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A NEW MIX DEIGN METHOD FOR HIGH PERFORMANCE CONCRETE

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Abstract

Monitoring of workability is a critical issue for high performance concrete (HPC) since HPC is susceptible to small changes in mixture proportions that have a direct impact on hardened properties. In the present study, rheological tests were performed with a modified set up of parallel plate rheometer. Correlation between rheological parameters and the mix design parameters has been obtained and correlation charts have been used for the design of HPC mixtures. The procedure presented in this paper takes into account estimation of rheological parameters at the design stage.

Keywords: Rheology; high performance concrete; yield stress, plastic viscosity; mix design

1. Introduction

The objective of any mix design method is to determine an appropriate and economical combination of concrete ingredients that can be used for a first trial batch to produce a certain concrete which is close to that can achieve a good balance between various desired properties of concrete at the minimum cost. A mixture proportioning only provides a starting mix design that will have to be more or less modified to meet the desired concrete characteristics. In spite of the fact that mix design is still something of an art, it is unquestionable that some essential scientific principles can be used as a basis for calculations. Mix design of high performance concrete (HPC) is different from that of usual concrete because of the following reasons:

- Water-binder ratio is very low.
- Concrete quite often contains cement replacement materials that drastically change the properties of fresh and hardened concrete.
- Slump or compaction factor can be adjusted using high range water reducing admixture (HRWRA) without altering water content.

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There are many popular methods of mix design of HPC such as method proposed by Aitcin [1], ACI [2], Mehta and Aitcin [3] among other methods. These methods have been in use successfully by the engineers over the years. In these methods, the first step is selection of water- binder ratio for a given target strength, though water-binder is not a very good predictor of compressive strength of HPC [4]. Researchers agree that workability of HPC should be characterized in terms of fundamental parameters like yield stress and plastic viscosity [5,6]. For cementitious materials, rheological parameters help to describe workability of fresh state including mobility, placeability, compactability, pumpability and finishability. Rheological behavior affects the way concrete can be processed and therefore, measurement and control of rheological parameters are very important in the production of quality concrete. In existing mix design methods, there is no provision to have an idea of rheological parameters like yield stress and plastic viscosity. A new method of mix design procedure has been discussed in subsequent sections for design of high strength HPC taking into account the rheological properties at the design stage itself.

2. Experimental Program

2.1 Materials

The cement used throughout the experiment was Ordinary Portland Cement (OPC). The 28 day compressive strength and specific gravity of cement were 50.2 N/mm^2 and 3.10 respectively. Locally alluvial sand (medium; specific gravity=2.6) stored inside the laboratory was used throughout the experimental investigation unless otherwise mentioned. Crushed stone aggregate (specific gravity=2.6) of nominal maximum size 10 mm was stored in the laboratory was used. Aggregates were not sieved and were used as received directly from the stockpile. Ordinary tap water was used for all the mixes to prepare fresh concrete. The batch size was 16 liters in all the cases. Poly-carboxylic ether polymer (PC) with set retarding effect was used as high range water reducing admixtures (HRWRA).

2.2 Experimental set up

The rheological measurements were performed with the modified set up of parallel plate rheometer. The schematic diagram is shown in Figure 1. It consists of an AC single-phase induction motor driving a 150 mm diameter flat circular vane plate through a gearbox. Vane plate is mounted coaxially with a cylindrical container (effective diameter= 270mm) with sleeve and bearing arrangement to ensure accurate alignment. The cylindrical container is provided with vertical ribs of 20 mm projection at a pitch of 60 mm along the circumference. Ribs are also welded at the bottom of the cylinder. The effective gap between the bottom and the shearing surface is 75 mm. The effective concrete height above the vane plate is also75 mm. The no-slip condition at top of the cylinder is achieved by providing 20 mm high mesh of blades. The blade mesh can be detached as and when necessary. The torque of the motor and hence the vane plate is controlled by varying input voltage with a 10 ampere AC variac. The number of revolution of the vane plate is measured automatically with a non-contact infrared digital tachometer, by focusing at the retro-reflective tape glued to the spindle. The spindle has a pulley welded to it that is used for calibration purpose only.

The torque provided by the rheometer was calibrated in terms of input AC voltage. A spring balance anchored to a fixed object is fitted to the pulley of the spindle. When the motor is switched on, the spring balance blocks its rotor and the spring balance reading is noted. This arrangement gives the braking torques at different voltages. In the present study, stepwise increasing shear stress sequence followed by a decreasing shear stress was used and the down curve was taken to draw the flow curve. Concrete was sheared at each step for 30 sec and readings were taken at the end of each period. Calibration of torque was validated by testing a magneto-rheological fluid (MRF 132DG) and comparing the data with measurement made by RS1 rheometer. It was observed that both the readings agreed reasonably well. The detail of the set up was presented elsewhere [7].

2.3 Mixing

Concrete was mixed in a tilting mixer (laboratory type). The weight of the materials was taken with a digital weighing balance. Mixing sequence was as follows:

- Mix coarse aggregate, fine aggregate cement for two minutes;
- Add water during mixing and mix for two minutes more;
- Stop mixing for one minute;
- Add HRWRA to the mix and mix for three minutes;
- Pour the concrete mix.

2.4 Testing procedure

The prepared concrete was transferred to the cylinder with a trowel from the same height every time. The rheological test was carried out exactly after 15 minutes from addition of water. Each time new batch of concrete with the desired composition for a particular mix was prepared. The mixing sequence and the time at which the rheological test was performed were identical for each batch and for all mixes. Rheological parameters were obtained from flow curve.

3. Proposed Mix design Procedure

Rheological tests were performed for a series of high performance concrete mixes to investigate the effect of HRWRA dosage, maximum size of coarse aggregate, % sand and zone of sand on yield stress and plastic viscosity. It has been observed that above 7 liters/cu.m, HRWRA dosage does not significantly improve the rheological parameters. Between 27%-30% sand, yield stress and plastic viscosity are almost same when 7 liters/cu.m HRWRA dose is incorporated. Both the rheological parameters are minimum at sand content equal to 28%. The effect of sand zone and maximum size of aggregate was investigated and results are given in Table 1 as correction factors. The variation of yield stress and plastic viscosity with water content has been presented in Figures 2-3. Effect of water-cement ratio on Bingham parameters is shown in Figures 4-5. In addition to rheological tests, 28 day compressive strengths (cube strength) were also determined for each mix. The correlation of compressive strength with respect to rheological parameters is shown in Figures 6-7.

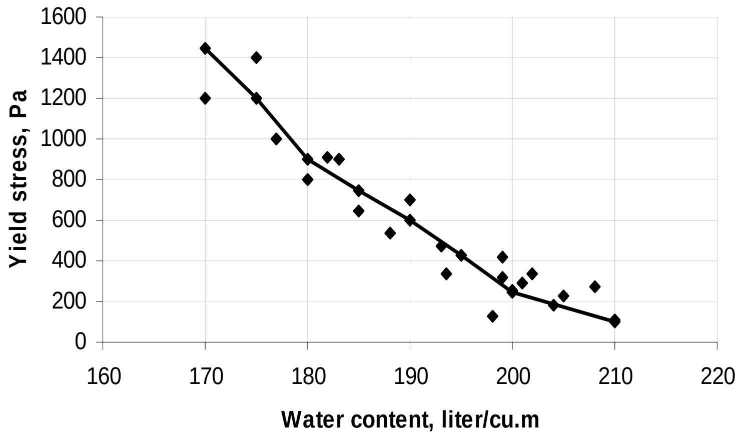

Figure 2. Variation of yield stress with water content

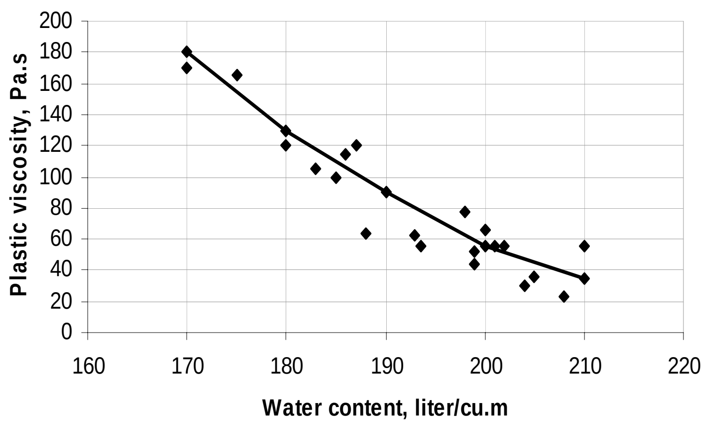

Figure 3. Variation of plastic viscosity with water content

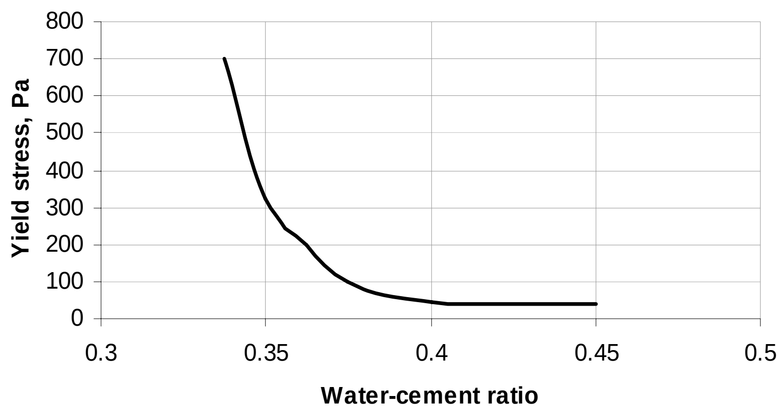

Figure 4. Variation of yield stress with water-cement ratio

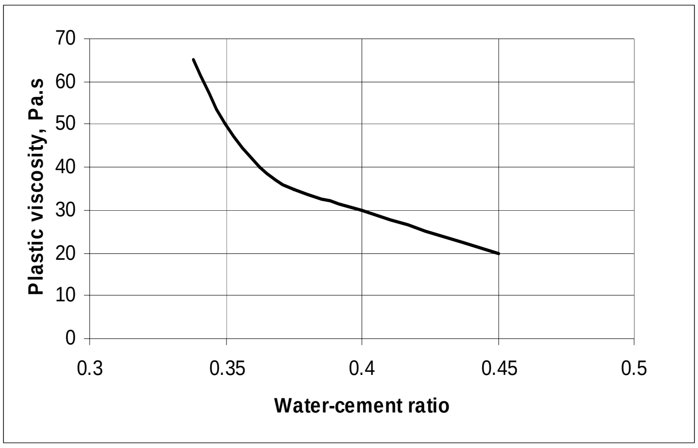

Figure 5. Variation of plastic viscosity with water-cement ratio

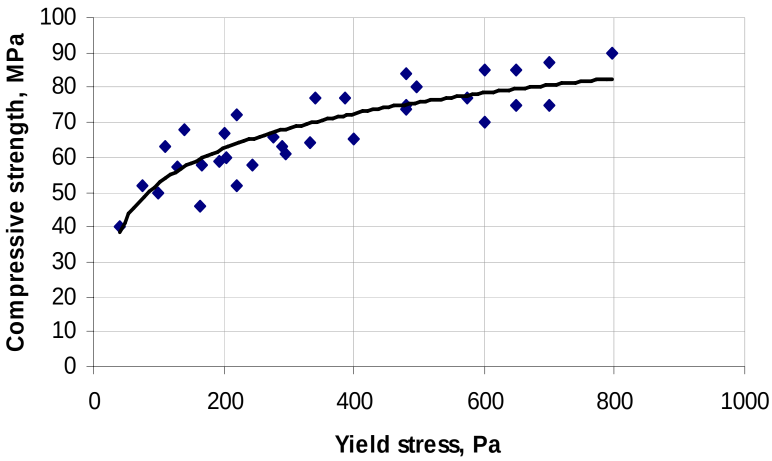

Figure 6. Variation of compressive strength with yield stress

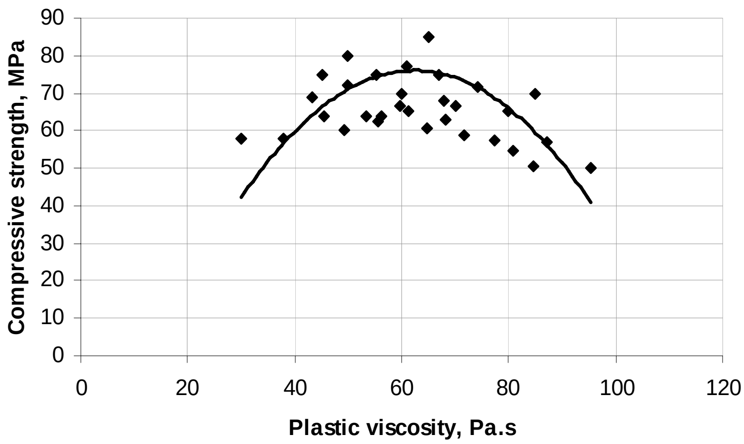

Figure 7. Variation of compressive strength with plastic viscosity

The design steps are as follows:

1. As per IS: 10262-1982 [8], assume sand= 28% and take air content as follows:

   For 10 mm nominal maximum size of aggregate (Msa): air= 3%

   12.5 mm and 16 mm: air= 2.5%

   20 mm: air= 2%.

2. From Figures 2-3, read τ_o , μ for target strength.

   Calculate correction factors: $K=k_1k_2$, $K^*= k_1^* k_2^*$.

   Corresponding to $K\tau_o$ and $K^*\mu$, read w/c ratios from Figures 4-5.

   Corresponding to $K^*\mu$ and $K\tau_o$, read water content from Figure 6-7.

3. Compute quantities of cement.
4. Calculate sand and coarse aggregate as follows:

$$V = \left[W + \frac{C}{S_c} + \frac{f_a}{S_{fa} p} \right] \frac{1}{1000} \text{ and } C_a = \frac{1-p}{p} f_a \frac{S_{ca}}{S_{fa}}$$

where V = absolute volume of fresh concrete,

W = mass of water per cu.m,

C = mass of cement per cu.m ,

S_c= specific gravity of cement,

p = % sand,

f_a , C_a are total masses of fine and coarse aggregates respectively,

S_{fa} and S_{ca} are specific gravities of fine and coarse aggregates respectively.

4. Illustration

i) Cement: OPC, sp gr=3.1, 53 grade as per IS: 12269-1987 [9].

ii) sand: zone III as per IS: 2386-1963 [10] , sp gr=2.6

iii) coarse aggregate: crushed, 16mm msa, sp gr=2.6

iv) HRWRA: Poly-carboxylic ether polymer, no mineral admixtures.

To design a mix for target strength=65 MPa.

4.1 Design calculations with present method

a) Assume air content=2.5%, PC=7.5 lit/cu.m, sand=28%.

b) From Figures 6-7, τ_o =300 Pa; μ =45 Pa.s.

c) Calculate $K\tau_o$ =1.6x0.67x300=332 Pa and $K^*\mu$ =2.2x0.7x45=69.3 Pa.s from Table 1.

d) From Figures 4-5, water-cement ratio=0.35 and 0.345 respectively for 332 Pa and 69.3 Pa.s. Take w/c=0.35.

e) From Figures 2-3, water content= 195 liters/cu.m (including HRWRA).

f) Cement content=195/0.35=557 kg; sand=437kg and coarse aggregate= 1124kg.

With the above mix proportion, rheological test was carried out and compressive strength (cube strength) was determined after 28 days of moist curing. The results were as follows:

τ_o = 289 Pa; μ =55.7 Pa.s;
Slump = 195 mm;
28 day cube strength = 63 MPa.

Table 1. Correction factors for τ_o and μ

Particulars	Yield stress	Plastic viscosity
Sand zone II (Medium)	k_1=1	k_1^*=1
Sand zone I (Coarse)	k_1=1.45	k_1^*=2.0
zone III (Fine)	k_1=1.6	k_1^*=2.2
Msa= 10 mm	k_2=1	k_2^*=1
Msa= 12.5 mm	k_2=0.9	k_2^*=0.75
Msa= 16 mm	k_2=0.67	k_2^*=0.7
	$K= k_2\ k_2$	$K^*= k_1^*\ k_2^*$

4.2 Design calculations with Indian Standard (IS: 20262: 1982) method

IS code has no provision for incorporating HRWRA. Assume that desired workability is 0.8 Compacting factor.

i) Choose water-cement ratio=0.30 from the water-cement ratio versus compressive strength curve.
ii) Assume air content=2.5% for 16 mm nominal size coarse aggregate.
iii) For the standard reference condition given in the code such as, choose the following from the table of the code:

Water content= 200 kg/cu.m;
% sand= 28;

The standard conditions are: w/c ratio=0.35, workability= 0.8 Compacting factor, sand= zone II (medium).

iv) Adjust water content and % sand as per the code as follows (Table 2):

Table 2. Adjustment in water content and % sand

Change in conditions	Adjustments required in	
	Water content	% sand
Sand conforming to Zone III (fine)	0	-1.5
Increase in CF	0	0
For decrease in w/c ratio	0	-1.0%
Total	0	-2.5%

v) Sand proportion= 28-2.5= 25.5.
Water content= 200 kg/cu.m;
vi) Cement content= 200/0.3= 666 kg/cu.m.
vii) Absolute volume of total aggregate per cubic meter of concrete is given by

$$V_a = 1 - \left(200 + \frac{666}{3.1} \right) \frac{1}{1000} - v_{air} = 0.39$$

Fine aggregate=0.255 × 0.39 × 2.6 × 1000= 258 kg/cu.m;
Coarse aggregate= (1- 0.255) × 0.39 × 2.6 × 1000= 755 kg/cu.m.

It may be observed that as per IS code method calculation, cement content is very high and coarse aggregate content is very low. Concrete mix was prepared in the laboratory as per the mix proportions calculated as per IS code method with HRWRA at the rate 1.5% by weight of cement. It was observed that workability was very low as the mix was a no-slump mix. In such mixes, rheological models are not applicable. In fact, such mixes cannot be called a high-performance mix because in addition to high strength, high workability is also a criterion for high performance concrete. A minimum slump value 100 mm is recommended for high performance concrete [11].

5. Conclusion

Rheological tests were performed with a modified set up of a parallel plate rheometer to determine yield stress and plastic viscosity. 28 day compressive strength of each and every mixes was also determined to correlate compressive strength and rheological properties. Relation between water-cement ratio and rheological parameters, water content and rheological parameters were investigated and used in mix design. A new method of mix design of high performance concrete has been evaluated. It has been observed that it is possible to design a concrete mix based on yield stress and plastic viscosity at the design stage for a given target strength.

It is always difficult to develop a mix design method that can be used universally because same properties of fresh and hardened concrete can be achieved in different ways from same materials. Since materials from different sources can vary widely in their composition and physical characteristics, a trend drawn from data for a single material source should not be extended to all material sources. Thus, generalization of the trend in concrete rheology involves complication. In fact, a broad range of data from various sources is desirable for drawing general conclusions.

The method discussed in this paper is related to calculation of the composition of non-air entrained concrete containing poly-carboxylic ether polymer as HRWRA without incorporating any mineral admixture.

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