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AN EXPERIMENTAL STUDY TO INVESTIGATE THE RHEOLOGICAL PROPERTIES OF FRESH SCC USING NEW CONCRETE SHEAR BOX

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Abstract

Flow characterization and controlling fresh property of SCC is most critical. Even slight variations in ingredients can have adverse effect on fresh properties; strength and durability of hardened concrete. The material science approach to study rheological properties is essential in order to overcome the paucity posed while characterizing mixes by empirical methods such as the slump flow test.

In the present work, the Bingham parameters of SCC were assessed by using the new concrete shear box. The mixes were designed considering volume of paste based on absolute volume concept. Three different volumes of pastes (0.38, 0.40 and 0.42) with water contents of 170 and 190 lt/m^3 and cement contents of 300 and 450 kg/m^3 along with slag as filler was used. A unique test procedure was followed, by applying low normal stresses of 0.10, 0.20 and 0.30 MPa with three different displacement rates of 1, 5 and 15mm/min under static condition. The results indicate that the new concrete shear box shall effectively put to use, as an additional tool for evaluating the rheological properties of SCC viz., yield stress and plastic viscosity.

Keywords: *- Slump test, Rheology, SCC, Yield Stress and Plastic Viscosity, New Concrete Shear Box, Bingham Model*

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1. INTRODUCTION

Concrete as a building material has created revolution in construction industry. The present day architectural requirements, demand for high structural performance resulted in the use of high percentage of reinforcements in structural elements with complex shapes. In addition, durability, an important aspect of any structure, is directly related to the degree and quality of consolidation achieved. To overcome the problems of concreting in areas congested with reinforcement and to improve the durability and speed of construction, utilization of Self-Compacting Concrete (SCC) is gaining importance. SCC is different from conventional vibrated concrete (CVC) with higher pow-der content and having wide range of filler materials. In addition, the use of superplasticizer (SP) influences the fresh properties depending on its base, dosage and time of mixing, to name a few. Sometimes SCC also incorporates viscosity-modifying admixture (VMA). The use of such variety of materials in preparation of SCC mixes mandates scientific approach to study on fresh properties since it is important, critical and vulnerable [1].

There are many guidelines proposed [2] by institutes and organizations to characterize the SCC mixes by several test methods [3]. However SCC is more sensitive to the changes in the material properties than that of CVC. Amongst test methods, the slump test in more commonly used and is universally accepted as a measure of workability for all type of mixes from conventional concrete to high performance concrete mixes, like SCC. The slump test is a static test, not a dynamic one. Though the test is simple, it is quite incapable of differentiating two concretes mixes of different composition. Fig-ure 1 shows two mixes having the same slump flow despite having different mix pro-portions. The two concrete mixes may behave differently during placement though their slump flow values may be the same. Concrete flow property cannot be characterized by empirical tests which are generally single parameter tests. The slump flow test does not indicate variations in mix proportioning which is, in fact, very crucial for concrete mixes; especially for SCC mixes since a small variation in mix proportioning can lead to problems with workability affecting the hardened properties.

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2. RHEOLOGY OF SCC

Rheology is a scientific approach, which studies flow and deformation of material under the influence of stresses [8]. Often, it is used to describe the flow characteristics of complex fluids with respect to shear stress and shear rate [9]. Rheology of Fluids is established and widely accepted. Basically, fluids are classified as Newtonian and Non-Newtonian fluids and fresh concrete is assumed as a Non-Newtonian Bingham fluid [10]. Fresh concrete is examined considering it as suspension of granular aggregates of varying sizes in a viscous medium viz., cement paste [10].

In rheological approach, the flow of concrete is characterized by minimum two properties; viz, yield stress(□□) and plastic viscosity (□) [10, 11, 12]. The yield stress is related to concrete slump; it is defined as *"the minimum force required to break down the structure of concrete and initiate flow"*. The plastic viscosity describes the resistance to flow, once concrete is flowing and it is related to the time of concrete slumping (speed of the flow) during the test [12]. Both values are necessary to understand how the processing parameters are linked to the rheological behavior of concrete. These rheological properties are measured by constitutive equations or rheometers. Based on shear stress and shear rate, constitutive equations (about six) are developed to characterize concrete flow [12]. The general form of the equations are simply represented graphically which are shown in Figure 2.

(a) Powder=550 kg/m^3; Water=180 lit/m^3;SP=0.5%; Slump flow=700mm (avg).

(b) Powder=580 kg/m^3; Water=190 lit/m^3; SP=0.5%; Slump Flow=700mm (avg).

Fig 1: Different SCC mixes showing same slump flow with constant dosage of superplasticizer

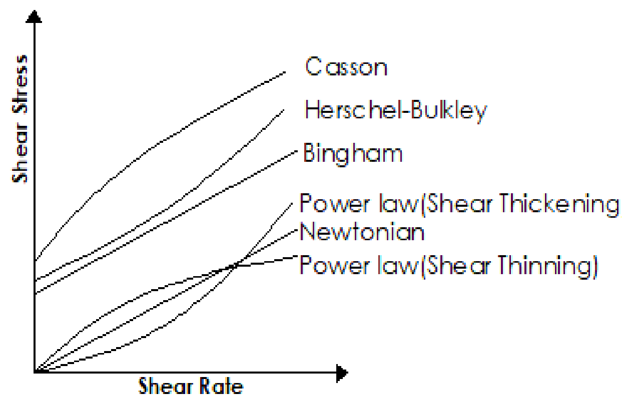

Fig 2: Basic Constitutive Relationships for Flow [12]

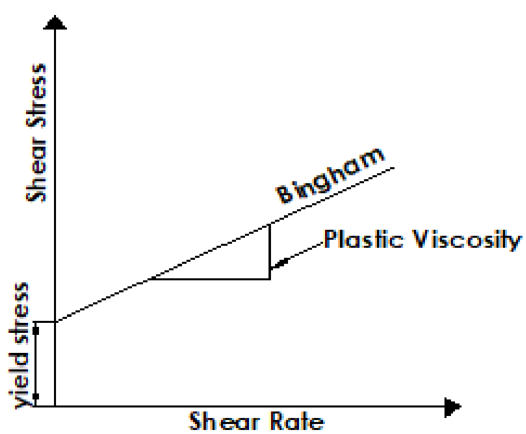

Fig 3: Bingham model [12]

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The rheology of fresh concrete can be measured by relationship between shear stress and shear rate through flow curves. Amongst these, most of researchers agreed in using Bingham equation for flow characterization of concrete [13]. When compared to Newtonian equation, the Bingham equation (Figure 3) incorporates□□□and□□[12, 13]. The general form of Bingham equation (Equ 1) is given by

$$\tau = \tau_o + \mu\gamma \qquad \textit{(Equ. 1)}$$

Where; τ= shear stress (Pa);τ_o= yield stress (Pa);μ= plastic viscosity (Pa-s) and γ = shear rate (1/s).

Rheometer(s) is a device used to measure shear stress at varying shear rates from its fundamental properties [9] and using these values one can predict behavior of concrete or find rheological properties. Rotational type rheometers are used for concrete typically due to precision in measuring rheological parameters in fundamental units as compared to other types of rheometers.. Basically the stimulus provided by rheometers to sample is dynamic in nature and generally measures dynamic yield stress and concrete is subjected to very high shear rates. In field, at the time of placing, concrete will not experience such high shear rates. Eachrheometer has it is own limitations such as geometry restrictions or tendency to cause segregation; which we must overcome prior towidespread use [12]. The values of□□□and□compiled by Ferraris using different types of rheometers for the same concrete mix shows disagreement in measured values [17]. Additionally, Andraz et.al. study [18] also shows different absolute values for yield stress and plastic viscosity amongst rheometers.

In order to overcome the some of the limitations of rheometers, there is need a study *"the flow"* of fresh concrete (SCC) adopting Bingham model by using *new concrete shear box* which itself employs a unique new procedure to determine the Bingham parameters under static condition.

3. CONCRETE SHEAR BOX

Based on the Herschel, Pisapia and L'Hermite [19] works, Girish. S and R. V. Ranganath [20-26] designed and developed an instrument called the *'concrete shear box'*. The basic working principle of direct shear box is alike; with additional features relevant to test fresh concrete. It has two halves with lower half fixed and the upper moves when a horizontal force is applied along with a normal stress during testing. The schematic diagram of the concrete shear box is shown in Figure 4. This new tool is capable of applying a displacement rate that range from 1 to 100 mm/min and normal stresses up to 3.0 MPaalong with stress regulator through a pneumatic actuator. The values are recorded using a servo-controlled electronic data acquisition system. The instrument has been designed to test the sample size of 150mm and coarse aggregate of maximum size 25mm.

Figure 5 shows the *new concrete shear box* used. The key factor being its ability to operate at low shear rate; which is synonymous with field condition concrete experiences and the static condition of the test.

4. EXPERIMENTAL WORK

4.1 Materials

Ordinary Portland cement (OPC - 53 grade) complying IS 12269-2013 and having specific gravity 3.13 and Blaine fineness 260 m^2/kg was used. Natural River sand (Confirming to Zone II as Fine Aggregate); crushed angular granite (as coarse aggregate) of size 20 mm (70%) and 12.5 mm (30%). The bulk specific gravities of fine and coarse aggregate were 2.6 and absorption values were 2.0% and 0.9% respectively. Filler was Ground Granulated Blast-Furnace Slag (GGBS) conforming to IS 12089 - 1987 and the specific gravity and Blaine fineness values were 2.9 and 425 m^2/kg. The polycarboxylic ether based superplasticizer was used as high range water reducer confirming to IS 9103 and IS 2645 standards.

4.2 Methodology

Based on the previous study in the same laboratory and published literature [27, 28], SCC mixes were developed by a new mix design by absolute volume concept starting with a volume of paste (Vp) [29]. The method developed by Girish [29] based on extensive trials is unique and simple. SCC mixes can be developed by one-go approach, that is, the mixes can be developed even with single trials. In this method volume of paste is chosen based on the type of aggregates, required slump flow and the mixes are proportion based on absolute volume. The volume of paste can be in the range of 0.37 to 0.43. Higher volume of paste when flow required is more, and in cases of unfavorable quality of coarse aggregate like crushed angular and elongated. The volume fraction of fine aggregate and coarse aggregate is then decided either by trials or based on the published literature [27,28]. The SP dosage (optimum value) was established through Marsh cone test for the chosen powder and water content.

In the present work, 12 different SCC mixes were developed with varying paste contents (0.38, 0.40 and 0.42), water contents (170 and 190 lt/m^3) and cement contents (300 and 450 kg/m^3). The w/c ratio ranged from 0.37 to 0.63. The

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proportion of coarse aggregate to fine aggregate was taken as 40:60. This was chosen based on the study conducted in the same laboratory. Further coarse aggregate chosen were a combination of aggregates of size 20mm down and 12.5 mm down in the ratio 30:70 respectively.

For different mixes, Marsh cone test was conducted for each of the chosen powder and water contents to arrive at the optimum dosage and the same was kept constant throughout the experiments. Viscosity modifying admixture has not been employed in the current study since all the mixes were developed under laboratory-controlled conditions. Table 1 show the mix proportion used in this study. The developed mixes were tested for rheological properties under three different displacement rates (1, 5, 15 mm/min) with three normal stresses (0.10, 0.20, 0.30 MPa). The numbers of trials were exhaustive and totals 108.

Slump flow, J-ring and V Funnel tests were conducted based on EFNARC guidelines [30] and ACI code [2] to ascertain the fresh properties requirements of filling ability, passing ability and segregation resistance. The detailed fresh properties result are not shown here, but discussion on flowability is discussed later and barring few mixes all the mixes with different paste and cement contents satisfied the EFNARC guidelines [30]. The method of mixing is very important when SP is used which can influence in enhancing the workability of SCC. It should be ensured that the mixing energy is sufficient to evenly distribute water and SP and take advantage of adsorption of molecules of poly-carboxylate ether or acrylic copolymer based SP. The SP having longer lateral chains of molecules require mixing of water in installments. A modified mixing procedure based on number of trials on SCC mixes were developed earlier by Girish (29) and a detailed discussion is given elsewhere [29]. In the modified procedure the mixing sequence of ingredients are different and initially major portion of water along with superplasticizer is considered before mixing the other ingredients. Finally, remaining water and superplasticizer is added in installments.

4.3 Rheological Properties of Fresh Concrete: Procedure

The step by step procedure to find rheological properties of SCC is given below and shown graphically in Figure 6.A unique procedure followed to find the Bingham parameter (Figure 6) of fresh concrete is based on published literature [26]. A brief description of procedure for one of the mixes (Mix S1) studied is as follows;

Step – 1

Place fresh concrete in new concrete shear box mold after through mixing and specific normal stress and displacement rates were applied. Initial testing Shear stress starts decreasing after reaching the peak value (point of dilatancy) or becomes constant, and this marks the end for test trial. Graph of shear stress versus shear strain was plotted, as indicated in Figure 7 representing such behavior. The maximum or peak shear stress for a certain displacement rate and normal stress was found. Further, keeping the normal stress constant, trials were repeated for different displacement rates and in each trials, maximum shear stress were found. The obtained peak shear stress value are tabulated in Table 2.

Step - 2

Using values of the maximum shear stress (Table 2) obtained in step 1, straight line fits are derived between the maximum or peak shear stress and normal stresses for each of the displacement rates. Maximum shear stress is obtained at zero normal stress (ZNS) for different displacement rates individually after extrapolating the line to the readings on the ordinate. The intercept on axis representing the shear stress gives the yield stress of concrete (at ZNS) (Figure 7). It is interesting to note that the shear stress at zero normal stress can be obtained even though the experiment cannot be carried out at without applying normal stress. L'Hermite has termed this as intrinsic shear strength (when the normal stress is zero) and can be consider as yield stress of concrete at ZNS.

Step - 3

Further, yield stress at ZNS (Table 3) obtained in the previous step are plotted against different displacement rates and the straight line fits are plotted. The intercept of the trendline on the ordinate gives the yield stress and its slope is plastic viscosity of the concrete, similar to the Bingham parameters (Figure 8). It is to be noted that the yield stress value obtained corresponds to zero displacement rate. This procedure is unique, since yield stress and plastic viscosity corresponds to zero displacement rates after obtaining the peak shear stress at ZNS; their values are tabulated in Table 4.

5. RESULTS AND DISCUSSION

The values of peak shear stress obtained for different values of normal stress and displacement rate for each of the mixes has been tabulated in Table 2. It is seen, for a given mix with a particular displacement rate, the normal stress and peak shear is directly proportional. This may be due to with increased normal stress, the particles get closer causing interlocking of aggregates; leading to increased resistance, higher peak values.

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This phenomenon remains true for all mix proportions under all displacement rates. Also, for the majority of mixes, results show that for a given mix subjected to a particular normal stress, as the displacement rate increases, the peak shear stress decreases. It is likely that the chosen value of displacement rate influences the results and hence the Bingham parameters. Table 3 shows values of shear stress at ZNS for various displacement rates. The observed trend is that for a given mix, as the displacement rate increases, the value of shear stress at zero normal stress is also observed to increase with some mixes showing exceptions.

The final results obtained from flowability and rheological tests are tabulated in Table 4.

The slump flow values varied from 680 mm to 850 mm for different paste volume, aggregate volume and water content. The values of □□□and □□obtained experimentally are termed as relative, since values are not absolute. It can be observed, for a given cement and water content, with increase in Vp, the yield stress decreases. This can be attributed to the fact that higher Vp leads to better reduced friction between aggregate particles which in turn reduces the inter-particle friction between the aggregates. Also, higher paste content means lower aggregate content; lower fraction of aggregates results in inter-particle spacing between the aggregates; thus reduced resistance to flow. Under low paste contents, the inter-particle friction dominates and results in higher relative yield stress. This phenomenon is clearly brought out by the concrete shear box test. It may be pointed out that the trend is similar to the results obtained with rheometers i.e., higher the flow, lower are the yield stress (□□□ and plastic viscosity (□□. This could be attributed to particle interference (or friction) during shearing at low rates. These values are lower in rheometers due to high shear rates and concrete exhibits shear thinning behavior.

An important aspect is that the SCC is extremely sensitive to variations in mix proportioning and even slight variations can lead to wide variations in workability and there is a need to maintain equilibrium with the various constituents. The influence of various ingredients cannot be represented in simple empirical tests and *rheological methods* are more relevant for more advanced types of concrete, which are used today.

6. CONCLUDING REMARKS

The results of this experimental study have shown the effective use of *newconcrete shear box* in determining the rheological properties of fresh concrete (SCC) and can be an effective additional tool. The test is unique with consistent results and the values are obtained with normal stress and displacement rate at *'zero'* values. The Bingham parameters obtained through these studies were termed as *'relative yield stress'* and *'relative plastic viscosity'*; partly due to higher than those reported in the literature as determined by rheometers with high shear rate.

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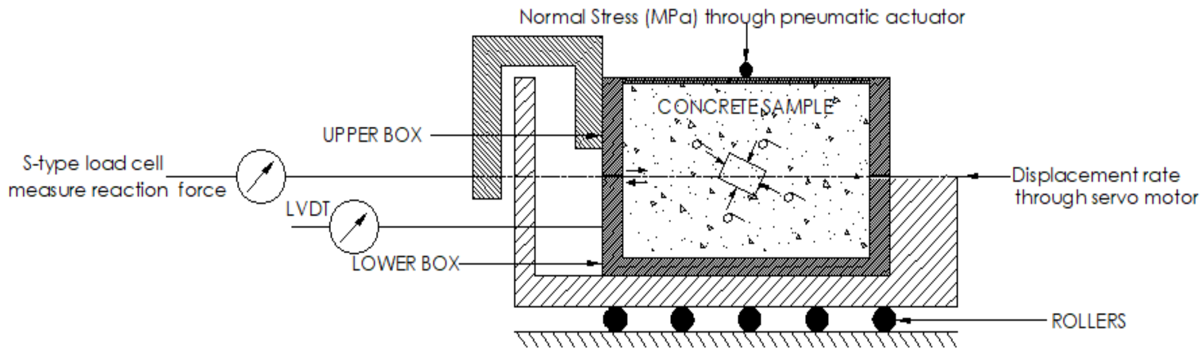

Fig 4: Schematic Representation of Concrete Shear box

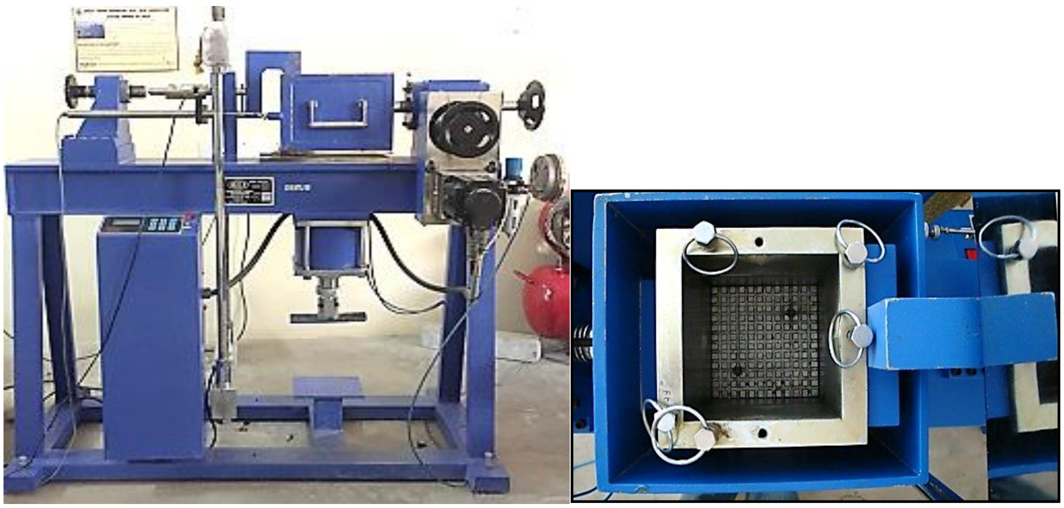

Fig 5: New Concrete Shear box (fabricated)

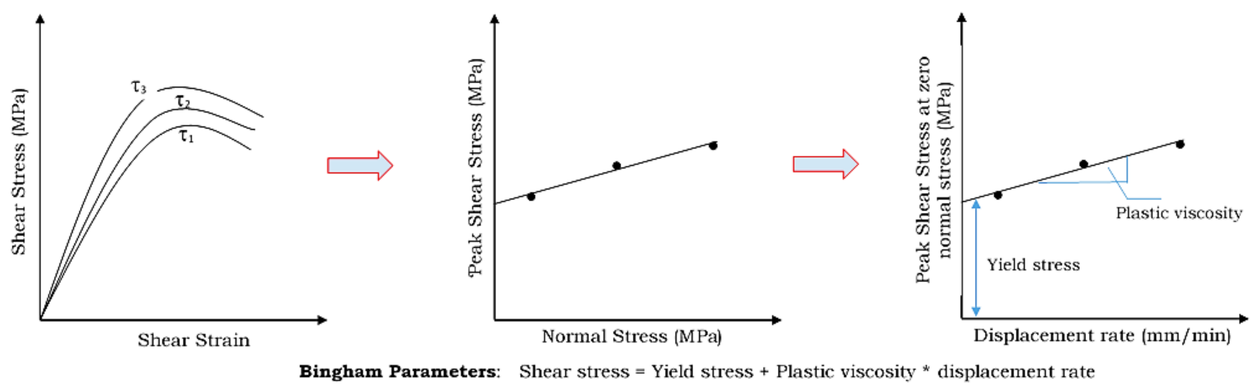

Fig 6: Unique Generalized Procedure for finding the Bingham Properties by using Concrete Shear Box [26]

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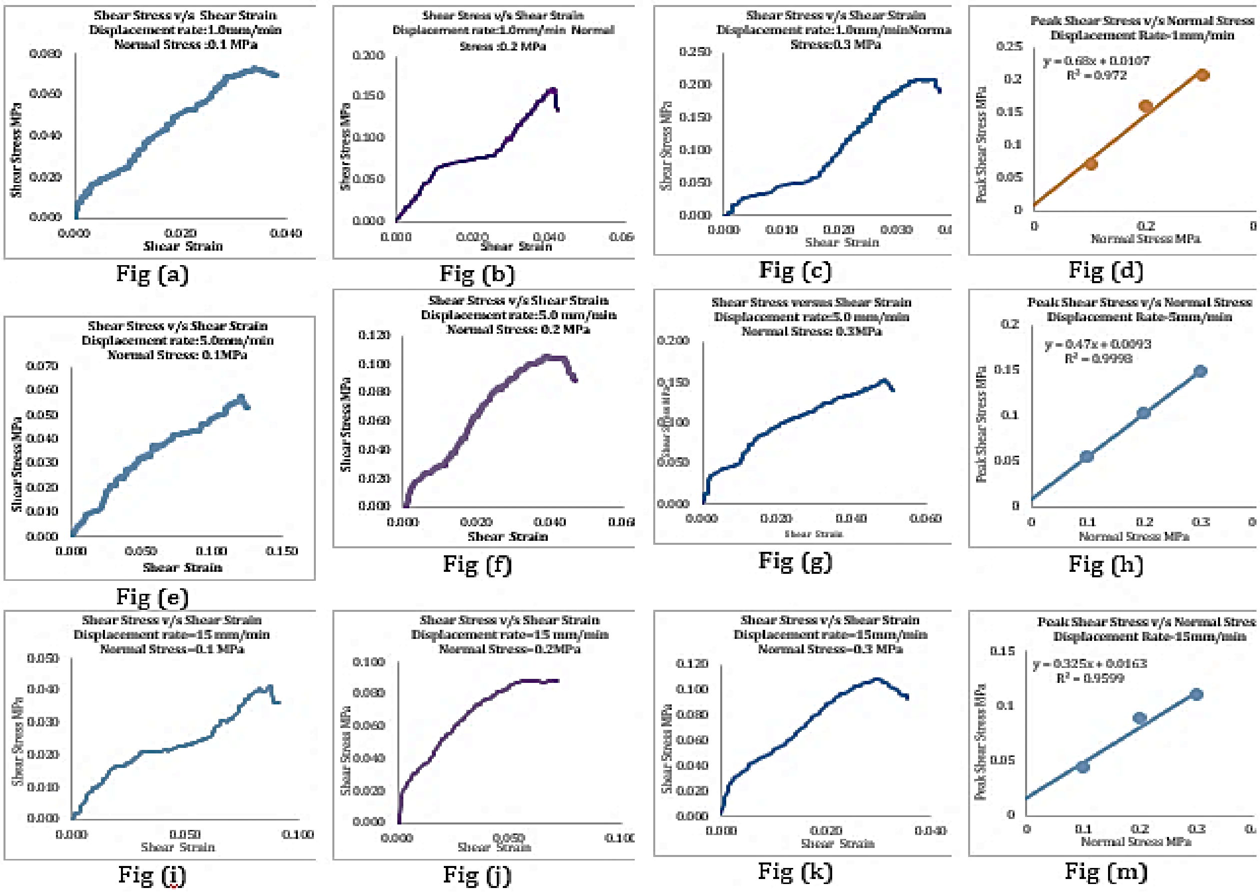

Fig 7: Relation between Shear stress v/s Shear Strain and Peak Shear Stress v/s Zero Normal Stress (Mix-S1)

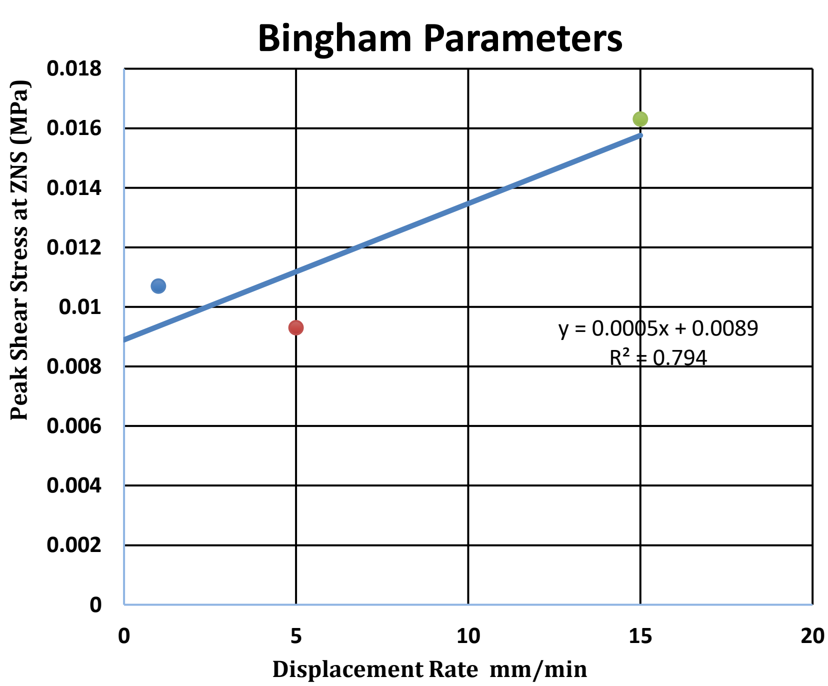

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Fig 8: Bingham Parameters for Mix –S1

Table 1: Details of Mix Proportions

Mix	Ce (kg/m^3)	FA (kg/m^3)	CA (Kg/m^3)	GGBS (kg/m^3)	Water (lt/m^3)	Powder (kg/m^3)	SP (%)	Vp
S1	300	945	654	279	170	579	0.75	0.38
S2		915	634	337		637	0.75	0.40
S3		885	613	395		695	0.80	0.42
S4	300	945	654	221	190	521	0.45	0.38
S5		915	634	279		579	0.50	0.40
S6		885	613	337		637	0.55	0.42
S7	450	945	654	136		586	0.65	0.38
S8		915	634	194	170	644	0.85	0.40
S9		885	613	252		702	0.95	0.42
S10	450	945	654	78		528	0.35	0.38
S11		915	634	136	190	586	0.40	0.40
S12		885	613	194		644	0.55	0.42

Note: Ce-cement; FA-fine aggregate; CA-coarse aggregate; SP-superplasticizer; Vp-volume of paste

Table 2: Peak Shear Stress values

Disp. Rate mm/min	Normal Stress (MPa)	Peak shear stress (MPa)											
		S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
1	**0.10**	0.072	0.060	0.084	0.112	0.106	0.090	0.123	0.066	0.030	0.080	0.080	0.075
	0.20	0.160	0.089	0.150	0.187	0.206	0.164	0.160	0.163	0.100	0.160	0.220	0.116
	0.30	0.208	0.160	0.250	0.300	0.300	0.260	0.320	0.240	0.250	0.200	0.250	0.200
5	**0.10**	0.056	0.056	0.066	0.067	0.078	0.065	0.060	0.046	0.041	0.070	0.063	0.060
	0.20	0.104	0.128	0.117	0.177	0.131	0.121	0.110	0.100	0.062	0.140	0.158	0.100
	0.30	0.150	0.152	0.153	0.200	0.197	0.147	0.150	0.140	0.110	0.165	0.178	0.135
15	**0.10**	0.045	0.050	0.069	0.075	0.070	0.054	0.055	0.059	0.030	0.060	0.051	0.049
	0.20	0.089	0.126	0.088	0.190	0.127	0.110	0.100	0.070	0.050	0.100	0.108	0.085
	0.30	0.110	0.136	0.110	0.218	0.154	0.105	0.130	0.150	0.080	0.120	0.120	0.095

Table 3: Shear Stress at Zero Normal Stresses (ZNS)

Disp. Rate mm/min	Peak shear stress at ZNS (MPa)											
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
1	0.0107	0.003	-0.004	0.012	0.010	0.001	0.004	-0.010	-0.010	0.0267	0.0133	0.0053
5	0.0093	0.016	0.025	0.015	0.016	0.029	0.016	0.001	0.002	0.030	0.0180	0.0235
15	0.0163	0.018	0.048	0.018	0.033	0.038	0.020	0.002	0.0025	0.0333	0.0240	0.0303

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Table 4: Fresh Properties of SCC mixes along with rheological values

Mix	Cement (kg/m^3)	Water (lt/m^3)	Vp	Slump (mm)	T_{500mm} (s)	V-funnel (s)		J-ring (mm)	Yield Stress (Pa)	Plastic viscosity (MPa-s)
						V0	V5			
S1	300	170	0.38	750	4.7	8.0	8.0	4.0	8900	4.5
S2			0.40	770	3.8	8.5	8.9	3.0	6000	8.1
S3			0.42	850	3.5	10.0	10.8	5.0	3600	3.5
S4	300	190	0.38	720	2.0	5.0	5.0	10.0	12200	3.6
S5			0.40	730	2.2	5.2	5.5	3.0	8200	14.6
S6			0.42	750	2.5	5.5	6.0	10.0	6600	20.7
S7	450	170	0.38	690	3.2	8.0	8.5	0.0	6700	9.0
S8			0.40	800	3.0	8.0	9.0	0.0	4300	6.3
S9			0.42	850	2.8	8.5	10.0	5.0	3300	6.0
S10	450	190	0.38	680	2.7	7.0	7.2	5.0	26900	3.6
S11			0.40	700	2.3	7.4	7.8	5.0	13300	6.3
S12			0.42	725	2.4	8.5	8.8	5.0	8700	14.4