論文　A Study on Rheology of High Flowing Concrete

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ABSTRCT: In this paper, the detail study of rheology has been performed on high flowing concrete. Bingham model is used for the rheology study. The relation between concrete and mortar rheology with standard test methods has also been studied. An effort has been made to propose a generalized equation of rheology from the mix proportion, assuming that the concrete behaves as Bingham fluid. It is found that, some high flowing concrete does not follow the Bingham model. The flow curve of these concretes does not follow linear model.

KEY WORDS: Rheology, Self-compacting Concrete, Fresh Concrete, High flowing Concrete, Rheometer.

1. INTRODUCTION

In this paper, rheology study and its relation with traditional test methods of high flowing concrete (HFC) have been studied. The concrete is referred, here, as high flowing concrete not the self-compacting concrete (SCC) [1]. Because the variation of mix proportion used in this study does not fall into the small range of mix proportion of self-compacting concrete. With one or two exceptions, all the concretes exhibited high slump flow and self-leveling capacity in U-box without reinforcement. The main difference between these two concretes is that the SCC has the capacity of passing the blocking test, but HFC does not. This research has been divided into two parts, firstly tests on mortar, and secondly tests on concrete. The mortar is prepared separately to achieve the same mortar property of previously tested concretes. Wet screening has been evaded to obtain the mortar; instead separate mixes have been used. In this research slump flow test, V-funnel test, rheology test have been performed on both mortar and concrete. Some mix proportions have also been designed to perceive the behavior of self-compacting concrete. An effort has been made to propose a generalized equation of rheology from the mix proportion, assuming the concrete behaves as Bingham fluid. It is found that SCC does not follow the Bingham model. The flow curve of these concretes does not follow linear model.

2. MATERIALS USED AND DESCRIPTION OF EXPERIMENTS

The materials used in this study are readily available in the Japanese market. In this research, Ordinary Portland Cement (OPC), Ground Granulated Blast Furnace Slag (GGBS), Sand, Gravel, and Superplasticizer have been used. Ordinary Portland Cement and GGBS, complying with JIS A 6206 have been used. River sand – with specific gravity 2.63, fineness modulus 3.21 and solid volume content 64.3 percent, and crushed stone – with specific gravity 2.71, fineness modulus 6.45 and solid volume content 57.5 percent, have been used in this research. Maximum size of gravel was limited to 10 mm to avoid using larger size of rheometer and lot of concrete for tests. The grading curve of fine aggregate and gravel is shown in Fig. 1. It should be noted from these figures that grading curves of the coarse aggregate is not uniform and no effort has been done to make the

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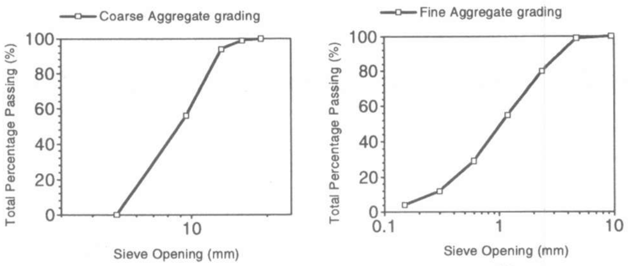
grading uniform. The aggregate supplied from the contractor has been used directly in the research. SP-8Sx$_2$ has been used as superplasticizer. The amount of superplasticizer used in the concrete mixes, is decided from the mortar tests; and that amount is kept constant for all mixes.



(a) (b)

Fig. 1 Grading curve for (a) coarse and (b) fine aggregate.

Two different sets of concrete mixes have been used. In the first set the sand to aggregate ratio and powder content and water to powder (hereafter, w/p) ratio have been varied (Fig. 2 (a)). This set is referred as high flowing concrete. In the second set (Fig. 2 (b)) G/G_{lim} (Solid volume of Gravel (G), Maximum solid Volume of Gravel (G_{lim}) present in mix) and water to powder ratio have been varied with constant V_s/V_m (0.4) (Volume of Sand (V_s), Volume of mortar (V_m)) ratio. This set is referred as self-compacting concrete. There is also another difference between these two sets, the amount of GGBS replacement. For the first set it is 30 percent and for the second set it is 60 percent. In this research for mortar and concrete - slump flow test, V-funnel test and rheology test are done. Concentric cylinder rheometer has been employed to assess the rheology parameters. Two different sizes of cylinder has been utilized for mortar and concrete. Inner and outer diameters of the cylinder utilized for mortar are 120 mm and 220 mm, respectively; and for concrete are 100 mm and 250 mm, respectively. The height for the both cylinder is 250 mm.

The mixing procedure has been kept identical for mortar and concrete, to obtain the matching mortar properties with the previously designed concrete. For concrete - first Cement, GGBS and all aggregate is mixed for 60 seconds then water and superplasticizer is added and mixed for another 60 seconds then mixture is stopped and again the concrete is further mixed for 60 seconds before it is discharged from the mixture. For mortar - first cement, GGBS and sand has been mixed for 60 seconds, then water and superplasticizer is added and mixed for 60 seconds then mixture is stopped and then mortar is further mixed for 60 seconds. For concrete, pan type mixture is used whose capacity is 100-liter. For mortar 60-liter mortar mixer is used.

3. RHEOLOGY THEORY

Many types of rheometer rely on rotational motion to achieve a simple shearing flow. For such instruments, the means of inducing the flow are two-fold: one can either drive one member and measure the resulting couple or else apply a couple and measure the subsequent rotation rate. There are two ways that the rotation can be applied and the couple measured: the first is to drive on member and measure the couple on the same member, whistle the other method is to drive one member and measure the couple on the other. In this research the second method is exercised. If the gap between two concentric cylinders is small enough and the cylinders are in relative rotation, the test liquid enclosed in the gap experiences an almost constant shear rate.

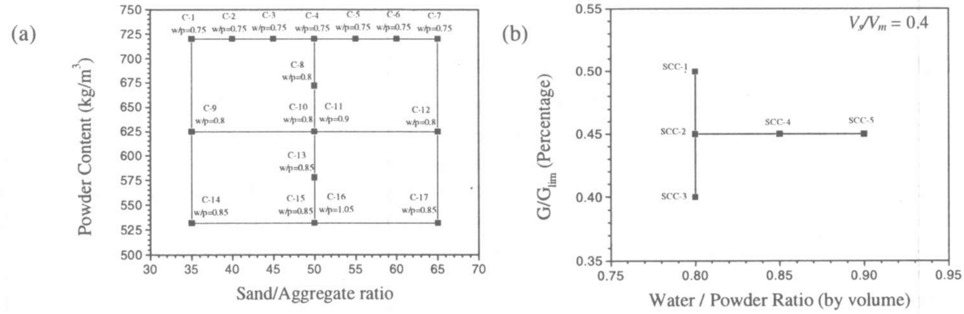


Fig. 2 (a) High flow concrete mix data, and (b) Self-compacting concrete mix data.

Specifically, if the radii of the outer and inner cylinders are r_o and r_i, respectively, and the angular velocity of the inner in Ω_1, (the other being stationary) the shear rate $\dot{\gamma}$ is given by

$$\dot{\gamma} = \frac{r_o \Omega_1}{r_o - r_i} \tag{1}$$

For the gap to be classed as "narrow" and the above approximation to be valid to within a few percent, the ratio of r_i to r_o must be greater than 0.97. The limitations of very narrow gaps in the concentric-cylinder rheometer are associated with the problems of achieving parallel alignment and the difficulty of coping with suspensions containing large particles. For these reasons, in many commercial rheometers the ratio of the cylinder radii is less than that stated earlier; thus some manipulation of the data is necessary to produce the correct rheology. The shear rate in the liquid at the inner cylinder is then given by

$$\dot{\gamma} = \frac{2\Omega_1}{n(1 - b^{2/n})} \tag{2}$$

Where b is the ratio of the inner to outer radius (i.e. $b=r_i/r_o$). The shear stress in the liquid at the inner cylinder is given by

$$\tau = \frac{T}{2\pi r_i^2 L} \tag{3}$$

The value of n can be determined by plotting T versus Ω_1 on a double-logarithmic basis and taking the slope at the value of Ω_1 under consideration [2]. This method is employed to estimate the rheology parameters in this research.

Two methods have been adopted to calculate the flow curve for concrete and mortar. In first method speed of the rheometer is gradually increased and then gradually decreased. This type introduced high segregation in the concrete. In second method the speed is set to high speed and from that value it is decreased slowly. First method is employed for first set of mix and second method is employed for SCC.

4. RHEOLOGY MODEL FOR FRESH CONCRETE

In addition to assess rheological parameters for various concretes, the modeling of rheological parameters for those concretes was also investigated. Two types of models were exploited: 1) theoretical, using Farris Equation [3], and 2) empirically developed equations. The identical input parameters were used for all models.

4.1.1 Model Input Parameters

The aggregate parameters are: sand volume fraction (S), and maximum solid volume (S_{lim}), gravel volume fraction (G) and maximum gravel solid volume (G_{lim}) for viscosity, and water to powder ratio, sand to aggregate ratio and total aggregate apparent aggregate volume for yield stress. The total apparent aggregate volume is defined as summation of S/S_{lim} and G/G_{lim} .

4.1.2 Viscosity Modeling

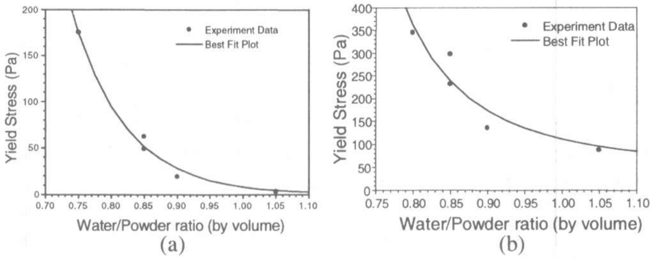
For viscosity model, Farris model [3] has been employed. Since the Farris model is based on the theory that the particles within the solid phase of the suspension can be divided into two or more specific size fractions, and concrete is typically divided into coarse and fine aggregate, this model seemed applicable. Therefore, within the bounds of this research, the Farris model was used in following form:

$$\eta_c = \eta_p \left(1 - \frac{S}{S_{lim}}\right)^{-[\eta^{FA}]S_{lim}} \left(1 - \frac{G}{G_{lim}}\right)^{-[\eta^{CA}]G_{lim}} \tag{4}$$

The fine aggregate fraction is denoted with FA, while the coarse aggregate fraction is denoted with CA. These FA and CA are just two constant power of the apparent viscosity, which is denoted by $[\eta]$, which will be derived by fitting the experimental data.

4.1.3 Yield stress Modeling

As no model is available that predicts the yield stress of a material with Bingham characteristics, this research attempt to do so. The yield stress of the concrete is assumed to be a function of yield stress of mortar and the volume fraction of aggregate. The yield stress of the concrete must be equal to the yield stress of mortar if the gravel content is zero. With these model conditions in place the development of a yield stress model is explored. This model is completely empirical one based on experimental data on mortar and concrete experiment. With this in mind the proposed empirical equation is as follows:



(a) (b)

Fig. 3 Relation between yield stress and w/p for (a) mortar and (b) concrete.

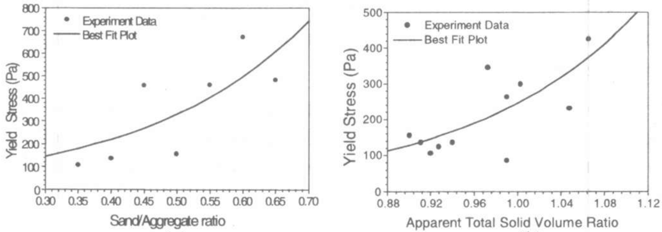
$$\tau_c = \tau_m + f(ts) \tag{5}$$

Total apparent solid volume is denoted by *f(ts)*. τ_m and τ_c is the yield stress of mortar and concrete respectively.

4.2 DISCUSSION ON RESULTS

4.2.1 Yield stress

It makes sense that the best case will be when there is no yield stress in concrete. If there is yield stress, then one should input some energy to overcome this and start the flow. To control this, one should know the effect of the variables that controls the flow. In this paper, an effort has been made to perceive the effect of various factors affecting yield stress and compare this yield stress with traditional testing methods for high flowing concrete.



(a) (b)

Fig. 4 Relation between yield stress and (a) sand/aggregate, (b) apparent total solid volume.

4.2.1.1 Water powder ratio

Water to powder ratio is a major variable to investigate. From Fig. 3., it can be said that there is a clear relationship between the yield stress and the w/p ratio. An increase in the w/p produced a decrease in the yield stress for both mortar and concrete. If concrete displays Bingham behavior, aggregates presumably will be present, and then regardless of w/p, the concrete will have a yield stress. In above figures it can be seen that yield stress and w/p confirm well to an exponential decay equation of the following form for both cases.

$$\tau = a \times e^{(w/p \times b)} \tag{6}$$

Here, *a* and *b* are constants of the equation, which can be derived from the best fit curve.

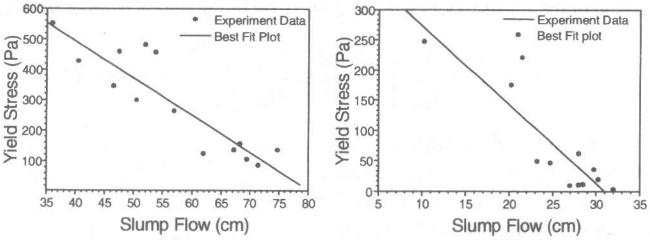
4.2.1.2 Volume fraction of aggregate

This is one of the key factors affecting the yield stress of concrete. From Fig. 4., it can be seen the effect of sand aggregate ratio and apparent total solid volume on yield stress. It is found that the greater the sand aggregate ratio and apparent total solid content, the higher the yield stress.

4.2.1.3 Relationship between traditional test methods

The rheology tests are generally carried out in the laboratory; whereas the slump flow test is easily carried out on site. It is very useful to know the relationship between the test results so that they can properly interpreted.

Fig. 5 shows relationship between slump flow with yield stress for mortar and concrete. It is clear that there is good correlation between slump flow and yield stress, but there is no direct relationship found between viscosity and slump flow. Therefore, slump flow can be considered an alternative index for the yield stress of the concrete and mortar. It can be seen that the higher the slump flow the lower the yield stress. V-funnel flow time does not have any correlation with yield stress.



(a) (b)

Fig. 5 Relation between yield stress and slump flow for (a) concrete and (b) mortar.

4.2.2 Viscosity

Once the yield stress overcomes, the viscosity decides how fast the material will flow. The same variables affect the yield stress affect the viscosity.

4.2.2.1 Water powder ratio

The w/p ratio affected the plastic viscosity directly; an increase in w/p ratio produced a decrease in the plastic viscosity (Fig. 6). As discussed with yield stress an attempt is made to describe the relationship between plastic viscosity and w/p with an exponential decay equation.

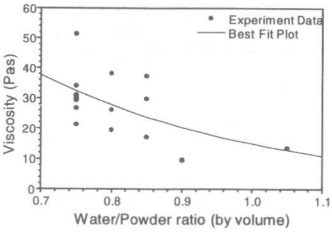
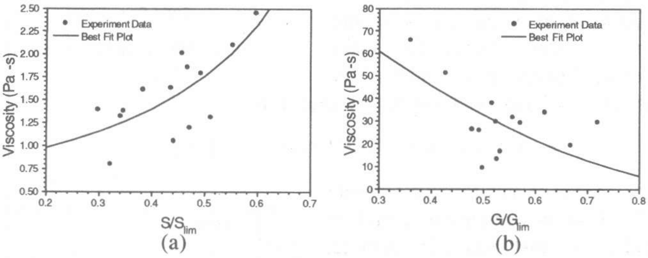


Fig. 6 Viscosity vs. w/p ratio.

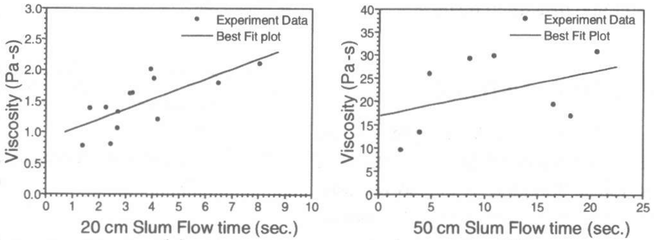


(a) (b)

Fig. 7 Relation between viscosity and (a) S/S_{lim} for mortar (b) G/G_{lim} for concrete.

4.2.2.2 Volume fraction of aggregate

As the viscosity model describe earlier is based on the S/S_{lim} and G/G_{lim} the relation between these with the viscosity is plotted in Fig 7. It can be seen that if the sand content increases the viscosity decreases and opposite is the case for gravel content. This is because in a total constant volume of aggregate if the sand content increases the gravel content decreases.



(a) (b)

Fig. 8 Relationship between viscosity and (a) 20 cm slump flow time for mortar (b) 50 cm slump flow time for concrete.

4.2.2.3 Relationship with traditional test methods

The slump flow does not have any direct relationship with the viscosity but the time for 20 cm flow for mortar and 50 cm flow for concrete has (Fig. 8). The increase of the time indicates the increase of the viscosity. V-funnel flow has direct relation with viscosity. It is seen from the Fig. 8 that with the increase of V-funnel time the viscosity of both mortar and concrete increases.

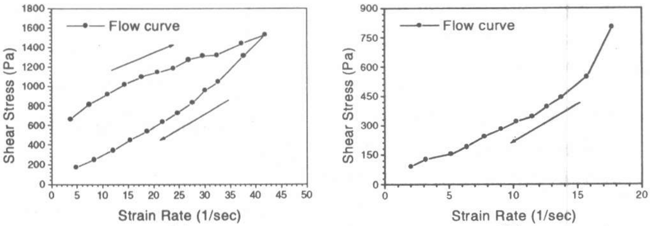
All the results discussed in this section are for the first set of mix but all these are also valid for SCC, except for the yield stress. If we model the SCC with the Bingham model it has been found that all the yield stress for SCC is negative. This indicates that the flow curve (Fig.9) is highly non-linear for SCC. It is better not to use Bingham model for very high flowing concrete. Detail description is beyond the scope of this pa per.

5. PROPOSED MODEL EQUATIONS

After analyzing the viscosity data given in Fig 7 (a) and Fig 7(b) the following empirical modified version of the Farris model was developed, by fitting the each curve separately and combining them.

$$\eta_c = C\left(1-\frac{S}{S_{lim}}\right)^{-[2.0]S_{lim}}\left(1-\frac{G}{G_{lim}}\right)^{[3.0]G_{lim}} \quad S>0 \text{ and } G>0 \tag{7}$$

In this formula constant C (60 for this research) should be decided to satisfy specific concrete values by few experiments. Because no model was available for the prediction of yield stress, it was decided to explore empirical model and analyzing the Fig 3(a) and Fig. 4(b) the following equation is proposed, following the same procedure above. The main difference between Eq. 7 and Eq. 8 is that former is based on theory but the latter is not.

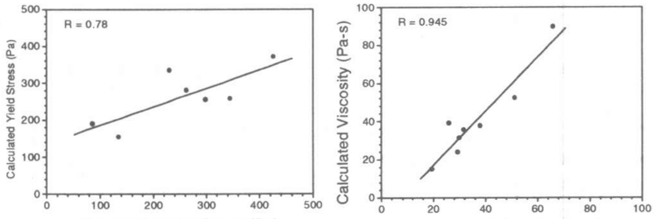


(a) (b)

Fig. 9 Flow curve for (a) first set mix and (b) second set mix.

$$\tau = 1.75\times10^{6}e^{-(w/p*12.28)} + D*ts^{7.4} \quad ts>0 \tag{8}$$

Again in this formula constant D (200 for this research) should be decided to satisfy specific concrete, by few experiments. Fig. 10 shows the comparison between calculated result and measured result.



(a) (b)

Fig. 10 Comparison between calculated and measured (a) yield stress (b) viscosity.

6. CONCLUSIONS

It is possible to predict the plastic viscosity of the concrete with the Farris equation. It is also possible to predict the yield stress of concrete based on a model developed from the experimental results of this research. Comparison of the results of the slump flow with yield stress gives the confidence that the slump is measuring useful rheological characteristics. It has an inverse relation with yield stress. The V-funnel flow test can also be considered as a measurement of the concrete viscosity. It has a direct relation with viscosity. The 50 cm slump flow time for concrete and 20 cm slump flow time for mortar also gives good indication of the corresponding viscosity. It is found that SCC does not follow the Bingham model. So, non-linear analysis is suitable for high flowing concrete, like SCC.

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