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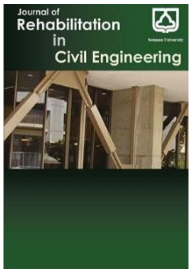

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Rheology of Fresh Concrete - a Review

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ABSTRACT

Concrete is a heterogeneous, complex composite construction material. Fresh property of concrete is a critical property with significant effect on quality, cost of construction, strength, and durability. Even to this day the workability of fresh concrete is measured by empirical test, notably by slump test in-spite of its drawbacks and sometimes with misleading results with less practical significance. There is an urgent need to characterize the flow of fresh concrete by its rheological properties based on material science approach to overcome the inadequacies of the empirical test methods. Fluid rheology approach is the most fundamental one and describes the concrete flow by at least two parameters namely yield stress and plastic viscosity by considering fresh concrete as a Bingham fluid. Understanding and controlling the two fundamental fresh properties of concrete allow for more economical and better performing concrete mixes with the use of wide range of ingredients. This paper brings out the importance of rheology and advocates the use of fundamental science approach with two parameter tests along with advantages and limitations of using rheometers. Also highlights the use of concrete shear box static tests for wide range of workability requirements with the use of new and marginal materials in concrete industry.

1. Introduction

Concrete is a heterogeneous, complex, composite construction material. Fresh concrete properties, especially workability is of very much significance since it has bearing on the quality, cost of construction, strength, and durability [1]. The technological control of concrete is mostly performed in hardened state, through a series

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of resistance tests under axial compression. Notwithstanding, the control of its properties in fresh condition is absolutely necessary, given their importance in the structural execution and in the subsequent attributes of the hardened state [2]. Therefore, the technological control of fresh concrete must take into account its different properties (consistency, cohesion, segregation, exudation and the amount of air entrained in the mixture) in order to achieve the suitable workability for each situation, which is vital in the production of high quality concrete [3].

The slump test is the most commonly used test method to assess the flow properties of fresh concrete [4]. In 1913, Chapman [4] invented the workability test method called slump test by using cylinders. Later 1918, Abram [4] modified the Chapman cylinder to cone, popularly known as Abram's cone and the method came to be called slump cone method. In 1922, it was approved as an ASTM standard test method and, since then, it remains the most common test method to assess the consistency of fresh concrete [4].

For simplicity, concrete industry accepted the slump test and made it a standard test. But slump test is static test and is incapable to differentiate the mixes, which in-turn can affect the workability, strength, and durability [5,6].In addition, slump test quite often produces false or misleading results [7-9]. Other empirical methods like compaction factor test, vee-bee test, flow table test etc., fail to provide satisfactory information and are too complex to use in site conditions [7-9].

In 1983, Tattersall carried out systematic studies on workability and has summarized the findings in a book [10] and emphatically argued that all existing test methods are empirical and indicate single value with respect to either time or distance. These test methods are called as single point test [11,12].

In 2008, ACI: 238-01R [13] recommended material science approach to describe the flow behavior of concrete in fresh state. Rheological techniques are preferred for better understanding and measuring the flow characteristics of concrete to overcome the deficiencies of the single point tests. Therefore, there is a necessity to study the fresh concrete behavior by its fundamental material science approach by rheological methods.

2. Rheology of fluid

Rheology is a branch of science which deals with "Study of flow and deformation of complex materials" [14]. The term rheology was coined by Bingham [14]. "Rheo" is derived from the Greek words "pantarhei", meaning 'everything is in flow', so the name rheology means the theory of deformation and flow of matter [15].

Basically, fluids are classified as Newtonian & non-Newtonian fluids [15]. The rheology is more importantly applied for Non-Newtonian fluids (complex fluids), where it consists of high–molecular weight fluids and suspensions [16,17]. In reality, fluids cannot behave ideally, e.g. blood, paints, polymers, food, cementitious materials, macro-molecular solutions, melts, soap solutions etc., which behave in unexpected ways, and such complex fluids cannot obey Newton's law and shear rate is varied with constant shear stress for the same proportion and such type of fluids is called as non-Newtonian fluids [16,17]. The theory of rheology is based on the principle of continuum mechanics to describe the flow characterization of complex fluids [18,19]. Fig.1 shows the concept of rheology.

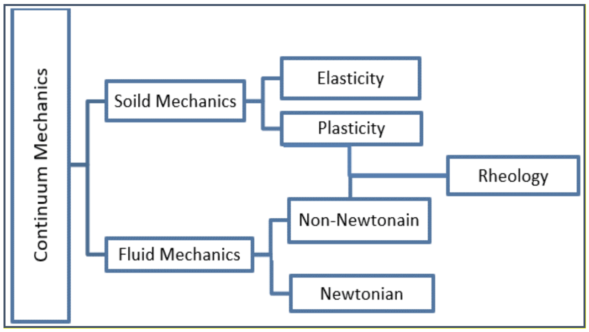

Fig.1. Concept of rheology [19].

The complex fluids exhibit a combination of elastic, viscous and plastic behavior by combination of elasticity and fluid mechanics [19]. These complex fluids are highly viscous, and viscosity is no longer constant for all shear rates and difficult to describe the viscosity by using simple Newtonian equation. Therefore, for such complex fluids, constitute equations or mathematical models are used for better characterizations of flow and it describes the viscosity of fluids [20]. Rheological approach is applied in different fields like asphalt, ceramics, paint industries, polymer, food technology, pharmacy, lubricants, and others [20].

3. Rheology of fresh concrete

In rheological approach, fresh concrete is assumed as non-Newtonian fluid which does not obey Newtonian law of viscosity of linearity between shear stress versus shear rate [21]. The fresh concrete is examined considering it as suspension of granular aggregates of varying sizes in a viscous medium viz., cement paste [22].

In 1962 Ritchie [23] applied rheology concept for the first time to the fresh concrete. His work was innovative, as it had one major limitation, that is, the parameters associated with the rheology of fresh concrete had been identified but, there was no apparent relationship among them.

In 1976, Tattersall [24] for the first time carried out systematic study on concrete rheology. He considered fresh concrete as a non-Newtonian fluid [24], where in it contained large range of particles size range from 20 mm to 1.0 mm size, that is, coarse aggregates are suspended in mortar, mortar is suspended in cement paste and in-turn cement is suspended in water [25]. Due to this complexity, no definite method for predicting the inherent flow behavior of fresh concrete from its physical constituents exists. However, compared to empirical methods, rheological method is providing better characterization of the flow properties of fresh concrete [25,26]. The Fig.2 show the relation between rheology of fresh concrete and three parameters.

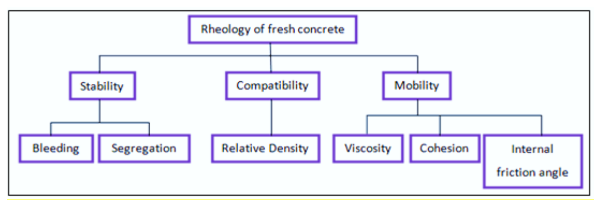

Fig.2. Relation between workability of concrete and rheological properties [26].

4. Measurement of rheological properties

There are two types of measurements for concrete rheology: the flow curve test and the stress growth test [27]. In general, concrete rheology is measured by flow curve test using rheometers [27]. Rheometers measures the shear stress of concrete for various shear rates and these measured values are fit into flow curves and then the rheological properties of the mix were determined (Fig.3).

There are 6 flow curves, among them, Bingham model is the most widely used for flow characterization of fresh concrete [28-30]. The general form of Bingham model is shown graphically in Fig.4 and it gives two parameters namely yield stress (τ_0) and plastic viscosity (μ). The plastic viscosity is correlated to the time of concrete slumping and the yield stress is correlated to concrete slump [28-30].

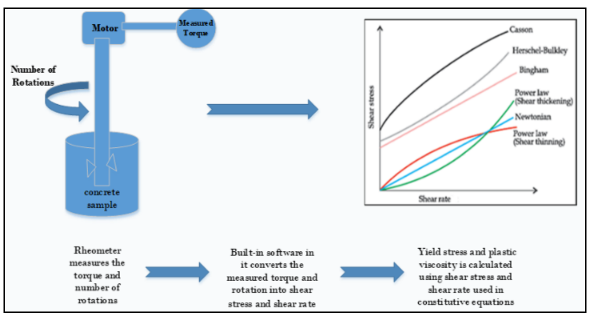

Fig.3. Generalize procedure for determining the rheological properties by flow curve method (schematic representation) [28].

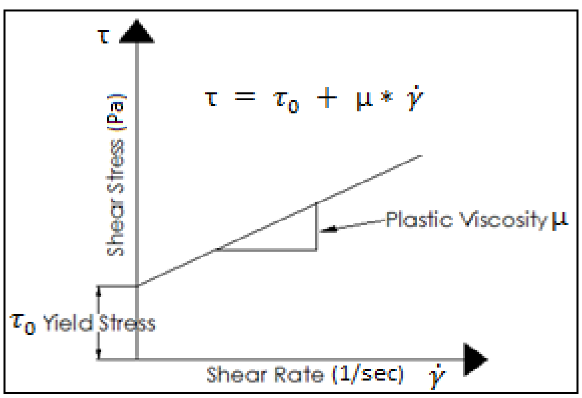

Fig.4. Bingham model [28-30].

The Bingham model is generally applicable for determining the flow properties of concrete. However, in certain cases, the flow curve obtained for self-compacting concrete (SCC) using the Bingham model gives a negative value of yield stress which is physically not possible [31,32]. Therefore researchers, suggests non-linear equations Herschel-Bulkley model or Modified Bingham model to describe the flow of SCC [31,32].

5. Concrete rheometers

Rheometer is an instrument that measures both shear stress and shear rate of the sample from its fundamental properties [33]. The rheometer classified as two types that is extensional and shear rheometers [33]; whereas extensional rheometers measures the normal stress applied on fluid and shear rheometer measures the shear stress applied on fluid [33]. Since fresh concrete involves mixing, casting, and pumping under shear stresses, shear rheometer provides better results when compared to extensional rheometer. The shear rheometers are further divided into two types: capillary rheometer and rotational rheometer. For concrete, rotational rheometer methods are used to measure the response of the concrete to flow properties [21]. The different types of fluid rheometers exist and are shown in Fig.5 [21].

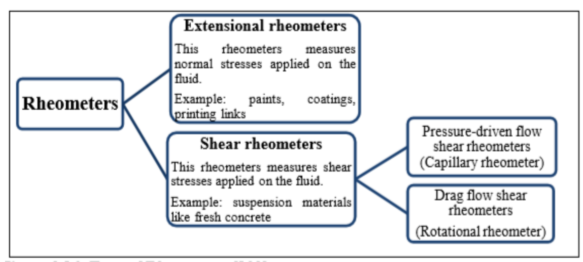

Fig.5. Types of rheometers [21].

In capillary rheometer method the concrete sample is made to flow under applied force through a narrow tube and in rotational method the concrete sample is sheared between two surfaces with anyone or both rotating continuously. The rotational methods are generally better and are in usage especially for concentrated suspensions like gels, cement paste and concrete. Concrete rheometers fall into three different configurations - coaxial cylinders, parallel plate, and impeller-type [21] and are shown in Fig 6.

There are several concrete rheometers available in the industry and only few are chosen for review. The working principles, advantages, and limitations of some of the rheometers are discussed briefly in the subsiding sections.

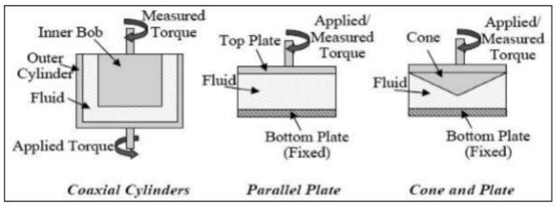

Fig. 6. Different configuration of rotational rheometers [21].

5.1 Two-point rheometer

It is one of the oldest rheometer and introduced by Tattersall [34] in 1976, and as such called Tattersall two-point rheometer. The principle of two-point rheometer is simple. Impeller is inserted into the concrete sample and rotated at various speeds either in axial or planetary motion. Torque is measured at different speeds by using tachometer and along with the rotation with respect to torque using pressure transducer [34].

There are two different impellers are available. They are helix and H-shape impeller. The type of impeller depends on the slump values. Above 50mm slump concrete, helix shape impeller (MK-II apparatus) is used. It contains 300mm x 254mm cylinder (Fig.7); it requires approximately 12.5 kg of concrete sample; the impeller is fixed at the top and rotated in axial motion. The concrete gets sheared at varies rate of shear from 0.05 to 1.4 rps [5,6]. For slump below 50mm, H-shape impeller (MK-III apparatus) is used, and it rotates in planetary motion. It contains 300mm x 360mm cylinder and requires 20 kg of concrete samples which is sheared at rate of 0.70 to 1.90 rps [5,6].

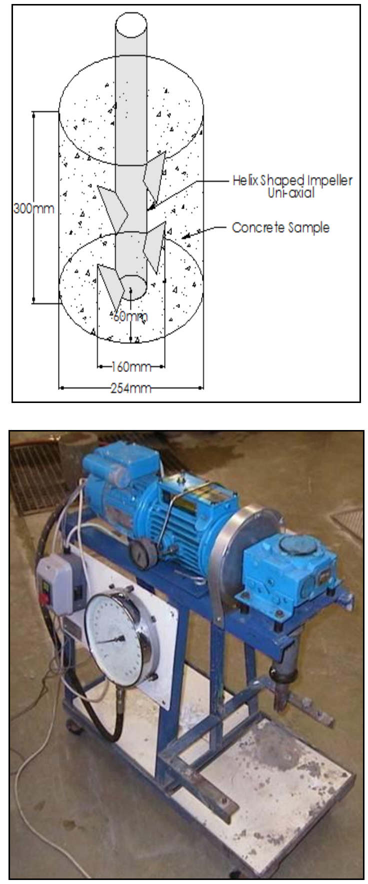

Fig.7. Two-point rheometer.

This rheometer determines the fundamental Bingham parameters for low, medium, and high slump concretes including vibration effect [5,6]. The apparatus is bulky and suits for laboratory conditions only. The main limitation is the large gap between blade and concrete as such the force is not transferred fully from impeller blades to peripheral concrete and creates dead zone. To avoid dead zone, high shear rate is applied which will influence the result.

5.2. Bml viscometer

The BML viscometer was developed in Norway in 1987 by Wallevik and Gjorv [5,6].

It is a coaxial cylinder type of rheometer and working principle is a combination of plastometer and two-point workability rheometer [5,6]. The rheometer consists of stationary inner cylinder and outer variable cylinder. The concrete gets sheared at varies shear rate (0.001-0.9rps) in between the cylinders [35,36]. The torque is measured at inner cylinder as the outer cylinder rotates at variable angular velocity (Fig.8).

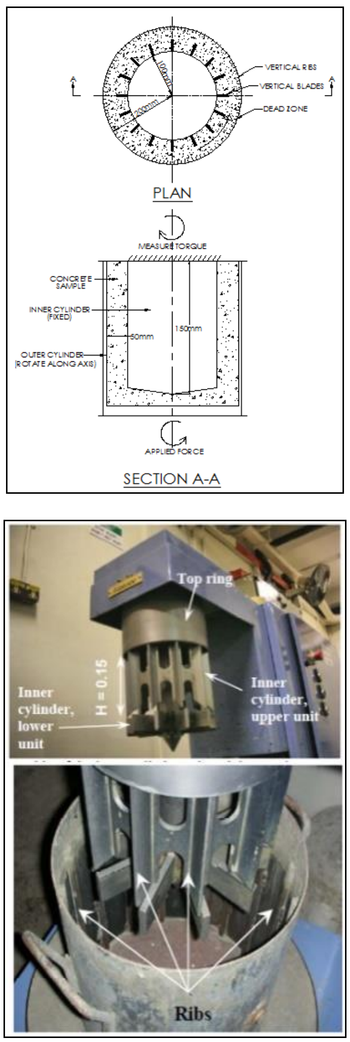

Fig.8. Bml-Viscometer.

The instrument has in-built software which will convert the measuring value of torque and angular velocity into shear stress and shear rate, it can be related to yield stress and plastic viscosity respectively [35]. This viscometer determines the fundamental Bingham parameters for medium to high workability concrete mixes. For low workability concrete mixes, the inner cylinder can be replaced with a blade impeller system [35,36].

It is complex and expensive device. The main limitation of this rheometer is the dead zone and slippage problem. Due to dead zone, the amount of torque measured is reduced at a given rotation speed. For stiff concrete, it shows inadequate the workability (for slump below 50 mm); for low viscosity concrete, it shows tendency of segregation.

5.3. Btrheom rheometer

It is a parallel plate type of rheometer and developed by Larrard and others [5,6]. The Fig.9 shows typical sketch, where the rheometer consists of a hollow cylinder with top and bottom blades and concrete get sheared in between the plates. One blade is fixed at the bottom of the cylinder and the other blade rotates at top of the cylinder. The torque from the resistance of the concrete sheared is measured through the top blades at a series of different rotation speeds (0.63 to 6.3rps) [37,38].

The device is helpful for measuring the concrete under vibration and 'dilatancy' effects. It is best suited for theoretically approach study of rheology. And the output rheological results can be validating with FEM programs. It is complex and expensive for everyday site work; higher maintenance cost; it does not measure low workability concretes (generally with slumps less than 100mm). It will calculate approximately the values of shear stress and shear rate because it ignores the discontinuity in flow at the boundary of the moving and stationary parts of the cylinder.

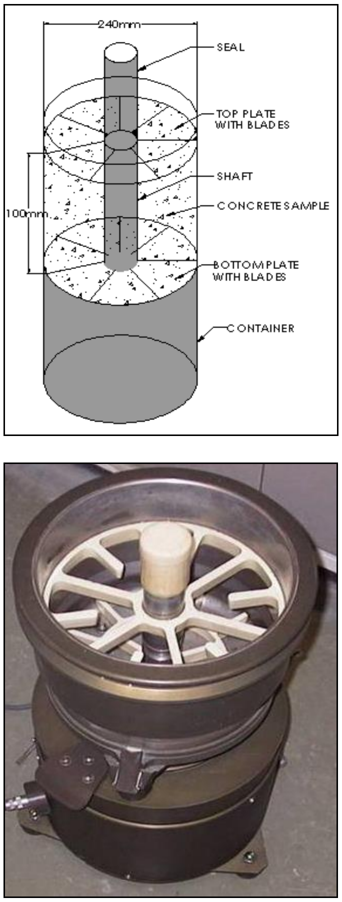

Fig. 9. Btrheom Rheometer.

5.4. IBB rheometers

This rheometer is the extension of two-point rheometers [5,6]. The basic principle is same as two-point rheometer, but the shape of impeller is changed, and it was developed by Beaupre from Canada [5,6]. It is a vane type of rheometer. It is invented to study the behaviour of high performance wet-process shotcrete, later it is extended to the study on fresh concrete.

The basic function of the rheometer is the application of shear rate through the vane or impeller which rotate either in a planetary motion or in an axial rotation and shear the concrete.

The torque produce by impeller is measured through a load cell and respective rotation speed measured through tachometer. This device has in-built software. It automatically calculates the plastic viscosity and yield stress [5,6]. The general view of IBB Rheometer is shown in Fig. 10.

Some advantageous of rheometer are; it measures torque at various rotations speeds; it is useful for wide range of concrete workability; the device can measure the effects of vibration on concrete and the apparatus has a self-calibration capacity.

Some limitations of rheometer are; the rheological properties are not given in terms of Pascal and Pascal-sec respectively. It is too bulky for regular field condition; compared to other rheometer, it requires more volume of concretes; during the experiment there will be chance of segregation of concrete.

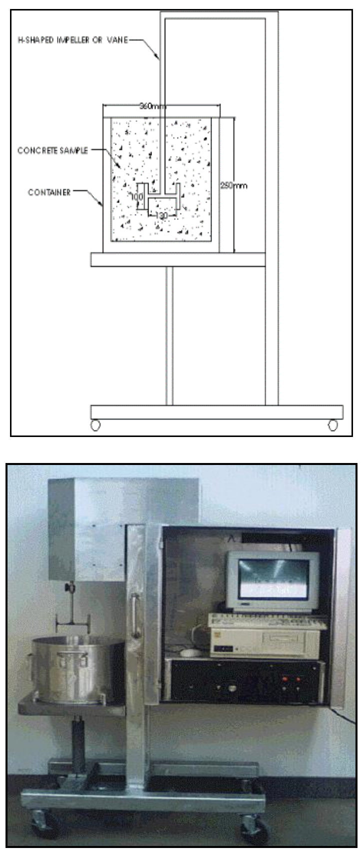

Fig. 10. IBB rheometer.

5.5. EBT-2 rheometer

It is a compact type of rheometer developed by Schleibinger Testing Systems, Germany [39]. The rheometer consists of 260mm x 500mm dia cylinder (Fig.11); it requires approximately 20kg concrete sample. The measurement system has two rods mounted vertically to the circular traveling through concrete and measures the force. The rods are arranged at different distances from the center of rotation, it will measure the torque (0-3 Nm) and angular velocity (0-4 m/s) and automatically converts those values in-terms yield stress and plastic viscosity [19].

The advantages are that is easy to handle. This rheometer measures three different speeds at the same time. The work involved is very less in measuring when compared to other rheometers and suitable for remarkably high flowable concrete like SCC. For very stiff concrete it is not suitable.

Fig.11. eBT-2 rheometer [39].

5.6. ICAR rheometers

Due to some of the draw backs of existing concrete rheometers, mainly high initial cost, large size and limited availability, the Koehler and Fowler developed the ICAR Rheometer [40]. It is a rotating impeller or vane type rheometer. Fig.12 shows the ICAR Rheometer, it consists of container to hold the sample, electric motor, torque meter, driver, and vane blade.

ICAR rheometer working principle is same as IBB rheometer. The main difference was ICAR is potable type of rheometer and well suited for use in the field. It computes both static as well as dynamic yield stress & plastic viscosity values of the sample in the fundamental units [40]. It is capable of measuring concretes having medium slump (50 to 75 mm).

The limitations of rheometer are that it is expensive. For very stiff concrete, slump below 50 mm it is not suitable because of its the maximum torque capacity of 50 Nm. Normally stiff concrete requires high shear rate when compared to high slump concrete.

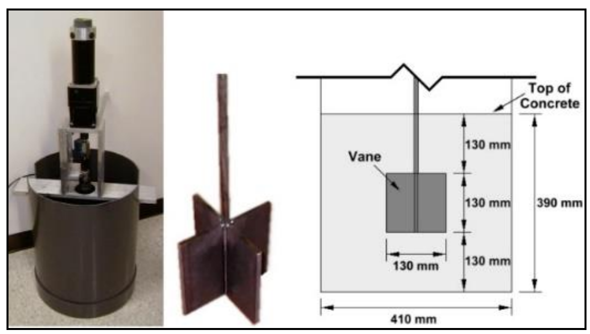

Fig.12.ICAR rheometer [40].

5.7. Concrete truck mixer

The authors [41] used the concrete mixer as a rheometer (Fig.13) since the existing rheometers are expensive, complex and many a time bulky. The working principle is simple. In the truck rotational speed of the drum is related to the shear rate in concrete and power consumption or oil pressure is related to torque [41].The plot of oil pressure versus drum speed; will provides the Bingham parameters.

Fig. 13. Concrete mix truck as a rheometer [41].

6. Limitation of rheometers

It is difficult to select the rheometer for particular work because each work depends on separate criteria. Interpretation of results is particularly important; otherwise it does not show accurate values. All the rheometers discussed have some limitations.

Most of the concrete rheometers discussed are not suitable for low workability concrete. For the low workability mix, the torque required to shear the sample is much greater than what is required for medium workability mixes. Also yield stress to plastic viscosity ratio is higher for dry mixes and the presence of dead zone is more likely.

Dead zones are the areas where the samples are not sheared, and the material is static. The presence of dead zone introduces significant errors in the measured values from the experimental results and cannot be compared with determined fundamental parameters analytically. Most importantly the shear rate that are applied to shear the concrete in most of the rheometer are in variance to the actual field condition.

Aminul Islam Laskar [42] mentioned about approximate shear rate value, when 50 mm thick layer concrete is flowing with the speed ranging from about 0.1 m/s to 0.5 m/s (2 sec^{-1} to 10 sec^{-1}). Table.1 shows ranges of applied shear rate in rheometers, all values are slightly higher than compared to above value.

Table.1. Applied rate of shear in different rheometers.

Name of Rheometers	Applied Shear rate
Two-point rheometers	1.5 m/s
BML	1.25 m/s
BTRheom	0.5 m/s
IBB Rheometer	1.5 m/s
ICAR Rheometer	0.76 m/s
Concrete Mix Truck	2.0 m/s

The results of the study conducted by Ferraris [43], by considering the same material using different rheometers are shown in Fig.14.

As can be seen from values there is no concurrence on yield stress& plastic viscosity and no agreement of the measured values among the different types of rheometers.

Similarly, Andraz Hocevar et al., [44] and Feys and Khayat [45], works show that same mixes show different yield stress and plastic viscosity values among different types of rheometers.

In other words, there is no concurrence in the rheological values measured by different rheometers. Despite these limitations, concrete rheometers do provide important information about fresh concrete flow properties.

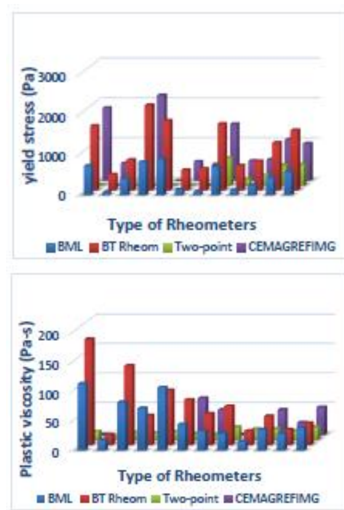

Fig. 14. Yield stress and plastic viscosity values obtained with different rheometers [43].

7. Other measurements methods

As early as 1948, L'Hermite [46] and co-workers used shear box test for fresh concrete, to study the resistance in terms of shear stress.

Ritchie [46] used a tri-axial test method to study the fresh properties of concrete and found that the cohesion of the particle and angle of internal friction between the particles can be discovered through the test.

Roza Paiovici [47] carried out experimental work on characterization of the rheological properties of fresh concrete by using size distribution and packing density of the materials and proposed rheological models for measuring the plastic viscosity and yield stress.

Cho-Liang Tsai et al. [48], investigated the rheology of concrete and other construction materials by analytical method, which is based on Stokes flow. They measured the Bingham parameters for clay grout, fresh mortar, and fresh concrete and concluded that the proposed new method can be effectively used to characterize the rheological behavior.

Sam Wong [49] conducted the experimental investigation on rheological properties of concrete (low slump) by using Vibrating Slope Apparatus (VSA). The results show that the apparatus is feasible in finding the workability of low workability concrete.

Many authors and researchers have attempted several experimental and analytical studies to calculate the rheological properties of fresh concrete other than rheometers. These include using numerical simulation, analytical FEM models and based on this developed the correlation between slumps, slump flow, vee-bee and flow test to rheological values [22].

The yield stress value depends upon floe process whether being static or dynamic. During pumping of concrete, it is subjected to dynamic condition i.e. dynamic yield stress is measured. Whereas when the concrete is placed in the formwork, it is subjected to static condition i.e. static yield stress is measured.

8. Research significance

Considering the above it is of interest and a need to study the flow behavior of fresh concrete by static condition to correlate to field applications. In this direction in 2009 Girish et al [50] developed a systematic method to determine the rheological properties of fresh concrete using the direct shear box.

Further, Girish designed and developed a new concrete shear box instrument (Fig.15) specifically for finding the rheological properties of all types concrete mix.

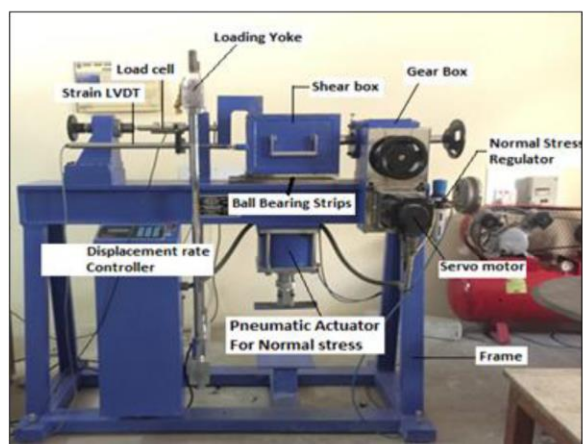

Fig.15. Concrete shear box.

Girish and Santhosh [51-54] carried out systematic studies in finding the rheological properties of normal concrete using a new concrete shear box. The detailed discussion on concrete shear box is given elsewhere [51-54].

In recent year, Girish and Ajay [55-60] has carried out the studies on rheological properties of normal concrete and SCC using concrete shear box successfully under static condition through Bingham model. The advantage of the new instrument is it can be used for all types of workability of fresh concrete.

9. Concluding remarks

Concrete is a heterogeneous, composite, complex material with the use of wide range of different types of materials, some with time dependent property. Concrete behavior cannot be fully defined by a single parameter and the empirical test, in particular the slump test, in spite of being simple and inexpensive has its own short comings in measuring the workability. In general, empirical test are single point tests and quantitative fundamental science approach is more suitable and needed for characterizing the fresh concrete with minimum of two parameters.

The emergence of concrete rheology as a new technology based on the well-established fluid rheology to characterize the workability of fresh concrete is promising since it provides a scientific description of the flow properties of concrete than the empirical tests. Better method to understand concrete workability is the need of the hour in improving the quality of concrete with better use of new and marginal materials with reduced construction cost. Rheometers along with new concrete shear box can be of use for determining the rheological properties of fresh concrete.

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