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Plastic viscosity based mix design of self-compacting concrete with crushed rock fines

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Abstract. With the increasing demand in the production of concrete, there is a need for adopting a feasible, economical and sustainable technique to fulfill practical requirements. Self-Compacting Concrete (SCC) is one such technique which addresses the concrete industry in providing eco-friendly and cost effective concrete. The objective of the present study is to develop a mix design for SCC with Crushed Rock Fines (CRF) as fine aggregate based on the plastic viscosity of the mix and validate the same for its fresh and hardened properties. Effect of plastic viscosity on the fresh and hardened properties of SCC is also addressed in the present study. SCC mixes are made with binary and ternary blends of Fly Ash (FA) and Ground Granulated Blast Slag (GGBS) with varying percentages as a partial replacement to Ordinary Portland Cement (OPC). The proposed mix design is validated successfully with the experimental investigations. The results obtained, indicated that the fresh properties are best achieved for SCC mix with ternary blend followed by binary blend with GGBS, Fly Ash and mix with pure OPC. It is also observed that the replacement of sand with 100% CRF resulted in a workable and cohesive mix.

Keywords: crushed rock fines; self-compacting concrete; plastic viscosity; compressive strength; mix design; GGBS; fly ash

1. Introduction

Concrete being second largest consumed material in the world needs an attention to address the issue of achieving sustainability. Raw materials used in concrete play an important role in attaining the desired properties as per the requirements of a laboratory or a site. Since the concept of Self-Compacting Concrete (SCC) is introduced into the construction industry, the need for producing efficient mixes which satisfies both fresh and hardened properties have become a challenge for researchers as well as for construction sector. Due consideration should also be given to the usage of locally available materials. Non-seasonal scarcity on the availability of river sand hit the construction sectors in the recent past in India. Crushed Rock Fine (CRF), extracted from quarry is one such alternate to address the scarcity of materials. Compared to river sand, CRF has less organic impurities as well as fines present in CRF leads to a good workable mix especially for SCC. Self-Compaction is a term which represents the ability of a concrete to flow under its own weight without segregation.

Proper compaction is attained without the need to use vibrators. Okamura is the first person to propose the concept of SCC in 1986, followed by Ozawa in developing 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 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 CO_2 emission. Supplementary Cementitious Materials (SCMs) like Ground Granulated Blast Slag (GGBS) and Fly Ash (FA) will reduce the impact of CO_2 emission and increase the sustainability of the mix. The main characteristics of SCC are its stability and flow ability. To obtain a good flow able and stable mix the percentage of coarse aggregate should be minimum, size of coarse aggregate should be less than 20mm and water to powder ratio should be reduced Okamura (1998). Superplasticizer addition to the concrete mixture will result in the high amount of flow-ability. Enhancing the viscosity of the mix will overcome segregation and bleeding during transportation and placing

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of SCC mix. Reduction in coarse aggregate will increase the usage of high volume of cement which further increases cost of the mix and temperature rise during hydration Khayat (1999) Khayat and Guizani (1997). 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). Admixture dosage is an important factor for strength gain of SCC mixes with fly ash, the increase in the dosage reduces the strength. (Glesoglu *et al*. 2009) worked on the effects of binary, tertiary & quaternary blends of cementitious materials on the properties of SCC. It is observed that the ternary blend of GGBS and silica fumes to be more durable when compared with other blends of mineral admixtures. Mahdikhani and Ramezanianpour (2014) investigated the effect of silica fume and nano silica on the compressive strength and chloride permeability of self-consolidating mortars. They concluded that the addition of nano silica resulted in higher compressive strength and also enhanced the durability with reduced chloride permeability. 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. (Yuan-Yuan 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. Fathi and Lameie (2017) studied the effect of two different types of aggregates on the behavior of self-compacting concrete subjected to varying temperatures. They found that Scoria type aggregate showed less sensitivity compared to ordinary aggregate and it has resulted in less strain too. Increasing heat produced gradual symmetric stress-strain diagram. (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. Khan *et al*. (2016) developed a statistical model to proportioning the high-strength self-compacting concrete mix mixes using Response Surface Methodology. They have considered cost to be the influential parameter for the mix proportioning. They came up with optimum combinations of cement, fine aggregate, fly ash and superplasticizer using statistical model. (Shi *et al.* 2015) studied different mix design methods that were developed for SCC. The flow behavior of SCC in its fresh state has a great influence on the hardened properties. Therefore, there is a need for understanding the rheology of SCC mixes with different compositions. 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 τ_y and plastic viscosity η. Plastic viscosity is considered to be an important parameter which depends on the plastic viscosity of the paste and composition of the mix. The paste is a combination of Cement or Cementitious materials+ water uperplasticizer. Paste being a homogeneous viscous fluid unlike SCC mix which is non-homogeneous in nature, rheological parameters can be calculated accurately using a rheometer or viscometer. But for SCC mix a hectic process is involved when tested using a viscometer. (Alireza Mohebbi *et al.* 2011) investigated the influence of various parameters on the rheological properties of self-consolidating concrete using Artificial Neural Network (ANN). They have determined optimum percentage of additives based on the analysis of the model. They concluded that the optimal percentages of silica fume, metakaolin, calcium carbonate and limestone is 15%, 15%, 20% and 20% by cement weight. 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.

The present study deals with the formulation of a new mix design procedure for SCC based on assumed plastic viscosity of the mix with 100% CRF as fine aggregate and suitable additions of supplementary cementitious materials like fly ash and GGBS as. (Karihaloo *et al*. 2015) developed a similar mix design with limestone powder as filler. In the present study, a successful attempt has been made to design a mix without limestone as a filler, considering the eco-friendly nature, and economical aspects of locally available materials. 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. Methodology

In the models developed by (Ghanbari and Karihaloo 2009), the concrete is considered to be a two-phase suspension, solid phase and viscous liquid phase. The plastic viscosity of the liquid phase η_{c0} (cement, water and superplasticizer) can be measured accurately using a rheometer. The increase in the plastic viscosity of the viscous liquid phase due to the addition of solid phase consisting of fine and coarse aggregate is predicted by the two-phase suspension model as proposed by Ghanbari and Karihaloo (2009). The viscosity of the two-phase suspension is given by the product of the viscosity of the liquid phase and a function f_i (Φ_i) that depends on the volume fraction of the solid phase Φ_i and the shape of the particles (Dhaheer *et al.* 2015). The function f_i (Φ_i) depends on the volume fraction of solid phase Φ_i, at low concentrations of the solid phase, that is $\Phi_i < 10\%$, Einstein proposed an equation for the function f_i (Φ_i) given by

$$f_i(\phi_i) = 1 + [\eta]\phi_i \tag{1}$$

At higher concentrations i.e., $\Phi_i > 10\%$, (Krieger and Dougherty 1959) proposed Eq. (2).

$$f_i(\phi_i) = \left(1 - \frac{\phi_i}{\phi_m}\right)^{-[\eta]\phi_m} \tag{2}$$

Where (η) is non-dimensional intrinsic viscosity which is a measure of the individual particles effect on viscosity. A value of η = 2:5 is adopted when the particles are rigid spheres and the distance between them is large compared with the mean particle diameter However the value is 0.74 for hexagonal close packing, and 0.637 for random hexagonal packing (Struble and Sun 1995).

Plastic Viscosity of SCC mix is given by

$$\eta_{mix} = \eta_{paste} * f_1(\phi_1) * f_2(\phi_2) .... * f_n(\phi_n) \tag{3}$$

The product of (η) and ϕ_m on an average will be equal to 1.90. (η) And ϕ_m are inversely proportional to each other with respect to their change (Kruif *et al*. 1985). The contribution of volume fraction of fine and coarse aggregate will be more than 10% for most of the SCC mixes to increase the known plastic viscosity of the paste as given by Eq. (2). The volume fraction of the air voids is assumed to be 2%, and the same is included in the plastic viscosity of the paste in Eq. (4)

$$\eta_{mix} = \eta_{paste} * \left(1 - \frac{\phi_{FA}}{\phi_m}\right)^{-1.9} * \left(1 - \frac{\phi_{CA}}{\phi_m}\right)^{-1.9} \tag{4}$$

When the packing is loose with the addition of first solid phase, it is assumed that the packing is cubic in shape and with addition of solid phases, packing density will increase. Finally, with the addition of last solid phase packing takes the shape of a hexagonal closed packing.

3. Mix design procedure based on plastic viscosity

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 cement ratio is calculated using equation given by (Abo Daheer *et al*. 2015).

$$f_{cu} = \frac{195}{12.65^{(w/cm)}} \tag{5}$$

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

The percentage replacement of cement with GGBS and Fly ash is assumed to be 25% (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

1. 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.

2. 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 (Fig. 1). The corresponding values are tabulated in Table 2.

3. 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).

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

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

1. 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.

2. 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 assumed plastic viscosity values of 7, 9 and 11 Pa-s based on the different trials are adopted.

4. Experimental procedures

4.1.1 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, in 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, and Karnataka. The physical and chemical composition of GGBS is shown in

Fig. 1 Brookfield Viscometer DV3T for measuring plastic viscosity of paste

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

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: 1970. CRF was 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.

• Coarse Aggregate: Basalt type coarse aggregate with a 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 10 mm 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 25^0 is adopted.

• Water: Potable tap water is used for mixing and curing purposes based on its usual satisfactory performance.

• 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 2.

Table 2 Mix proportions of SCC for 1 Cum

Mix Composition	PV of mix	PV of Paste	W/B	OPC (kg/m^3)	Fly Ash (kg/m^3)	GGBS (kg/m^3)	Water (kg/m^3)	CRF (kg/m^3)	Coarse Aggregate (kg/m^3)	SP (kg/m^3)
SCCC100	7	0.17	0.57	379	0	0	217	870	823	2.46
SCCC80F20		0.16		296	74	0	212	915	770	2.4
SCCC75G25		0.18		285	0	95	218	871	811	2.47
SCCC50F25G25		0.20		187	94	94	215	869	790	2.43
SCCC100	9	0.17	0.57	364	0	0	209	895	838	2.35
SCCC80F20		0.16		285	71	0	204	940	784	2.30
SCCC75G25		0.18		272	0	91	209	895	829	2.34
SCCC50F25G25		0.20		179	90	90	206	896	806	2.32
SCCC100	11	0.17	0.57	352	0	0	202	909	852	2.28
SCCC80F20		0.16		276	69	0	198	951	799	2.24
SCCC75G25		0.18		264	0	88	202	907	845	2.29
SCCC50F25G25		0.20		174	87	87	200	913	817	2.25

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

Table 3 Recommendations for SCC-EFNARC Guidelines (2005)

	Slump Flow (mm)	T_{50} (sec)	J-Ring Spread (mm)	V-Funnel (sec)	L-box Blocking ratio H_2/H_1
Minimum	650	2	-	6	0.8
Maximum	800	5	-	12	0.1

Table 4 Details of SCC mixes

Mix	Target Plastic Viscosity	Actual Plastic Viscosity	Vol. of Paste	Vol. of Solid	Paste/Solid (by vol)
SCCC100	PV-7	7.206	0.35	0.65	0.54
SCCC80F20		7.206	0.35	0.65	0.54
SCCC75G25		7.176	0.35	0.65	0.54
SCCC50F25G25		7.17	0.36	0.64	0.56
SCCC100	PV-9	9.208	0.33	0.67	0.49
SCCC80F20		9.2	0.34	0.66	0.52
SCCC75G25		9.166	0.34	0.66	0.52
SCCC50F25G25		9.163	0.34	0.65	0.52
SCCC100	PV-11	11.185	0.32	0.68	0.47
SCCC80F20		11.182	0.33	0.67	0.49
SCCC75G25		11.129	0.33	0.67	0.49
SCCC50F25G25		11.133	0.33	0.66	0.5

• 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.

• Testing Program: Four combinations of mixes designated as SCCC100, SCCC75G25, SCCC80F20, SCCC50F25G25 representing Self-Compacting Concrete with 100% Cement, 75% Cement+25% GGBS, 80% Cement+20% Fly Ash, 50% Cement+25% Fly Ash+25% GGBS are adopted in the current experimental program. Three different values of plastic viscosity of mix are assumed to be 7, 9 and 11 Pa s. Each of the combination of

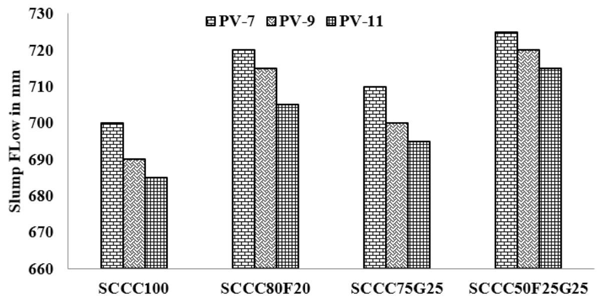

Fig. 2 Slump flow for SCC mixes

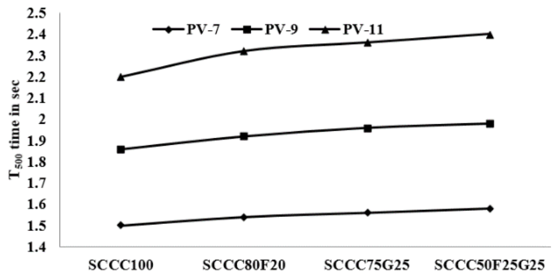

Fig. 3 T50 for SCC mixes

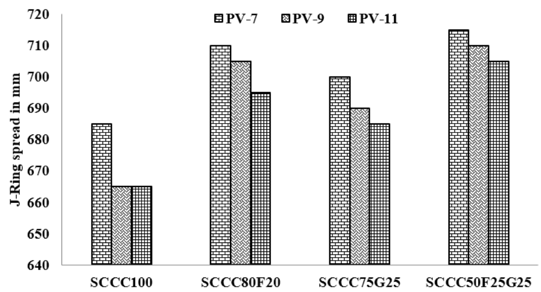

Fig. 4 J-Ring spread for SCC mixes

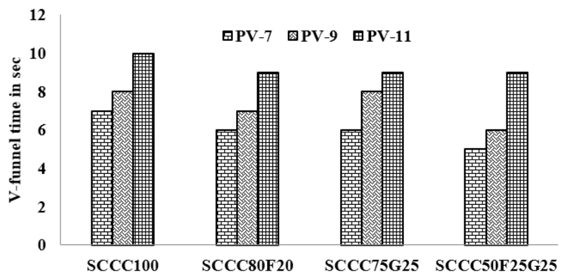

Fig. 5 V-Funnel time for SCC mixes

the four mixes has a separate measured plastic viscosity values as shown in Table 2.

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

5. Results and discussions

5.1.1 Fresh properties

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 for fresh properties as per EEFNARC guidelines are as per Table 3. The properties tested are Slump flow diameter, Slump flow time (T_{50}), V-funnel flow time, J-ring flow diameter. All the SCC mixes have shown a satisfactory flow values ranging from 685 mm to 725 mm (Fig. 2). 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 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.

For all the SCC mixes, the slump flow time recorded (i.e., T_{50}) is ranging from 1.5 to 2.4 seconds (Fig. 3). 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.

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. Spread for J-Ring is measured and the values are ranging from 665 mm to 710 mm (Fig. 4).

As the major portion of 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. 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 (Fig. 4). Viscosity and filling ability in terms of duration of flow of mix is investigated using V-funnel test. V-funnel time measured for SCC mixes ranged from 6 to 10 seconds (Fig. 5) 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 fine aggregate is also an influencing factor for the better performance of the mix.

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 (H_2/H_1), are recorded. If the ratio is less than 0.8, then this test is more sensitive to blocking. All the SCC mixes are within the range of 0.8 to 1.0 (Fig. 6) as per EFNARC standards. Because of the presence of CRF in the mix, it enhances 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. Filling and passing as per standard tests are shown in (Fig. 7).

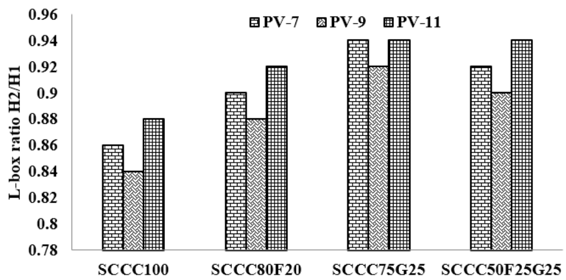

Fig. 6 L-box for H2/H1 SCC mixes

(a) Slump flow

(b) J-Ring

(c) V-Funnel

(d) L-box

Fig. 7 Fresh properties of SCC

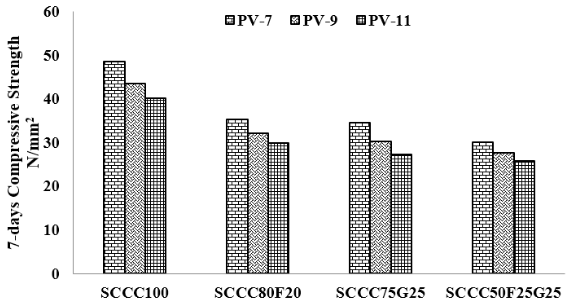

Fig. 8 7-days Compressive strength for SCC mixes

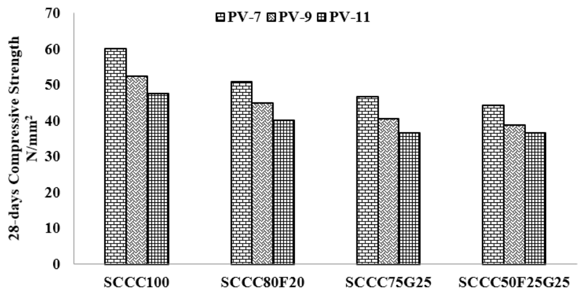

Fig. 9 28-days Compressive strength for SCC mixes

5.1.2 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. 8 and 9) the following observations are made for different combinations of SCC mixes. SCC mix with 100% OPC resulted in maximum compressive strength of 48.16 MPa, 43.5 and 40.14 for and 60.14, 52.4 and 47.56 MPa 28 days for plastic viscosities of 7, 9 and 11 because of the dominant presence of calcium. SCC mixes with 25% replacement of GGBS resulted in a compressive strength of 35.3, 32.2, and 29.94 for 7 days and 50.76, 44.8, and 40.14 for 28 days for plastic viscosities of 7, 9 and 11. SCC mix with 20% Fly ash resulted in strength of 35.3, 30.2, and 27.38 for 7 days and 46.72, 40.6 and 36.62 for 28 days for plastic viscosities of 7, 9 and 11. Due to the presence of pozzolanic reactions in GGBS and fly ash the strength decreases because of its high C_2S content. SCC mixes with ternary combinations resulted in a strength equal to 30.12, 27.6 and 25.88 for 7 days and 44.3, 38.7 and 36.66 for 28 days for plastic viscosities of 7, 9 and 11. There is a significant reduction in strength 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.*

Table 5 Assumed and calculated plastic viscosity

Mix Composition	Assumed Plastic Viscosity	Calculated Plastic Viscosity	% difference
SCCC100	7	7.206	2.86
SCCC80F20		7.206	2.86
SCCC75G25		7.176	2.45
SCCC50F25G25		7.17	2.37
SCCC100	9	9.208	2.26
SCCC80F20		9.2	2.17
SCCC75G25		9.166	1.81
SCCC50F25G25		9.163	1.78
SCCC100	11	11.185	1.65
SCCC80F20		11.182	1.63
SCCC75G25		11.129	1.16
SCCC50F25G25		11.133	1.19

2014). With the increase in plastic viscosity of the mixes, the compressive strengths decreased as the cementitious content decreased. An assumed plastic viscosity of 9 Pas is found to be suitable for the adopted M40 grade of concrete based on the requirements of the construction.

Table 5 shows that, the percentage difference between assumed and calculated values of plastic viscosity of all the SCC mixes are within the proposed limits of $\pm$5%. It is also observed that the water to cement ratio adopted for the four mixes is under predicting the strength characteristics of binary and ternary mixes with fly ash after 28 day. At a higher water to cement ratio, cement paste gets diluted which in turn leads to shrinkage cracks. More water in a SCC mix will enlarge the spacing of cement particles weakening the bond at aggregate and mortar interface leading to the formation of micro cracks (D.P. Bentz, et al, 1999). The mixes with plastic viscosity of 7 Pas are exceeding the maximum water content as per EFNARC guidelines and hence should be avoided because of the aforementioned reason.

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:

• It is observed that the plastic viscosity of the paste has an influential role on the compositions of the mix. It mainly depends on the type of cementitious material, water to cement ratio and superplasticizer dosage.

• Measured values of T_{50} time and V-funnel time, indicates that both the values are in good agreement with the proposed mix design with assumed plastic viscosity of the mix. There is a direct correlation between plastic viscosity and T_{50}.

• Slump flow diameter and time are in par with the standard EFNARC guidelines, which indicates that the proposed mix design has got good flowability and stability for SCC mixes.

• With the increase in the plastic viscosity of the mix, slump flow, T_{500} and J-ring spread increased but V-funnel and L-box decreased.

The use of CRF as a fine aggregate resulted in a very good flowable and stable SCC mix which

• Encourages the use of locally available materials as an alternate to river sand.

• Increase in plastic viscosity of the mix for a constant water to cement ratio has a significant effect on the fresh properties as well as compressive strength of concrete.

• It is also recommended to adopt a plastic viscosity of 9 for a ternary mix with CRF as fine aggregate to proportion the chosen M40 grade of concrete.

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