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Measurement of Rheological Properties of High Performance Concrete: State of the Art Report

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Abstract

The rheology or flow properties of concrete in general and of high performance concrete (HPC) in particular, is important, because many factors such as ease of placement, consolidation, durability, and strength depend on the flow properties. Concrete that is not properly consolidated may have defects like honeycombs, air voids, and aggregate segregation. Such an important performance attribute has triggered the design of numerous test methods. Generally, the flow behavior of concrete approximates that of a Bingham fluid. Therefore, at least two parameters, yield stress and viscosity, are necessary to characterize the flow. Nevertheless, most methods measure only one parameter. Prediction of the flow properties of concrete from its composition or from the properties of its components is not easy. No general model exists, although some attempts have been made.

This report gives an overview of the flow properties of a fluid or a suspension, followed by a critical review of the most often used tests for concrete rheology. Particular attention is given to tests that could be used for HPC. Tentative definitions of terms such as workability, consistency and rheological parameters are provided. An overview of the most promising tests[1] and models for cement paste is given.

Keywords: Building Technology; Rheology, cement paste, mortar, concrete, rheology test methods, flow properties, suspension, workability, measurements, prediction, models.

[1] The names of manufacturers are identified in this report to adequately describe the experimental procedure. Such an identification does nor imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material identified is necessarily the best available for the purpose.

Table of Contents

Table of Figures

List of Tables

1. INTRODUCTION

The rheology or flow properties of concrete are important for the construction industry because concrete is usually put into place in its plastic form. This importance can be attested to by the large body of literature existing on concrete rheology [1,2,3,4]. Unfortunately, due to the complex composition of the material, no definite method for predicting the flow of concrete from its components exists. Even measurements of the rheological parameters are not easily performed, due to the large range of particle sizes found in concrete (from 1-μm cement grains to 10-mm coarse aggregates). Therefore, the flow of a given concrete is usually measured using one of the many standard tests available that only partially measure the intrinsic flow properties of the material. Flow tests are of little value unless they measure the intrinsic rheological properties of concrete. A better understanding of the flow properties of concrete is needed to be able to predict the flow of concrete from the properties of the components.

The purpose of this report is to assess the state-of-the art in measurements of flow properties of concrete. A critical review of the tests available is given with special emphasis given to tests for high performance concrete (HPC). Clear definitions of terms commonly used in the field and their link to the materials properties are provided.

2. THEORETICAL BACKGROUND

2.1. CEMENTITIOUS MATERIALS REPRESENTATION

2.1.1. Fluid and suspension rheology

Concrete and mortar are composite materials, including as main components aggregates, cement and water. Concrete is really a concentrated suspension of solid particles (aggregates) in a viscous liquid (cement paste). Cement paste is not a homogeneous fluid and is itself composed of particles (cement grains) in a liquid (water).

Because concrete, on a macroscopic scale, flows as a liquid, equation (1) is applicable. If a shear force is applied to a liquid as shown in Figure 1, a velocity gradient is induced in the liquid. The proportionality factor between the force and the gradient is called the viscosity. The velocity gradient is equal to the shear rate $\dot{\gamma}$. A liquid that obeys this law is called Newtonian [1].

$$F/A = \tau = \eta \dot{\gamma} \qquad (1)$$

where
η = viscosity
$\dot{\gamma}$ = shear rate = dv/dy (see Figure 1)
τ = shear stress = F/A
F = force of shear
A = area of plane parallel to force

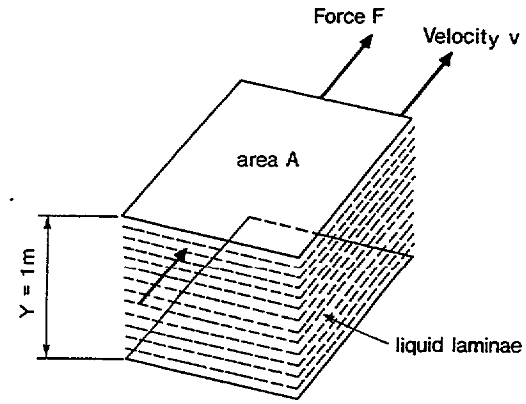

Figure 1: Newton's law of viscous flow [4]

Most of the equations used for concentrated suspensions, such as concrete, try to relate the suspension concentration to the viscosity or the shear stress to the shear rate, thus assuming that there is only one value for the viscosity of the whole system.
Table 1 and Table 2 give the most commonly used equations in the two approaches. Equations from Table 1 are used to describe the flow of cement paste [5], but they are not applicable to concrete due to the complexity of the suspension (aggregates in a suspension (cement paste)). Table 2 gives equations commonly used for concrete.

Table 1: Equations relating viscosity to concentration of suspension

Equation name	**Equation**	**Hypothesis**
Einstein [6]	$\eta = \eta_o (1 + [\eta]\, \phi)$	No particle interaction
Roscoe [6]	$\eta = \eta_o (1 - 1.35\, \phi)^{-K}$	considering particle interaction
Krieger-Dougherty [5]	$\frac{\eta}{\eta_o} = \left(1 - \frac{\phi}{\phi_{max}}\right)^{-[\eta]\phi_{max}}$	relation between viscosity and particle packing. Takes into account the maximum packing factor
Mooney [6]	$\eta = \eta_o \exp\left(\frac{[\eta]\phi}{1 - \frac{\phi}{\phi_{max}}}\right)$	takes into account the maximum packing factor
Variable definitions η = Viscosity of the suspension ϕ = Volume fraction of solid ϕ_{max} = Maximum packing factor		η_o = Viscosity of the liquid/media $[\eta]$ = Intrinsic viscosity of the suspension, (2.5 for spheres)

Table 2: Equations relating shear stress and shear rate

Equation name	**Equation**
Newtonian [1]	$\tau = \eta \dot{\gamma}$
Bingham [4]	$\tau = \tau_o + \eta \dot{\gamma}$
Herschel and Buckley [7]	$\tau = \tau_o + K \dot{\gamma}^n$
Power law [7]	$\tau = A \dot{\gamma}^n$ $n = 1$ Newtonian flow $n > 1$ shear thickening $n < 1$ shear thinning
Vom Berg [8], Ostwald-deWaele [4]	$\tau = \tau_o + B \sinh^{-1} (\dot{\gamma}/C)$
Eyring [7]	$\tau = a \dot{\gamma} + B \sinh^{-1} (\dot{\gamma}/C)$
Robertson-Stiff [7]	$\tau = a (\dot{\gamma} + C)^b$
Atzeni et Al. [9]	$\dot{\gamma} = \alpha \tau^2 + \beta\tau + \delta$
Variable definitions τ = Shear stress τ_o = Yield stress A,B,b,C,K, α,β,δ = constants	 η = Viscosity $\dot{\gamma}$ = Shear rate

It should be noticed that most of the equations described in Table 2 acknowledge the existence of a second factor, the yield stress. The physical interpretation of this factor is that the yield stress is the stress needed to be applied to a material to start flowing. The yield stress is calculated as the intersection point on the stress axis and the viscosity is the slope of the shear stress-shear rate plot (see Figure 2). A liquid that follows this curve is called a Bingham liquid.

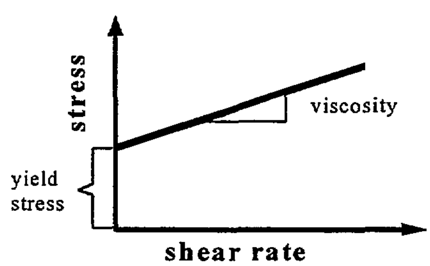

Figure 2: Bingham's law for a fluid

The Figure 3 shows some of the idealized types of curves that can be obtained when shear stress is plotted against shear rate. All the curves depicted can be described by one of the equations of Table 2. The liquids following the power law are also called pseudo-plastic fluids.

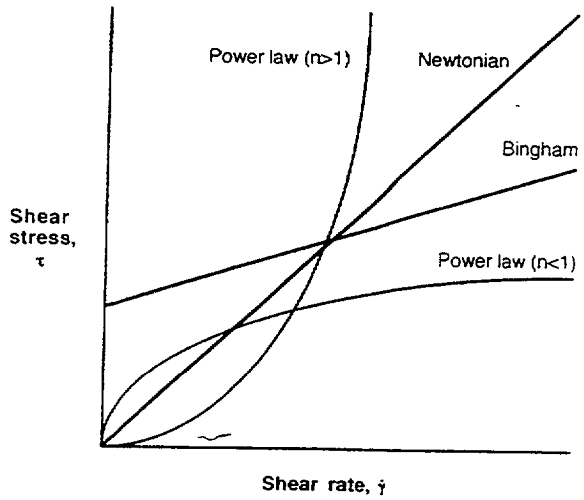

Figure 3: Summary of shapes of shear stress-shear rate curves [1]

Atzeni et al. [7] have compared the various equations and proposed a modification of the Ehring equation as the best fit for concentrated suspensions such as cement paste. Unfortunately the parameters of the Ehring equations are not physical values, but fit variables. Therefore, these parameters cannot be measured independently or modeled, but are calculated by a best fit routine.

The main conclusion that can be deduced from studying the equations proposed, is that all (with the exclusion of the Newtonian liquid) use at least two parameters to describe the flow. In the case of a concentrated suspension such as concrete, it has been shown [4,5] that a yield stress exists. The equations that have at least two parameters, with one being the yield stress, are the Hershel-Buckley and Bingham equations. The Hershel-Buckley equation contains a parameter, n, that is defined by fitting the curves. Therefore, the best equation available today is the Bingham equation, because the parameters used are factors that can be measured independently (Figure 2) and because the flow of real concrete seems to follow this equation fairly well [4]

2.2. Concrete rheology

In the construction field, terms like workability, flowability and cohesion are used, sometimes interchangeably, to describe the behavior of concrete under flow. The definitions of these terms are very subjective. Table 3 lists some of the major definitions of workability. It is clear that the definitions are descriptive and no agreement can be found. In the field the situation is often worse because these terms are used differently by the various persons involved. Tattersall's interpretation of workability is "the ability of concrete to flow in a mold or formwork, perhaps through congested reinforcement, the ability to be compacted to a minimum volume, perhaps the ability to perform satisfactorily in some transporting operation or forming process, and maybe other requirements as well" [4].

Kosmatka et al. [10] mention three terms while referring to concrete rheology: workability, consistency and plasticity. The definitions given are:

- "Workability is a measure of how easy or difficult it is to place, consolidate, and finish concrete"
- "Consistency is the ability of freshly mixed concrete to flow"
- "Plasticity determines concrete's ease of molding"

From the previous list, all the terms used are defined according to the feelings of the person and not from the physical behavior of the material. Richtie [11] attempted to define the flow of concrete by linking it to various properties (Figure 5). These descriptions, at least, link words commonly used with physical factors that can be measured. But, we believe that this is not enough, i.e. all these terms should be discarded in favor of physically measurable parameters. For instance, we could say that a concrete has a higher viscosity, instead of referring to a higher workability. Tattersall [4] summarize very clearly the concrete workability terminology by classifying it in three classes: qualitative, quantitative empirical and quantitative fundamental. The following items fall in the three classes.

- Class I: qualitative

Workability, flowability, compactibility, stability, finishability, pumpability, consistency, etc.

To be used only in a general descriptive way without any attempt to quantify

- Class II: quantitative empirical

Slump, compacting factor, Ve-be, etc.

To be used as a simple quantitative statement of behavior in a particular set of circumstances.

- Class III: quantitative fundamental

Viscosity, yield stress, etc.

To be used in conformity with the British Standard Glossary [12]

Table 3: Examples of definition of workability by various societies [13].

Name of Societies	Definition
Society of Civil Engineers, Japan	That property of freshly mixed concrete or mortar which determines the ease with which it can be placed due to consistency and the degree with which it resists separation of the materials
Society of Construction Engineers, Japan	The ease with which the unsolidified mortar or concrete can be mixed, placed and compacted.
Association of Concrete Engineers, Japan	That property of freshly mixed concrete or mortar which determines the ease with which it can be mixed, placed and compacted due to its consistency, the homogeneity with which it can be made into concrete, and the degree with which it can resist separation of materials
Association of Standards, Japan	That property of freshly mixed concrete or mortar which determines the ease and consistency with which it can be mixed, placed, compacted due to its consistency and the degree with which it resists separation of materials until formation of homogeneous concrete
American Concrete Institute	That property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished
British Standards Institution	That property of fresh concrete, mortar, or the like, which determines the ease with which it can be manipulated and fully compacted

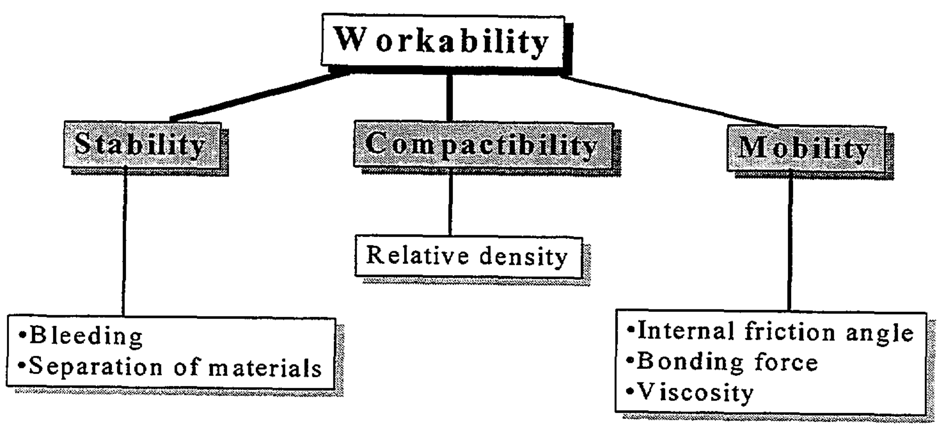

Figure 4: Elements that constitute workability [11]

As stated in Section 2.2, the properties that could be used to describe the concrete flow are the yield stress and the viscosity. Any test that describes the flow behavior of concrete should at least measure these two properties. Unfortunately, most existing tests measure only one factor, either related to the yield stress or to the viscosity. Description of these tests will be given in Section 3.1. Tests measuring both parameters exist but are neither cheap nor easy to carry out, so they are not widely used. Section 3.2 describes these tests.

The other aspect of concrete rheology is the prediction of the flow from the properties of the components (i.e., cement paste, mortar) or from the mix design (i.e., w/c ratio, aggregates content, type of cement and admixtures dosage). No attempt to develop a prediction model has yet been successful. One difficulty comes from the fact that the size range of the particles is very wide (micrometers to tens of millimiters). Also, the factors influencing the flow properties of concrete are more than the factors influencing the rheology of the parts (cement paste and aggregates). Ferraris et al. [14] identified a possible relationship between the rheology of the cement paste and concrete: the gap between the aggregates. Cement paste was shown to have a different rheological behavior depending on the gap between the plates of a rheometer. Knowing that the plates of the rheometer simulated aggregates, it can be inferred that a method to link cement paste rheology with concrete is to measure the cement paste in conditions (shear rates and gaps) similar to the situation in concrete. This approach was followed also by Yang et al.[15] to determine the influence of mixing methods on the flow properties of cement paste. Details of cement paste testing will be described in Section 4.

It should be kept in mind that all the definitions given here assume that the concrete is formed of particles but no interparticle forces are directly considered. The only indirect reference to particle interaction is the acknowledgment that all properties are time-dependent, implying that phenomena, such as flocculation of the cement particles and hydration, are continually taking place.

2.3. High Performance concrete

High performance concrete (HPC) is defined by CERF [16] as "concrete with improved constructibility, improved durability and improved mechanical properties". On the account of rheology, HPC should have the following property: "HPC places and compacts easier" [16]. In a recent detailed characterization of HPC, given by Goodspeed et al. [17], the reference to rheology is: "Ease of placement and consolidation without affecting strength".

To achieve this property special precautions need to be taken. According to Malier [18], a workable HPC can be obtained in two ways: either by reducing the flocculation of cement grains or by widening the range of grain size (see Table 4). Examining Malier's method, it is apparent that the first approach relates uniquely to the cement paste, while the second approach relates to the aggregates' size distribution as well as the influence of fillers. This last statement is in agreement with Shilstone's point of view [19].

Table 4: Two ways to obtain flowable HPC [18]

Reduce the Flocculation of Cement Grains	Widen the Range of Grain Sizes
Plasticizers, e.g., • Melamine formaldehyde sulfonate • Naphthalene formaldehyde sulfonate	Cement additives: • Silica Fume • Calcareous Fillers • Aggregates size wide distribution

Aitcin [20] raised several questions on the production of a flowable HPC:

- "How to evaluate simply rheological reactivity of portland cement and its compatibility with given superplasticizers?
- How to evaluate simply in the laboratory and in the field, the workability of a concrete having a very low water/cement ratio by means other than the slump test?
- How to diminish the rheological reactivity of a given portland cement in the domain of low water/cement ratio?
- How to optimize the use of supplementary cementitious materials when making low water/cement ratio concrete?"

According to Aitcin, "rheological reactivity" is the ability to flow, or workability.

Today, the workability of HPC is evaluated using the same tests as used for normal concrete. However, the specific characteristics of HPC hinder the correct interpretation of current tests. This situation is demonstrated when the yield stress, as measured by a slump cone, is in the range desired but the viscosity (not measured in a slump cone test) may be so high that the mix is labeled "sticky" and is difficult to place in the molds even with vibration.

Therefore, new tests are being designed specifically for HPC, as will be described in Section 3.2.3.

2.4. SUMMARY

Concrete is a composite suspension, including particles which may range from less than 1μm to over 10 mm. The flow properties of such a suspension can often be described approximately using a Bingham model, defined by two factors, viscosity and yield stress. Most of the widely-used tests are unsatisfactory in that they measure only one parameter, which does not fully characterize the concrete rheology. Figure 5 shows how two concretes could have one identical parameter and a very different second parameter. These concretes may be very different in their flow behaviors. Therefore, it is important to use a test that will describe the concrete flow, by measuring (at least) both factors.

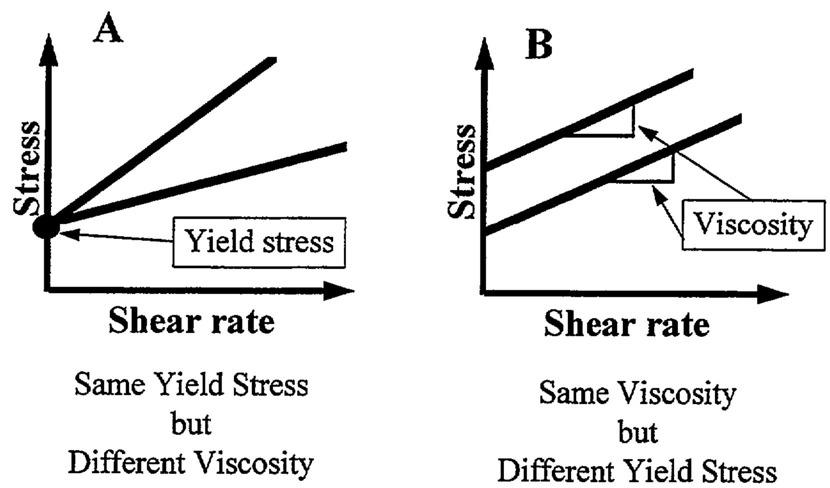

Figure 5: Concrete rheology

3. TEST METHODS

Tests methods for flow properties of concrete can be divided into two groups in regards to whether the output of the experiment gives one or two parameters. As was discussed in Section 2.2, to fully define the rheology of concrete both the yield stress and the viscosity need to be measured.

3.1. ONE-FACTOR TESTS

The more currently used tests measure only one rheological value or factor. The relationship between the factor measured and either of the two fundamental rheological parameters is not obvious. In most cases the fundamental parameter cannot be calculated from the factor measured, it can only be assumed to be related. The tests that are discussed here are:

1. Slump
2. Penetrating rod: Kelly ball, Vicat, Wigmore test
3. Turning tube viscometer
4. K-slump test
5. Ve-Be time or remolding test (Powers apparatus)
6. LCL apparatus
7. Vibration testing apparatus or settling curve
8. Flow cone
9. Filling ability
10. Orimet apparatus

Tests 1 through 4 are related to the yield stress because they measure the ability of concrete to start flowing. Tests 5 to 10 are related to the viscosity because they measure the ability of concrete to flow after the stress exceeds the yield stress. The stress applied is either by vibration (Tests 5-7) or by gravity (Tests 8-10).

3.1.1. Slump Test

A truncated metal cone is filled with concrete, and lifted quickly. The slump or drop of the concrete is measured as shown in Figure 6. This measurement is widely used due to its simplicity. In this test, the stress consists in the weight of the concrete (per area) itself. The concrete will slump or move only if the yield stress is exceeded and will stop as soon as the stress (or weight of the concrete/area) is below the yield stress. Therefore, the slump test can considered to be related to the yield stress. Some researchers have tried to simulate the slump test [21] using the finite element method. Assuming that concrete follows the Bingham law, they were able to produce pictures of the concrete slump versus time (Figure 7), but no prediction from the concrete composition was possible because no material properties for the components (cement paste, aggregates) were used.

The variability in the slump measurements is attributed mainly to the test operator and to variations in mixture properties. This test is a good quality control tool because it can help detect changes in the composition of concrete delivered, i.e., if water content was modified from the original specification. This test is a USA-standard (ASTM C143 [22]) and is used in other countries as well.

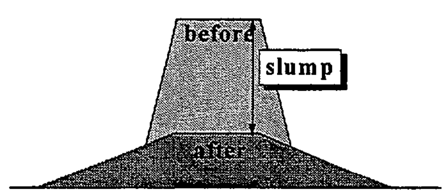

Figure 6: Schematic view of the slump test

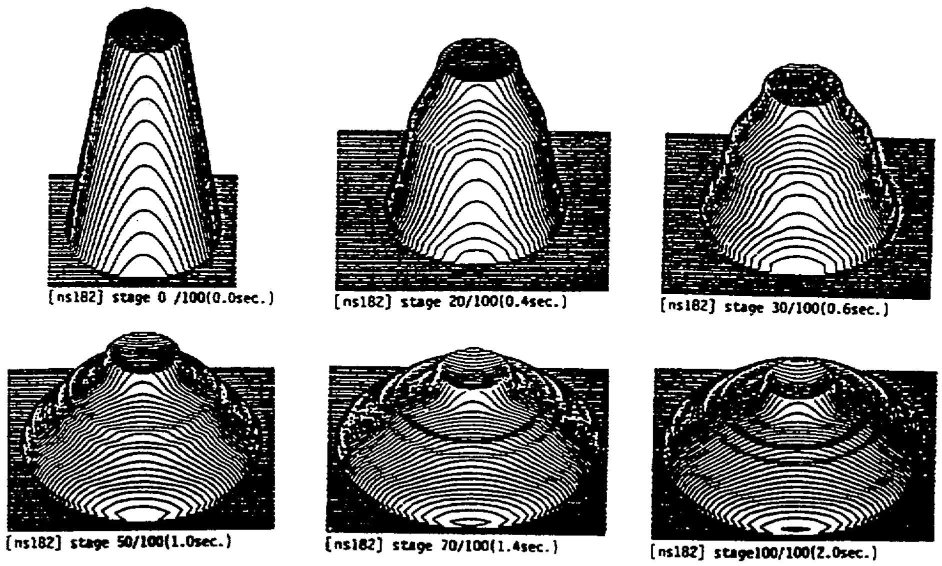

Figure 7: Finite element simulation of a slump cone test [21]

A modification of the slump test, used for concretes with very high slump (almost 305mm (12 in.)), is to measure the spread instead of the height drop. This measurement, although used as needed, is rarely reported and is not a standard. A second modification of the slump cone is the test used in Germany (DIN 1045 [23]) (22). The slump cone is placed on a special metal sheet. After the cone is lifted, the metal sheet is lifted and dropped a predetermined number of times. The spread of the concrete is measured. If the concrete slumps (or spreads), this version of the slump cone test is related to the viscosity, and not to the yield stress, because dropping the metal sheet subjects the concrete to a stress that is greater than the yield stress. Therefore the measurement is related to the flow of concrete when the yield stress is exceeded. If the concrete does not slump or spread, than this measurement is meaningless because the yield stress was not exceeded and the concrete did not flow.

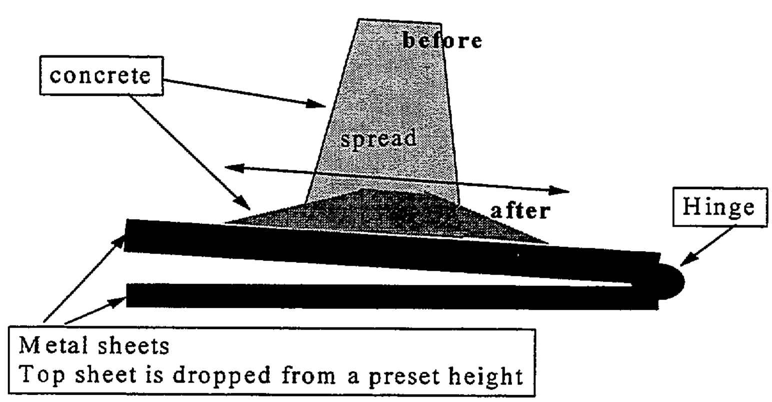

Figure 8: Slump cone according to DIN 1045 [22]

3.1.2. Penetrating rod: Kelly ball, Vicat, Wigmore test

The principle of these tests is that an object will penetrate deeper into concrete depending on the yield stress of the material. The weight or the force applied on the penetrating object will measure the yield stress of the concrete. Usually the mass or the force is pre-established, i.e., it does not vary depending on the sample. Therefore, these tests really measure whether the force applied is higher or lower than the yield stress of the concrete. Similar to the slump test, these tests are useful mainly on work sites as quality control tools to determine if the composition (mainly the water content) has been modified from the specification. These tests are also frequently used to determine the setting time of concrete. Figure 9 shows two of the most common instruments. Other test descriptions can be found in ASTM C 403 [24] or, for the Vicat needle, in ASTM C 953 [25].

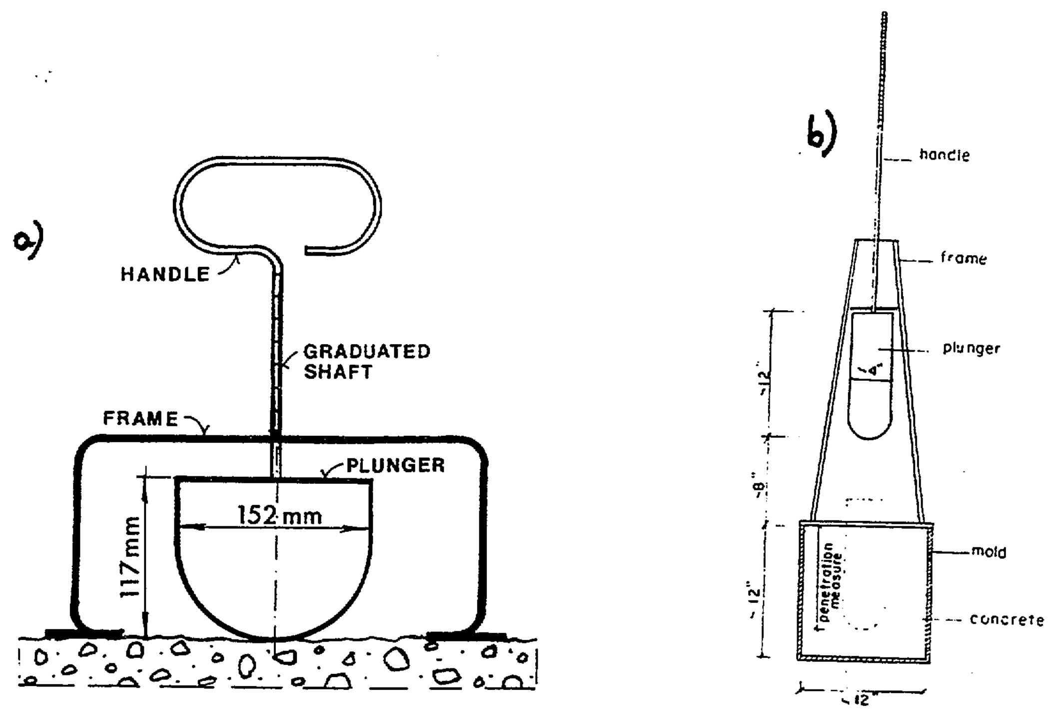

Figure 9: Penetration tests: a) Kelly ball [26]; b) German penetration apparatus [23]

3.1.3. Turning tube viscometer

The turning tube viscometer consists of a tube that can be filled with the material to be measured [27]. A ball is then dropped in the fluid and its velocity measured between two points. Using Stokes law, the viscosity is calculated. This instrument is shown on Figure 10. This instrument was used for cement paste. It is not recommended for concrete, because the diameter of the ball should be significantly larger than that of the aggregates. Otherwise, the concrete cannot be considered to be a uniform medium in which the ball is freely falling.

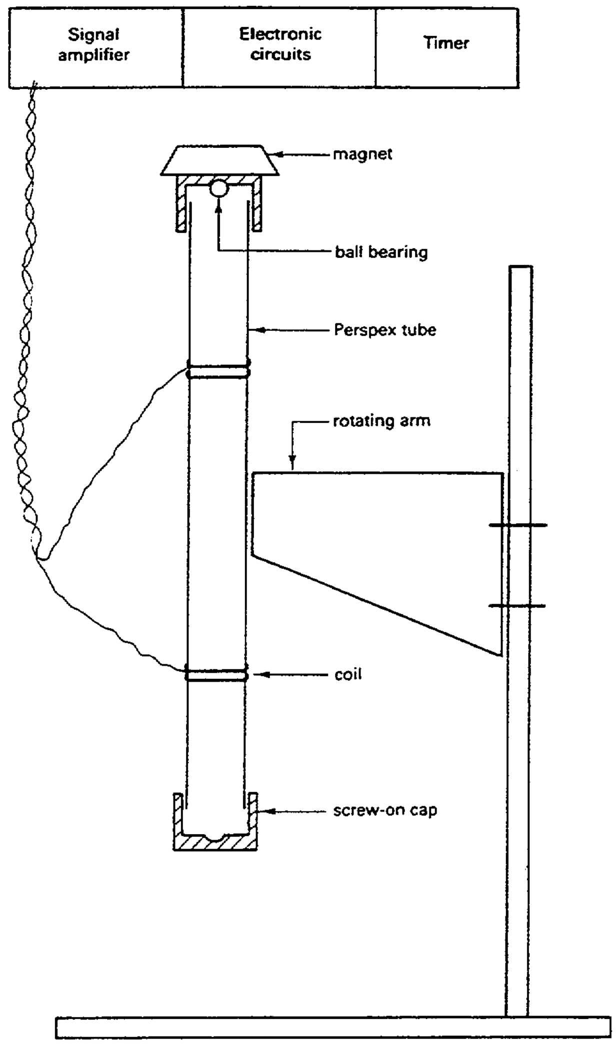

Figure 10: Schematic drawing of the turning-tube viscometer [27]

3.1.4. K-slump test [28]

This test has been widely used [28]. It is not a standard, although it has been proposed as a ASTM test and is under review by ASTM Committee C09. Its schematic design is shown in Figure 11. The probe is inserted in the concrete to be tested. The mortar portion of the concrete flows in the hollow portion of the probe through the perforated exterior tube. A floater or measuring rod, placed inside the perforated tube, measures how much mortar was able to flow into the probe. A higher volume corresponds to a higher ease of placement of the mortar. It is assumed that the mortar flow is directly related to the concrete rheological properties. If we compare this test to the two fundamental parameters (yield stress and viscosity) characterizing the rheology of concrete, this test will give a value related to the yield stress of the mortar, because the mortar will not move into the probe unless the yield stress is overcome. The stress is applied by the weight of the surrounding material. This test is suitable only for low yield stress because the probe is not inserted very deeply in the concrete, therefore the stress applied by the material around the probe is not very high. Nasser et all [28] showed that the values obtained with this test correlate with slump test results, although the scatter of the data is relatively high.

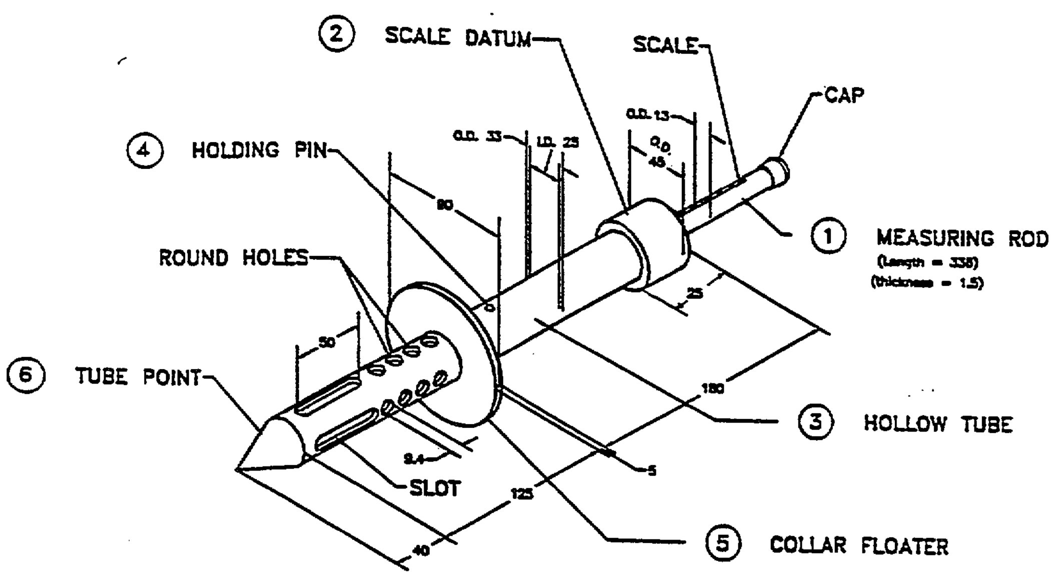

Figure 11: Schematic design of the probe for the K-slump test

3.1.5. Ve-Be time or remolding test (Powers apparatus)

These tests are a measurement of the capability of the concrete to change shape under vibration [30]. In both tests, concrete is placed in a truncated cone (Figure 12). The time to reshape itself into a cylinder is the output of these tests. Due to the vibrations, the concrete starts flowing after the yield stress has been overcome. Therefore, these tests can be assumed to be related to the viscosity. Nevertheless, the relationship is not direct. The advantage of remolding tests is that they simulate placement of concrete under vibration, related to the field usage of concrete.

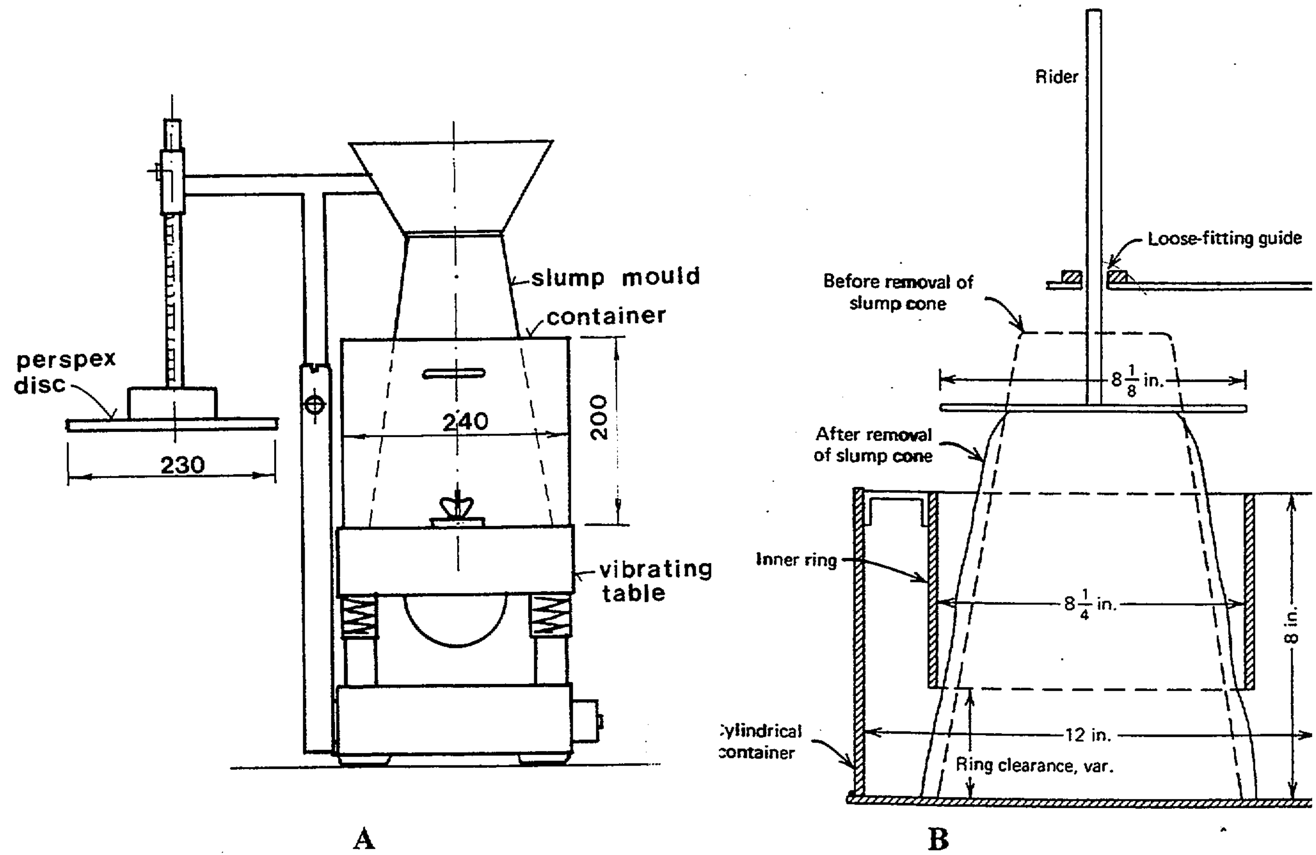

Figure 12: Remolding tests: a) Ve-Be tests [1] (dimensions in mm) b) Powers apparatus

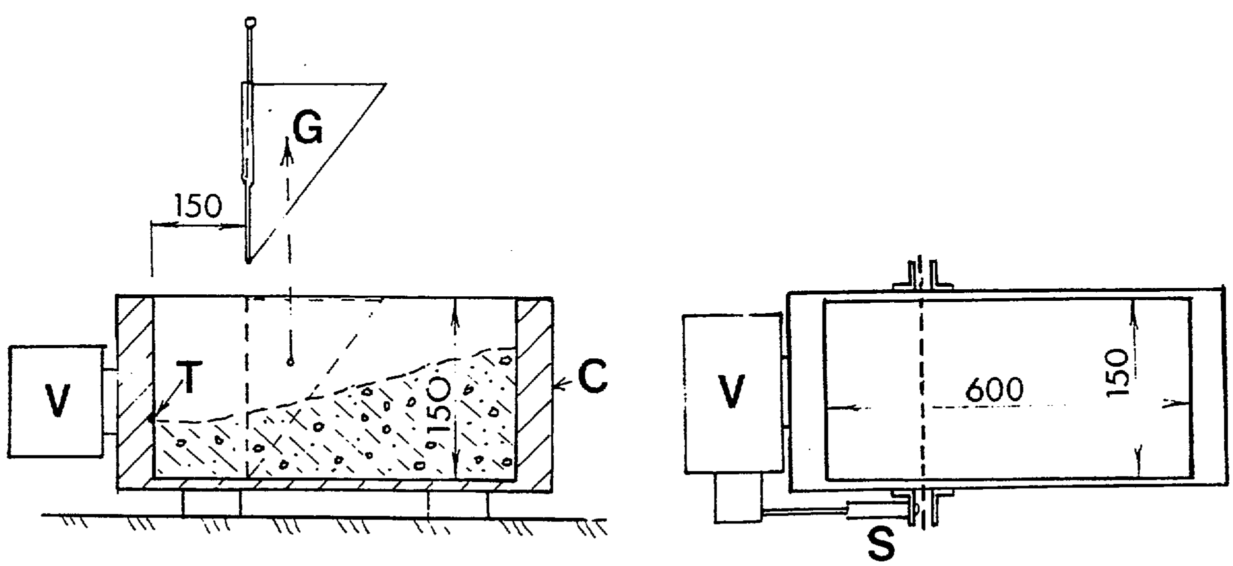

Figure 13: Schematic picture of the LCL apparatus (units in mm)

3.1.6. LCL apparatus

The LCL [29] apparatus is a French test that simulates, as the remolding test, the time for a concrete to flow into a new form (Figure 13). The main difference with the previous two tests is the geometry. The specimen is poured into a prismatic mold behind a wedge. The wedge is removed and the vibration, at a preset intensity, is turned on. The time for the concrete to flow and occupy the whole prism is considered a measure of the workability. The yield stress is likely overcome when the vibration is turned on, therefore the measurement is related to the viscosity of the material. If the vibration is slowly raised until the concrete starts flowing, a value related to the yield stress can be obtained.

3.1.7. Vibration testing apparatus and settling curve [30]

This test measures the ability for concrete to remold or to be consolidated. Figure 14a shows a schematic drawing of the apparatus. A concrete sample is placed in a container with a vibrator. The time to obtain full consolidation, i.e., time when the lid is not descending anymore, is measured. The viscosity is the only parameter that can be related to this measurement. But as previously, the viscosity cannot be calculated from this value. A compaction factor can be calculated. A settling curve (Figure 14b) is determined by plotting the height of the lid versus time of vibration. The height after vibration, h_f, is represented by the asymptote of the settling curve.

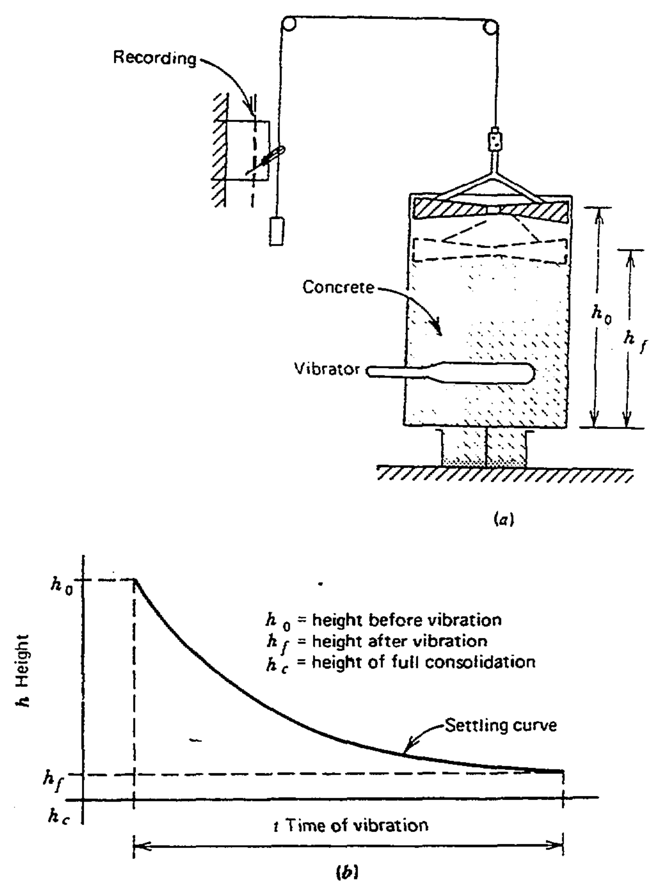

Figure 14: Vibration testing apparatus after Fritsch

3.1.8. Flow cone

The flow cone [31] is widely used for oilwell cement slurries and has been adapted for use with concrete. It consists of a funnel. The time for a set volume of concrete to pass through the orifice is measured. The dimensions of the funnel are given on Figure 15. The amount of concrete needed is 10 liters and the maximum aggregate diameter is 20 mm. If the concrete starts moving through the orifice, it means that the stress is higher than the yield stress, therefore, this test measures a value that is related to the viscosity. If the concrete does not move, it shows that the yield stress is greater than the weight of the volume used.

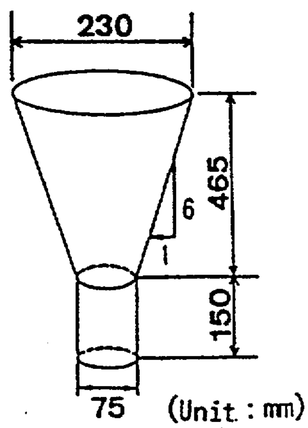

Figure 15 : Flow cone schematic

3.1.9. Filling ability

Two slightly different tests exist to measure the filling capacity of concrete, i.e., the capability of concrete to flow into a form, as shown on Figure 16. In the first test (Figure 16a [32]), the concrete is "pushed" through the opening partially obstructed by reinforcing bars, by applying a static pressure of about 2400 Pa. In the second test Figure 16b [29], the concrete is dropped in to the mold through a funnel. In both cases, the yield stress of the concrete is exceeded, therefore the value measured here is related to the viscosity. If the stress applied is lower than the yield stress, no measurement is obtained.

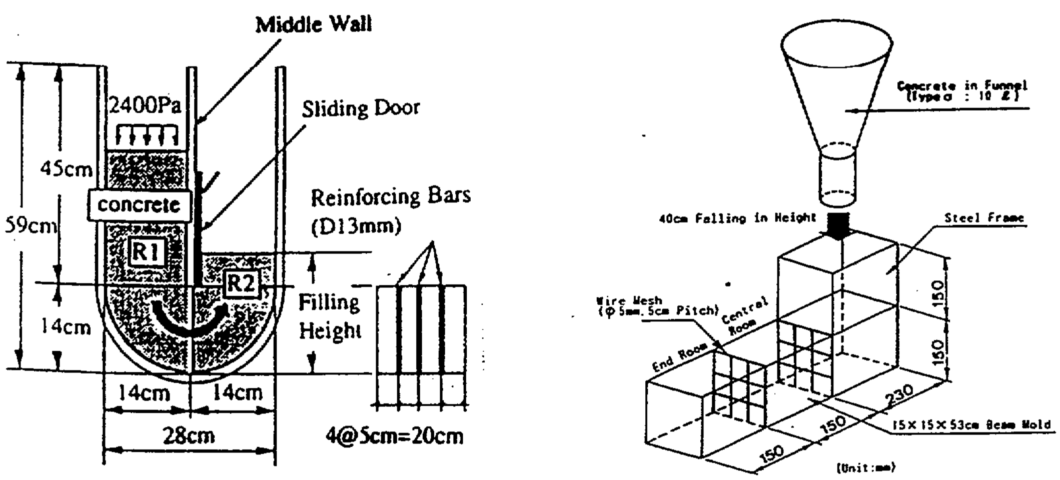

Figure 16: Apparatus to evaluate the filling ability of concrete

3.1.10. Orimet apparatus [1]

This instrument consists of a long tube closed at the bottom by an openable trap. The time for the concrete to flow through the long tube is recorded. The test method of the Orimet is similar to the flow cone. This test was used for underwater concrete. Figure 17 shows a schematic view of the apparatus. The instrument is more flexible than the flow cone because the orifice can be changed to accommodate different aggregate sizes.

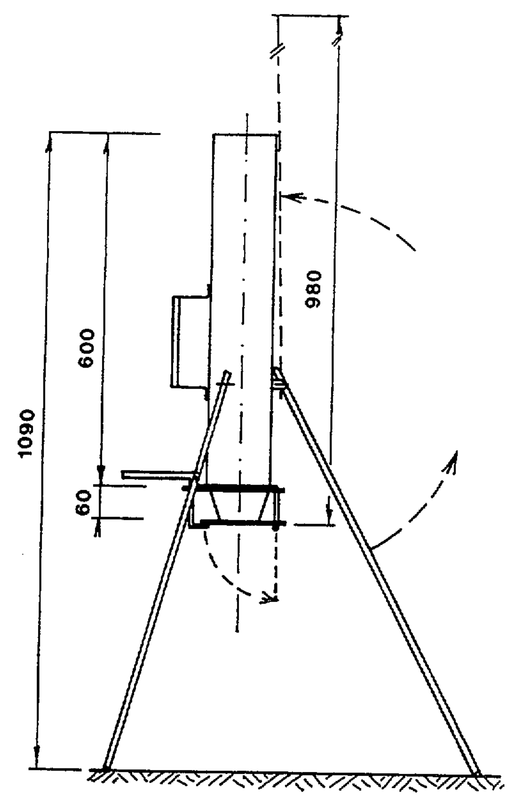

Figure 17: Orimet test apparatus [1]. Dimensions in mm

3.2. TWO FACTOR TESTS

We now examine the tests whose output gives two parameters. The values measured by these tests do not allow a direct calculation of the viscosity and yield stress. The factors measured are indirectly related to the two fundamental parameters in a non-trivial way. The difficulty in designing correct rheological tests, tests that allow direct measurement of the fundamental parameters is due to the size of the coarse aggregates. Having aggregates with size of 10 mm or greater would force the dimensions of the instrument to be huge, because the smallest dimension between the surfaces of shear must be at least 2-3 times the size of the maximum size of the aggregates.

3.2.1. Tattersal two-point test [4]

This is the first and most widely known instrument for measuring the flow properties of concrete. The apparatus (Figure 18) consists of a bucket containing the concrete to be tested. A vane of special geometry is lowered into the sample. The vane starts rotating and the resistance on the vane due to the material, i.e. torque, is measured. As the speed of rotation of the vane is increased a curve of the torque versus the speed is recorded. The graph obtained is linear, therefore the stress is extrapolated to the torque at zero speed to give the yield stress and the viscosity is related to the slope of the curve.

Tattersall [4] designed the first instrument, but others, Gjorv [33] and Wallevick [34], have improved and commercialized it. The main improvement was to automate the instrument. The torque and the speed are automatically recorded using a computer. The instrument is now for sale as the BML viscometer [33] (Figure 19). Figure 20 shows some typical results obtained with the Tattersal test. The interpretation of the curves obtained is given in Figure 21. The values obtained, g and h, are related to the yield stress and the viscosity, respectively. Assuming that the effective average shear rate is proportional to the speed of the vane, Tattersall [4] gave the following equation.

$$T = (G/K)\,\tau_0 + (G\,\eta\,)N \qquad (3)$$

where:

T = torque
G = constant obtained by calibration with Newtonian fluids
K = constant obtained by calibration with non-Newtonian fluids
N = Speed of the impeller
τ_0 = yield stress
η = viscosity

Therefore, $\tau_0 = g/(G/K)$ and $\eta = h/G$, where g and h are the two values measured.

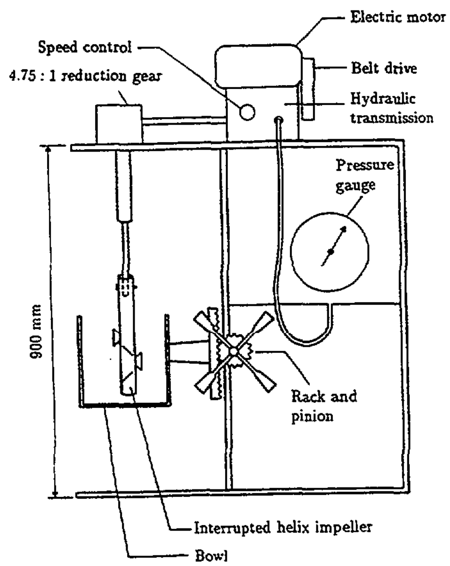

Figure 18: Tattersall Two-Point rheometer

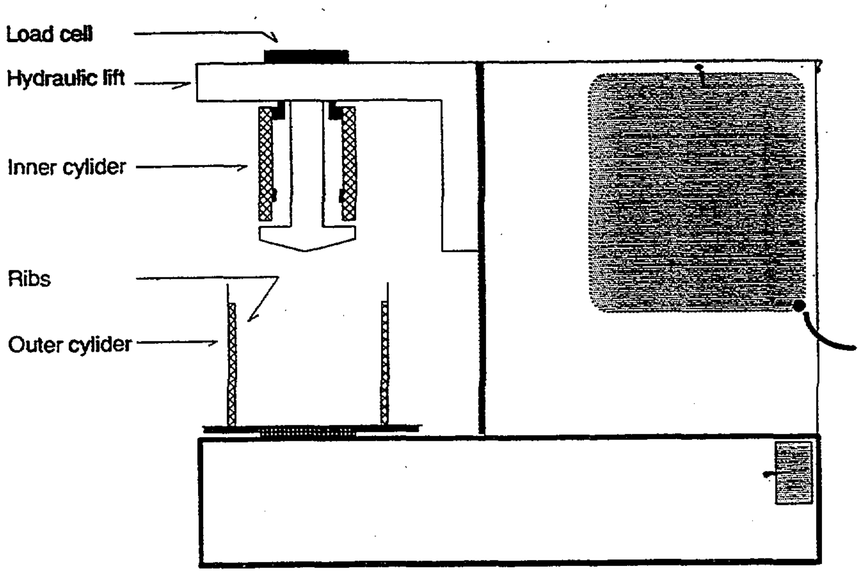

Figure 19: BML [1] [33]Viscometer

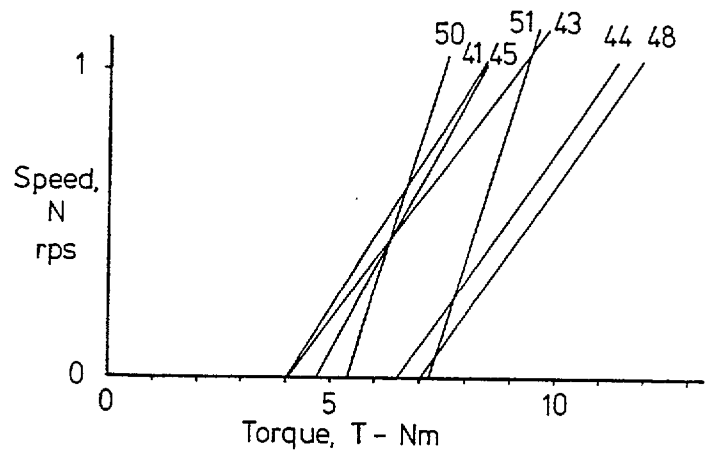

Figure 20: Typical graph obtained from the Tattersall device.
(the definitions of the notation are given in the equation)

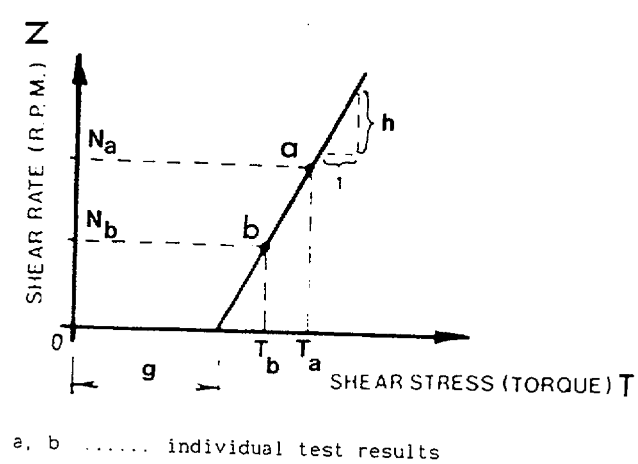

Figure 21: Interpretation of the results obtained from the Tattersal device.

3.2.2. Bertta apparatus [35]

This test apparatus was developed at the Technical Research Centre of Finland. Concrete is placed between two concentric cylinders. The outer cylinder rotates in an oscillatory mode. Frequency and amplitude are selected by the operator. The torque induced by the movement is measured in the inner cylinder (Figure 22). This configuration allows the operator to calculate the viscosity and the yield stress of the concrete as a function of frequency. The advantage of this instrument is that it allows the operator to calculate the intrinsic values of the materials and not only two related values, such as g and h (Tattersal device). Unfortunately, this instrument is not commercially available.

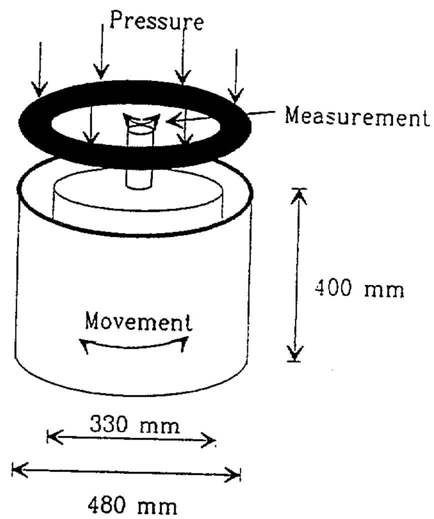

Figure 22: Bertta test apparatus [35]

3.2.3. The BTRHEOM rheometer

The newest rheometer, BTRHEOM, was developed at the Laboratoire Central des Ponts et Chaussées (LCPC) by de Larrard et al. [36]. It consists of a bucket with a serrated bottom, and a rotating top wheel (Figure 23) resting on the concrete. The geometry of shear (Figure 24) allows direct calculation of the viscosity and yield stress according to the following equations based on the assumption that the concrete is a Bingham fluid. If this assumption is not correct, the following equation will not give the viscosity and yield stress of the concrete. Nevertheless, the shear stress - shear rate curves generated will provide valuable information.

$$\tau_o = \frac{3\,\Gamma_o}{2\,\pi\,(R_2^3 - R_1^3)}$$

$$\eta = \frac{2\,h\,(\partial\Gamma/\partial\Omega)}{\pi\,(R_2^4 - R_1^4)} \qquad (4)$$

where: τ_o = shear yield stress
η = viscosity
R_1 and R_2 = inside and outside radii of the apparatus
h = height of the sheared part of the sample
Γ = Torque applied to the sample
Ω = angular velocity of the rotating part
Γ_o and $\partial\Gamma/\partial\Omega$ = ordinate at origin and slope of the experimental straight line $\Gamma(\Omega)$

The instrument was used to collect data on shear stress versus shear rate. The results confirmed that the assumption of concrete being a Bingham fluid is correct under certain conditions. These are that the concrete is relatively fluid or soft (typically a slump higher than 80 mm) and the range of shear rate is between 0.5 to 8 s^{-1}. De Larrard found that, over a wider range of shear rates, concrete behaves more like a coarse granular suspension following the Herschel-Buckley equation (see Table 2). This apparatus permits measurements to be done under vibration. Therefore, the yield stress and the viscosity of the material can be obtained under a variety of situations.

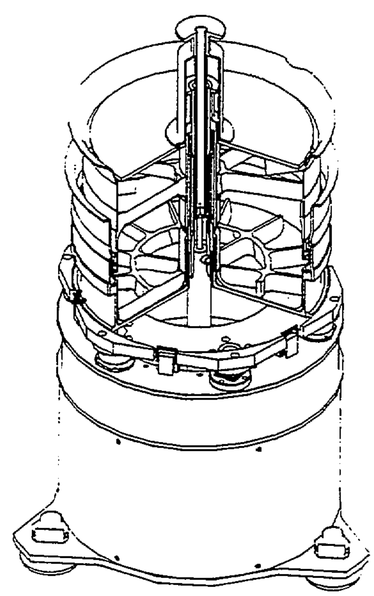

Figure 23: De Larrard instrument

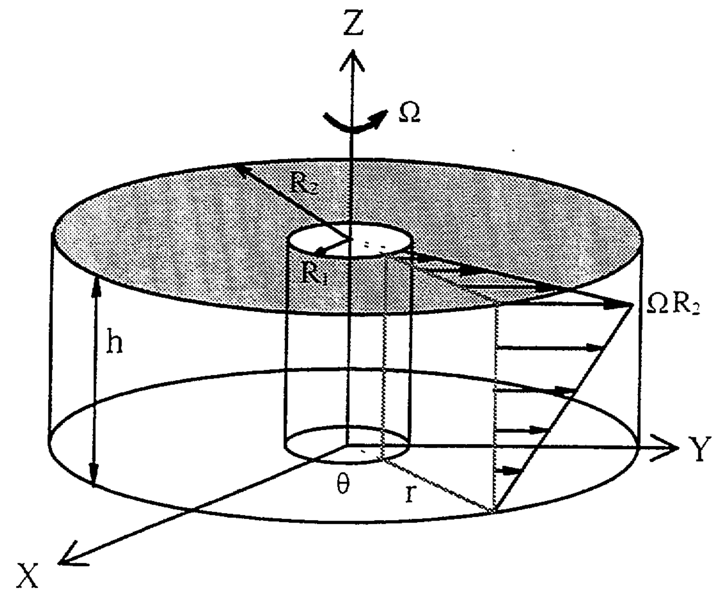

Figure 24: Geometry of shearing of de Larrard instrument [36]

3.3. Other Tests

There is a set of tests that are occasionally used but that cannot be classified in either of the two preceding sections: the compaction tests. These tests are a measurement of the energy needed to compact concrete but they cannot be related to a measurement of viscosity or yield stress.

3.3.1. Intensive Compaction test [37]

This test is not widely used but is commercially available. It is suggested that it should be used for any "slump" concrete. It measures the density of a sample after various cycles of compaction as illustrated on Figure 25. The most used compaction method in the field is vibration, which is not the method used in this test., Therefore, as this test does not reflect field compaction methods (the movement and stress applied are different from field conditions), it gives at best just an indication of the compaction ability of a given concrete.

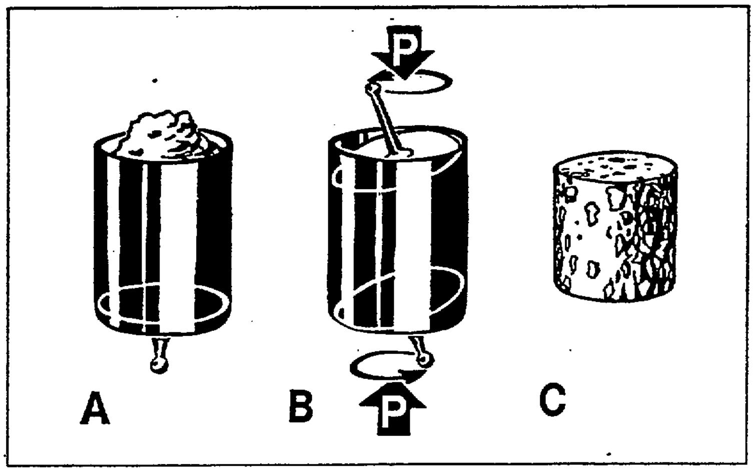

Figure 25: Different stages of workability test [37]

3.3.2. Compaction factor apparatus [38]

This test is a UK-standard BS 1881. A schematic design of the set-up is given in Figure 26. The top hopper is filled with concrete, that is free to drop into the lower buckets (Figure 26). When the concrete is all in the lower bucket, the mass of the concrete in the full bucket is measured (M_d in the equation 5). Concrete is then fully consolidated in the bucket and the bucket filled as necessary with extra material. The new mass of the material in the bucket is measured (M_C in equation 5). The compaction factor is calculated from the following equation:

$$CF = \frac{M_d}{M_C} \qquad (5)$$

Where M_d = Mass of concrete in the bucket after dropping
M_C = Mass of the concrete after consolidation

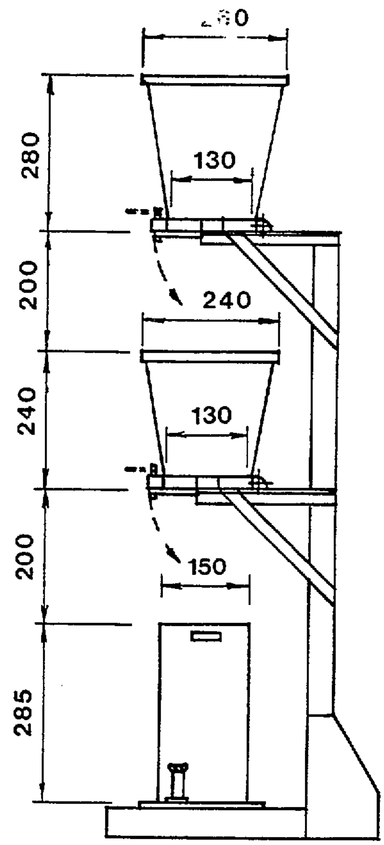

Figure 26: Compaction factor apparatus [38]. Dimensions in mm.

3.4. SUMMARY

Most of the tests for measuring the flow properties of concrete give only one parameter that is either related to viscosity or to yield stress or some ill-defined combination of both. As can be expected, most of these tests try to simulate field conditions so that the results cannot easily be related to fundamental parameters of rheology. Their usage should be limited to quality control, to check that specifications were not changed between batches. Of course, combining two of the tests, one related to yield stress and one related to viscosity, might give a better description of the concrete flow. Most tests measure only one factor. However, they are simple to perform and are relatively cheap. The most complete test that was successfully used for HPC is the apparatus developed by LCPC [36].

In conclusion, there is a need for a more fundamental approach to the rheology of concrete by measuring the fundamental factors, yield stress and viscosity. Figure 27 shows the possible impact resulting from the fulfillment of this goal.

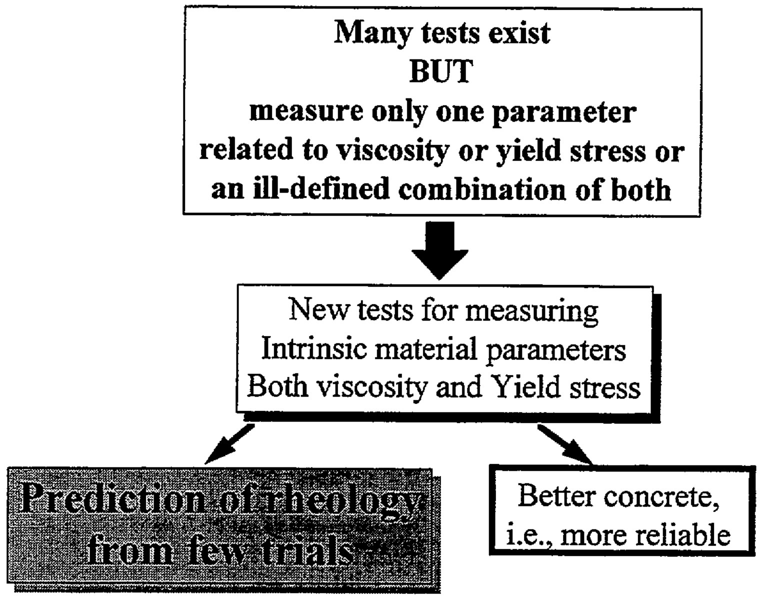

Figure 27: Impact of a better testing methodology for concrete rheology

4. CEMENT PASTE TESTS

Until now, we have examined the tests used for concrete or mortar. As the main component that can be modified chemically, by addition of HRWRA or w/c for instance, is the cement paste, we need to examine some of the specific experimental work that was published in this field.

The most recent works and the most fundamental for the understanding of the flow of cement paste could be classified into two categories:

- Determination of flow properties of cement paste in bulk (Struble et al. [39,40])
- Determine cement paste flow in the conditions similar to those encountered in concrete (Ferraris and Gaidis [14], and Yang and Jennings [15])

The distinction between the two approaches is that in concrete the cement paste flow properties cannot be considered bulk properties due to the confined space, or gap between the aggregates. Only the second approach takes this interaction into consideration. We will concentrate on the second approach because the aim of this report is the rheological description of HPC and not cement paste.

4.1. FLOW PROPERTIES OF CEMENT PASTE

Flow properties of cement paste have been extensively studied. Cement paste is similar to a Newtonian or a Bingham fluid depending on the composition. For instance, a completely non-flocculated cement paste can show a yield stress equal to zero, i.e., a Newtonian fluid. The research performed to date can be divided into two areas:

- relation between the cement paste composition and prediction of flow properties
- measurements of viscosity, either static or dynamic, using a fluid rheometer.

In the first case, cement paste is consider to be similar to a concentrated suspension of cement particles in water. As such the yield stress and viscosity depends on the particle size distribution and on their concentration. Struble [41,5] proved experimentally that the viscosity could be approximated by the Krieger-Dougherty equation (Table 1), provided that the suspension is fully dispersed, i.e., not flocculated. Figure 28 shows the fit obtained with one cement by varying the concentration of cement particles. Experimental measurements were done by using two main techniques: strain-rate controlled and stress-rate controlled viscometer. In either cases the viscometer had a concentric cylinder configuration where the gap between the two cylinders was 0.7 mm.

In the second case, although cement paste has been studied for many years, the most thorough study was recently performed by Struble et al. [42]. The originality of this work consisted in separating the study of cement paste into two areas: shear stresses smaller than the yield stress and higher than the yield stress. The main idea is that the material behaves like a solid below the yield stress and as a fluid above the yield stress. This methodology allows for a better definition of the yield stress as well as a study of the impact of the material microstructure on the yield stress.

The method for studying the cement paste below the yield stress is creep/recovery [43] consisting in applying a stress and holding it for a specified length of time. The sample response was recorded during (creep) and after (recovery) the applied stress. The type of response varied if the material was still a solid or had become a fluid (yield stress exceeded), leading to a very accurate determination of the yield stress.

To determine the material behavior at stresses higher than the yield stress, a shear stress/shear rate curve was measured. The viscosity can be calculated from the slope of the curve.

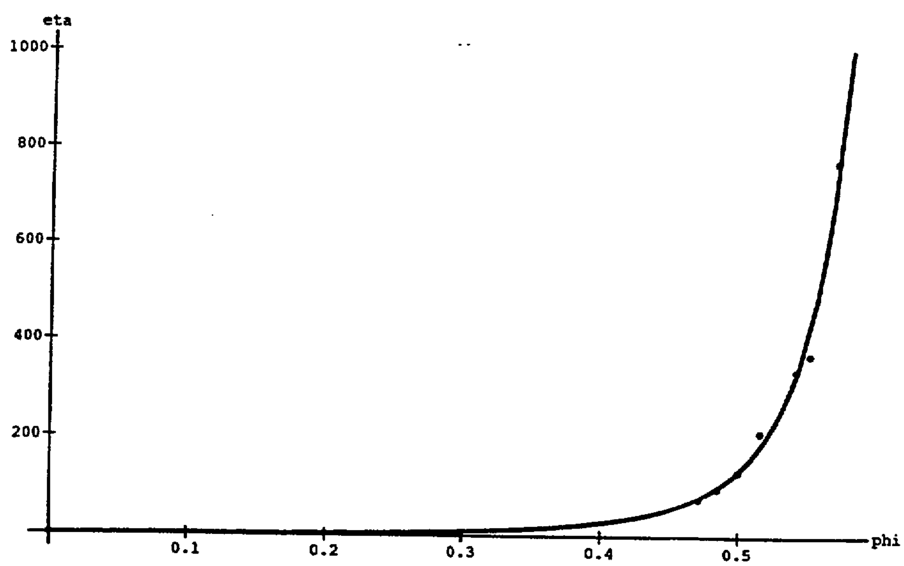

Figure 28: Viscosity relative to viscosity of the liquid phase (eta) versus volume fraction (phi), showing measured data points at a strain rate of 25 s^{-1} and the best fitting of Krieger-Dougherty equation [41]

4.2. CEMENT PASTE FLOW BETWEEN TWO PLATES

In this work it was assumed that, in order to compare cement paste flow and concrete, the cement paste flow must be measured in conditions similar to those encountered in concrete. The cement paste in concrete is squeezed between aggregates, thus a measurement of cement paste flow should reflect this situation. Ferraris and Gaidis [14] describe a novel experiment that consisted in measuring the cement paste rheology using a parallel plate rheometer. The two plates represent the aggregates. This idea was further improved by the work of Yang and Jennings [15]. In their work, the relationship between shear stress and shear rate was defined. It was established that the cement paste behavior varied significantly depending on the gap between the plates. Figure 29 shows this dependance. The gap between aggregates in concrete/mortar is determined by the cement paste content and by the aggregates size distribution.

Both teams established the notion of limiting or minimum gap. This gap is the minimum gap at which flow of a given cement paste (w/c, cement particle size distribution and admixtures dosage) is possible without encountering a shear stress "too" high. The formal definition [15] is somewhat arbitrary and the best one is given by Yang et al. The limiting (or minimum) gap is the gap at which the ratio τ_h/τ_H is equal to 3. τ_h is the peak shear stress at a shear rate of 2 s^{-1} (Figure 30) and τ_H is the shear stress at large gap (gap larger than 0.4 mm).

This concept was used in both studies to characterize the influence of the mix design of the cement paste. This knowledge could be linked to the rheology of mortar or concrete by establishing the composition of the cement paste and the minimum cement paste content needed for easy placement. In the rheometer, the gap is of course the distance between the plates. In concrete the gap between the aggregates is determined by the cement paste and the size distribution of the aggregates. Therefore, it might be possible to establish a relationship between the cement paste flow at a given gap with the mortar flow properties at a given cement paste content. In the same way, the concrete flow properties will be linked to the mortar flow properties by the mortar content (Figure 31). This is a partial multiscale approach, similar to that outlined for other properties of concrete [44,45].

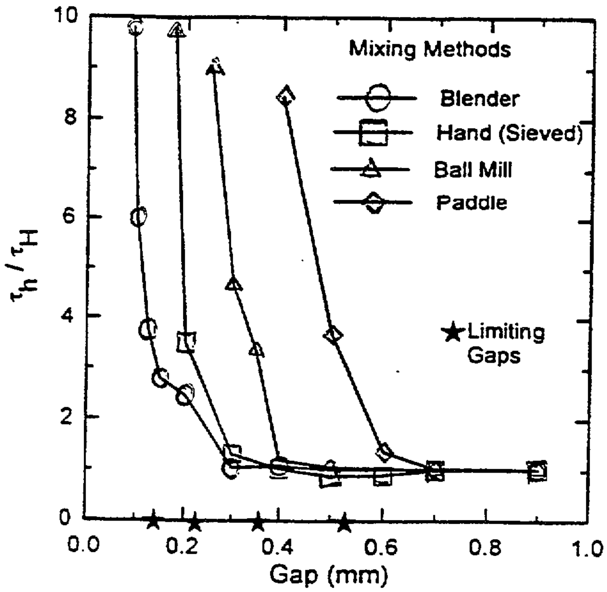

Figure 29: Influence of gap on shear stress at a fixed shear rate [15]

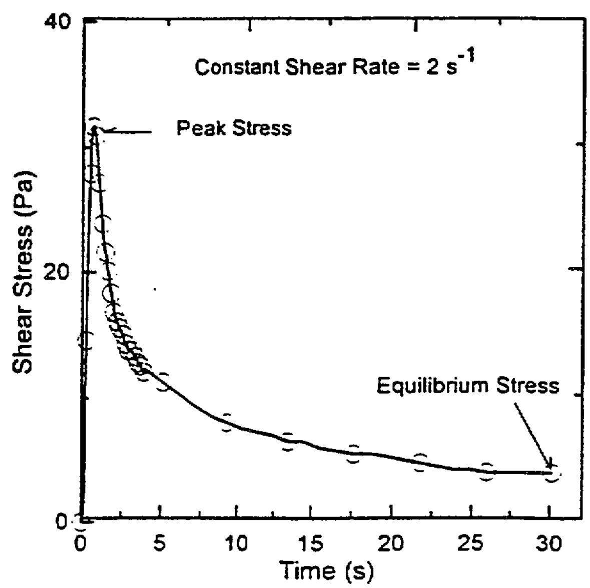

Figure 30: Shear stress versus time of cement paste under constant shear rate of 2 s^{-1} [15]

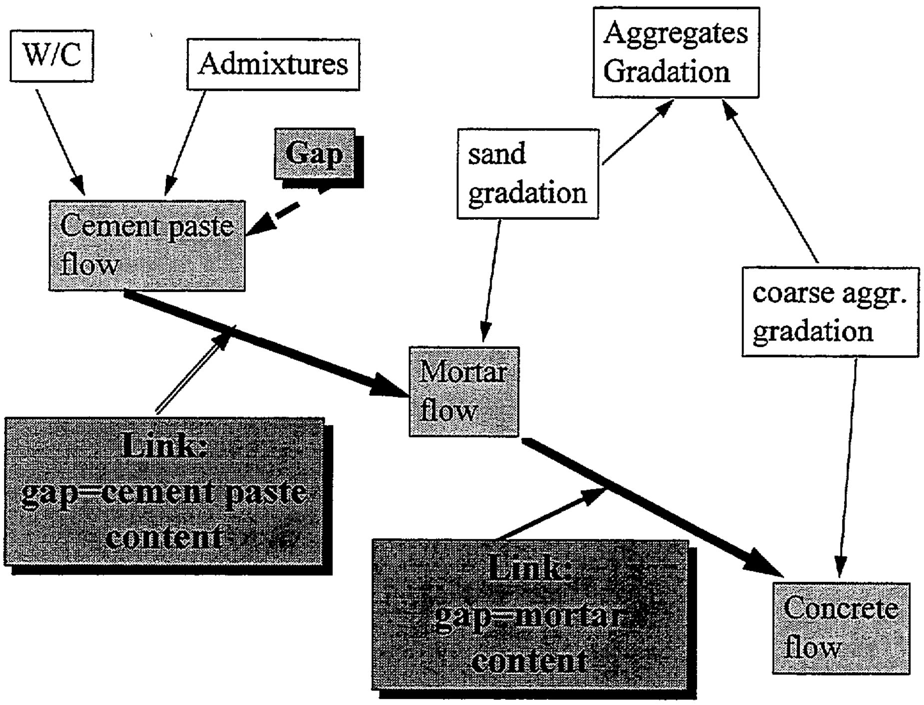

Figure 31: Linking rheology of cement paste to concrete rheology

5. SUMMARY

In summary, HPC could be considered similar to a Bingham fluid. Therefore at least two parameters must be determined to fully characterize the flow of concrete. The parameters that should be selected are the yield stress and the viscosity. The yield stress determines the stress above which the material becomes a fluid. The viscosity is a measure of how easily the material will flow, once the yield stress is overcome. Therefore, good tests, such as Tattersall and BTRHEOM, should be able to determine both factors,.

Another approach is to determine the factors, yield stress and viscosity, from the measurements of the components flow and by knowing the mixture design of HPC. This approach is tempting but has not been fully researched.

This literature review pointed out that most of the tests available are quantitative but empirical. This is not a satisfactory situation for three reasons:

- It is hard if not impossible to compare results obtained with different tests
- The factors measured are not linked to independently measurable factors
- The prediction of the rheology of concrete from its components is not possible.

The author would like to emphasize that more research and novel tests should be developed to better characterize the rheology of concrete in general and HPC in particular.

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