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Influence of plastic viscosity of mix on Self-Compacting Concrete with river and crushed sand

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Abstract. In view of the increasing utility of concrete as a construction material, the major challenge is to improve the quality of construction. Nowadays the common problem faced by many of the concrete plants is the shortage of river sand as fine aggregate material. This led to the utilization of locally available materials from quarries as fine aggregate. With the percentage of fines present in Crushed Rock Fines (CRF)or crushed sand is more compared to river sand, it shows a better performance in terms of fresh properties. The present study deals with the formulation of SCC mix design based on the chosen plastic viscosity of the mix and the measured plastic viscosity of cement pastes incorporating supplementary cementitious materials with CRF and river sand as a fine aggregate. Four different combinations including two binary and one ternary mix are adopted for the current study. Influence of plastic viscosity of the mix on the fresh and hardened properties are investigated for SCC mixes with varying water to cement ratios. It is observed that for an increasing plastic viscosity of the mix, slump flow, T500 and *J*-ring spread increased but *V*-funnel and *L*-box decreased. Compressive, split tensile and flexural strengths decreased with the increase in plastic viscosity.

Keywords: crushed rock fines; Self-Compacting Concrete; plastic viscosity; compressive strength; mix design; GGBS; fly ash

1. Introduction

With the demand for high rise structures, there is a significant challenge to the designer to bring out a sustainable as well as environment-friendly concrete. Another important aspect in producing concrete is to make use of the locally available material. Majority of the construction happening in the world is of concrete. So there is a dire need to adopt innovative methodologies in making concrete more usable. Raw materials used in concrete play an important role in attaining the desired properties as per the requirements of a laboratory or a site. This brings in the usage of High-Performance Concrete (HPC) which is the combination of performance and homogeneity in concrete mixes. HPC has the characteristics which conventional concrete fails to bring in during casting, curing and placing (Mehta *et al*. 2006). A concrete can be termed as HPC if it has the high durability, strength and reliability (Golaszewski *et al*. 2004).

Self-Compacting Concrete (SCC) is one type of HPC which has good characteristics in terms of achieving desired workable mixes. Since the concept of SCC was introduced into the construction industry, the need for producing efficient mixes which satisfies both fresh and hardened properties has become a challenge for researchers as well as for construction sector.

One of the challenging aspects in most of the constructions is to make use of locally available materials to reduce the overall economy of the project. In the recent past, there is a shortage of river sand in India which led to the stoppage of many of the construction works leading to overshooting of the budget for many of the construction projects. Situations like these can be avoided by utilizing the locally available materials like stone dust, manufactured sand, crushed rock fines which are obtained from quarries.

Okamura is the first person to coin the concept of SCC in 1986, followed by Ozawa. They have developed a prototype at the University of Tokyo in 1988 (Ozawa *et al*. 1989). Over the last two decades, a significant growth is seen in the production of Self-Compacting Concrete. SCC has many advantages compared to conventional concrete, including a) reduction of labor cost, noise pollution and time consumption; b) capacity to fill highly congested structural members; c) increase the durability of structures; d) improve the overall performance of structures (Caijun Shi 2015). There will be a release of 1 ton of Carbon dioxide to the atmosphere in the production of 1 metric ton of cement (Concrete Fact Sheet 2008). For SCC mixes to achieve sustainability there is a need for reduction in the amount of cement consumption in the concrete mixes to ensure that there will be a significant reduction in CO2

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emission. Supplementary Cementitious Materials (SCMs) like Ground Granulated Blast Slag (GGBS) and Fly Ash (FA) will reduce the impact of CO2 emission and increase the sustainability of the mix. The main characteristics of SCC are its stability and flow ability. Based on the desired fresh and hardened properties of concrete suitable Cement Replacement Materials (CRMs) or SCMs may be used as a partial replacement of Cement (Mindess *et al*. 2003). They can be used as binary mixes or ternary mixes in combination with OPC. Replacement levels of Fly ash can be as high as 80% (Khatib 2008). It is observed that the ternary blend of GGBS and silica fumes to be more durable when compared with other blends of mineral admixtures. (Liu 2010) worked on different levels of fly ash on SCC. A replacement level of up to 80% of fly ash is tested. Replacement of fly ash up to 20% did not show any significant effects on the properties of concrete. But it is observed that fly ash content may be restricted to 40% as after that the results obtained were not satisfactory. (Dinakar *et al*. 2013) developed a new mix design methodology for the usage of GGBS into SCC. The results indicated that GGBS up to a replacement of 20 to 80% can only be used and concretes up to strength of 30 to 100 MPa can only be developed. (Chen *et al*. 2013) studied the effect of amount of paste on the properties of SCC mix with fly ash and GGBS. The results showed that higher the unit weight of concrete, higher the compressive strength and lesser the cement used, lesser will be the early strength and higher the long term strength. (Raharjo *et al*. 2013) worked on optimization of concrete mix using silica fumes, fly ash and iron slag. Various mixture compositions with superplasticizer dosages from 0.5 to 1.8% of cementitious had been adopted and silica fumes from 10 to 20% of fly ash weight. The main of this work was to arrive at an optimal mix which would satisfy the fresh and hardened properties of concrete and must also be cost-effective. (Chen *et al*. 2013) studied the effect of amount of paste on the properties of SCC with fly ash and GGBS. Different water to binder ratios and paste contents are used and a densified mixture design algorithm is created and applied to SCC. The study focuses on the calculation of sufficient paste amount and a dense blended aggregate which provides a less early strength and a higher long-term compressive strength. The results showed that higher the unit weight of concrete, higher the compressive strength and lesser the cement used, lesser will be the early strength and higher the long-term strength. It is also concluded that lower the paste content, higher the quality of concrete. Nepomucenco *et al*. (2014) worked on developing a new mix design methodology for SCC using different blends of mineral additives. It is inferred that, the flow ability of SCC depends on the fine aggregate volume fraction and the coarse aggregate volume fraction and it is also concluded that the self compactibility depends on type of cement.

Rheology plays an important role in construction industry to address the plastic state behavior of concrete especially SCC. The flow of a viscous non-Newtonian fluid like SCC is best described using Bingham Constitutive model (Dransfield 2003). Two main influential material properties of this model are yield stress τy and plastic viscosity η. The yield stress has very low values of around 200 Pa for SCC mixes in comparison to thousands of Pascal for normally vibrated concrete. Plastic viscosity is considered to be an important parameter which depends on the plastic viscosity of the paste and composition of the mix. Paste being a homogeneous viscous fluid unlike SCC mix which is non-homogeneous in nature, rheological parameters can be calculated accurately using a viscometer. But for SCC mix a hectic process is involved when tested using a viscometer. It was also proved that (Brower 2003, Hocevar *et al*. 2013), no two rheometers would result in similar values of plastic viscosity and yield stress for the same SCC. Plastic viscosity of the SCC mix can be accurately estimated using a micromechanical model developed by Ghanbari and Karihaloo (2009) from the known value of plastic viscosity of the paste. Plastic viscosity of the paste also depends on several parameters like type of cementitious material, water to cement ratio, superplasticizer dosage, type of rheometer or viscometer used etc. Abo Dhaheer *et al*. (2015) proposed a mix design procedure based on the target compressive strength & plastic viscosities of SCC mix. This procedure uses target compressive strength and plastic viscosity of the SCC mix as its inputs. Using this concept, a set of mixes for plastic viscosities ranging from 3 to 15 Pa s and compressive strengths of concrete varying from 30 to 80 Mpa were designed. Design charts were also prepared based on the data obtained above which would make the design process easy.

Farid *et al*. (2017) addressed the robustness involved in designing the mixes of SCC. They studied the influence of paste volume on the water to powder ratio. Results indicated that the mixtures with a low yield stress and a high plastic viscosity decreased the robustness. They also suggested that the robustness can be reduced by increasing water to powder ratio as the plastic viscosity plays a role in maintaining the stability of mixtures.

Long *et al*. (2017) recommended a suitable mix design of SCC based on optimal packing density in order to maintain ecological sustainability. Their proposal resulted in the reduction of required binder content by 16% and CO2 emissions by 33.98%. and material cost by 6.24%.

CRF is obtained by crushing rocks in quarries to a size which would completely pass through 4.75 mm sieve (Chow *et al*. 2013). This material can be used as a viable partial and full replacement for natural sand in concrete (Chow *et al*. 2013, Mundra *et al*. 2016, Prakash *et al*. 2016). Natural sand generally contains organic impurities due to which the properties of concrete prepared using natural sand would decline. CRF eliminates these problems as it is free from all these impurities. The percentage of fines present in CRF, when compared with natural sand, is higher. The workability of concrete prepared using CRF for a replacement of 30% of fine aggregate declined when compared with conventional concrete (Prakash *et al*. 2016). This reduction in workability of concrete due to CRF can be compensated by adding mineral admixtures like Fly Ash and reduce the aggregate size. The physical properties of the aggregate such as specific gravity and water absorption are almost similar to that of natural sand in the range of 2.6

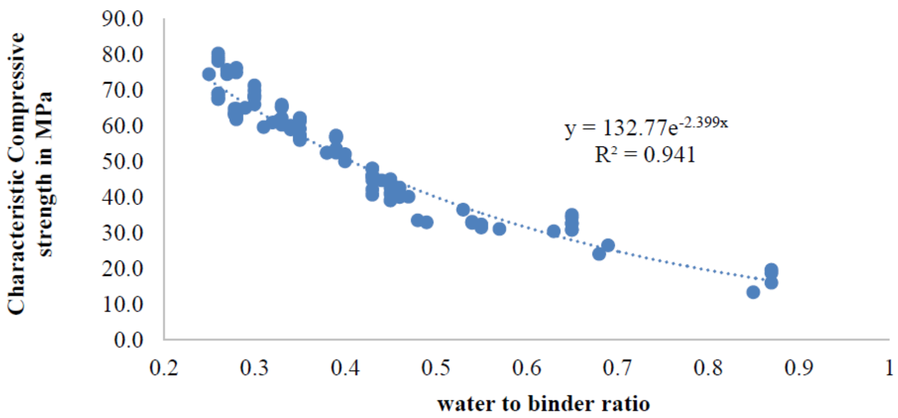

Fig. 1 Regression curve for water to cementitious ratio

-2.7 and 0.5-1% respectively (Mundra *et al*. 2016, Prakash *et al*. 2016). The durability of concrete made with CRF is high when compared with natural sand due to a reduction in problems like bleeding, segregation etc. (Chow *et al*. 2013). The hardened properties (Compression, Flexure and Split tensile strengths) of concrete due to the addition of this material increased when compared with conventional concrete due to the fines filling the voids in the cement paste (Mundra *et al*. 2016, Prakash *et al*. 2016). Apart from usage in concrete, CRF can also be used for backfills, in asphaltic concrete as a fine aggregate, granular filters etc (Chow *et al*. 2013).

The present study deals with the experimental investigation on the fresh and hardened properties of SCC with river sand and CRF as fine aggregates. SCC proportioning is done based on the assumed plastic viscosity of the mix and the compressive strength of the concrete with 100% CRF as fine aggregate and suitable additions of supplementary cementitious materials like fly ash and GGBS as. Crushed Rock Fines, which is an extract from quarry, is considered as a fine aggregate in the present study. The study also includes with estimation of plastic viscosity of cement pastes using Brookfield Viscometer D3VT.

2. Mix design procedure based on assumed plastic viscosity of the mix

According to Abram's law of water to cement ratio, the compressive strength of concrete depends on the water-cement ratio adopted and the strength is inversely proportional to water to cement ratio (in terms of mass). Based on this law it is clear that the strength of SCC also depends on the water to binder ratio. In order to establish a relation between the strength of concrete and the water to cement ratio, a set of values for water to cement ratio and the resulting 28 day-compressive strength using various mineral admixtures are adopted from (Boukendakdji *et al*. 2012, Douma *et al*. 2016, 2014, Uysal *et al*. 2012, Uysal and Tanyildizi 2012, Uysal and Sumer 2011, Gesoglu *et al*. 2009, Siddique *et al*. 2011, Alqadi *et al*. 2013, Raheman and Modani 2013, Aggarwal and Aggarwal 2011, Pathak *et al*. 2012, Guneyisi *et al*. 2010, Beycioğlu *et al*. 2014). Using this data, regression analysis is performed to obtain the best fit curve as shown in (Fig. 1) which is Abram's type power curve with R^2=0.941. The expression for compressive strength in terms of *w/b* ratio is given by

$$f_{cu} = \frac{132.77}{11^{(w/cm)}} \tag{1}$$

The following step-by-step process is followed for the mix design of SCC:

1. First a trial plastic viscosity value is chosen considering that slump cone T_{50} increases with the increase in plastic viscosity.

2. Water to cementitious ratio is calculated using Eq. (1) based on the regression curve obtained from (Fig. 1).

3. Choose the water content following EFNARC guidelines in the range of 150 to 210 kg/m^3.

4. The percentage replacement of cement with GGBS and Fly ash is assumed to be 25% (Abo Daheer *et al*. 2015) and 20% (Abhijeet *et al*. 2015). Based on one to one interaction with industry experts, for triple blended mixes, the amount of GGBS and Fly Ash is assumed to be 25%+25%. A trial superplasticizer dosage of 0.45% to 1.25% of cementitious material is adopted. Glenium Sky 8233 is used as superplasticizer in the present study.

5. Plastic viscosity of the paste (η_{paste}) for 75% OPC+25% GGBS, 80% OPC+20% Fly ash and 50% OPC+25% GGBS+25% Fly ash are estimated using Brookfield viscometer. The corresponding values are tabulated in Table 2.

6. Mass of fine aggregate and coarse aggregate are calculated based on their volume fractions using Eqs. (6) and (7). Volume fractions of fine and coarse aggregate are estimated using a randomization computer code such that the amount of fine and coarse aggregate does not exceed the limits as per EFNARC guidelines (The European Guidelines for Self-Compacting Concrete-EFNARC 2005).

$$\phi_{FA} = \frac{\dfrac{FA}{\rho_{FA}}}{\left(\dfrac{cem}{\rho_{cem}} + \dfrac{w}{\rho_w} + \dfrac{SP}{\rho_{SP}} + 0.02\right) + \dfrac{FA}{\rho_{FA}}} \tag{6}$$

Table 1 Chemical and physical properties of Ordinary Portland Cement, fly ash and GGBS

Chemical Composition (%)	OPC	Fly Ash	GGBS
CaO	65.232	1.78	40.64
SiO_2	18.635	60.13	35.15
Al_2O_3	5.716	28.37	19.60
Fe_2O_3	4.538	5.10	0.53
SO_3	4.324	0.11	1.89
K_2O	0.591	2.16	0.40
TiO_2	0.499	1.42	0.92
Physical Properties			
Specific Gravity	3.15	2.16	2.85

$$\phi_{CA} = \frac{\frac{CA}{\rho_{CA}}}{\left(\frac{cem}{\rho_{cem}} + \frac{w}{\rho_w} + \frac{SP}{\rho_{SP}} + \frac{FA}{\rho_{FA}} + 0.02\right) + \frac{CA}{\rho_{CA}}} \tag{7}$$

7. The total volume of the mix should be equal to 1 m^3. If not, suitable corrections are to be applied for the raw materials to attain a total volume of 1 m^3.

8. The measured plastic viscosity of the mix is compared with the assumed plastic viscosity (step 1). The assumed value of plastic viscosity of mix is in good agreement with the estimated value if the difference between the two is within $\pm$5%. If not, choose different volume fractions of solid phase ingredients i.e., fine and coarse aggregates and repeat the steps 7 and 8.

For the present study M40 grade concrete and an assumed plastic viscosity values of 9 Pas and 13 Pas based on the different trials are adopted

3. Experimental procedures

3.1 Materials used

• *Cement:* Ordinary Portland Cement (OPC) of 53 grade is used for the present study. The physical and chemical composition of cement is shown in Table 1.

• *Fly Ash:* Class F Fly ash with low calcium content used for the present study is obtained from National Thermal Power Coal Plant, Ramagundam, Telangana. The physical and chemical composition of fly ash is shown in Table 1.

• *GGBS:* Ground Granulated Blast Slag is obtained from Jindal Steel Works, Vijayanagar, Karnataka. The physical and chemical composition of GGBS is shown in Table 1.

• *Fine Aggregate:* Locally available Crushed Rock Fines (CRF) is used as a fine aggregate for the present study. It confirmed to IS 383: 2016. CRF is chosen over river sand to ensure that the organic impurities are minimized. The specific gravity used in the present study is 2.61. Fineness modulus of 2.00 is obtained and it belongs to Zone II. River sand is also used for the some of the mixes in comparison with CRF. The specific gravity of river sand is 2.56.

• *Coarse Aggregate:* Basalt type coarse aggregate with a

Table 2 Measured plastic viscosity of cement pastes for Case I (SCC mix with plastic viscosity 9 Pas and river sand as fine aggregate) and Case II (SCC mix with plastic viscosity 9 Pas, 13 Pas and Crushed sand as fine aggregate)

Cementitious material combinations	Paste plastic viscosity (Pa s)	
	Case I	Case II
100% OPC	0.25	0.24
75% OPC+25% GGBS	0.26	0.25
80% OPC+20% Fly ash	0.235	0.22
50% OPC+25% GGBS +25% Fly ash	0.275	0.26

Table 3 Mix proportions of SCC with river sand as fine aggregate for 1 Cum (Case-I)

Mix ID	SCCC 100	SCCC 75G25	SCCC 80F20	SCCC 50G25F25
Cement (kg/m^3)	428	320	327	206
GGBS (kg/m^3)	0	107	0	103
Fly Ash (kg/m^3)	0	0	82	103
Water (kg/m^3)	214	204	204	206
Coarse Aggregate (kg/m^3)	755	753	753	752
River Sand (kg/m^3)	886	882	900	877
Super plasticizer (kg/m^3)	4.28	4.27	4.09	4.12

maximum particle size of 20 mm is used for the present investigation. All the mixes for the current study adopted a combination of 10 mm and 20 mm size aggregates. The specific gravity and water absorption used in the present study are 2.71, 4.6% for 10mm and 1.6% for 20 mm aggregates.

• *Admixture*: Master Glenium Sky 8233, a light brown liquid made of a new generation based on modified polycarboxylic ether is used as a superplasticizer for the current study. The specific gravity of 1.07 at 25° is adopted.

• *Proportioning of Mixes*

• For the experimental investigations, SCC with two binary mixes and one ternary mix are considered apart from the control mix with pure OPC. In addition to cementitious materials, fine aggregate, coarse aggregate, water, superplasticizer, are used and their corresponding proportions are given in Table 3 and Table 4.

• *Mixing, Casting and Curing*

• Forced type pan mixer is used for mixing the raw materials in required proportions. The entire mixing sequence is finished within 10 min for all the mixes.

Three assumed plastic viscosities are adopted for four combinations of mixes for the entire experimental study as given in Table 2.

4. Results and discussions

The properties of SCC for its fresh state are assessed to check the requirements of filling, passing and segregation resistance. All the tests are performed as per the European guidelines given in EFNARC. The standard range of values

Table 4 Mix proportions of SCC with CRF as fine aggregate for 1 Cum (Case-II)

Mix Composition	PV of mix	PV of Paste	OPC (kg/m^3)	Fly Ash (kg/m^3)	GGBS (kg/m^3)	Water (kg/m^3)	Crushed Sand (kg/m^3)	Coarse Aggregate (kg/m^3)	SP (kg/m^3)	SP/CM %
SCCC100	9	0.245	426	0	0	213	904	755	4.27	0.01
SCCC80F20		0.256	326	82	0	204	918	753	4.08	0.01
SCCC75G25		0.23	319	0	106	213	900	753	4.25	0.01
SCCC50F25G25		0.27	206	103	103	206	894	752	4.11	0.01
SCCC100	13	0.24	400	0	0	200	937	772	5.011	0.0125
SCCC80F20		0.22	309	77	0	193	964	754	4.833	0.0125
SCCC75G25		0.25	300	0	100	200	937	772	5.009	0.0125
SCCC50F25G25		0.26	194	97	97	194	943	756	4.855	0.0125

PV - Plastic viscosity, W/B - Water to Binder ratio, OPC - Ordinary Portland Cement, GGBS - Ground granulated blast furnace slag, SP - Superplasticizer.

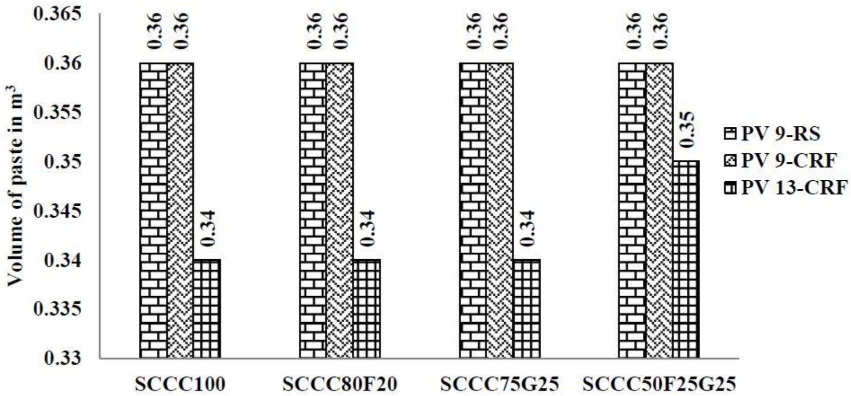

Fig. 2 Volume of paste for SCC mixes for Case I and Case II

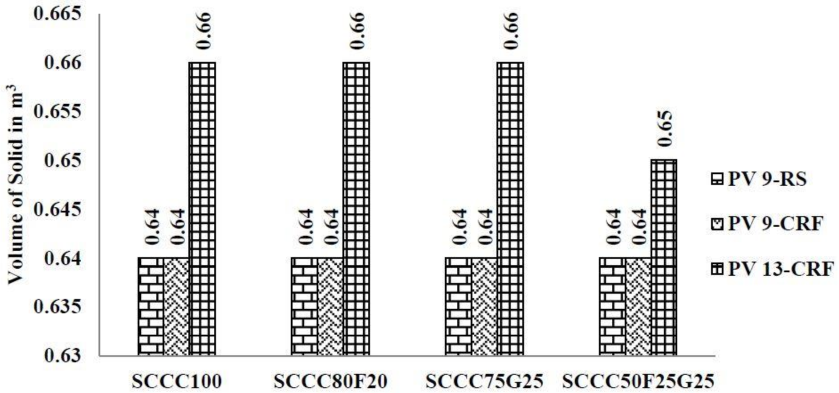

Fig. 3 Volume of solids for SCC mixes for Case I and Case II

Table 5 Fresh properties of SCC-EFNARC guidelines

	Slump Flow (mm)	T_{50} (sec)	*J*-Ring Spread (mm)	*V*-Funnel (sec)
Minimum	650	2	-	6
Maximum	800	5	-	12

for fresh properties as per EEFNARC guidelines are as per Table 5. The properties tested are Slump flow diameter, Slump flow time (T_{50}), *V*-funnel flow time, *J*-ring flow diameter. From the (Fig. 2) and (Fig. 3) with the increase in the plastic viscosity of the mix there is a reduction in the volume of paste due to a decrease in cement content and an increase in the volume of solids due to the increase in aggregate content. When river sand is used the volume of paste and solid almost remained the same as that of CRF.

All the SCC mixes have shown satisfactory flow values ranging from 695 mm to 760 mm as shown in (Fig. 4). Mixes with fly ash resulted in good deformability due to its own weight compared to mixes with GGBS. As the fly ash particles are spherical in shape, a partial replacement of cement with fly ash and GGBS will increase the paste content which in turn increases the cohesiveness and workability of the mix. With the increase in the plastic viscosity of the mix slump flow decreased. Reduction of paste content with increase in solid content for an increasing plastic viscosity will decrease the slump flow. The mixes with CRF resulted in better deformability compared to river sand as the fines in CRF are more compared to river sand. Also the fact that the river sand has more silt content compared to CRF, the flow of SCC mixes will be less for river sand and the flow is reduced by 2.11%

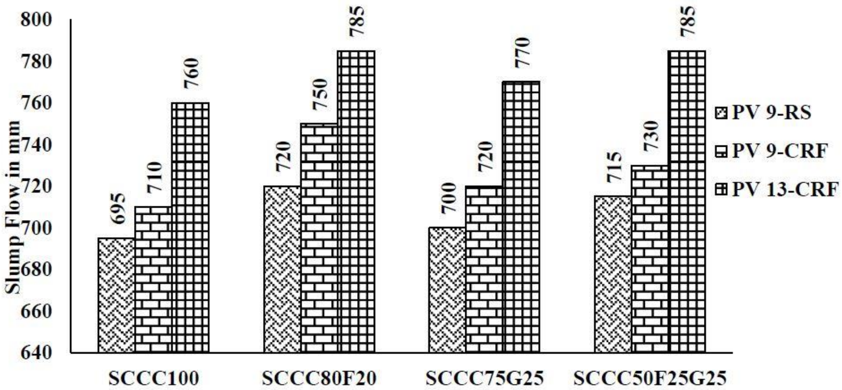

Fig. 4 Slump flow for SCC mixes for Case I and Case II

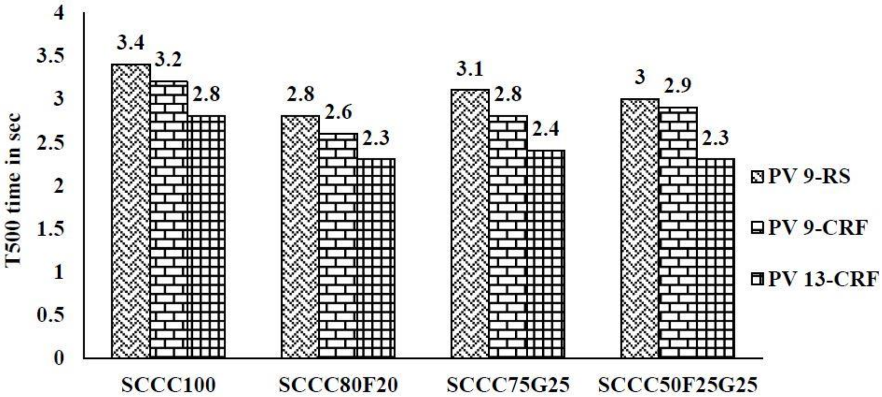

Fig. 5 T_{500} time for SCC mixes for Case I and Case II

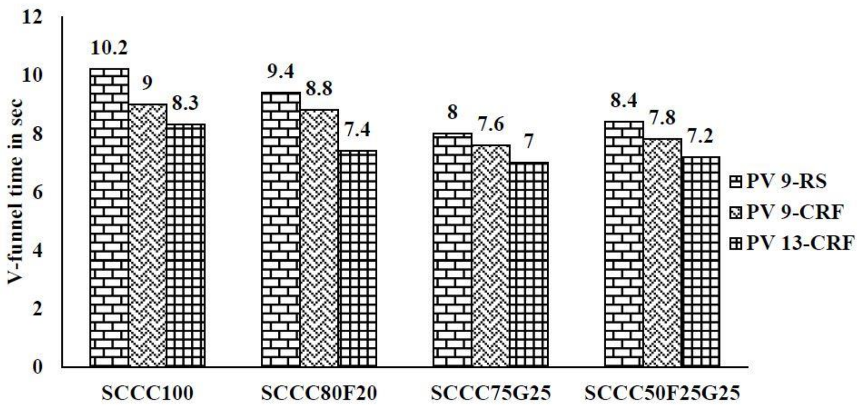

Fig. 6 *V*-funnel time for SCC mixes for Case I and Case II

for SCC mix with 100% OPC, 2.04% for the binary mix with fly ash, 2.78% for the binary mix GGBS and 4.67% for the ternary mix.

For all the SCC mixes, the slump flow time recorded (i.e., T_{500}) is ranging from 2.3 to 3.4 seconds as shown in (Fig. 5). T_{500} is an indicative measure of the viscosity of the mix. It increased with increase in the plastic viscosity of the mix. This property is an indicative tool when there is a requirement for the good surface finishing. As the proposed mix design is based on the plastic viscosity of the mix, the obtained values for T_{500} are in good agreement with the viscous behavior of SCC mixes. It is also observed that mixes with river sand resulted in higher time periods compared to CRF.

As the major portion of the size of aggregate used is less than 20 mm, blocking is minimal and the mix has got a good spread passing through the obstacles in the form of reinforcement. To assess the passing ability of SCC mixes, *J*-Ring in combination with slump cone mold is used to find the distance of lateral flow of concrete The difference between slump flow and *J*-Ring flow for all the mixes is less than 25 mm which is in good agreement with (ASTM C 1621/C 1621M) indicating a good passing ability of the concrete. The rate of flow reduction with the introduction of J-ring is low for SCC mix with river sand compared to SCC mixes with CRF for a plastic viscosity of 9 as shown in (Fig. 7). Spread for *J*-Ring is measured and the values are ranging from 675 mm to 745 mm. Viscosity and filling

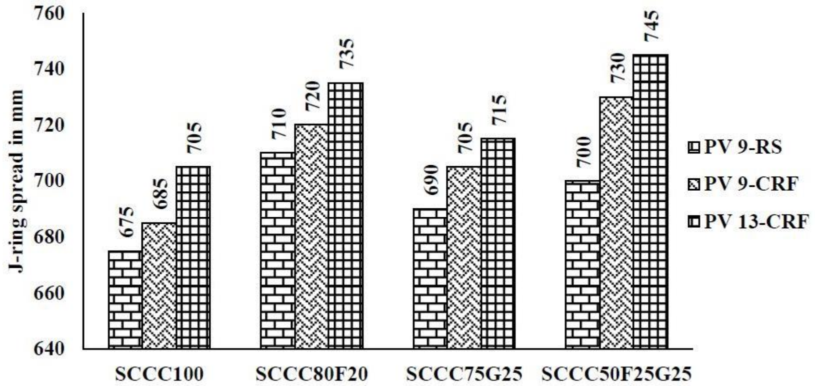

Fig. 7 *J*-ring spread for SCC mixes for Case I and Case II

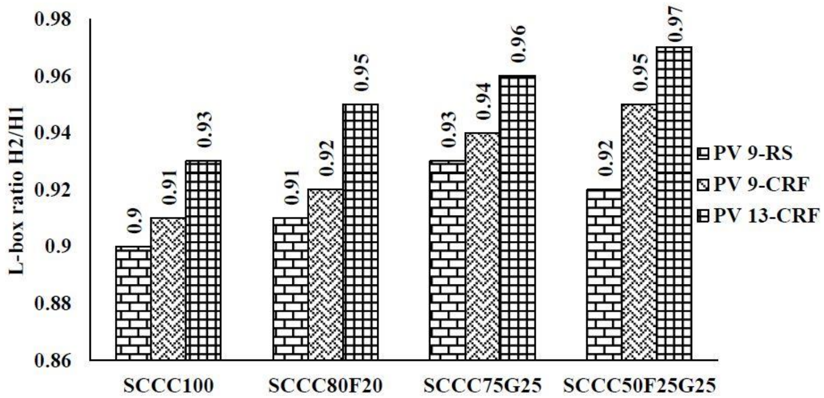

Fig. 8 *L*-box ratio for SCC mixes for Case I and Case II

ability in terms of duration of flow of mix is investigated using *V*-funnel test. *V*-funnel time measured for SCC mixes ranged from 7 to 10.2 seconds as shown in (Fig. 6) which are in good agreement with EFNARC guidelines. *V*-funnel time for SCC mixes is also an indication that the proposed mix design based on plastic viscosity is reliable and compatible with the existing standard guidelines. Mixes with increasing plastic viscosity because of the decreasing paste content increased the flow time. The usage of 100% CRF as a fine aggregate is also an influencing factor for the better performance of the mix compared to the usage of river sand as a fine aggregate.

To assess the filling and passing ability of SCC, *L*-Box test is performed. The ratio of heights at the two edges of *L*-box (H2/H1) is recorded. If the ratio is less than 0.8, then this test is more sensitive to blocking. From (Fig. 8) all the SCC mixes are within the range of 0.8 to 1.0 as per EFNARC standards. Because of the presence of CRF in the mix, it enhanced the overall performance of flowing and passing ability of the mix. The fines present in CRF acted as an inert material thus increasing the powder content without reacting with water making the mix more cohesive. The use of CRF in combination with SCMs will result in energy efficient SCC mixes which will be practically feasible and economically viable. It also encourages the utility of locally available materials for the construction.

4.2 Hardened properties

A 300 Ton Compressive Testing Machine is used to estimate the compressive strength of concrete. Compressive strength depends on many parameters such as water to cement ratio, type of cement replacement materials, percentage of coarse aggregate, plastic viscosity of the paste and assumed plastic viscosity of mix.

From (Fig. 9) and **(**Fig. 10) following observations are made for the SCC mixes with various combinations. SCC mix with 100% OPC resulted in the maximum compressive strength of 48.88, 52.38 and 47.52 for days and 57.21, 61.3 and 58.14 MPa for 28-days for plastic viscosities of 9 with river sand and CRF and 13 with CRF. SCC mixes with 25% replacement of GGBS resulted in a compressive strength of 40.24, 44.46 and 40.95 for 7-days and 49.07, 54.06 and 51.38 for 28-days for plastic viscosities of 9 with river sand and CRF and 13 with CRF. There is a decrease of 17.68%, 15.12%, and 13.83% in the 7-days compressive strength and 14.23%, 11.81% and 11.63% decrease in 28-days compressive strength of SCC mixes with 25% GGBS replacement. SCC mix with 20% Fly ash resulted in the strength of 37.56, 41.26 and 38.51 MPa for 7-days and 47.87, 51.94 and 47.36 MPa for 28-days for plastic viscosities of 9 with river sand and CRF and 13 with CRF. There is a decrease of 23.16%, 221.23% and 18.96% in the 7-days compressive strength and 16.33%, 15.27% and 18.54% decrease in 28-days compressive strength of SCC mixes with 20% fly ash replacement. SCC mixes with ternary combinations resulted in a strength equal to 30.05, 33.42 and 30.18 MPa for 7-days and 40.11, 44.54 and 42.66 MPa for 28-days for plastic viscosities of 9 with river sand and CRF and 13 with CRF. There is a decrease of 38.52,

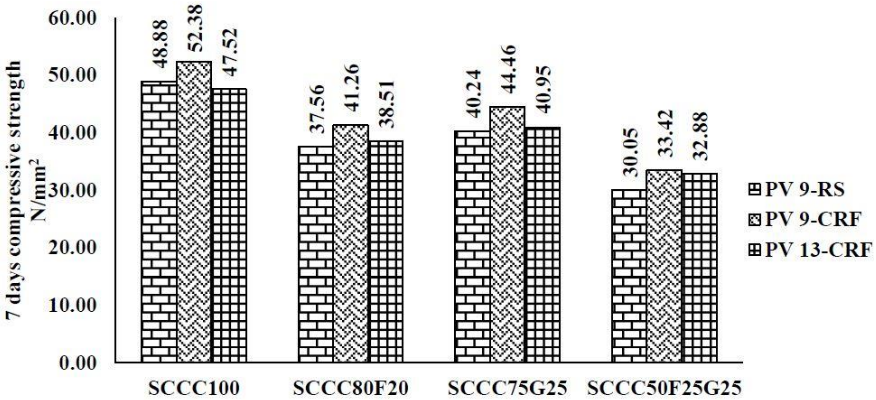

Fig. 9 7-days compressive strength of SCC mixes for Case I and Case II

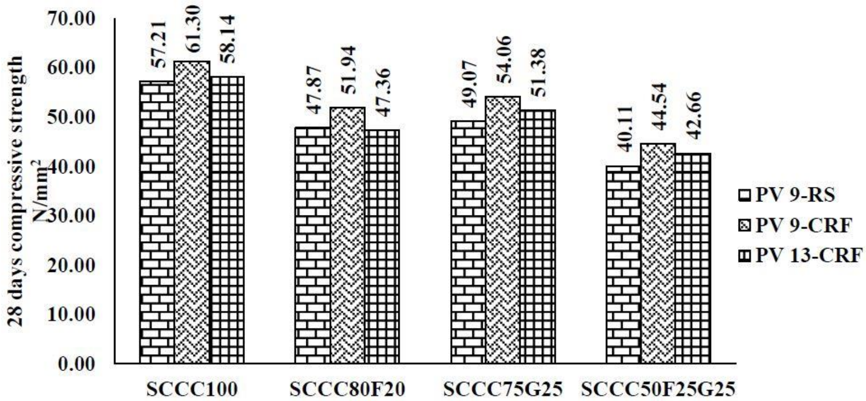

Fig. 10 28-days compressive strength of SCC mixes for Case I and Case II

36.2% and 36.49% in the 7-days compressive strength and 29.89%, 27.34% and 26.63% decrease in 28-days compressive strength of SCC mixes with 25% replacements of both fly ash and GGBS. It is also observed that the compressive strengths of SCC mix with CRF are more than that of SCC mixes with river sand. For SCC mix with 100% OPC, there is a reduction of 6.68% and 6.67% at 7-days and 28-days' strengths with river sand as a fine aggregate. For binary mix with fly ash replacement, there is a reduction of 8.97% and 7.84% at 7-days and 28-days' strengths. For binary mix with GGBS replacement, there is a reduction of 9.49% and 9.23% at 7-days and 28-days compressive strengths. For the ternary mix, there is a reduction of 10.08% and 9.95% at 7-days and 28-days compressive strengths.

An indirect method to test the tensile strength of SCC mixes is carried out using splitting tensile strength. A cylindrical specimen of diameter 150 mm and height 300 mm with an aspect ratio of 2 is adopted for the test. SCC mix with 100% OPC resulted in a maximum tensile strength followed by binary mix with 25% GGBS for both the plastic viscosities of 9 Pa s and 13 Pa s. There is a reduction in tensile strength of SCC mixes with river sand compared to mixes with CRF for a plastic viscosity of 9 Pa s as shown in (Fig. 11). There is a reduction of 10.29% for SCC mix 100% OPC, 13.77% reduction for binary mix with fly ash, 11.44% reduction for binary mix with GGBS and 15.18% reduction for the ternary mix.

A 100 Ton Universal testing machine is used to estimate the flexural strength of SCC mixes. A prism of size 500×100×100 mm is used for the test. Three-point bend test is adopted for the conducting the test. From (Fig. 12) SCC mix with 100% OPC resulted in the maximum flexural strength followed by binary mix with GGBS. Flexural strength decreased for SCC mixes with river sand compared to mixes with CRF for a plastic viscosity of 9 Pa s. There is a reduction of 14.39% for SCC mix 100% OPC, 14.25% reduction for binary mix with fly ash, 13.82% reduction for binary mix with GGBS and 15.28% reduction for the ternary mix.

There is a significant reduction in strength of ternary mixes compared to binary mixes. The reduction is mainly influenced by the 25% of fly ash present in the mix. There is a significant percentage reduction in 28-days' strength of mix with 20% fly ash replacement when compared to mix with 100% OPC. Replacement of cement with fly ash will reduce the heat of hydration which sacrifices the early strength. Sometimes the process of hydration for mixes with fly ash will be prolonged from 90 days to 365 days depending upon the reactive particles in fly ash. It is also observed that the strength loss in fly ash mixes is mainly due to its slow pozzolanic reaction and the dilution effect (Wongkeo *et al*. 2014).

With the increase in plastic viscosity of the mixes, the compressive strengths decreased as the cementitious content decreased. An assumed plastic viscosity of 13 Pa s with CRF is found to be suitable with 0.5 water to binder ratio for the adopted M40 grade of concrete based on the

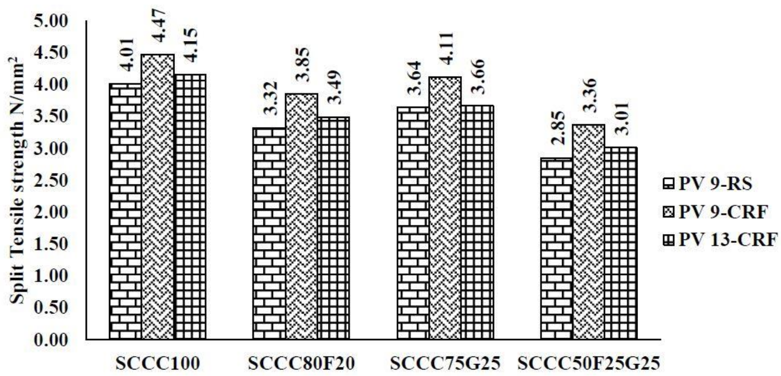

Fig. 11 Split tensile strength of SCC mixes for Case I and Case II

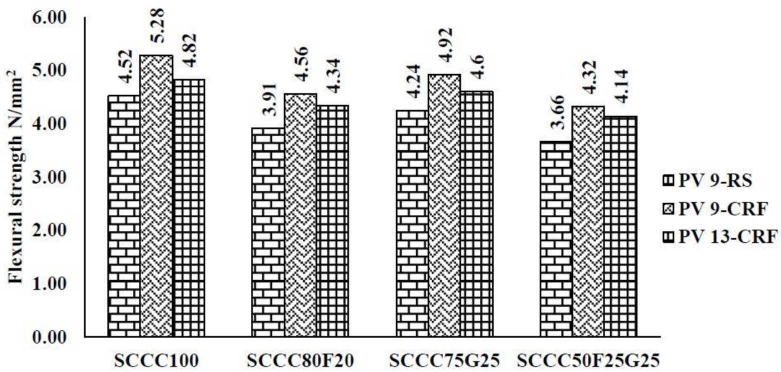

Fig. 12 Flexural strength of SCC mixes for Case I and Case II

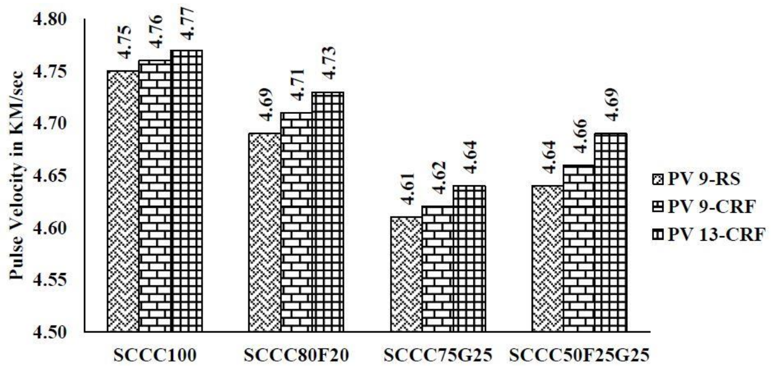

Fig. 13 Pulse velocity of SCC mixes for Case I and Case II

requirements of the construction.

In general, mixes with CRF performed better compared to river sand in terms of compressive, split tensile and flexural strengths.

To determine the homogeneity of concrete, the presence of cracks, voids and deficiencies UPV test is performed for all SCC mixes as per IS 13311 (Part I):1992. From (Fig. 13) the test results indicated that for the plastic viscosity of 9 Pa s with river sand and CRF, for 13 Pa s with CRF the values are relatively comparable. All the test values satisfied requirements and termed as good quality as per IS 13311 (Part I).

6. Conclusions

Plastic viscosity based mix design approach for SCC with a combination of 100% CRF and ternary blends has been successfully attempted for the first time. Based on the analytical formulations and experimental investigations, the following are the observations:

• Plastic viscosity of cement pastes decreased with the increase in water to binder ratio and superplasticizer dosage

• The volume of paste decreases and volume of solids increases with an increase in plastic viscosity of the mix, which is an indication of an increase in aggregate content and decrease in cement content.

• SCC mixes with CRF resulted in better deformability compared to mixes with river sand. The maximum reduction in slump flow of 4.67% is observed for ternary SCC mix with CRF.

• Filling and passing abilities of SCC mixes from various tests indicated that the mixes with CRF have shown better performance compared to the mixes with river sand.

This is attributed to the presence of a larger amount of fines in CRF and silt content in river sand.

• Compressive strength, split tensile strength and flexural strength decreased with the increase in plastic viscosity of the mix due to the reduction of the volume of paste and increase in the volume of solids. Maximum strength is observed for SCC mix with 100% OPC for all the chosen plastic viscosities.

• For a given plastic viscosity of the mix, compressive strength, split tensile strength and flexural strength decreased for SCC mixes with river sand compared to SCC mixes with CRF.

• For M40 grade concrete, an assumed plastic viscosity of 13 Pa s with water to binder ratio of 0.5 is found to be suitable for proportioning SCC mixes to satisfy the fresh and hardened properties in making the mixes practically feasible.

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