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CONTROLLING THE QUALITY OF FRESH CONCRETE - A NEW APPROACH

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ABSTRACT

Traditionally, the slump test has been used to measure concrete consistency. However, many researchers contend that the slump alone is not a sufficient measure of consistency and that other quantifiable rheological properties such as shear yield stress and plastic viscosity are more representative and should be considered. A SLump Rate Machine (SLRM) was adapted and calibrated, to consistently measure the plastic properties for a number of concrete mixes, namely slump rate and slump flow. Furthermore, a theoretical model was developed to correlate the slump flow and slump rate with the shear yield stress and plastic viscosity of fresh concrete, respectively. Employing the SLRM and the theoretical model has resulted in an efficient new approach to adequately predict the rheological behaviour of fresh concrete as well as to provide reasonably accurate values for shear yield stress and plastic viscosity.

INTRODUCTION

The quality of fresh concrete is determined by its homogeneity, and the ease with which it can be mixed, transported, compacted and finished. Flowability, moldability, cohesiveness and compactibility are the workability properties that are primarily associated with the quality of fresh concrete. Flowability is related to consistency since the latter determines the ease with which concrete flows. Concrete with similar consistencies, however, can exhibit different workability characteristicsⁱ. Cohesiveness, which is a measure of compactibility and finishability, is another component of workability, and is generally evaluated by ease of trowelling and visual judgement of resistance to segregationⁱⁱ.

Workability is mostly affected by the water content of the concrete mixture, and is influenced by the quantities of paste and aggregates, plasticity of the cement paste, the maximum size, shape, surface characteristics and grading of the aggregates. Given the broad definition of workability and its dependence on many factors, developing a reliable approach for quantifying the flow and deformation properties of fresh concrete for controlling its quality is important.

Tattersallⁱⁱⁱ have shown that fresh concrete behaves as a Bingham fluid, i.e. the shear stress is linearly proportional to the shear strain rate, and that there is a minimum shear stress at which no flow occurs. Based on Bingham model, two parameters are required to characterise the flow properties; namely, the plastic viscosity and the yield stress. A two-point test method was put forward by Tattersall and Bloomer^{iv} and Tattersall and Banfill^v for estimating the rheological properties of fresh concrete. This approach has led to the development of a Coaxial Cylinders Viscometer (CCV). At present, the flow properties of fresh paste, mortar and concrete can be measured by rotation viscometer^v, sphere lifting test^{vi}, LAFARGE rheometer^{vii}, ViscoCorder rheometer^{viii}, CEMAGREF-IMG rheometer^{ix}, rotation viscometer with inserted sphere^x and BTRHEOM, the new rheometer for soft to fluid concrete^{xi}.

Despite the extensive research work carried out on defining the flow properties of fresh concrete, these test methods have yet to yield similar rheological properties for the same concrete. The variations are most likely due to the differences in the experimental techniques and apparatuses used^{xii}. Furthermore, the majorities of the current test procedures are generally complicated, require skill, and are not easy to carry out in the field.

Research efforts by Tanigawa et al.^{xiii,xiv,xv} and Kurokawa et al.^{xvi} for estimating the rheological constants of fresh concrete by measuring its slump and the slump flow have resulted in the development of a simpler test method. This method maintains a constant lifting velocity of 124 mm/sec for the slump cone that is greater than the 43 to 100 mm/s range specified by ASTM C 143-1990^{xvii}. To comply with the ASTM requirements for the lifting speed and slump cone dimensions, the Tanigawa et al. approach was modified by Chidiac^{xviii} and an automated slump testing device, called the Slump Rate Machine (SLRM), was developed.

The SLRM, schematically illustrated in Figure 1, is fully automatic and is controlled by a computer that also records the information necessary to determine the yield stress and plastic viscosity of fresh concrete. Because of its simple operation and its conformity to current standard ASTM C 143-90, the SLRM was adopted in the present study.

In this paper, a description of the proposed methodology for estimating the rheology of fresh concrete is presented. Several concrete mixes with variable compositions were tested and their measured rheological properties are compared with those estimated by the proposed method and by other analytical methods reported in the literature.

RHEOLOGY OF FRESH CONCRETE

Theoretical models

The flow of fresh concrete has been found to conform to Bingham modelⁱⁱⁱ, and is described by

$$\tau = \tau_y + \eta \dot{\epsilon} \quad (1)$$

Where τ is the applied shear stress, τ_y the yield shear stress, $\dot{\epsilon}$ the strain rate and η the plastic viscosity. In this study, the slump-flow testing method and the rheological model of Tanigawa and Mori^{xix} have been adopted and further developed to quantify the rheological properties, i.e. the yield stress and the plastic viscosity, of fresh concrete.

Yield stress

Tanigawa et al.^{xv} have established a relationship between the slump and the shear yield stress using the principles of applied mechanics. They assumed fresh concrete to be incompressible and its slumped shape to remain a simple cone. Based on these assumptions, a relationship between a shape factor α , and the slump, Sl (m), and the slump-flow, Sf (m) was established

$$\alpha = \frac{1 + a + a^2}{3} = \frac{4V}{\pi Sf^2(H - Sl)} \quad (2)$$

where V and H are the volume (m^3) and height (m) of the slump cone, respectively. The quantity a is defined as the ratio of the top radius to the bottom radius of the cone, Figure 2.

Assuming the bearing stress, σ_b , at the bottom of the concrete cone to be only due to the weight of the fresh concrete, it can be expressed by

$$\sigma_b = \frac{\rho g V}{\pi r_b^2} = \alpha \rho g H \quad (3)$$

in which ρ is the density of the material (kg/m^3), g the gravitational acceleration ($9.806 m/s^2$), and r_b the radius of the base of the slump cone. Based on the Hohenemser and Prager constitutive law^{xx}, a material will flow when the quadratic invariant of its deviatoric stress $\sqrt{\sigma J_2}$, exceeds the yield limit, σ_y . This occurs at the base of the cone and is represented by the following relation:

$$\tau_y = \sqrt{\sigma J_2} \leq \frac{\sigma_b}{\sqrt{3}} = \frac{\alpha \rho g H}{\sqrt{3}} \quad (4)$$

However, equilibrium is established when the fresh concrete slumps to its final shape, i.e.,

$$\tau_y = \frac{\alpha \rho g (H - Sl)}{\sqrt{3}} = \frac{\alpha \rho g z_y}{\sqrt{3}} \quad (5)$$

where z_y is the height of the slumped fresh concrete. Eq. (5) is the relationship proposed by Tanigawa et al.^{xv} for estimating the shear yield stress. However, adopting a single value for α to compute the yield stress as suggested by Tanigawa et al.^{xv} cannot discriminate between materials with different cohesiveness. Substitution of Eq. (2) into Eq. (5) results in a revised relationship for computing the yield stress as a function of the density and the slump-flow of the fresh concrete, i.e.,

$$\tau_y = \frac{4 g V}{\sqrt{3} \pi} \frac{\rho}{S f^2} = \beta_1 \frac{\rho}{S f^2} \quad (6)$$

where β_1 is a constant.

Eqs. (5) and (6) for estimating fresh concrete shear yield stress may be compared to Eq. (7), proposed by Murata and Kikukawa^{xxi}, and to Eq. (8), suggested by Hu et al.^{xi}.

$$\tau_y = 715 - 474 \log(100 Sl) \quad (7)$$

$$\tau_y = (30 - 100 Sl) \frac{\rho}{27} \quad (8)$$

Eqs. (7) and (8) were empirically derived, using the measured yield stress data from a coaxial viscometer and from the BTRHEOM, respectively.

Plastic viscosity

The evaluation of plastic viscosity of fresh concrete is critical for predicting consistency in high fluidity concrete. In this study, two different approaches for estimating the plastic viscosity of fresh concrete were investigated; namely Method A derived from the work of Murata and Kikukawa^{xxi} which consisted of developing an equation to quantify the plastic viscosity based on the concrete mixture; and Method B which follows Tanigawa et al.^{xv} estimation of the plastic viscosity of fresh concrete based on measured values for slump and slump flow.

Closer examination of Tanigawa et al.^{xv} proposed relationship between z_y and the slump, i.e.,

$$z_y = \frac{Sl - sl(t)}{100} \quad (9)$$

leads to zero height above which the fresh concrete would yield, i.e. complete collapse. Instead, the height should correspond to the relation given in Eq. (5), i.e.,

$$\begin{aligned} z_y &= H & @t &= 0 \\ z_y &= H - sl(t) & @t &\geq t_{slump} \end{aligned} \quad (10)$$

where t is the time measured from the beginning of the slumping process and t_{slump} is the total slumping time.

Using Eq. (9), Tanigawa et al.^{xv} have proposed the following relationship for the slump,

$$sl = Sl - \frac{1}{\frac{\alpha \rho g}{600\eta} t + \frac{1}{Sl}} \quad (11)$$

referred to as Method B. The incorporation of the new boundary conditions for z_y from Eq. (10) into Eq. (11) yields

$$sl = H - \frac{1}{\frac{\alpha \rho g}{6\eta} t + \frac{1}{H}} \quad (12)$$

To be consistent with the z_y - slump relationship of Eq. (9), a calibration factor of magnitude equal to 100 was introduced into Eq. (12), i.e.,

$$sl = H - \frac{1}{\frac{\alpha \rho g}{600\eta} t + \frac{1}{H}} \quad (13)$$

It should be noted that Eq. (13) applies only during the slump time and therefore is further modified to take into effect the time of slump, i.e.

$$\begin{aligned} sl &= H - \frac{1}{\frac{\alpha \rho g}{600\eta} t + \frac{1}{H}} & 0 \leq t \leq t_{\text{slump}} \\ sl &= Sl & t > t_{\text{slump}} \end{aligned} \quad (14)$$

This revised approach is referred to as Method C.

Since Eq. (14) is consistent and continuous, it was further re-arranged to establish a relationship between the plastic viscosity and the slump, slump flow and total time of slump,

$$\eta = \frac{\rho g H V}{150 \pi Sl Sf^2} t_{\text{slump}} = \beta_2 \frac{\rho}{Sl Sf^2} t_{\text{slump}} = \frac{\beta_2}{\beta_1} \frac{\tau_y}{Sl} t_{\text{slump}} \quad (15)$$

According to Eq. (15), an estimate of the rheological properties of fresh concrete require the measurements of slump, slump flow and time of slump. To this end, the SLRM^{xviii} was adopted for obtaining the necessary measurements.

Slump Rate Machine, SLRM

SLRM consists of a) two displacement transducers for measuring the cone lifting displacement and slump displacement with time; b) a slump cone for measuring the concrete slump and flow; c) a computer and a data acquisition unit to monitor and record the readings of both transducers; and d) an electric motor to control the withdrawal rate of the slump cone. The fully automatic and computer controlled SLRM, was first tested and calibrated. For standards compliance purposes, the cone lifting speed and the measured slump are made to comply with ASTM C 143-90^{xvii} recommended values.

Calibration and testing

During the lifting of the cone, the interfacial friction generated between the fresh concrete and the slump cone can affect both the withdrawal rate and the reproducibility of the results. Two extreme conditions were investigated; the lifting speed of an empty cone; and the lifting speed of a weighted cone.

The results, as given in Table 1, show that the average speed of the lifting cone varies by 5, 8, and 13 percent when the weight of the cone is increased by 2, 4, and 8 kg, respectively. The reproducibility of the results was checked by repeating the test 7 times. As anticipated, the weight added to simulate the friction does affect the speed of the lifting cone, but it remains within the tolerable withdrawal range of ASTM C 143-90 for the slump test (5 ± 2 s). Furthermore, the results indicate that the average speed, corresponding to power level 5 in the current test program, lies within the range of ASTM C 143-90 recommended values of 43 to 100 mm/s.

The SLRM measures the slump using a tracking steel rod that is continuously in contact with the fresh concrete. A 63.5mm circular plate is attached to the contacting end of the rod for distributing the weight of the rod. The effect of the added weight on the slump values was determined, and the results are given in Table 2. Prior to the addition of a counter weight, the weight of the steel rod resulted in an 83 percent difference between the SLRM values and the results obtained from a standard slump test. Accordingly, a 158g counter weight was added to the SLRM apparatus to ensure compliance with ASTM C 143-90.

The results given in Table 3 represent the average of 2 repetitions with a maximum difference of less than 3% between them. The mix used for the calibration of the SLRM contained 296 kg/m³ cement and 1172 kg/m³ coarse aggregate.

EXPERIMENTAL

Concrete mix design

As shown in Table 3, six concrete mixes were prepared with the variables being the water cement ratio (W/C), sand to total aggregate ratio (S/A), water reducer (WRA) and air entraining agent (AEA) contents. The mixes were designed with high W/C ratio to simulate the workability and strength of concrete mixes used in the construction of residential basement walls and foundations. Each mixture was designed for an average 28 day compressive strength of 20 MPa and a target minimum slump of 175 mm. These strength and slump values are within the range of basement concrete mixes in Canada.

The mixes consisted of ordinary Type 10 Portland cement and local coarse and fine aggregates. The coarse aggregate was crushed limestone, with maximum size of 25 mm, while the fine aggregate was silica sand with a maximum size of 4.75 mm. The gradation analysis for the fine and the coarse aggregates was conducted according to ASTM C 33-85^{xxii}, and the results are shown in Figure 3. The fineness modulus for the fine aggregates was 2.6 and was calculated according to ASTM C 136-84^{xxiii}. A lignosulfonate water reducing admixture (WRA) and a synthetic detergent air entraining agent (AEA) was used alone or in combination in some of the mixes.

The concrete was mixed using a pan mixer according to ASTM C192-81^{xxiv}. The specimens were cured under controlled room temperature at 20° C and at a relative humidity of 50 %.

Results

The recorded SLRM measurements of the fresh concrete slump as a function of time are shown in Figure 4 while the measured average slump rates are shown in Figure 5. The average slump rate is equal to the total travel distance divided by the total travel time. The measured slump time, average slump rate, and the corresponding values of slump are also summarised in Table 4.

A comparison between the slump values measured using SLRM, and those using the manual slump cone, Table 4, indicates that the former to be slightly larger. Maximum differences of 15 and 17 percent were obtained for Mixes 2 (A) and 5, respectively. These variations are within the tolerance range for slump.

The measured average slump rates, Figure 5, show that the rates for Mix 1 (A), 1 (B), 3 (A) and 5, are not smooth, and that the slump accelerates and decelerates during travel time of the concrete cone. For these mixes the initial high rate of slump is attributed to the poor inter-particle cohesion due to excessive amount of free water. As the free water is allowed to escape and separate from the other components of the mix, the rate of slump decreases significantly.

COMPARATIVE EVALUATION WITH OTHER RHEOLOGICAL MODELS

Shear yield stress

Four different relations for estimating the shear yield stress of fresh concrete are evaluated; namely, Eqs. (5), (6), (7) and (8), which are proposed by Tanigawa et al.^{xv}, present study, Murata et al.^{xxi} and Hu et al.^{xi}, respectively.

Following Tanigawa et al.^{xv} approach, values of the shape factor, α , given in Eq. (2) were first calculated using the experimentally measured values for slump and slump flow. The corresponding maximum and minimum computed values of α , shown in Table 5, are 1.05 and 0.53, respectively. The corresponding maximum and minimum values for “a” are 1.05 and 0.43, respectively. The average value of α may be taken as 0.87. Theoretically, the value of the parameter “a” larger than 1.0 implies that the top radius of the slump cone is greater than the bottom one. For fresh concrete with a large slump value, the cone tends to collapse into a shallow cylinder, thus resulting in a maximum value of “a” equal to 1.0. Thus for α values greater than 0.583, the geometry of the collapsed cone will take the form of a cylinder rather than a cone, with its diameter equal to the slump-flow.

By applying Eq. 5, together with the measured slump value of the fresh concrete, the yield stress can be computed. As shown in Figure 6, α equals to 0.583, as suggested by Tanigawa et al.^{xv}, produces yield stress values that do not agree with those obtained using Eq. 6. The results shown in Figure 6 indicate that the computed yield stress values using a value of α in the range of 1.0 are in closer agreement with those from Eq. 6. From Table 5 it can be observed that with the exception of Mix 1 (B) and 3 (C), the values of α are greater than 0.87. It should also be noted that Mix 1 (B) and 3 (C) have the highest sand to total aggregates ratio for the W/C ratio equal to 0.83 and 0.65, respectively. Thus increasing the ratio of sand to total aggregates increased the inter-particle cohesion, resulting in a reduction in the values of both the slump-flow and slump. These results confirm that when computing the shear yield stress, adopting a single value for the shape factor, as suggested by Tanigawa et al.^{xv}, can not adequately represent the various mix proportions.

The relationship proposed by Murata and Kikukawa^{xxi} produces maximum and minimum shear yield stress values of 130 and 35 Pa, respectively. These maximum and minimum values, as shown in Table 6, correspond to the slump values of 172 and 272 mm, respectively.

Hu et al.^{xi} empirical relationship shows that the yield stress is linearly proportional to the product of the slump and the fresh concrete density. The corresponding results are given in Table 6 and illustrated in Figure 6. The results, shown in Figure 6, computed in accordance with Eq. 6, are significantly larger in comparison to those computed using the empirical relationship suggested by Murata and Kikukawa^{xxi}. However, the computed values using the Hu et al. relationship are found comparable to those obtained using Eq. 6. Further comparison shows that the computed values are within the range of the typical values reported by Tanigawa^{xiii} and Banfill^{xii}. Figure 6 clearly displays the difference between the yield values obtained from Eq. 7 and those obtained from Eqs. 6 and 8.

Plastic viscosity

Computed values of slump versus time using method B^{xv}, method C the present study and the experimental data are shown in Figure 7 to Figure 14, for Mix 1 (A) to Mix 5, respectively. The computed plastic viscosity and the time of slumping are summarised in Table 7. The measured slump time values are given in Table 4 while the corresponding

computed values are reported in Table 7. Except for Mix 1 (B) values, the two time sets are found to be generally in agreement.

Examination of the slump curves shows that the proposed relationship gives representative slump curves for all the tested mixes, except for Mix 1 (A). The results are in good agreement with the measured slump curve, provided the curve is concave. For Mixes 1 (A), 1 (B), 3 (A), 4, and 5, one can observe a convex slump curve. The computed values for plastic viscosity according to method A^{xxi} are 1.33 and 1.35 Pa.s for the W/C ratio of 0.83 and 0.65, respectively. These values are very low. The computed plastic viscosity according to method B is 75 Pa.s for W/C ratio of 0.83 and in the range of 100 to 300 Pa.s for the W/C ratio of 0.65. Referring to Figure 4, one can observe that the velocity of deformation of Mixes 2(A) and 2(B) exhibits similar trend, an indication that the plastic viscosities of the two mixes are close to each other, with Mix 2(B) being slightly higher. Estimating the plastic viscosity of Mix 2 (B) by Method B gives a value approximately 200 percent greater than that of Mix 2 (A). Further Mixes 3(A), 4 and 5 exhibited similar trend, but the estimated plastic viscosity showed a very wide range of variation. Revisiting the results obtained using method C, it can be observed that the predicted plastic viscosity for Mixes 2 (A) and 2 (B) are in close proximity with that of Mix 2 (B) being slightly larger. The plastic viscosity for Mixes 3 (A), 4 and 5 are 31, 33 and 21 Pa.s, respectively, values which follow the trend. The predicted plastic viscosity of 59 Pa.s for Mix 3 (C) corresponds to the low rate of slump.

The proposed new relationship (Method C) gave a range of plastic viscosity values between 5 to 11 Pa.s for the W/C = 0.83 and a range of 21 to 74 Pa.s, for the W/C = 0.65. The computed plastic viscosity values using methods C show very consistent results, and the computed slump curves are in agreement with the experimental data. Further, the computed plastic viscosity values are within the range of plastic viscosity values reported by Tanigawa et al.^{xiii} and Banfill^{xii}.

Observations

The results clearly indicate that an increase in the AEA and WRA contents, or in the W/C decreases the values of the shear yield stress, the plastic viscosity, and the total time of slump. Furthermore, it was observed that the plastic viscosity is equally affected by the changes in AEA, WRA and W/C. The water to cement ratio has the most influence over the shear yield stress, followed by the water reducer admixture and the air entraining agent. In comparison to the WRA content and the W/C ratio, the air entraining agent has significantly more influence over the total time to slump. The increase in the ratio of fine to total aggregates has a direct effect on the rheological properties. The plastic viscosity and the total time of slump are the most influenced by S/A, with the shear yield stress being marginally affected.

PROPOSED QUANTITATIVE APPROACH FOR CONCRETE WORKABILITY

Experimental results revealed the inter-relationship between slump, slump-flow, total time of slump, and shear yield stress and plastic viscosity. These inter-relationships are represented by Eqs. (6) and (15) for the shear yield stress and the plastic viscosity, respectively.

Assessment of workability in terms of the rheological properties, i.e. the shear yield stress and the plastic viscosity, which are calculated based on the slump, slump flow, density of fresh concrete, and time of slump values, can provide a powerful tool for control of concrete production. Using the above relationships, design curves have been established for controlling the quality of fresh concrete as illustrated in Figure 15 and Figure 16. These curves can be used to determine the necessary slump and slump-flow for the required rheological properties, or to control the uniformity of the fresh mix. Although the proposed curves may require further refinement, the proposed approach for controlling the quality of the fresh mix appears promising. Since there are no standard methods for quantifying or measuring the yield stress and the plastic viscosity of fresh concrete, and recognising the wide variation from one testing method to another, it is suggested that the calculated values of shear yield stress and plastic viscosity be used as indicators of the rheological behaviour of fresh concrete.

CONCLUSIONS

Based on the results of the current experimental and analytical investigation, the following conclusions are drawn for mixes with high w/c ratio typically used in the construction of residential basements and walls:

1. The Slump Rate Machine (SLRM) is a convenient and reliable device for the consistent measurement of the slump, slump rate and flow properties of concrete mixes.
2. The present test data suggest that the yield shear stress is directly proportional to the product of slump and fresh concrete density, and inversely proportional to the square of the slump flow.
3. The plastic deformation is related to the plastic viscosity and the slump time as well as to the concrete density and the slump cone height. An expression can be developed to explicitly relate slump rate to the above parameters in a mix.
4. The plastic viscosity and yield value increase with decreasing water/cement (W/C) ratio.
5. For the same W/C ratio, higher sand/total aggregate ratio appears to produce higher yield stress and viscosity.
6. For the same W/C ratio, the addition of admixtures, such as water reducing (WRA) and air entraining admixture (AEA) result in a reduction in plastic viscosity and yield stress.
7. Analytical expressions have been derived to estimate the values of the yield stress in the absence of SLRM equipment.

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REFERENCES

Table 1: Calibration of the effect of lifting cone speed scale for SLRM

Weight	0 kg	2 kg	4 kg	8 kg
Power level	Average speed (mm/sec)			
3	15.8	15	14.5	13.8
4	33.8			
5	81.2			
6	100.9			
7	114.7			
7.5	125.2	124.4		
8	140.1			
10	210.9			

Table 2: The effect of the tracking steel rod weight on concrete spreading

Mix Name	W/C	S/A	Slump cone (mm)	SLRM		Difference (%)
				Counter weight (g)	Slump (mm)	
A	0.50	0.41	76.2	free	139.7	83
B	0.51	0.41	45	210	41.4	-8
C	0.53	0.41	75	210	46.7	-38
D	0.60	0.41	139.7	210	126.1	-10
E	0.60	0.41	165	158	165	0
E*	0.60	0.41	141	158	145	3

* Mix E was re-mixed for 30 seconds before repeating the test

Table 3: Mix design for basement concrete in the current investigation

Mix No.	Cement(kg/m ³)	W/C	Coarse aggregate (kg/m ³)	S/A (%)	Density (kg/m ³)	WRA (ml/m ³)	AEA (ml/m ³)
1 (A)	275	0.83	947	0.52	2333		
1 (B)	275	0.83	750	0.6	2338		
2 (A)	286	0.65	976	0.49	2376		
2 (B)	275	0.65	980	0.49	2377		
3 (A)	275	0.65	980	0.49	2318	687.5	
3 (C)	275	0.65	923	0.52	2292	687.5	
4	275	0.65	980	0.49	2257		137.5
5	275	0.65	923	0.52	2224	687.5	55

Table 4: Measured slump time, average slump rate and slump

Mix Name	Slump time (s)	Average slump rate (mm/s)	Slump (mm)		Difference (%)
			Cone	SLRM	
1 (A)	3.7	73.51	250	272	9
1 (B)	4.6	52.40	240	241	0
2 (A)	10.5	18.67	170	196	15
2 (B)	9.2	20.00	165	184	12

3 (A)	7.6	30.26	205	230	12
3 (C)	11	15.60	168	172	2
4	7.2	27.08	195	207	6
5	6.6	35.45	200	234	17

Table 5: Effect of shape factor on the yield stress value

Mix No.	Density (kg/m ³)	Slump (mm)	Slump-flow (mm)	α	a	Yield stress (Pa)			
						Eq. 6	Eq. 5		
							$\alpha=0.5$	$\alpha=0.87$	$\alpha=1.0$
1 (A)	2333	272	488	1.05	1.05	388	194	338	388
1 (B)	2338	241	475	0.53	0.43	411	206	358	776
2 (A)	2376	196	270	0.92	0.92	1292	646	1124	1404
2 (B)	2377	184	245	1.01	1.01	1570	785	1366	1570
3 (A)	2318	230	315	1.01	1.01	926	463	806	926
3 (C)	2292	172	293	0.64	0.58	1058	529	920	1653
4	2257	207	292	0.88	0.87	1049	525	913	1192
5	2224	234	318	1.05	1.05	872	436	759	872

Table 6: Comparison of estimated shear yield stress

Mix No.	Yield stress (Pa)		
	Eq. 6	Eq. 7 ^{xxi}	Eq. 8 ^{xi}
1 (A)	388	35	242
1 (B)	411	60	511
2 (A)	1292	103	915
2 (B)	1570	116	1021
3 (A)	926	70	601
3 (C)	1058	130	1087
4	1049	92	777
5	872	66	544

Table 7: Computed slump time and plastic viscosity values

Mix No.	Slump time (s)	Method A ^{xxi} (Pa.s)	Method B ^{xv} (Pa.s)	Method C (Pa.s)	
				curve fitting	Eq. 15
1 (A)	4	1.33	75	5	5
1 (B)	7.5	1.33	75	11	7
2 (A)	10.3	1.34	100	59	60
2 (B)	10	1.35	300	74	68
3 (A)	8.9	1.35	300	31	26
3 (C)	11.1	1.35	300	59	59
4	7.5	1.35	100	33	32
5	6.5	1.35	150	21	21

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