

A UNIQUE PROCEDURE FOR FINDING THE RHEOLOGICAL PROPERTIES OF FRESH PORTLAND CEMENT CONCRETE USING CONCRETE SHEAR TESTS

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ABSTRACT

The lack of viable concrete workability test method has aroused the need to characterize fresh concrete by its rheological properties based on material science approach to overcome the inadequacies of traditional empirical tests. Rheological properties are characterized by flow behavior and are described by Bingham parameters. Rheometers are used to find the rheological properties which use high torque and the stimulus provided is dynamic and no concurrence in the measured values. This paper describes a unique procedure hitherto not attempted previously for the determination of rheological properties of fresh concrete using a newly designed and fabricated concrete shear box. The uniqueness is that after finding the peak shear stress, shear stress at zero normal stress and zero displacement were found before finding the Bingham parameters. The significance is the reproducibility of the test results, besides low shear rate applied to the concrete and static condition of the test.

Keywords: rheology, yield stress, plastic viscosity, rheometers, concrete shear box

INTRODUCTION

Many activities like pumping, spreading, molding and compaction, all depend on rheology and thanks to an increasing scientific urge to characterize the fresh concrete by its rheological properties based on material science approach to overcome the

inadequacies of empirical tests. The slump test is the most widely used single-point test and concrete flow cannot be defined by a single parameter.

Rheology is the science of the deformation and flow of matter. Fluid rheology is a well established widely used science which can be applied to the properties of fresh concrete. It can be said that fresh concrete is a concentrated suspension of aggregates in cement paste. To characterize and understand the fresh properties of concrete at least two physical properties, namely yield stress and plastic viscosity, are to be measured. Yield stress commonly occurs in multi phase fluids such as concentrated suspensions. The solid particles interact to form a flocculated, three-dimensional network structure that resists flow at sufficiently low stresses. The yield stress is related to the force required to break down this structure and initiate flow. The concept of yield stress is readily seen in concrete slump test. Most researchers agree that the flow of concrete can be described reasonably well using a Bingham equation. It describes a linear relationship between the stress acting to shear concrete (shear stress = τ) and the rate at which it is sheared (shear rate = $\dot{\gamma}$). The relation is as follows:

$$\tau = \tau_0 + \mu\dot{\gamma}$$

with viscosity (μ) being the slope in this relationship and the y intercept marks the yield stress (τ_0). The term yield stress and viscosity provides a more comprehensive description of fresh concrete. Bingham flow model commonly assumes that if lower shear rates could be measured the flow curves would continue back and intercept shear stress axis (1). Accurate data at low shear rates are needed to confirm that flow curves can truly be extrapolated to a zero shear rate. Static measurement of yield stress when the material is initially at rest are typically higher than obtained from dynamic measurements of the flow curves and also the rheometers show that at low shear rates viscosity is very high. It is assumed that yield stress is a relevant parameter to be measured and the actual measured value can vary significantly depending upon the test method used.

Commonly rheological properties can be measured in capillary tube viscometers or rotational rheometers. Rotational rheometers are used predominately to determine the rheological parameters in fundamental units and are generally better for concentrated suspensions, gels, and pastes despite the fact that capillary tube methods tend to be more precise in measuring plastic viscosity (2). Additionally they are able to shear a sample continuously in order to achieve equilibrium and to monitor changes over time.

Rheometers usually measure shear stress at varying shear rates and are basically dynamic tests. Some of the concrete rheometers used are BML, BTRHEOM, THE TWO POINT, CEMAGREF-IMG coaxial rheometer and IBB. The list is not complete and the authors have listed only a few rheometers which are commonly used. While traditionally rheometers have been successfully used for fine particle suspensions, concrete presents unique challenges. Many of the rheometers that were tried have their own drawbacks and authors have discussed in general the drawbacks elsewhere

(3). However some of drawbacks are; size of coarse aggregates, concrete segregation, time dependence of flow properties, complexity of size and geometry, limited availability, high cost, problem of dead zone (where material does not flow) , range of shear rate applied in variance with the field requirement, thixotropy, large volume of sample for testing and many more (4). Added to this the values of yield stress and plastic viscosity compiled by Ferraris et. al., (5) from different rheometers, but measured on identical concrete mixtures show that there is no agreement of the measured values among the different types of Rheometers.

CONCRETE SHEAR BOX

Attempts have been made long ago to measure the resistance of freshly mixed concrete in terms of shear stress and as reported by Newman [6], Herschel and Pisapia and later L'Hermite and his coworkers used direct shearing apparatus of the kind used for testing the strength of soils. They considered shearing stress in a freshly mixed concrete to be due to internal friction analogous to the friction between a solid body and a plane solid surface when that body is resting on the surface. When the graph was plotted between shear stress verses shear strain for various normal stresses, keeping the displacement rate constant, they found that initially the shear stress increases linearly with the degree of distortion only upto a certain value and then started decreasing and finally leveling off. This was called 'dilatancy'. The reason attributed is the formation of a sliding plane with further distortion and the coarse particles originally interlocked take up positions which have less resistance to movement.

Based on the experience from the previous study (7) from using the smaller size direct shear box (60x60x25mm) a new tool namely concrete shear test apparatus which was essential with the required features for finding the rheological properties of fresh concrete was designed and fabricated. The test apparatus is similar to the direct shear box in principle but with added features that is essentially needed to shear the medium size sample of the fresh concrete. The new tool is first of its kind for testing the fresh concrete sample. The important characteristics is the static condition of the test and very low shear rate applied on the specimen during testing which is similar to the condition experienced by the concrete in the field. The detailed description of the test apparatus is published by the authors elsewhere (3, 8) and only the main features are given here. Sample of size 150 mm can be sheared with 25 mm maximum size of coarse aggregate. The strain rate for shear load ranges from 1 mm/min to 100 mm/min. The shear stress developed at such a faster rates is captured using servo-controlled data acquisition system. The loading unit has different normal stresses up to maximum of 30 N/mm².

MATERIALS AND METHODOLOGY

Ordinary Portland cement (C 53 grade), conforming to IS 12269-1987 (ASTM C 150-85A) was used. The specific gravity value and Blaine fineness were 3.15 and 265 m²/kg. Natural river sand was used as fine aggregate (Zone II) and crushed angular granite stone of maximum size 20 mm as coarse aggregate. The bulk specific gravities of the coarse aggregate and fine aggregate were 2.68 and 2.67 respectively and their absorption values were 0.35 and 2 % respectively. In this study, mixes with three different cement contents of 300, 390 and 450 kg/m³ and water contents of 160, 170, and 180 lt/m³ were used. The range of w/c ratio covered was from 0.40 to 0.60 practically the range used in practice. The concrete mixes were proportioned based on absolute volume concept. Total of 81 trials consisting of three different strain rates of 5, 15, 25 mm/min, in combinations with three different normal stresses of 0.015, 0.025, 0.035 N/mm², were used. Chemical admixture was not used in order to avoid its influence on the properties of fresh concrete.

PROCEDURE FOR THE DETERMINATION OF RHEOLOGICAL PROPERTIES

The unique procedure to determine the Bingham parameters using Concrete shear box for the first time has been published by the authors elsewhere (3, 8). This section illustrates the procedure only for the mixes with cement content 300 kg/m³ and water contents 160 and 180 lt/m³ with emphasis on the reproducibility of the test results which reinforces the procedure for certainty. For all the mixes freshly mixed concrete was placed in the concrete shear box and a particular displacement rate ($\dot{\gamma}$) and a normal stress was applied on the sample. The test was stopped when the shear load started to decrease (point of dilatancy) or when it became almost constant. The tests were repeated for different displacement rates keeping the normal stress constant. Similarly for other displacement rates chosen further tests were conducted for different normal stresses. One such plot for the mix is shown (Figure 1) for cement 300 kg/m³ and water 160 lt/m³. Figure 1(a) shows the plot of shear stress versus shear strain for displacement rate of 5 mm/min for normal stress of 0.015 N/mm². From this relation, the maximum shear stress (τ') for the normal stress 0.015 N/mm² was found. For the same normal stress, similar procedure was followed for the mix for finding the Peak (maximum) shear stress with the displacement

Figure 1: Relation between Shear Stress Vs Shear Strain (Cement: 300 kg/m³ and water 160 lt/m³)

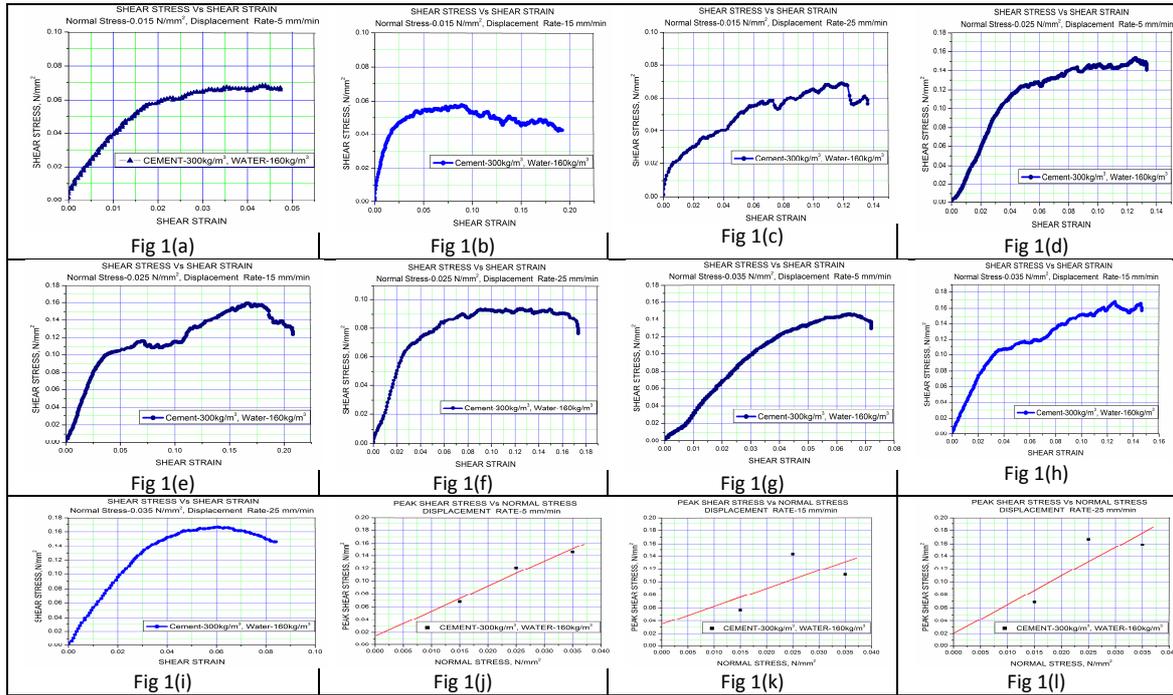
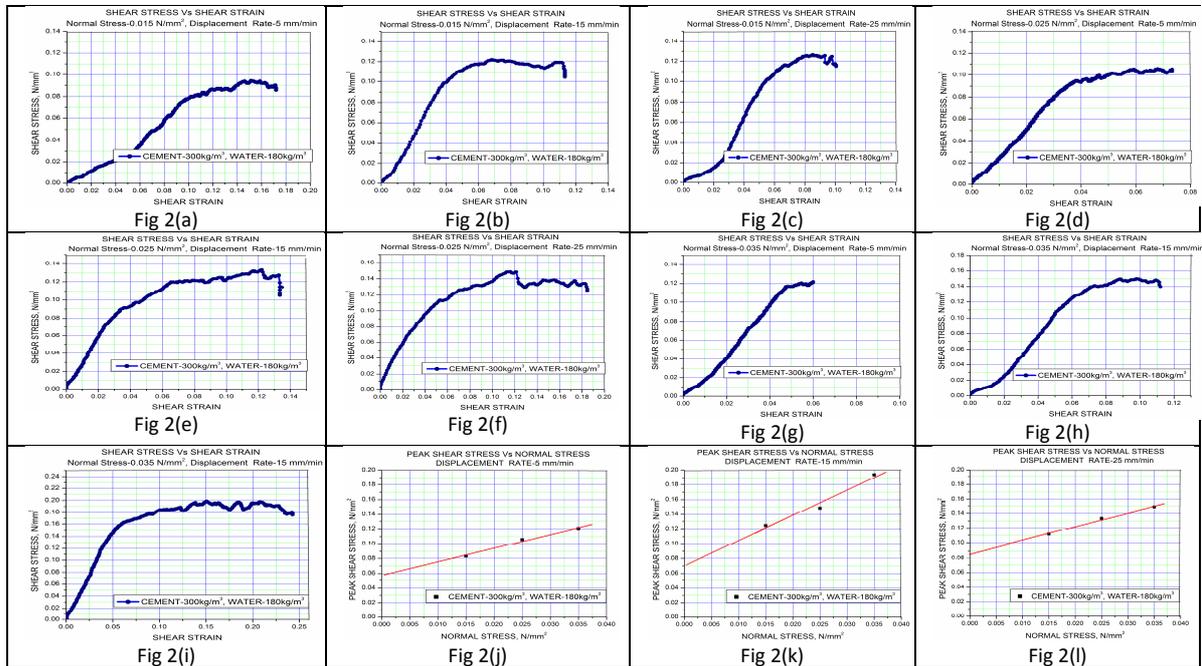


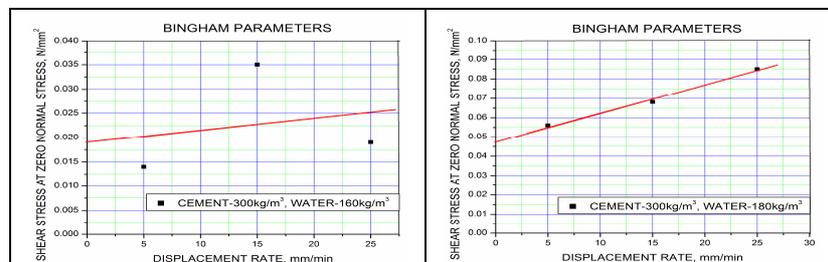
Figure 2: Relation between Shear Stress Vs Shear Strain (Cement: 300 kg/m³ and water 180 lt/m³)



rates of 15 and 25 mm/min and the plots are shown in Figure 1 (b) and 1(c). Similar plots of shear stress versus shear strain for the displacement rates of 5, 15 and 25 mm/min were obtained for other normal stresses 0.025 and 0.035 N/mm² (Figures 1

(d) to 1 (i)) and maximum shear stresses were obtained. With the values of peak shear stress for each displacement rate and for different normal stresses, graphs are plotted and straight line fits were made (Figure 1(j) to (l)). The line intersecting the y-axis (shear stress axis) gives the peak shear stress (ζ'_o) of concrete at zero normal stress for a particular displacement rate, as the concrete shear box test cannot be carried out at a zero normal stress. Similar straight line fits were made for all displacement rates and peak shear stress at zero normal stresses were obtained. This peak shear stress can be considered as yield stress at zero normal stress. Further, graph was plotted between displacement rates and the peak shear stress at normal stress obtained for different displacement rates (Figure 3) for different mixes. The intercept of the line on the y-axis (ζ'_o , yield stress axis) can be regarded as the relative yield stress (ζ_o) and the slope of this line as the relative plastic viscosity (μ) similar to Bingham parameters.

Figure 3 : Relation between Yield Stress at Zero Normal Stress Vs Displacement Rate



Similar procedure was followed for finding the maximum shear stress and Bingham parameters for the same cement content with water content 180 l/m³(Figures 2 and 3). Most importantly the test is carried out at very low shear rate applied on the specimen, which is similar to the condition experienced by the concrete in the field and also the static condition of the test. The uniqueness of the procedure is that the shear stress at zero normal stress and zero displacement was found which is of interest, before finally finding both the relative yield stress and the relative plastic viscosity.

RESULTS AND DISCUSSION

Table 1 shows the peak shear stress values for all the mixes for different normal stresses and displacement rates along with Bingham parameters. As the normal stress increased for the same mix with a particular displacement rate, the peak shear stress is also increased possibly due to particle getting closer to each other at higher normal stress with better interlocking of the aggregates leading to higher resistance. This is true for all the mixes and displacement rates. Also, the peak shear stress increased as the displacement rate increased and likely to be one of the factors influencing the results. The test result has shown clearly the reproducibility of the test results. This

demonstrates that the concrete shear box can be used as a tool to determine Bingham parameters effectively as a static test by following the unique procedure developed. The values are called relative yield stress and relative plastic viscosity because the values are not absolute.

When the water content is increased for the same cement content or vice versa the relative yield stress of concrete decreased. This phenomenon is attributed to higher paste content (cement + water) with better lubrication of the aggregate particles thereby reducing the inter-particle friction. Also higher paste content means lower aggregate content and lower volume fraction of aggregates result in increased spacing between aggregates and thus lesser resistance to flow. At lower paste content the interparticle friction dominates resulting in higher relative yield stress which is clearly brought out by the concrete shear box test. Similarly, the relative plastic viscosity values are higher for the same water content with higher cement content as the mix becomes more cohesive. Relative yield stress and relative plastic viscosity obtained in this study are higher than

Table 1: Results of Peak shear stress and Bingham parameters

Cement (Kg/m ³)		300	390	450	300	390	450	300	390	450
Water (lt/m ³)		160			170			180		
Normal Stress MPa	Disp. Rate mm / min	Peak Shear Stress (MPa)								
		0.015	5	0.12800	0.10755	0.09066	0.09111	0.09866	0.08355	0.08333
	15	0.13111	0.11333	0.11644	0.11222	0.10844	0.10666	0.11177	0.09466	0.09466
	25	0.13066	0.12755	0.11288	0.10888	0.11644	0.12711	0.12444	0.11366	0.11366
0.025	5	0.14888	0.12088	0.12133	0.10488	0.11688	0.11333	0.10577	0.10177	0.10177
	15	0.13644	0.14488	0.18711	0.13955	0.12711	0.11866	0.13333	0.12066	0.12066
	25	0.15644	0.14666	0.13066	0.14955	0.15555	0.12088	0.14844	0.15955	0.15955
0.035	5	0.17777	0.13422	0.13955	0.14944	0.14933	0.11822	0.12044	0.11911	0.11911
	15	0.16666	0.14666	0.19111	0.15066	0.15644	0.12888	0.14844	0.13466	0.13466
	25	0.16711	0.15377	0.14755	0.18444	0.16977	0.14311	0.19377	0.16333	0.16333
Bingham Parameters										
Relative Yield Strength (Pa)		80800	75400	44900	51000	50995	49033	46091	45110	35304
Relative Plastic Viscosity (Pa-Sec)		2.759	3.150	4.075	5.40	10.08	17.28	13.68	16.56	18.10

those reported in the literature using rheometers. This could possibly be due to particle interference or friction during shearing at low rates. But the trends reported are similar to the results obtained using rheometers i.e., higher the paste content the lower the yield stress (5).

CONCLUDING REMARKS

The concrete shear box can be used as a tool to determine Bingham parameters effectively as a static test by following the unique procedure developed, as an alternative /additional to rheometers which use high shear rate. The values arrived at are by considering both the normal stress and displacement rate at zero values and the stimulus provided to the concrete is similar to the field practice. The test result has shown clearly the reproducibility of the results. The values are named as relative values since they are higher than those reported in the literature as determined by rheometers.

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