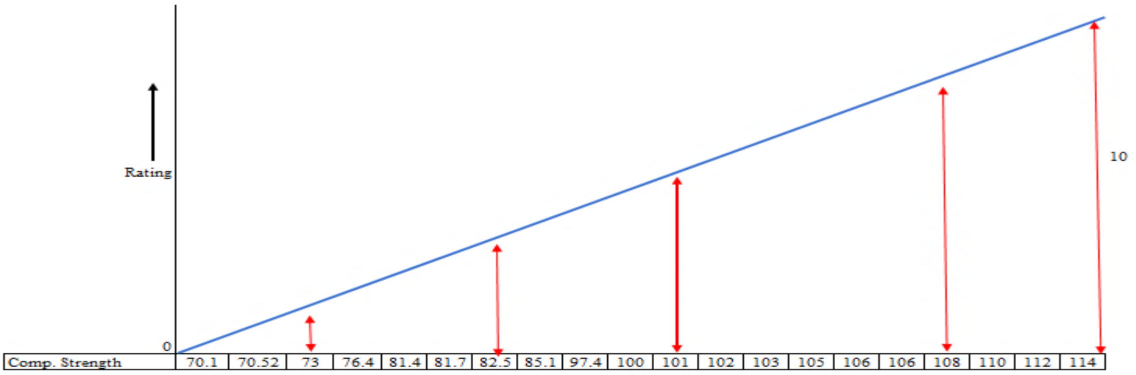
The results of Rheology, strength and durability test obtained are converted into performance ratings on the scale of 0-10 with 10 being the best and 0 representing the worst



Yield	247	225	210	208	105	101	101	90.9	86.9	85.8	78.8	76.2	73.4	72	67.1	55.9	52.4	47.1	38	37.1
Viscosity	213	148	112	81.9	78.8	67.1	66.8	59	57.7	56.4	50.1	49.4	46.5	44	43.3	42.2	41	40.5	39.6	31.3

Yield stress Rating	0	1	2	2	7	7	7	7	8	8	8	8	8	8	9	9	9	10	10	10
Viscosity Rating	0	4	6	7	7	8	8	8	9	9	9	9	9	9	9	9	9	9	10	10

(a)



Comp. Strength	70.1	70.52	73	76.4	81.4	81.7	82.5	85.1	97.4	100	101	102	103	105	106	106	108	110	112	114

WA (%)	1.74	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.47	1.45	1.45	1.42	1.41	1.4	1.4	1.4	1.4	1.35	1.35	1.2
WP (mm)	10	10	9	8	8	8	7	6	6	6	5	5	4	4	3	3	0	0	0	0
RCPT (columb)	3141	3100	3047	2950	1608	1508	1361	1300	1200	1200	1200	1188	1079	1079	950	884	650	600	500	450

Comp. Strength Rating	0	0	1	1	3	3	3	3	6	7	7	7	7	8	8	8	9	9	10	10

WA Rating	0	1	3	3	3	4	4	4	5	5	5	6	6	6	6	6	6	7	7	10
WP Rating	0	0	1	2	2	2	3	4	4	4	5	5	6	6	7	7	10	10	10	10
RCPT Rating	0	0	0	1	6	6	7	7	7	7	7	7	8	8	8	8	9	9	10	10
Avg. Durability rating	0	0	1	2	3	4	5	5	5	6	6	6	7	7	7	7	9	9	9	10

(b)

Fig. 12 Linear interpolation rating results of yield stress, viscosity, compressive strength and durability based on experimental results obtained

performer. For an example, lowest value of yield, viscosity, hardened concrete water absorption along with RCPT is rated as 10 whereas highest value of yield, viscosity, harden concrete water absorption, water permeability along with RCPT is rated as 0 in the performance rating. Similarly, highest value of strength is rated as 10 and lowest value obtained is rated as 0. The intermediate values of rating obtained through linear interpolation method as shown in Fig. 12 (a) and (b).

Specifically, this study presents the combination of rheology, strength and durability and the combined parameters are termed as *rheo- strength* and *rheo- durability* in this study. These parameters are reported in Table 7. It is observed from Table 7 that the washed sand based mixes shows better rheo- strength and rheo- durability when compared with that in other sand mixes. The UFS with washed crushed sand seems to be good solution for high rise construction in terms of highest scoring *rheo- strength* and *rheo- durability* performance.

It is also observed from Table 7 that the washed sand based mixes shows better rheo-strength and rheo-durability when compared with that in other sand mixes. The UFS and Micro silica 7.5% replacement as SCM with washed crushed sand as fine aggregate seems to be good solution for high rise construction in terms of optimum *rheo-strength* and *rheo-durability* performance.

This research could help in improving the current judgmental rating systems in India by providing contextual benchmarks and evaluation of results obtained with targets criterion for fresh and hardened concrete properties. A database of specification for rheology, strength and durability along with their standard deviation and related raw material parameters is a prerequisite for any performance based ratings. This initiative uses statistical procedures to arrive at a performance based rating methodology and rheo-strength and rheo-durability benchmarks in order to obtained optimum HS-HCC mix suitable for high rise building construction.

Table 8 Performance rating for *rheo-strength* and *rheo-durability* properties

	Description	Yield Stress rating	Viscosity rating	Strength rating	Durability rating	Rheo- Strength rating	Rheo- Durability rating	Combined Rating.
OPC -100% OPC	WS-SCC-OP	10	10	7	0	27	20	47
	CRF -SCC - OP	9	9	8	3	26	21	47
	PS -SCC- OP	9	9	7	4	25	22	47
	NS -SCC- OP	8	8	7	3	23	19	42
PFA - 30% Fly Ash	WS-SCC-PFA	10	9	3	4	22	23	45
	CRF -SCC - PFA	9	9	3	5	21	23	44
	PS -SCC- PFA	8	7	3	5	18	20	38
	NS -SCC- PFA	7	6	1	6	14	19	33
GGBS - 50 % GGBS	WS-SCC-GGBS	10	8	1	3	19	21	40
	CRF -SCC - GGBS	8	7	0	4	15	19	34
	PS -SCC- GGBS	2	4	3	5	9	11	20
	NS -SCC- GGBS	1	0	0	7	1	8	9
MS- 7.5% MS	**WS-SCC-MS**	**8**	**10**	**10**	**7**	**28**	**25**	**53**
	CRF -SCC - MS	7	9	7	8	23	24	47
	PS -SCC- MS	2	9	10	10	21	21	42
	NS -SCC- MS	0	8	9	9	17	17	34
UFS- 7.5% UFS	**WS-SCC-UFS**	**8**	**9**	**8**	**10**	**25**	**27**	**52**
	CRF -SCC - UFS	8	9	6	5	23	22	45
	PS -SCC- UFS	7	9	9	6	25	22	47
	NS -SCC- UFS	7	9	8	6	24	22	46

6. Conclusions

The extensive experimental investigations were carried out to study the effect of different types of fine aggregates in conjunction with different supplementary cementitious materials on *rheo- strength* and *rheo-durability* properties of High strength self-compacting concrete. Following are some of the broad conclusions deduced from the present study.

- The rheological properties and the demand of superplasticizer (admixture) in respect ofHS-SCC are strongly dependent on the properties of the fine aggregate. The shape and texture of the aggregate particles affects concrete workability.
- The higher dosage of superplasticizers with crushed fine aggregate is believed to mainly originate from the relatively high amounts of fines often found in crushed fine aggregates.
- The finer sand can reduce the flowing ability of HS-SCC. The V-funnel time and T_{500} flow time shows significant increase with the increase in fineness of fine aggregate almost in all SCM mixes.
- The fineness of the sands affects the rheology and strength of HS-SCC. The washed sand based mixes show agood rheology and better strength as compared to that in the mixes prepared using remaining types of sands used in the present study. The washing of crushed sand or washed graded crushed sand is recommended for HS-SCC.
- The high yield stress and the plastic viscosity resulting from the high amounts of fineness of sands can effectively be reduced using an appropriate type of supplementary cementitious materials (SCM) and by adjusting combined gradation of aggregates.
- The ultrafine slag (UFS) gives good rheology to the mix as compared to the micro silica (MS). However, it has slow hydration reaction with OPC as compared to that in MS. This is mainly attributed to low fineness and silica content (Sio_2) in UFS.
- The SCMs such as MS and UFS at 7.5% replacement in conjunction with washed crushed sand fine aggregates can be a good solution for high rise construction in terms of *rheo-strength* and *rheo-durability* performance.
- The rheo-strength and rheo-durability needs the development of methodology for proper performance based rating and benchmarking; and must be combined with regression and distribution analysis of the experiment results for selecting final HS-HCC mix for field application.

Acknowledgements

The permission accorded by the management of BASF Construction Chemicals for the experimentation at their research and development center at Mahape, Navi Mumbai along with the help extended by the technical and supporting staff in general and Mr. Zoyeb Mistry of the center, in particular is gratefully acknowledged.

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