Advances in Concrete Construction, *Vol. 5, No. 3 (2017) 183-199*
DOI: https://doi.org/10.12989/acc.2017.5.3.183

Experimental studies on rheological properties of smart dynamic concrete

Sunil D. Bauchkar[a] and H.S.Chore*

Department of Civil Engineering, Datta Meghe College of Engineering, Sector-3, Airoli, New Mumbai, 400708, India

(Received January 25, 2017, Revised March 30, 2017, Accepted April 17, 2017)

Abstract. This paper reports an experimental study into the rheological behaviour of Smart Dynamic Concrete (SDC). The investigation is aimed at quantifying the effect of the varying amount of mineral admixtures on the rheology, setting time and compressive strength of SDC containing natural sand and crushed sand. Ordinary Portland cement (OPC) in conjunction with the mineral admixtures was used in different replacement ratio keeping the mix paste volume (35%) and water binder ratio (0.4) constant at controlled laboratory atmospheric temperature (33°C to 35°C). The results show that the properties and amount of fine aggregate have a strong influence on the admixture demand for similar initial workability, i.e., flow. The large amounts of fines and lower value of fineness modulus (FM) of natural sand primarily increases the yield stress of the SDC. The mineral admixtures at various replacement ratios strongly contribute to the yield stress and plastic viscosity of SDC due to inter particle friction and cohesion.

Keywords: smart dynamic concrete (SDC); rheology; workability; ground granulated blast-furnace slag (GGBS); fly ash (FA); microsilica (MS); ICAR rheometer

1. Introduction

Concrete rheology exhibits a complex behaviour, both in fresh and hardened state. The flow of concrete is so complicated because it is a complex suspension of particles. Particles of coarse aggregates are dispersed in mortar and within the mortar, particles of fine aggregates are dispersed in cement paste and further within cement paste, cement particles are dispersed in water. Owing to this, the rheological behavior of fresh concrete cannot be described using Newtonian viscosity function, which is the simplest equation for describing the flow behavior of liquids. The Bingham model, which is the simplest form of non-Newtonian model, is frequently used for describing the flow behavior of ordinary concrete. However, some other types of concrete, especially the self-compacting concrete (SCC) exhibit different kinds of behavior and hence, need different non-Newtonian models to describe their behavior (Feys *et al.* 2008). Despite this, for simplicity, most of researchers follow Bingham model only. The smart dynamic concrete is classified as low fines self compacting concrete using special viscosity modifying admixtures (VMA) similar to the

*Corresponding author, Professor and Head, E-mail: hschore@rediffmail.com or chorehs@gmail.com
[a]Research Scholar, E-mail: sunil.bauchkar@basf.com

http://www.techno-press.org/?journal=acc&subpage=7 ISSN: 2287-5301 (Print), 2287-531X (Online)

VMA type self compacting concrete. The rheological behaviour of the concrete significantly affects its flow properties and pumpability.

2. Review of literature

There have been many research works involving the studies on the rheological behavior of self compacting concrete. Effect of mineral admixtures, cementitious materials, fine aggregates, chemical admixtures on the rheology of concrete have been studied by various researchers. Some of the prominent studies in this context are reviewed here.

Some of the researchers (Nevill 1996, Nehdi *et al.* 1998, Williams *et al.* 1999, Chidiac and Mahmoodzadeh 2009, Khayat *et al.* 2012) observed that ground granulated blast furnace slag (GGBFS) and fly ash (FA) could contribute to increase the flowability in the fresh state and densify microstructures and develop higher mechanical properties due to their latent hydraulic properties and Pozzolanic reaction, respectively. Further, the use of micro-silica (MS) can improve the workability when used at low replacement rates, but can reduce the workability when added at higher replacement rates. The addition of 2 to 3% micro-silica or silica fume by mass of cement can be used as a pumping aid for concrete.

Few researchers (Ferraris 1999, Cry *et al.* 2000, Ferraris *et al.* 2001, Daczco 2003, Park *et al.* 2004, Nagendra 2013) indicated that the yield stress of cement paste showed the same trend of slump in concrete, and the plastic viscosity was associated with the stickiness, placeability, pumpability, finishability and segregation in the concrete. Some of the researchers (Tattersall and Banfill 1983, Mork and Gjorv 1996) pointed out that, a threshold value of the silica fume replacement level exists for concrete mixtures such that below the threshold value, the use of silica fume reduces plastic viscosity but produces little change in yield stress. Above the threshold value, both yield stress and plastic viscosity increase with increasing levels of silica fume replacement.

In addition to the afore-mentioned works, there are several investigations (Westerholm 2008, Reddy and Gupta 2008, Pilegis *et al*. 2016) carried out for studying the effect of fine aggregates on rhelogical behavior of self-compacting concrete. The grading and particle shape of the fine aggregate was found to have significant effects on the rheology of the mortar formed. The concrete made up of manufactured sand was found to require a higher water cement ratio, admixture dosages for workability than that in the concrete made up from natural sand. The strength of such concrete was also found to exceed than that of concrete with natural sand.

Further, some of the researchers (Tattersall and Banfill 1983, Ramchandran 1992, Neubauer *et al.* 1998, Collepardi 2005, Jayasree and Gettu 2008, Aydin *et al.* 2009, Plank 2009, and 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.

ACI (2008) incorporated various parameters affecting rheology of concrete as pointed out in various investigations undertaken by the afore-mentioned researchers. Bauchkar and Chore (2014) reported the effect of natural sand and mineral admixture on the rheological properties of self-compacting concrete (SCC) in which the grade of concrete was M-60 and above and the paste volume, 42%.

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

Material	UoM	FA	GGBS	MS	OPC 53
Blaine fineness	(m^2/kg)	345	390		328
BET Surface Area	(m^2/kg)			22000	
Compressive strength as % of cement	(%)	84.2	92	156	100
Lime reactivity	MPa.	5.6		8.5	-
Autoclave expansion	(%)	0.06		NA	0.059
Sp. gravity	(%)	2.3	2.86	2.2	3.14
Loss on ignition (LOI)	(%)	1.2	0.37	2.6	2.81
Silica (SiO2)	(%)	60.72	33.72	92.3	20.68
Iron oxide (Fe2O3)	(%)	5.32	0.64	0.06	4.76
Alumina (Al2O3)	(%)	27.5	18.22	0.62	5.54
SiO2+Al2O3+Fe2O3	(%)	93.54	52.58	93.88	30.98
Calcium oxide (CaO)	(%)	1.42	34.51	0.3	61.39
Magnesium oxide (MgO)	(%)	0.48	11.22	0.3	1.07
Total sulphur (SO3)	(%)	0.21	0.22	0.05	2.5
Alkalies (Na2O+K2O)	(%)	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

3. Significance of the present work

With increased urbanization, mass housing is one of the great challenges that the developing country like India is facing when rapid construction is necessary for a burgeoning population, building material that is strong and suitable for fast construction is the need of the hour. Smart Dynamic Concrete (SDC) is one such. It flows under its own weight, allowing it to be easily and is quickly worked into different structures which are as strong as a regular concrete. It is durable, helps in saving the construction resources and time and reduces the need for maintenance, thus reducing overall carbon footprint. Its use is becoming more popular lately, especially in mass housing projects.

This concrete is designed to upgrade low grade high slump concrete (150-200 mm) to become self-compacting and robust concrete for day-to-day use at minimum extra cost. The centerpiece of this concept is Master Matrix, a high performance viscosity modifying agent (VMA), which allows for a quantum leap in concrete robustness. This concrete combines the advantages of both-traditionally vibrated concrete and self-compacting concrete. This concept makes unique mix-design optimization (by reducing fines) possible. Smart Dynamic Concrete adds economical, ecological and ergonomic values to concrete and has the potential to move the market up to the next level of advanced construction practice (Corradi *et al.* 2007, Brayan *et al.* 2011, Seow *et al.* 2011, and Bruce *et al.* 2012).

Plenty of studies have explored the effect of mineral and chemical admixtures along with the different types of aggregates on the rheological behavior of SCC. However, the studies with respect to the smart dynamic concrete (SDC) has not been yet reported. On this backdrop, the study on rheological properties of smart dynamic concrete is presented here. The main objective of

Table 2 Physical properties of aggregates

	IS Sieve Size (mm)	20	10	4.75	2.36	1.18	0.6	0.3	0.15	Silt content (%)	Fineness Modulus	Specific Gravity	Water Absorption
NS	% Passing	100	100	100	100	74.5	38.1	20.4	15.2	4%	2.32	2.6	0.50%
CS		100	100	93.9	65.2	43	28.9	17.6	10.4	12.50%	3.41	2.72	3%
20 mm		97.4	2.9	1.1	1.1	1.1	1.1	1.1	0	0.50%	6.94	2.82	1.50%
10 mm		100	82.6	3.4	2.8	2.8	2.8	2.8	0	0.50%	5.6	2.8	1.80%

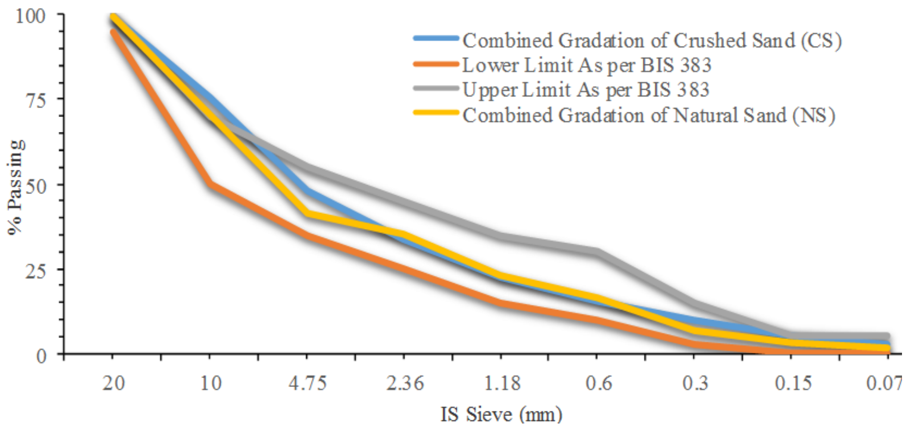

Fig. 1 Combined gradation curve for aggregate combination used in SDC mixes

this work is to evaluate the effect of the fine aggregate (fine Gujrat natural sand and Mumbai crushed sand) characteristics in conjunction with mineral admixtures on the rheological properties of SDC.

4. Materials and proportions of mixes

The matrix constituents included Ordinary Portland cement (similar to ASTM-Type-I) confirming to the requirement of IS 12269 (OPC 53). Fly ash (FA) meeting the requirement of ASTM C618 (class F) was used. Ground granulated blast furnace slag (GGBS) and silica fume (MS). Crushed basalt with maximum size of 20 mm, 10 mm, 4.75 mm crushed sand (CS) and good quality well graded natural (river) sand (NS) were used as coarse and fine aggregates, respectively. The physical and chemical composition of cement and supplementary cementitious materials, as obtained through systematic laboratory investigations carried out at the Research and Development centre of BASF India Ltd., Navi Mumbai, are summarized in Table 1.

Physical analysis of aggregate obtained following systematic laboratory investigations carried out at the Research and Development centre of BASF India Ltd., Navi Mumbai, are given in Table 2. Fig. 1 shows combined gradation curve of aggregate combination used in smart dynamic concrete mixes.

A specially formulated Poly Carboxilate Ether based MasterGlenium Sky 8632, high rage water reducer with inbuilt viscosity modifying admixture (Master Matrix) was used in this study. The physical properties of MasterGlenium Sky 8632 were evaluated using state of the art

Table 3 Physical properties of MasterGlenium Sky 8632

Aspect	Light brown liquid
Relative Density	1.04 ± 0.01 at 25℃
pH	>6
Chloride ion content	< 0.2%

Table 4 Mix proportions for laboratory trials and results of fresh properties

Mix Code	OPC	FA	GGBS	MS	MG 8632 Admixture	Flow	T_{500}	Yield stress	V funnel	Viscosity
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	(%)	(mm)	(sec)	(Pa)	(sec)	(Pa-s.)
NS OP 1	450	0	0	0	0.52	650	3.27	56.6	7.56	25.2
NS PFA 1	405	45	0	0	0.50	640	3.29	57	9.06	32
NS PFA 2	360	90	0	0	0.47	640	3.3	57.6	10	39
NS PFA 3	315	135	0	0	0.44	640	3.33	61	11	46.7
NS PFA 4	270	180	0	0	0.41	650	3.35	64.3	12	54.5
NS GGBS 2	360	0	90	0	0.48	640	3.36	66.7	11.96	56
NS GGBS 3	315	0	135	0	0.48	650	3.5	77	17	61
NS GGBS 4	270	0	180	0	0.45	640	3.69	86.9	21.5	66.4
NS GGBS 5	225	0	225	0	0.38	640	4.2	80	24	80
NS GGBS 7	135	0	315	0	0.35	650	5	93.9	28	92.1
NSMS2.5	438.8	0	0	11.25	0.60	650	3.3	65	8.7	29.3
NS MS 5	427.5	0	0	22.5	0.70	650	3.45	73	9.81	33.3
NS MS 7.5	416.3	0	0	33.75	0.80	630	3.35	75.2	10.06	25.5
NS MS 10	405	0	0	45	0.90	640	4.5	99.1	11.47	27.9
CS OP 1	450	0	0	0	0.60	640	2.43	61.8	10	17.2
CS PFA 1	405	45	0	0	0.55	640	2.9	60	12.5	23
CS PFA 2	360	90	0	0	0.51	640	3.3	56.6	15.12	27.7
CS PFA 3	315	135	0	0	0.50	650	3.4	63	20	32
CS PFA 4	270	180	0	0	0.47	650	3.45	68.8	24.6	38.8
CS GGBS 2	360	0	90	0	0.48	640	3.59	62.2	16.16	25.1
CS GGBS 3	315	0	135	0	0.48	650	3.62	72	19	27.9
CS GGBS 4	270	0	180	0	0.47	640	3.68	83.2	21.5	29.5
CS GGBS 5	225	0	225	0	0.43	650	3.85	71.5	23	35.8
CS GGBS 7	135	0	315	0	0.37	650	4	60.1	25	41
CS MS 2.5	438.8	0	0	11.25	0.65	650	2.6	36	12	19.4
CS MS 5	427.5	0	0	22.5	0.70	630	3	52.2	13.38	21.5
CS MS 7.5	416.3	0	0	33.75	0.85	640	3.4	69.7	15.36	17.8
CS MS 10	405	0	0	45	0.96	640	4.8	111	16.31	24.2

(OP1-100% OPC, PFA 1-10% PFA, PFA 2-20% PFA, PFA 3-30% PFA, PFA 4-40 % PFA, GGBS 2-20% GGBS, GGBS 3-30% GGBS, GGBS 4-40% GGBS, GGBS 5-50% GGBS, GGBS 7-70% GGBS, MS2-2.5% Micro silica, MS5-5% Micro silica, MS 7-7.5% Microsilica, MS10-10% Micro silica, NS-Natural sand, CS-Crushed sand.)

(a) (b)

Fig. 2 ICAR Rheometer set up and testing

available at the Research and Development Centre of BASF India Ltd., Navi Mumbai. These properties are presented in Table 3.

In the present work, twenty-eight different smart dynamic concrete designed containing ordinary Portland cement (OPC) and other supplementary cementitious materials as fly ash, ground granulated blast furnace slag, and micro silica were considered. These supplementary cementitious materials were replaced by various percentages, maintaining volume of the mix paste (35%), w/b ratio 0.4 and constant flow of concrete (650+/-10). All the measurements were taken at higher temperature (temperature of concrete and atmosphere varying between 33℃ to 34℃). The additional details on the mix proportions are provided in Table 4.

5. Experimental work

The ICAR Rheometer was deployed to measure rheology of smart dynamic concrete. The rheometer consists of a container to hold the fresh concrete, a driver head that includes an electric motor and torque meter, a four-blade vane that is held by the chuck on the driver, a frame to attach the driver/vane assembly to the top of the container; and a laptop computer to operate the driver, record the torque during the test and calculate the flow parameters. The container contains a series of vertical rods around the perimeter to prevent slipping of the concrete along the container wall during the test. The set-up of the ICAR rheometer, flow table, V-funnel used for the testing, is shown in Fig. 2(a) and (b).

The concrete was discharged directly from the pan mixer into the ICAR Rheometer container. Two types of tests were performed. 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

(a) Slump Flow (b)V-Funnel

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

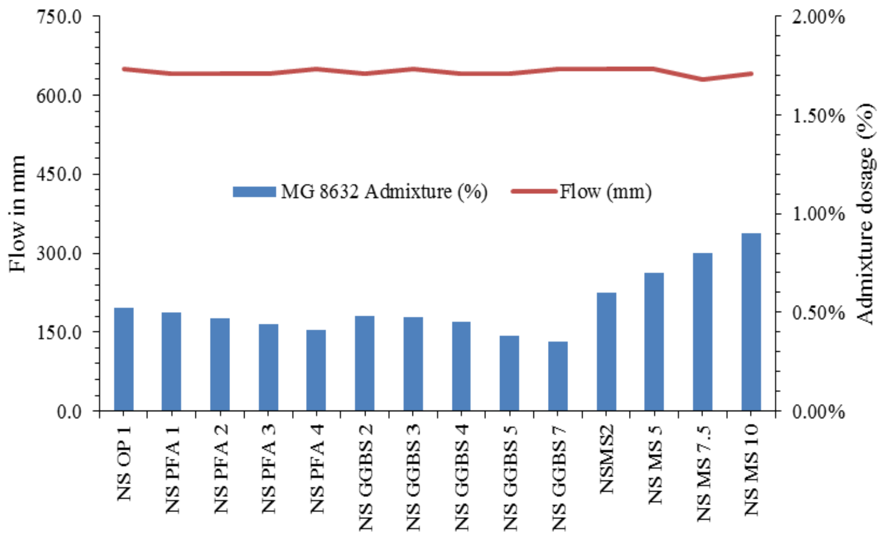

Fig. 4 The influence of natural sand and cementitious materials on admixture dosage for similar workability in SDC mixes

yield stress. The other type of test was a flow-curve test to determine the dynamic yield stress and the plastic viscosity.

In addition, the slump-flow test was performed by filling the concrete into a standard slump cone (ASTM C-143) that was centered on a level plastic plate (Fig. 3(a)). The slump cone was lifted and three measurements were made-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, which were determined based on the definition as given by Wallevik (2008), were made on a scale of 0 to 3, with 0 exhibiting excellent stability and 3 exhibiting poor

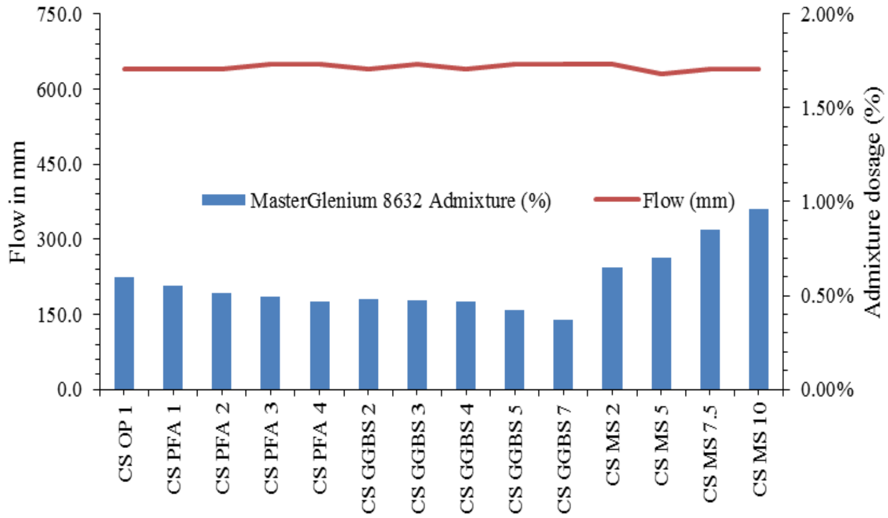

Fig. 5 The influence of crushed sand and cementitious materials on admixture dosage for similar workability in SDC mixes

stability. Other than slump- flow test, V-funnel test (Fig. 3(b)) was performed as per EFNARC (2005) standards.

6. Results and discussion

The various rheological properties of fresh smart dynamic concrete (SDC) with different cementitious materials and contents thereof are presented in Table 4. The influence of cementitious materials and replacement thereof on admixture dosage for similar workability in SDC mixes with respect to natural sand and crushed sand is shown in Figs. 4 and 5, respectively.

From the various parameters obtained in view of the rheology of fresh SDC concrete as reported in Table 4 and shown in Figs. 4 and 5, the slump flow is found to be between 630 and 650 mm. This indicates the good deformability of the fresh concrete. The effect of the mineral admixtures on the properties such as flow, V-funnel and T_{500} values, is observed to be significant in terms of its nature. Every mineral admixture has unique effect on the properties of fresh and hardened concrete. The fly ash is spherical in nature and its fineness is 345 kg/m^2 whereas GGBFS is flaky in nature and having fineness 390 kg/m^2. Both the materials behaves differently in fresh state. The fly ash gives ball bearing effect to the mix that will help to improve cohesiveness and good workability retention to coarser mix whereas GGBFS, due to flaky in nature and high fineness over fly ash, increase water and admixture demand; and impart stickiness to mix due to its interlocking properties.

As Microsilica (MS) is very fine in nature, it reacts with cement fast than fly ash or GGBS. The MS is spherical in shape, which adds ball bearing effect in concrete mix. This statement is true only for lower replacement of micro silica. As the percentage of replacement increases to 7.5% and above, fineness area gets drastically increased and leads to an increase in the demand of water and admixture. The MS increases both, the yield stress and the viscosity of SDC mixes at higher percentage of replacement.

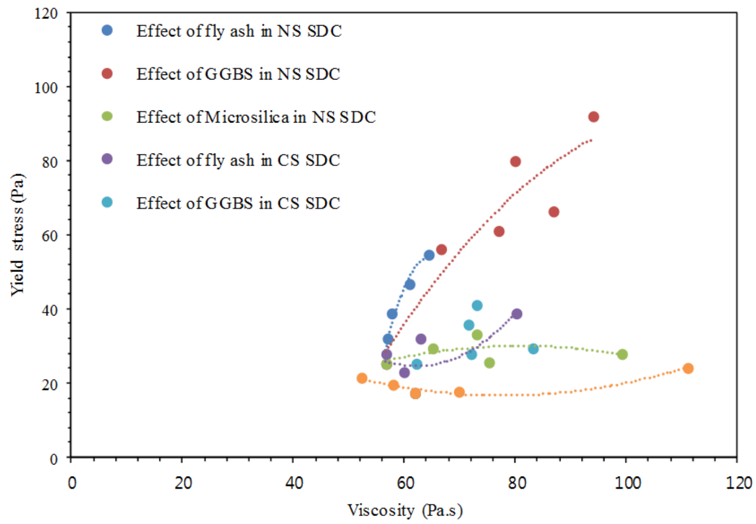

Fig. 6 Effect of replacement of fly ash, GGBS, Microsilica on rheology of SDC

6.1 Effect of cementitious materials on admixture dosage for similar flow

Though the paste volume of SDC mixes is constant, physical properties of fine aggregates (sand) influence the rheology of concrete. As per material properties and gradation report (Table 2), the natural sand (0-3 mm) is finer than crushed sand (0-4.75 mm) which, results in to more cohesive and densely packed concrete mix. The fineness of natural sand silt content is 3.5%, water absorption is 0.5% while for crushed sand silt content, the corresponding values are 12.5% and 4%, respectively. Hence, for similar initial flow, the SDC mixes with crushed sand are found to required higher dosage of Admixture (MasterGlenium Sky 8632) than that in the mix with natural sand. The mixes with crushed sand is found to require approximately 8-10% higher dosage of admixture than that in the mixes with natural sand, for similar flow value in SDC.

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 both the mixes, i.e., the mixes with natural and crushed sand (Figs. 4 and 5).

An increase in fines in 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 are required due to the presence of large amounts of ultra-fine particles (less than ~150 μ). At the construction site this can be interpreted as an addition of water to the concrete mixture so as 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 this it can be inferred that, the proper control of aggregate source and an understanding of the variance in fines is necessary to ensure good quality control of SDC concrete at the site.

6.2 Effect of contents of mineral admixtures on rheological properties

The effect of replacement of fly ash, GGBS, Microsilica in the different proportion on the rheological properties of SDC is illustrated in Fig. 6.

It is evident from Fig. 6 that, the addition in the replacement contents of fly ash, GGBS, Micro

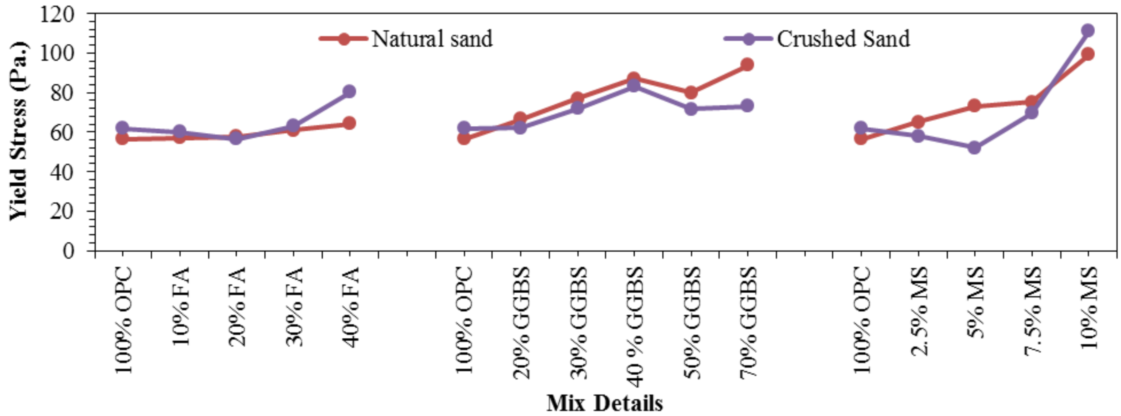

Fig. 7 Influence of the mineral admixtures on yield stress

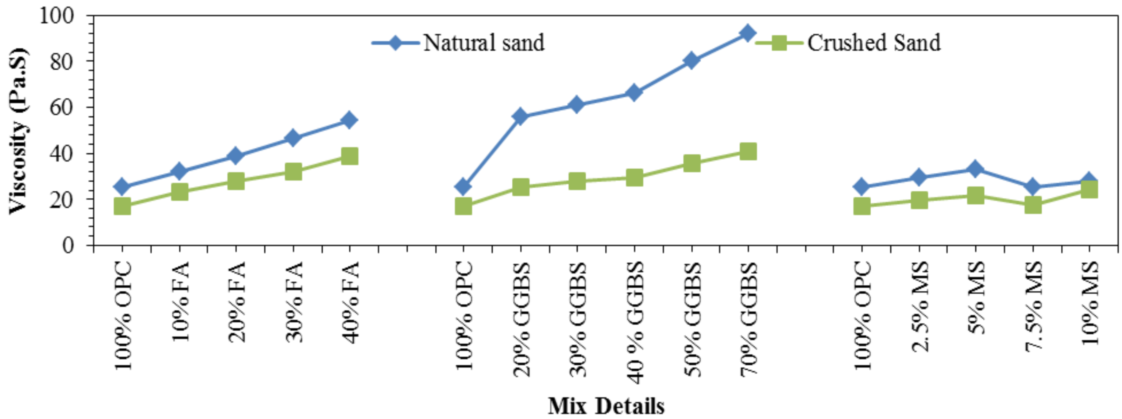

Fig. 8 Influence of the mineral admixtures on viscosity

silica in SDC mix with respect to a fixed ratio of water to cement and paste volume leads, to an increase in the rheological properties. The highest increase in plastic viscosity is observed in respect of SDC made with GGBS using natural sand. The increase in the fly ash and Microsilica also shows similar trend on the viscosity, but intensity of impact is observed to be lower than the GGBS.

Figs. 7 and 8 shows the influence of dosage of fly ash, GGBS and MS on the yield stress and viscosity in respect of SDC made with natural and crushed sand. The values are already indicated in Table 4.

As expected, it is found that the replacement of OPC by fly ash (PFA) in the increasing order improves the viscosity of the mix as compared to that obtained in case of the SDC mixes (both-natural and crushed sand based) made up of pure OPC cement. The increase in the fly ash content in the range of 0-40% is found to increase the static yield stress from 56.6 Pa to 64.3 Pa. in respect of the mixes made using natural sand. Similarly, such increase is found in the range of 61.8-80.2 Pa in respect of the mixes made using crushed sand. This increase in the yield stress is attributed to the effect of fines and shape of the fly ash. It is also observed during trials that the fly ash in the mixes with natural sand improves the cohesiveness significantly than that in the mixes with

Table 5 Effect of crushed sand on yield stress and viscosity of SDC mixes

Mix	NS Yield stress (Pa)	CS Yield stress (Pa)	Change in Yield stress (Pa.)	Change in Yield Stress (%)	NS Viscosity (Pa.s.)	CS Viscosity (Pa.s.)	Change In Viscosity (Pa.s)	Change in Viscosity (%)
100% OPC	56.6	61.8	-5.2	-9	25.2	17.2	8	32
10% FA	57	60	-3	-5	32	23	9	28
20% FA	57.6	56.6	1	2	39	27.7	11.3	29
30% FA	61	63	-2	-3	46.7	32	14.7	31
40% FA	64.3	80.2	-15.9	-25	54.5	38.8	15.7	29
20% GGBS	66.7	62.2	4.5	7	56	25.1	30.9	55
30% GGBS	77	72	5	6	61	27.9	33.1	54
40% GGBS	86.9	83.2	3.7	4	66.4	29.5	36.9	56
50% GGBS	80	71.5	8.5	11	80	35.8	44.2	55
70% GGBS	93.9	60.1	33.8	36	92.1	41	51.1	55
2.5% MS	65	58	7	11	29.3	19.4	9.9	34
5% MS	73	52.2	20.8	28	33.3	21.5	11.8	35
7.5% MS	75.2	69.7	5.5	7	25.5	17.8	7.7	30
10% MS	99.1	111	-11.9	-12	27.9	24.2	3.7	13

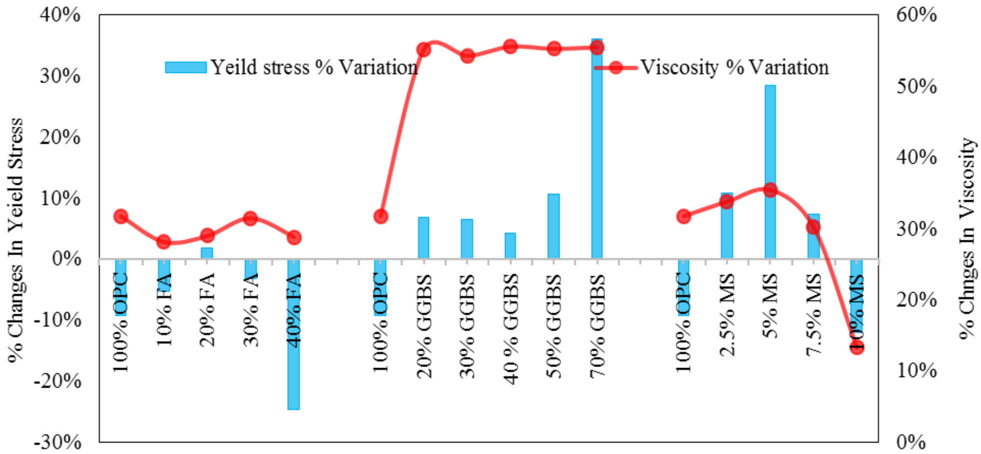

Fig. 9 Effect of crushed sand on the yield stress and viscosity w.r.t. natural sand

crushed sand mixes. The fly ash is a lighter material with spherical shape and high fines than OPC and this, contributes to the increase in the viscosity.

Ground granulated blast furnace slag (GGBS) was used to replace OPC on a mass basis at rates of 20, 30, 40, 50 and 70% (various percentages of GGBS which satisfies the IS 456-2000 code allowed limit). From Figs. 7 and 8, and Table 4, it is seen that the addition of GGBS in the increasing levels of GGBS increases the yield stress and viscosity. This may be attributed to the flaky particles. The change in the rheology of SDC mixes made with natural and crushed sand seems to be similar when the GGBS is used. The GGBS have sharp edges and angles; and stick shape with a bit smaller. The GGBS particles when compared with the particles of ordinary

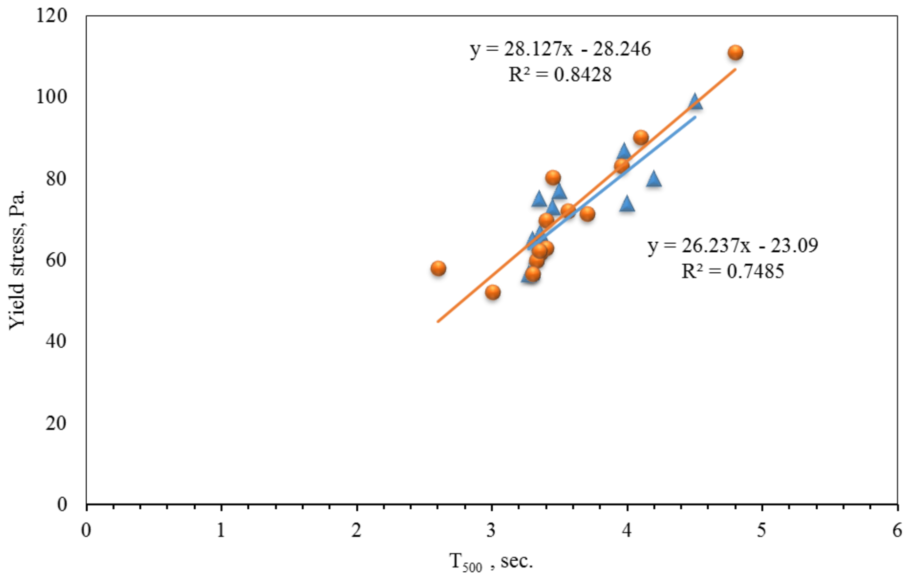

Fig. 10 Relationship between T_{500} slump flow time and yield stress

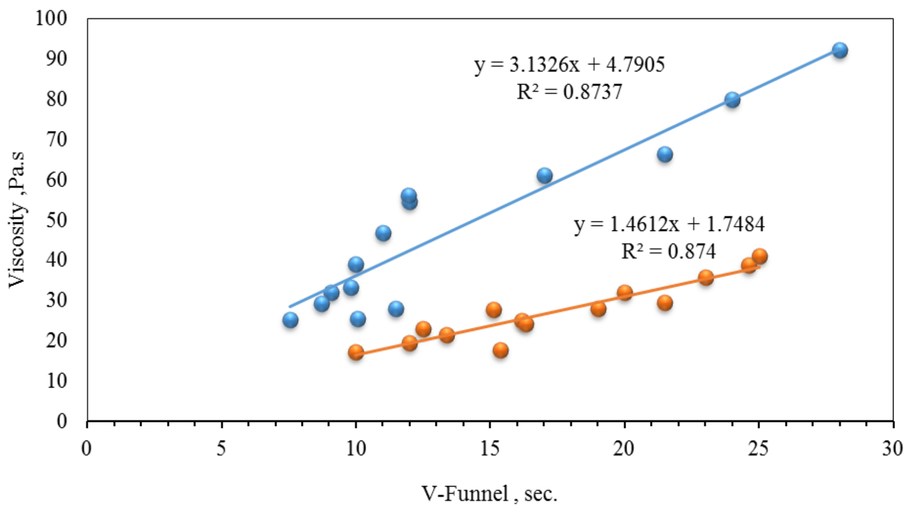

Fig. 11 Relationship between V-funnel time and viscosity

Portland cement, are not regular in their shape. Therefore, interlocking of the GGBS particles in the mix is found to increase both-the yield stress and viscosity of mix.

Along lines similar to that fly ash and GGBS, the micro-silica (MS) was also used to replace the OPC at the rates of 2.5,5, 7.5, and of 10%. The results are shown in Table 4 and also indicated in Figs. 8 and 9. The addition of MS has got a tendency to reduce the workability. Hence, higher dosages of superplasticizer (MasterGlenium 8632) were needed to keep the slump flow of MS based SDC mixes at 650 mm. It is also observed that the slump flow decreases with the increase in the percentage micro-silica. It is also seen from Figs. 7 and 8 that the addition of MS increases the yield stress in respect of the SDC mixes made using natural and crushed sand. On the other hand,

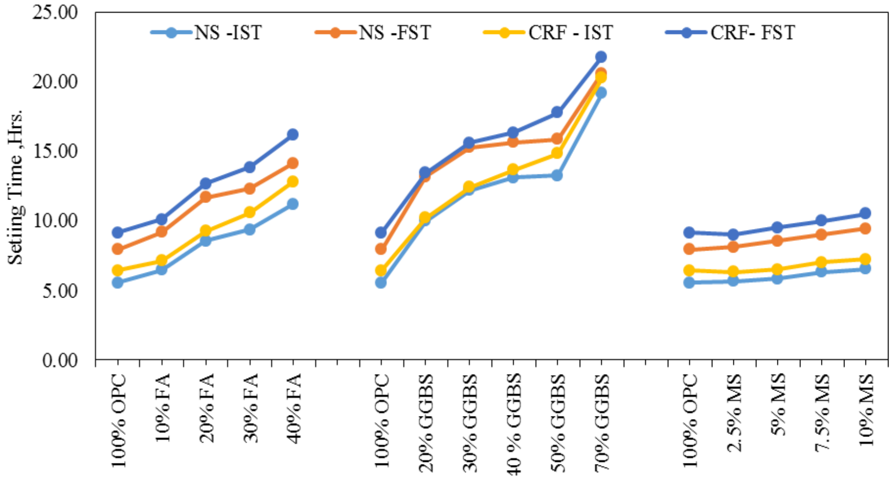

Fig. 12 Effect of cementitious materials on setting time

the dosage of MS up to 5% is found to improve the viscosity and at 7.5% and 10% dosage, however, significant decrease in the viscosity is observed. Some of the researchers reported the optimum content of MS to the tune of 7.5% for strength and durability of concrete. This observation also may also be considered valid for the rheology of concrete. The MS to some extent helps the SDC mixes made using crushed sand in order to achieve better cohesiveness, robustness and rheology.

6.3 Effect of crushed sand on rheology of SDC concrete

The effect of addition of various cementitious materials on the SDC mixes made with natural sand and crushed sand is also examined from the results obtained using the experimental data. The change in the yield stress and viscosity with respect to the use of either type of sand is obtained and is shown in Table 5 and also indicated in Fig. 9.

The effect of addition of the various mineral admixtures such as fly ash, GGBS and micro silica on rheology is not observed to be similar for the SDC mixes with crushed sand when compared with those with natural sand. In the mixes with similar contents of the cementitious materials, the crushed sand based SDC mixes is observed to show an increase in the viscosity (min. 13% and max 55%). It is clear that due to the use of crushed sand, viscosity and stickiness gets increased. The results also indicate that the yield stress increases in respect the mixes made with GGBS and Microsilica whereas in those with fly ash, the yield stress decreases. It is also noted from Table 5 that the percentage increase or decrease in the yield stress in crushed sand based SDC mixes is complex in nature; one can use similar fineness modulus sands to differentiate further. It is reported in the literature that the yield stress depends on the workability (flow/slump) of concrete. This may be the reason that all mixes in the present study are showing similar workability, which may affect the proper yield stress correlation in crushed and natural sand SDC mixes.

6.4 Significance of the relationship between traditional test method and rheology data

The establishment of the relationship between the fresh characteristics of the respective SDC

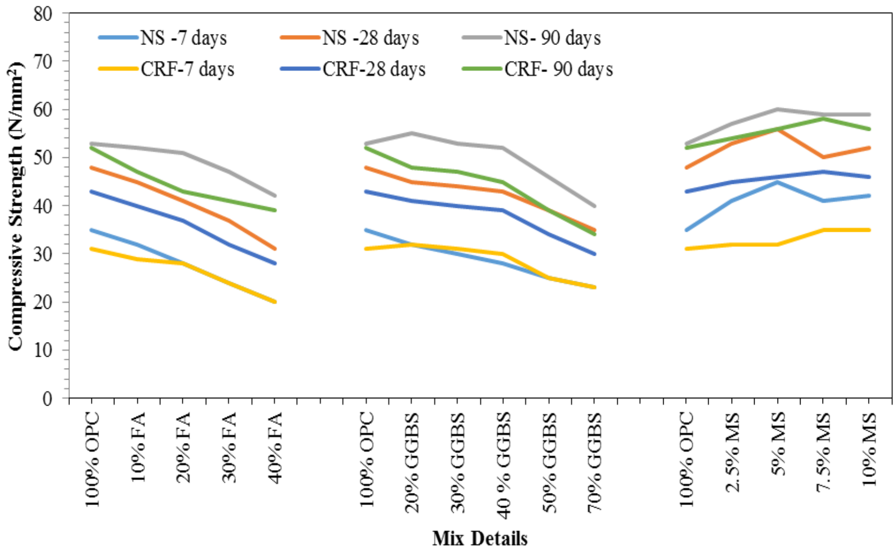

Fig. 13 Effect of sand and various cementitious materials on compressive strength

mixes will provide a very good platform for the determination of rheological parameters of the SDC mixes if T_{500} or V-funnel values are known without necessarily passing through the rigorous and tedious laboratory experimentation. The relationship between T_{500} slump flow time and the yield stress with respect to various cementitious materials is indicated in Fig. 10. Similarly, the relationship between V-funnel time and viscosity with respect to various cementitious materials is indicated in Fig. 11.

The results indicate that the slump flow spread and T_{500} time are the unique function of yield stress and V-funnel, respectively, with the viscosity; but rather a more complex function of both. The spread 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 T_{500} time is more dependent on both, the viscosity and the yield stress. Consequently, the following relationships are established between T_{500} and Yield stress and; V-Funnel and Viscosity for the SDC mixes.

$$\text{Yield Stress (Crushed sand SDC)}=28.127\ (T_{500}, \text{sec})-28.246 \tag{2}$$

$$\text{Yield Stress (Natural sand SDC)}=26.237\ (T_{500}, \text{sec})-23.090 \tag{3}$$

$$\text{Viscosity (Crushed sand SDC)}=1.4612\ (\text{V-funnel, Sec})+1.7484 \tag{4}$$

$$\text{Viscosity (Natural sand SDC)}=3.1326\ (\text{V-funnel, Sec})+4.7905 \tag{5}$$

6.5 Effect of admixtures on setting time

The effect of various mineral admixtures such as fly ash, GGBS, Micro-silica and the chemical admixture in the form of superplasticizer (MasterGlenium 8632) is shown in Fig. 12.

The fly ash and GGBS is found to have a retarding effect owing to the lower pozzolanic activity of the OPC. The increase in the dosage of admixture in crushed sand mixes further delays the setting time. Similar effect of fly ash on setting time is also reported in the literature (Webster *et al*. 2015). The micro silica does not have significant impact on the delay in setting time. The setting time of microsilica based crushed sand mixes shows delay in setting when compared with the natural sand mixes. This is mainly due to the addition of higher superplasticizer dosage.

6.6 Effect of natural and crushed sand on the development of strength

The compressive strength of the SDC mixes made using natural and crushed sand for 7 days, 28 days and 90 days' curing period for various proportions of admixtures was obtained and indicated in Fig. 13.

It is observed from Fig. 13 that the natural sand based mixes shows slightly better strength as compared to that in crushed sand mixes. It may be noted that the silt contents in the crushed sand affects the strength to some extent. The mixes with replacement of OPC by fly ash mix show decrease in strength whereas that by GGBS and Micro silica, enhancement in the strength. It is also seen that the replacement by GGBS up to 40% helps in maintaining the strength. However, the replacement above 40% replacement affects the strength. This could be due to the slow reaction of cementitious materials with OPC with the increasing contents of such materials.

7. **Conclusions**

From the experimental investigations carried out to study the effect of cementitious materials such as fly ash, GGBSMS and their influence on the rheology of smart dynamic concrete (SDC), following broad conclusions can be deduced:

• Flow properties of low fine SDC concrete are largely affected by the use of crushed sand when compared with the natural (river) sand.

• Crushed sand mixes shows low viscosity as compared to that natural sand mixes. This is mainly due to higher fineness modulus of crushed sand (3.41) than that of natural sand (2.32). Further, the natural sand is seen to have passed 100% through 2.36 mm sieve, which contributes in dense packing of the aggregates and thus, increases the yield stress and the viscosity.

• Viscosity values of crushed sand mixes is very low (average 27 Pa.s). The low viscosity affects stability of mix and create problems for pumping. When compared with the rheology of SCC reported in the past by the authors (Bauchkar and Chore 2014), the viscosity of SDC mixes is very low. Hence, more care is required for the design and execution of SDC. Low viscosity may lead to segregation of concrete and pump blockage if variation in moisture, w/b ratio or cementitious materials is not controlled at site.

• The rheological properties of SDC are highly dependent on the type of cementitious materials used in mixes and the contents thereof.

• The GGBS considerably increases the yield stress and the viscosity of concrete, i.e., beyond optimum limit as a result of which it may create pumping issues or high pump pressure.

• Crushed sand slightly helps in improving the lateral compressive strength of SDC due to better particle packing of aggregates.

• Higher admixture dosages in crushed sand based SDC mixes cause delay in setting and reduction in early strength, i.e., strength of even one day.

Due to the wide variation in the materials available for concrete production and the infinite number of possible combinations of these materials, the results presented herein are applicable applies only to general cases. For specific combinations of materials, trial batches can be tested to the confirm trends.

Acknowledgments

The support extended by the management of BASF Construction Chemicals in carrying out the experimentation in at their research and development centre is acknowledged. Certain inputs imparted by Dr. Viswanath Mahadevan, Head of Development, BASF Construction Chemicals, Asia Pacific, in the present study is also gratefully acknowledged.

References

American Concrete Institute (2008), *Report on Measurements of Workability and Rheology of Fresh Concrete*, Report No. 238.1 R-08.

Aydin, S., Hilmi, A.A. and Ramyar, K. (2009), "Effects of fineness of cement on polynaphthalene sulfonate based superplasticizer-cement interaction", *Constr. Build. Mater.*, **23**(6), 2402-2408.

Bauchkar, S.D. and Chore, H.S. (2014), "Rheological properties of self-consolidating concrete with various mineral admixtures", *Struct. Eng. Mech.*, **51**(1), 1-13.

Bruce, J.C. and Huebsch, C. (2012), "Solutions to support more sustainable construction practices", *Spec. Publ.*, **289**, 1-12.

Bryan, B, Roncero, J., Magarattom, R., Mara, S. and Khurana, R. (2011), "Friendly self-compacting concrete", *Concrete Plant Int.*, **21**, 60-66.

Chidiac, S.E. and Mahmoodzadeh, F. (2009), "Plastic viscosity of fresh concrete-a critical review of predictions methods", *Cement Concrete Compos.*, **31**(8), 535-544.

Corradi, M., Kluegge, J., Kar, N., Christensen, B. and Yang, J. (2007), "A new viscosity modifying agent (VMA) for low fines self-consolidating concrete", *Proceedings of the 5th International RILEM Symposium on Self-Compacting Concrete*, **2**, 875-880.

Cry, M., Legrand, C. and Mouret, M. (2000), "Study of the shear thickening effect of superplasticizers on the rheological behaviour of cement pastes containing or not mineral additives", *Cement Concrete Res.*, **30**(9), 1477-1483.

Daczko, J.A. (2003), "Stability of self-consolidating concrete-assumed or ensured?", *Proceedings of the 1st North American Conference on the Design and Use of Self-Consolidating Concrete*, Chicago, U.S.A., November.

EFNARC (2005), *The European Guideline for Self-Compacting Concrete (SCC): Specification for Production and Use*, 68.

Ferraris, C.F. (1999), "Measurement of the rheological properties of high performance concrete-state of the art report", *J. Res. NIST*, **104**(5), 461-478.

Ferraris, C.F., Obla, K.H. and Hill, R. (2001), "The influence of mineral admixtures on the rheology of cement paste and concrete", *Cement Concrete Res.*, **31**(2), 245-255.

Feys, D., Verhoeven, R. and De Schutter, G. (2008), "Why is fresh self-compacting concrete shear thickening?", *Cement Concrete Res.*, **39**(6), 510-523.

IS: 383 (1970), *Specification for Coarse and Fine Aggregates from Natural Sources for Concrete*, Bureau of Indian Standards, New Delhi, India.

Jayashree, C. and Gettu, R. (2008), "Experimental study of the flow behavior of super-plasticized cement paste", *Mater. Struct.*, **41**(9), 1581-1593.

Khayat, K.H., Omran, A.F., Naji, S., Billberg, P. and Yahia, A. (2012), "Field-oriented test methods to evaluate structural build-up at rest of flowable mortar and concrete", *Mater. Struct.*, **45**(10), 1547-1564.

Kwan, A.K.H. and Ng, I.Y.T. (2009), "Optimum super plasticizer dosage and aggregate proportions for SCC", *Mag. Concrete Res.*, **61**(4), 281-292.

Mork, J.H. and Gjorv, O.E. (1996), "Effect of Gypsum hemihydrates ratio in cement on rheological properties of fresh concrete", *ACI Mater. J.*, **94**(2), 142-146.

Nagendra, R., Bharti, G.S.H. and Suresh, M.R. (2013), "Rheology of SCC with pond ash as partial replacement to fine aggregate", *Proceedings of the International Conference on Innovation in Concrete*, Hyderabad, India, October.

Nehdi, M., Mindess, S. and Artcin, P.C. (1998), "Rheology of high-performance concrete: Effect of ultrafine particles", *Cement Concrete Res.*, **28**(5), 687-697.

Neubauer, C.M., Yang, M. and Jennings, H.M. (1998), "Interparticle potential and sedimentation behaviour of cement suspensions: Effects of admixtures", *Adv. Cement Base Mater.*, **8**, 17-27.

Neville, A.M. (1996), *Properties of Concrete*, Wiley Publication, New York, U.S.A.

Park, C.K., Noh, M.H. and Park, T.H. (2004), "Rheological properties of cementitious materials containing mineral admixtures", *Cement Concrete Res.*, **35**(5), 842-849.

Pilegis, M., Gardner, D. and Lark, R. (2016), "An investigation into the use of manufactured sand as a 100% replacement for fine aggregate in concrete", *MDPI J.*, **9**(6), 1-19.

Plank, J., Vlad, D., Brandl, A. and Chatziagorastou, P. (2009), "Colloidal chemistry examination of the steric effect of polycarboxylate superplasticizers", *Cement Int.*, **3**(2), 100-110.

Ramachandran, V.S. (1992), *Super-Plasticizers Progress in Cement and Concrete*, ABI Books (Part II), New Delhi, India, 345-375.

Reddy, B.V.V. and Gupta, A. (2008), "Influence of sand grading on the characteristics of mortars and soil-cement block masonry", *Constr. Build. Mater.*, **22**(8), 1614-1623.

Seow, K.H., Kar, N. and Qiuling, F. (2011), "The use of low fines self consolidating concrete (SCC) in everyday applications to improve productivity", *SCI Concretus Mag.*, **3**(1) 4-6.

Tattersall, G.H. and Banfill, P.F.G. (1983), *The Rheology of Fresh Concrete*, Pitman Publishing, Marshfield, Massachusetts, U.S.A.

Wallevik, J.E. (2008), "Rheological properties of cement paste: Thixotropic behavior and structural breakdown", *Cement Concrete Res.*, **39**(1), 14-29.

Wallevik, J.E. (2009), *The Bingham-Model: Retrieving the Bingham Parameters When Using the Coaxial Cylinders Viscometer*, Lecture Notes for the ICI Rheocenter, Rheology Course, Innovation Center Iceland, Reykjavik, Iceland.

Westerholm, M., Lagerblad, B., Silfwerbrand, J. and Forssberg, E. (2008), "Influence of fine aggregate characteristics on the rheological properties of mortars", *Cement Concrete Compos.*, **30**(4), 274-282.

Williams, D.A., Saak, A.W. and Jennings, H.M. (1999), "The influence of mixing on the rheology of fresh cement paste", *Cement Concrete Res.*, **29**(9), 491-1496.

CC