Fresh Concrete Rheology: Recent Developments

by

C. Ferraris
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899 USA

and

F. de Larrard
Laboratoire Central des Ponts et Chaussées
Nantes, FRANCE

and

N. Martys
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899 USA

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C. Ferraris
National Institute of Standards and Technology, Gaithersburg, Maryland

F. de Larrard
Laboratoire Central des Ponts et Chaussées, Nantes, France

N. Martys
National Institute of Standards and Technology, Gaithersburg, Maryland

> *"In science it is not enough to think of an important problem on which to work. It is also necessary to know the means which could be used to investigate this problem."*
>
> — Leo Szilard

The design of concrete with specified properties for an application is not a new science, but it has taken on a new meaning with the wide use of high-performance concretes. The following properties are related to fresh concrete: ease of placement and compaction without segregation. "Ease of placement" covers various other properties of fresh concrete, such as workability, flowability, compactibility, stability, finishability, pumpability, and/or consistency. These words are often used interchangeably without definition based on fundamental measurements of properties. Several attempts were made to better relate fresh concrete properties with measurable entities. Some researchers treated fresh concrete as a fluid and used the fluid rheology methods to describe concrete flow. This approach, the most fundamental one, is reviewed in this paper. The fundamental definitions of entities used to uniquely describe the flow of concrete are reviewed. An overview of tests that are commonly used to measure the rheology of fresh concrete is given. Methods to predict the flow of concrete from either composition or laboratory tests and the main parameters that affect the flow of fresh concrete, such as composition, placement, and mixing methods, are discussed. Two special applications of rheology are also discussed: pumpable concrete and self-compacting concrete.

Introduction

The design of concrete with specified properties for an application is not a new science, but it has taken on a new meaning with the wide use of high performance concretes (HPCs). Recently, an ACI task group (a subcommittee of the Technical Activities Committee on HPC, THPC) published a new definition of HPC.[1] This definition states: "HPC is a concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing." They continue by citing some of the properties that are critical for an application. The following properties are related to fresh concrete: ease of placement and compaction without segregation. The term "ease of placement" covers various other properties of fresh concrete, such as workability, flowability, compactibility, stability, finishability, pumpability, and/or consistency. These words are often used interchangeably without a definition based on fundamental measurements of properties. Typical qualitative definitions are "the ease with which concrete can be mixed, placed, compacted, and finished"[2] and "consistency is the ability of freshly mixed concrete to flow."[3]

Several attempts were made to better relate fresh concrete properties with measurable quantities. Ritchie[4] attempted to define the flow of concrete by linking it to various effects such as bleeding, sedimentation, and density. He distinguished three properties: stability, compactibility, and mobility. Stability is linked to bleeding and segregation, compactibility is equivalent to density, and mobility is linked to internal friction angle, bonding force, and viscosity. These descriptions, although subjective, at least link commonly used words with physical factors that can be measured. Other researchers[5–7] treat fresh concrete as a fluid and use fluid rheology methods to describe concrete flow. This approach, the most fundamental one, is reviewed in this paper. The fundamental definitions of entities used to uniquely describe the flow of concrete are reviewed. An overview of tests that are commonly used to measure the rheology of fresh concrete is given. Methods to predict the flow of concrete from either composition or laboratory tests and the main parameters that affect the flow of fresh concrete, such as composition, placement, and mixing methods, are discussed. Two special applications of rheology are also discussed: pumpable concrete and self-compacting concrete.

Concrete Flow Using Rheological Parameters

Concrete in its fresh state can be thought of as a fluid, provided that a certain degree of flow can be achieved and that concrete is homogeneous. This constraint could be defined by a slump of at least 100 mm and no segregation. This requirement would exclude, for example, roller-compacted concretes. The description of flow of a fluid uses concepts such as shear stress and shear rate as described in Refs. 5 and 8. Concrete, as a fluid, is most often assumed to behave like a Bingham fluid. In this case, its flow is defined by two parameters: yield stress and plastic viscosity. The Bingham equation is:

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

where τ is the shear stress applied to the material, $\dot{\gamma}$ is the shear strain rate (also called the strain gradient), τ_0 is the yield stress, and μ is the plastic viscosity. To determine the Bingham parameters, there are two possibilities:

1. The stress applied to the material is increased slowly and the shear rate is measured. When the stress is high enough the concrete will start flowing. The point at which the materials flow is the yield stress and the slope of the curve above this stress is the plastic viscosity.
2. The fresh concrete is sheared at high rate before the rheological test. Then, the shear rate is decreased gradually and the stress is measured. The relationship between the stress and shear rate is plotted and the intercept at zero shear rate is the yield stress, while the slope is the plastic viscosity.

In this review, we will assume that the fresh concrete has been sheared at a high rate before the rheological test, because this is the most commonly used procedure. The main reason that this procedure is the most widely used is that it is easier to develop a rheometer that is shear-rate-controlled (Procedure 2) than stress-controlled (Procedure 1).

In addition, some concretes, such as self-compacting concrete (SCC), do not follow the linear function described by Bingham.[9] In fact, the calculation of a yield stress using a Bingham equation in the case of SCC will result in a negative yield stress, as shown in Fig. 1. De Larrard et al.[10] use another equation that describes the flow of suspensions, the Herschel-Bulkley (HB) equation. This provides a relationship of shear stress to shear strain rate based on a power function:

$$\tau = \tau'_0 + a\dot{\gamma}^b$$

where τ is the shear stress, $\dot{\gamma}$ is the shear strain rate imposed on the sample, τ'_0 is the yield stress, and a and b are the new characteristic parameters describing the rheological behavior of the concrete. In this case, plastic viscosity cannot be calculated directly.

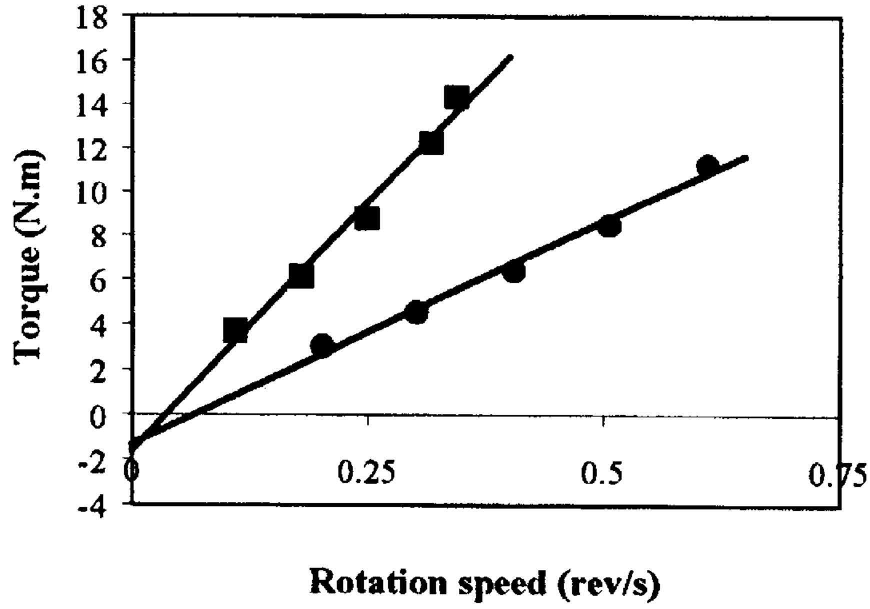

Figure 1. Self-compacting concrete flow measured with a parallel plate concrete rheometer, BTRHEOM.*[9] The torque is a measure of the shear stresses and the rotation speed is related to the shear rates.

De Larrard et al.[10] also investigated the possibility of reducing the number of parameters to two while still using the HB equation. The HB equation could be considered as a linear relationship for a "short" range of shear strain rate. The yield stress is calculated by the HB equation, while the viscosity is calculated using the following equation:

$$\mu' = \frac{3a}{b+2}\dot{\gamma}_{max}^{\,b-1}$$

where μ' is the slope of the straight dotted line in Fig. 2, $\dot{\gamma}_{max}$ is the maximum shear strain rate achieved in the test, and a and b are the parameters as calculated by the HB equation. This Bingham-modified equation is deter-

*Certain commercial equipment, instruments, or materials are identified in this review to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it implies that the materials or equipment identified are necessarily the best available for the purpose.

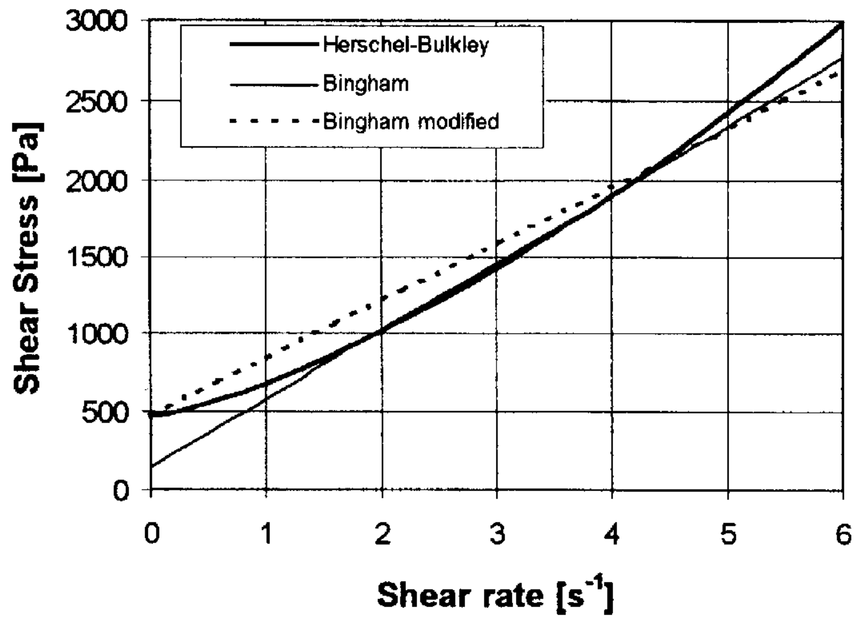

Figure 2. Calculation of the Bingham parameters based on the Herschel-Bulkley model. The dotted straight line departs from the same point as the HB model $(0, \tau'_0)$.

mined by approximation of the HB equation with a straight line, minimizing (using a least-squares method) the deviation between the two models, that is, HB and straight line (modified Bingham equation).

In summary, it should be noted that concrete must be defined by at least two parameters because it shows an initial resistance to flow, yield stress, and a plastic viscosity that governs the flow after it is initiated. Nevertheless, most commonly used tests to describe concrete flow are limited to the measurement of only one parameter, often not directly related to either of the Bingham parameters. Only recently were some instruments designed to better describe concrete flow.[11] A description of the available tests is given below.

Measurement Techniques for Fresh Concrete

As discussed earlier, a test characterizing the flow of concrete should be able to determine at least two parameters, such as yield stress and plastic viscosity. The design of a rheometer for concrete must take into account the dimensions of the coarse aggregate. The smallest gap in the instrument

Table I. Tests that measure only one parameter, either yield stress or viscosity

Test	Stress applied	Comments
Slump[13]	Gravity	Related to yield stress
Penetrating rod: Kelly ball,[14] Vicat,[15] DIN penetration test[24]	Applied stress, i.e. the weight of the ball or other device	Related to yield stress
K-slump test[16,17]	Gravity	Related to segregation
Turning tube viscometer[18]	Gravity	Related to viscosity
Ve-Be time or remolding test (Powers apparatus)[19]	Vibration	For concretes with high yield stress
LCL apparatus[20]	Vibration and gravity	
Filling ability[20,21]	Applied pressure or gravity	Measure of ability of concrete to flow between reinforcement bars
Vibration testing apparatus or settling curve[22]	Vibration	
Flow cone[23]	Gravity	Measure of the ability to flow through an opening
Orimet apparatus[19]	Gravity	Measure of the ability to flow through an opening
Slump drop test[24]	External pressure/gravity	

should be at least three times the largest diameter of the coarse aggregate to obtain a representative sample and to avoid interlocking of the aggregates, which will prevent flow. The difficulty in meeting this requirement led to the design of empirical tests that do not allow for the calculation of the yield stress and plastic viscosity in fundamental units. The design of such tests was to imitate the method of placement in the field. These tests very often measure only one value, which is not necessarily related to the fundamental parameter defined by Bingham. It is only recently that some instruments were designed to obtain two values that are related to the fundamental parameters.

There are numerous standard and nonstandard empirical tests to measure the flow of concrete. Because the results of such tests are not expressed in fundamental units, it is difficult to relate results from different tests. They can be used only for a direct comparison between concretes when using the same test.

As a full description of all the tests is beyond the scope of this review, we will limit ourselves to a list of the tests with some comments. There are two broad categories of tests: those that provide one parameter and those that provide two.

Table I gives a list of most common tests with some comments on the type of result that can be obtained. A discussion of the merits and results obtained can be found elsewhere.[11,12] To measure the viscosity, the yield stress must be exceeded. This can be achieved by various methods, but the two most common are gravity or vibration. In the gravity method, the stress applied is the weight of the materials, as opposed to an external applied stress. In the vibration method, the yield stress and flow behavior of the concrete are completely different from those observed without vibration. These tests are intended to simulate field performance in the laboratory.

The design of a rheometer for concrete allowing measurements of a flow curve describing the relationship between shear stress and shear rate can be taken from the science of fluid rheology. The most common rheometers are coaxial or parallel plate.

A coaxial rheometer is composed of two concentric cylinders. The outer cylinder is usually stationary and the inner cylinder rotates at a controlled speed. The shear stresses generated by the fluid are measured on the inner cylinder. To be able to compute the shear stress and shear rates as well as calculate the yield stress and plastic viscosity according to the Bingham equation, the gap between the cylinders needs to be relatively small as compared to their diameters. It is generally accepted that the ratio of the radii of the two cylinders should be between 1 and 1.1. For concrete, the gap needs to be at least three to five times the size of the coarse aggregate to avoid interaction between the aggregates and the walls of the rheometer. Therefore, for an aggregate maximum size of 10 mm, the minimum radius is 0.5 m, which will require the diameter of the outer cylinder to be between 0.53 and 0.55 m. These dimensions would have to be increased with the maximum size of the aggregate, rendering this type of instrument unsuitable for field use because it would not be easily transportable outside the laboratory. Such a rheometer was built by Coussot[25] and used for fresh concrete by Hu et al.[26] to validate the results obtained with the BTRHEOM rheometer developed at the Laboratoire Central des Ponts et Chaussées (LCPC).

To overcome the dimension limitations of the coaxial cylinder rheometer while maintaining the possibility of estimating the two Bingham parameters, Tattersall[5] designed a rheometer that consisted of a shaft with blades that rotated in a bucket of concrete at a controlled speed. The torque generated by the concrete is measured on the shaft. This method does not allow for the calculation of viscosity and yield stress in fundamental units, but it enables the sudy of concrete flow under various shear rates. This rheometer, referred to as the "two-point test," was modified and computerized by Wallevik and Gjørv.[27] The commercially available BML rheometer by Wallevik† has another modification involving the shape of the blades. The blades are fins attached radially on the shaft. This rheometer can be used to estimate the Bingham parameters in fundamental units if no plug flow occurs. Hu et al.[28] showed that plug flow occurs in concretes with a slump (measured according to the standards[13]) less than 200 mm. Beaupré[7] also developed a rheometer, referred to as IBB, with a different blade/shaft assembly and the shape of the letter H. The IBB rheometer is also a modification of the original two-point test. Further descriptions of these tests are found elsewhere.[8,12]

Another geometry that is commonly used for rheological measurements is a parallel plate. Here, an upper plate rotates at a preselected speed and the torque generated by the shear resistance of the material is recorded on the same plate. The bottom plate is stationary. The shear rate in such an instrument is not constant and depends on the radial position, that is, the shear rate is zero at the center of the plate and maximum at the edge. In most cases the shear rate and the shear stress at the edge are the measurements considered for the calculation of viscosity. This is not a serious problem if the fluid is Newtonian, because the viscosity does not depend on the shear rate, but it is for non-Newtonian fluids. For non-Newtonian fluids, an analytical calculation needs to be carried out. As before, the distance between the two plates must reflect the size of the aggregates. This distance should be at least three to five times the diameter of the largest aggregate.

There is only one rheometer that uses the parallel plate geometry: the BTRHEOM,[29] which was developed by de Larrard et al. at LCPC. It consists of a bucket that has a capacity of about 7 L, with a fixed wheel at the bottom and a wheel at the top rotating at any selected speed. The bottom wheel records the torque generated by the material reaction to shearing. The results of this test can be computed to obtain viscosity and yield stress in fundamental units.

Whereas the concentric cylinder rheometers described above are too large for field use, the BTRHEOM is relatively small and can be carried by one person. Data acquisition is made with a portable computer.

Nevertheless, there is a need for a simple, inexpensive test to be used in the field for quality control of the concrete. In a survey conducted by the National Ready-Mixed Concrete Association in 1997,[30] more than half of

†BML viscometer, the Icelandic Building Research Institute, O. Wallevik.

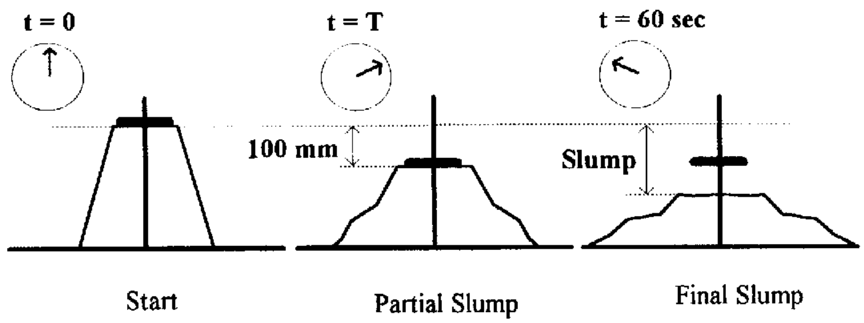

Figure 3. Schematic of the modified slump test. *T* is the slump time.

the participants indicated that although they considered the slump test adequate to describe workability, they felt that a better test was needed. They indicated that the slump test[13] did not give them a full description of the flow of concrete. For this reason, Ferraris and de Larrard developed at NIST a modified slump cone test.[31,32] Figure 3 shows the schematic of this test. The modification consists of measuring not only the final slump height but also the time it takes for the concrete to slump the first 100 mm, that is, the speed of slumping. There are two methods to measure the speed:

1. The original method consists of measuring the time for a plate to slide down with the concrete[32] a distance of 100 mm.
2. Researchers at Sherbrooke University[33] eliminated the plate and shortened the central rod so that its top was 100 mm below the full slump cone height. The test consists of measuring the time it takes for the concrete to slump to the height where the rod first becomes visible.

The second method has the advantage that there is no risk of the plate getting stuck, but has the disadvantage that it may be difficult to see the appearance of the rod. Painting the end of the rod in a bright color does not solve the problem,[33] because it is covered with cement paste.

From the final slump and slump time, the yield stress and plastic viscosity (in fundamental units) can be calculated using an empirical equation that was developed by comparing the modified test measurement with the values obtained with the BTRHEOM.[9,31,32]

This test is being evaluated in various laboratories in United States and France to determine the reproducibility of the results and the correlation of the slumping time and the final slump with the yield stress and plastic viscosity. When sufficient data have been collected, this test will be proposed to ASTM for consideration as a standard test.

In summary, while it can be seen that there are numerous tests to characterize the flow of concrete, few give results in fundamental units and therefore the rheological properties of concretes measured using different tests cannot be directly compared. Recently, new tests for characterizing concrete using a more fundamental approach have been developed. While not all researchers agree on which test is the most suitable for the wide range of concretes in use today, tests that can give results in fundamental units and that can be used on a construction site should be favored, because comparison between test results can be achieved.

Models to Predict Rheological Properties

For the engineer who needs to design concrete for a specific application or for a specific placement method, the challenge lies in the prediction of the fresh concrete's properties from its composition. Generally, there are procedures or codes to estimate the slump values depending on factors such as w/c ratio and chemical and mineral admixture dosage, but most of the time several trial batches are needed.

A model that could predict the rheological parameters, yield stress and viscosity, from the composition or from minimal laboratory tests would be beneficial. Three promising models will be reviewed here: the compressible packing model (CPM) developed by de Larrard, simulation of flow of suspensions developed by NIST researchers, and a semi-empirical model based on the Krieger-Dougherty equation developed by Struble.

Compressible Packing Model

LCPC developed this model for predicting concrete properties from its composition. Concrete is defined as a granular mixture (from cement to the coarse aggregates) in a water suspension. A concrete with no workability, that is, no flow, is defined as a concrete where the porosity is filled with water. This statement implies that there is no excess water between the solid components. Therefore, the yield stress can be correlated with the stress needed to initiate flow by overcoming the friction forces between the particles. These forces depend on the number and type of contacts between the particles.

Each component *i* of the mixture is defined by its close packing density, ϕ^*_i, and the volumetric fraction of solid material (with respect to a total volume of one), ϕ_i. A close packing density is defined as the maximum possible value of ϕ_i, with all the other ϕ_j ($j \neq i$) being constant. Also, the whole mixture is characterized by a close packing maximum, ϕ^*, and the volumetric fraction of the solid materials, ϕ.

The yield stress, τ_0, can then be defined as:

$$\tau_0 = f\left(\frac{\phi_1}{\phi_1^*}, \frac{\phi_2}{\phi_2^*}, \cdots \frac{\phi_n}{\phi_n^*}\right)$$

where f is an increasing function because the yield stress will increase with increasing value of ϕ_i / ϕ^*_i.

To determine the viscosity dependence on the volumetric concentration, we can assume that the speed of each particle under shear is the same and equal to the macroscopic speed. Therefore, it is assumed that the flow of the fluid between the particles is laminar and that the shear resistance will remain proportional to the overall gradient. Thus, if the Bingham equation is assumed to be valid, the plastic viscosity can be deduced to be:

$$\mu = \mu_0 g \frac{\phi}{\phi^*}$$

where μ_0 is the plastic viscosity of the suspending fluid and g is an increasing function, because the viscosity will increase with increasing concentration of particles.

These equations were tested by comparison with a series of 78 concrete batches in which rheological parameters were measured using the BTRHEOM. The close packing and the volumetric fraction of each component were calculated using the CPM.[9] The plastic viscosity was determined by a best-fit equation, given by the equation below, from the data shown in Fig. 4.

$$\mu' = \exp\left\{26.75\left[\left(\frac{\phi}{\phi^*}\right) - 0.7448\right]\right\}$$

The yield stress can be calculated by a linear combination of all the components' volume fraction/close-packing ratios. It appears that different coefficients need to be calculated for concrete with and without high-range water reducing admixtures (HRWRA). The data used were from the same set as used for the viscosity.

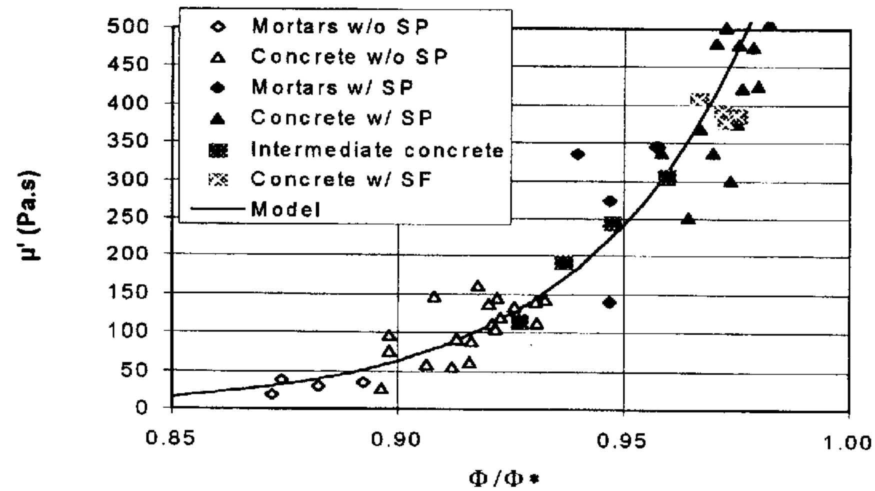

Figure 4. Plastic viscosity (μ') of the mortars and concretes as a function of their relative solid concentrations. SP = superplasticizers or HRWRA; SF = silica fume.

For mixtures without HRWRA the yield stress was:

$$\tau'_0 = \exp\,(2.537 + 0.540K'_g + 0.854K'_s + 1.134K'_c)$$

And, for the mixtures with 1% HRWRA (without silica fume), it was:

$$\tau'_0 = \exp\,(2.537 + 0.540K'_g + 0.854K'_s + 0.224K'_c)$$

In these equations, τ'_0 is the yield stress obtained by fitting the rheometer results in accordance with the Herschel-Bulkley model. The indices g, s, and c relate to gravel, sand, and cement, respectively. K_x is equal to $(1 - \phi_x / \phi^*_x)$.

These results were confirmed with other data sets resulting from variation of the coefficients used in fitting the data (Fig. 5).[34]

This model is part of a larger set of models that can take into account other properties of both fresh and hardened concrete. This model links the composition of the concrete with its performance.[34]

Simulation of Flow of Suspensions

Ferraris and Martys are developing a new procedure that includes simulation of the concrete flow. The procedure is based on the chart illustrated in Fig. 6. The cement paste rheological parameters, yield stress and viscosity, are measured using a laboratory fluid rheometer. The cement paste in this

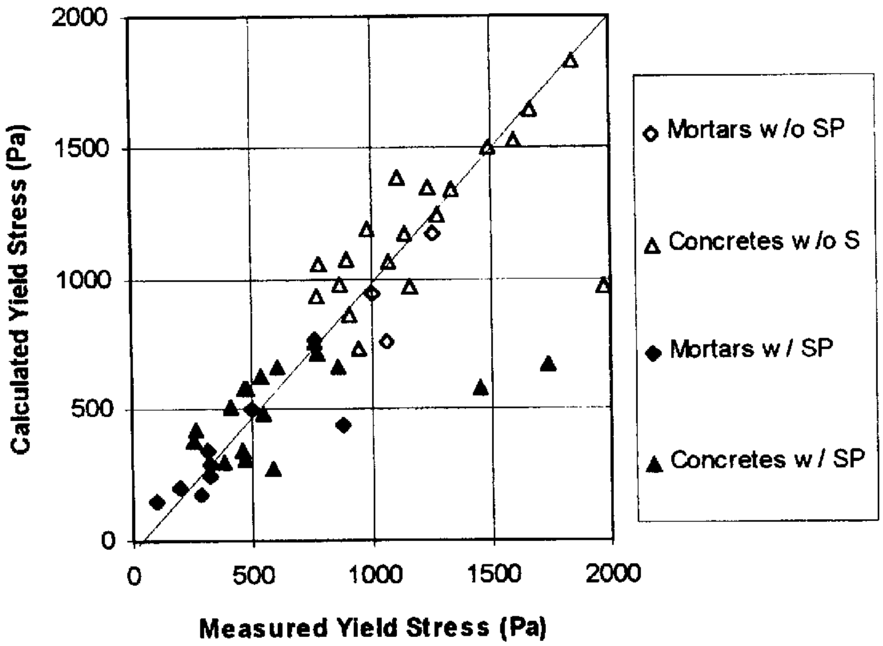

Figure 5. Comparison between experimental values and model values of the yield stress.[9]

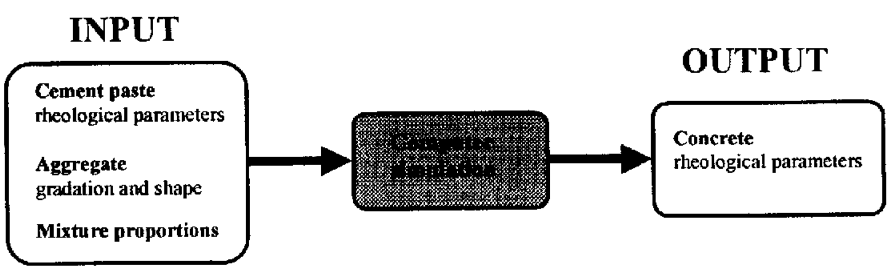

Figure 6. Principle of the procedure.

case includes any chemical and mineral admixtures that are selected. Then these values along with the mixture design of the mortar or concrete (i.e., gradation, shape, and total content of aggregates) are used as input to a computer simulation. The results are the rheological parameters of concrete. The simulation method is in the process of being developed and is presented below.

To be able to succeed in the procedure illustrated in Fig. 6, the rheology of the cement paste must be measured in the same conditions experienced in concrete, that is, at the same shear rate and the same temperature. Barrioulet et al.[35] studied a set of concrete mixtures having cement pastes of various compositions but with the same viscosity, and with various aggregates having the same shape and gradation. They found that the flows of these concretes were not the same. They attributed this difference to the fact that the rheology of the whole is not equal to the rheology of the parts if the interactions between the parts were not considered. It is believed that the error was to measure the viscosity of the cement paste without taking into account the condition of shear experienced by the cement paste in concrete. Therefore, the following three experimental parameters need to be monitored:

1. The gap between the aggregates. Cement paste is "squeezed" between the aggregates. The distance between the aggregates (the gap) depends on the paste content of the concrete considered.[36] Therefore, the rheometer geometry must be a variable geometry in which the gap can be changed. A parallel plate rheometer is a suitable device. To estimate the average gap between aggregates, NIST researchers used a mathematical method developed by Garboczi and Bentz[37] based on equations developed by Lu and Torquato.[38] The aggregates are treated as spheres suspended in a cement paste matrix. The volume of paste contained in a shell of thickness r around each aggregate is accurately given by the equations, even allowing for overlaps between shells. The value of r is computed where 99% of the paste is contained in the shells, and the gap is taken to be twice this value. The mathematical calculation has been shown to be very accurate for a wide range of concretes using numerical analysis.[39]
2. The shear rate during mixing: The mixing of cement paste must replicate the shear stresses experienced in concrete. Helmuth et al.[40] developed a methodology and identified the hardware required.
3. The temperature of the cement paste. That of the cement paste mixed alone is usually higher than the temperature of the cement paste in concrete. This discrepancy is due to the heat sink that the aggregates represent in concrete. Therefore, the cement paste needs to be correctly cooled during mixing. Helmuth et al.[40] identified the hardware needed to achieve such control.

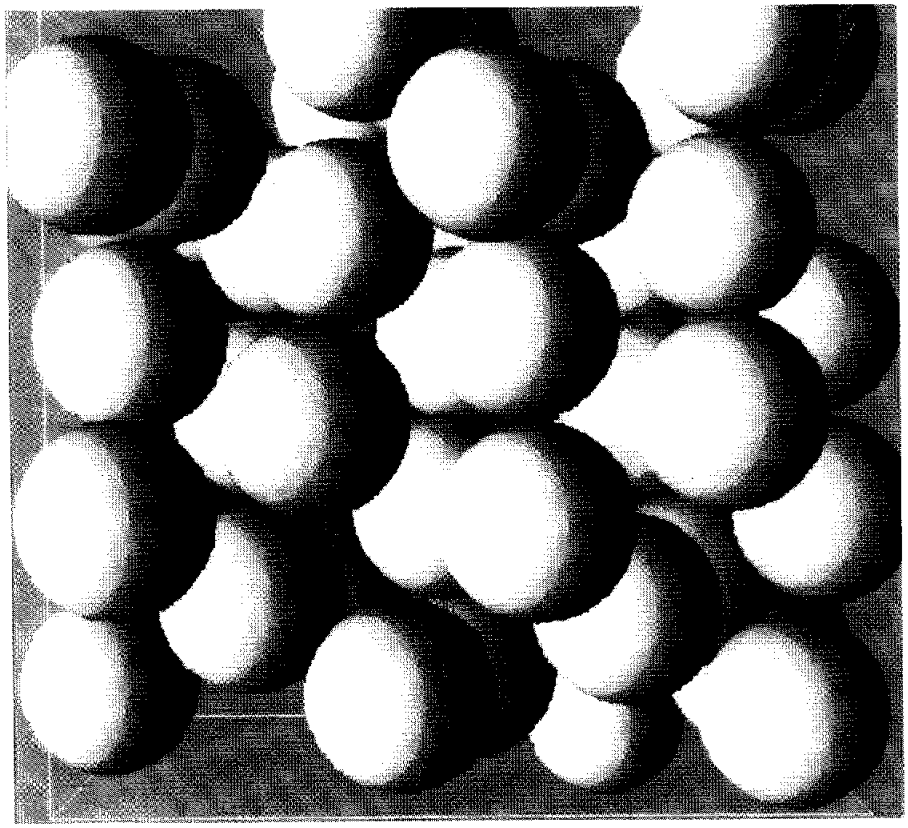

Figure 7. A configuration of densely packed monosized spheres at a solid fraction (volume of spheres/system volume) of 0.5. The system is composed of 52 spheres.

In Fig. 6, the link between the mixture design/cement paste rheology and the concrete rheology is a simulation model. The simulation of concrete flow is based on a mesoscopic model of complex fluids called dissipative particle dynamics (DPD),[41] which blend together cellular automata ideas with molecular dynamics methods. The original DPD algorithm used symmetry properties such as conservation of mass, momentum, and Galilean invariance to construct a set of equations for updating the position of particles, which can be thought of as representing clusters of molecules or "lumps" of fluid. Later modifications to the DPD algorithm resulted in a more rigorous formulation and improved numerical accuracy. An algorithm for modeling the motion of arbitrary shaped objects subject to hydrody-

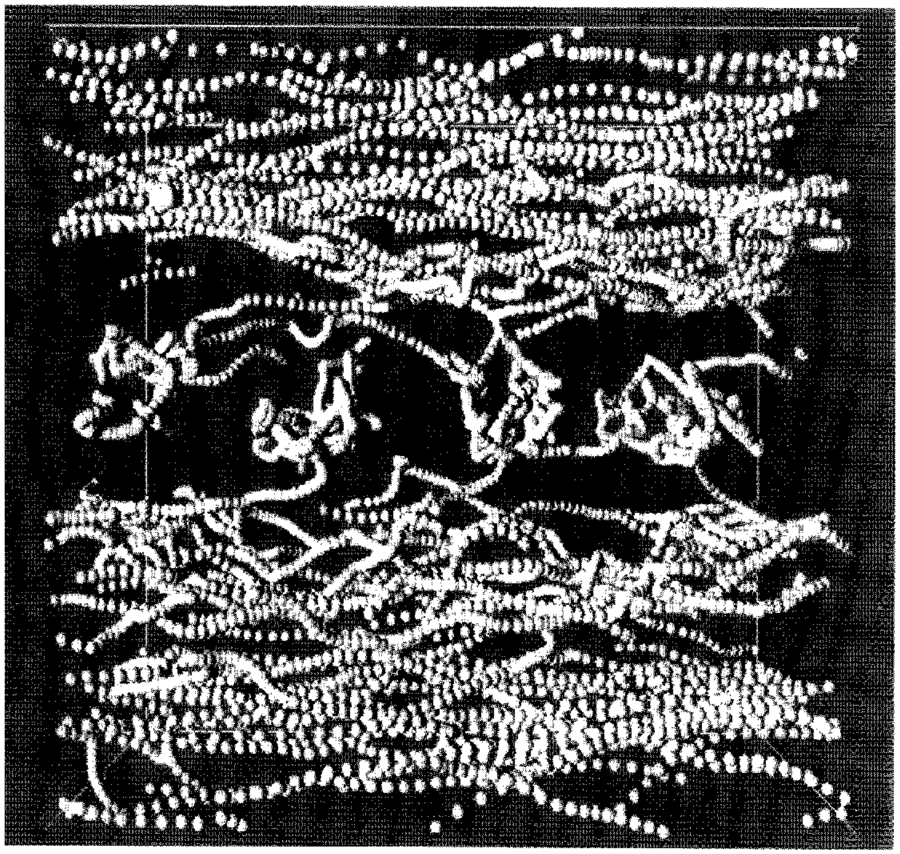

Figure 8. Traces of the centers of spheres moving under an applied shear strain. Near the top and bottom layers, the spheres move along relatively smooth paths. Near the center, the spheres move more slowly as the mean velocity is close to zero in this region.

namic interactions by DPD was suggested by Koelman and Hoogerbrugge.[42,43] The rigid body is approximated by "freezing" a set of randomly placed particles where the solid inclusion is located and updating their position according to the Euler equations.

Martys is currently extending the DPD method to model the flow of concrete as a function of mixture design. The Koelman-Hoogerbrugge procedure for representing rigid bodies is ideally suited for modeling the flow of concrete because this technique easily allows for the representation of wide

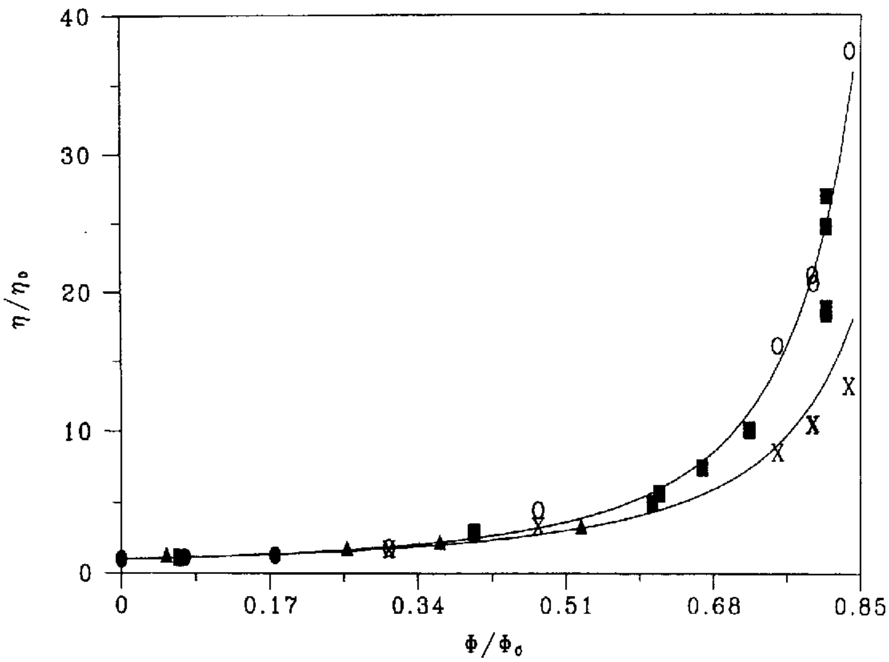

Figure 9. Viscosity, η, of suspension normalized to solvent viscosity, η_0 vs. solid fraction, ϕ, normalized to maximum random packing fraction, ϕ_0. The solid data points (squares and triangles) are computer simulation data, while the Xs and 0s are derived from experiments[44] on sheared hard sphere colloids. The Xs correspond to an infinite shear rate limit whereas the 0s correspond to the zero shear rate limit. The three simulation data points at the highest solid fraction correspond to different shear rates (approximately a factor of ten greater with decreasing viscosity on the figure).

distributions of particle size and shape such as are common in concrete. As a test of the DPD method, Martys studied the flow of a suspension of spheres of equal radii under shear as a function of solid fraction and shear rate. Figure 7 shows a configuration of densely packed spheres at a solid fraction (volume of spheres/system volume) of 0.5. A constant rate of strain is applied in opposite directions at the top and bottom of the system.

Figure 8 shows a trace of the sphere positions over several time steps. Near the top and bottom, the spheres flow more smoothly as they respond to the applied strain. In the middle horizontal region the spheres appear to diffuse more as the velocity is zero on average here. Figure 9 shows the effective viscosity as a function of the solid fraction divided by the maximum packing fraction of random spheres. Note that at higher solid fractions the suspension exhibits shear thinning.

We have begun to examine the effect of varying the distribution of sizes of the spheres. For instance, at a solid fraction of 0.4, 10% of the spheres were replaced with smaller spheres (about one-sixth of the radius) while fixing the total solid fraction. For this simple change in composition the viscosity decreased by about 8%. Similar results were found in physical experiments examining the flow of cement paste where some of the cement particles were replaced by fly ash, which are about a factor of 10 smaller in diameter.

Future studies will include evaluation of the effects of particle shape, as ellipsoids with varying aspect ratios replace spheres in the DPD simulations. We will also investigate the effects of the roughness of the walls on the plastic viscosity and yield stress.

To validate the DPD method, rheological properties should be measured using a rheometer that allows the calculation of the rheological parameters in fundamental units. We are in the process of validating the model with data from concrete and cement paste made using the same raw materials.

Krieger-Dougherty Modified Model

Another approach in predicting the viscosity of concrete from the measurements of cement paste was developed by Struble.[45] She based her model on the Krieger-Dougherty equation. This equation shows that there is an increase in the viscosity of the medium when particles are added. This increase depends on the concentration of the particles:

$$\frac{\eta}{\eta_0} = \left[1 - \left(\frac{\phi}{\phi_m}\right)\right]^{-[n]\phi_m}$$

where $[\eta]$, the intrinsic viscosity, is equal to 2.5 for spheres, ϕ is the volume concentration of particles, ϕ_m is the maximum packing, η is the viscosity of the suspension, and η_0 is the viscosity of the medium. Therefore, if the viscosity of the cement paste and the concentration of the aggregates are known and the maximum packing of the particles is determined, then the viscosity of the concrete can be calculated. Struble used a coaxial rheometer with a gap between the cylinders of 0.7 mm. This gap, although small, is not quite as small as the mean gap between the aggregates in concrete (0.12–0.26 mm).[11] The concrete rheological properties are measured using a rheometer similar to the BTRHEOM. This model has not been validated for concrete. Struble is currently designing a program to validate the model.

Factors Affecting the Rheology of Concrete

As stated earlier, workability and other flow properties are related to the rheology of concrete, which requires at least two parameters, such as the Bingham parameters, for adequate description. What are the principal factors that influence the rheological parameters of concrete? The first factors are the composition of the concrete, including the chemical and mineral admixture dosage and type; the gradation, shape, and type of the aggregates; the water content; and the cement characteristics. The same mixture design can result in different flow properties if secondary factors are not taken into account. These are:

- Mixer type: pan, truck, and so on. These may induce various levels of deflocculation and air entrainment.
- Mixing sequence, that is, the sequence of introduction of the materials into the mixer.
- Mixing duration.
- Temperature.

To determine the rheological characteristics needed for a specific application, the following items need to be considered:

- Method of delivering the concrete to the forms, for example, pumping, bucket.
- Method of consolidation, for example, vibration, tamping, none.
- Type of finishing method.

In considering the application, some of these items will be automatically selected. For instance, if a structure with a very high amount of reinforcement is built, the concrete needs to be self-consolidating because it will be impossible for a vibrator to reach all the concrete.

Another variable that should be addressed is the time dependence of the rheological parameters. This phenomenon is often called slump loss or excessive retardation. The placement of the concrete becomes either difficult (slump loss) or the demolding is retarded and strength development is delayed.[46]

A detailed review of how the various factors mentioned above will influence the flow, and specifically the Bingham parameters, will not be attempted here, but a good review is given by Khayat et al.[47] We will examine in more depth some special cases that are of interest for high-performance concrete usage: pumpable concrete and self-consolidating concrete.

Pumpable Concrete

Pumping is one of the most popular techniques worldwide to transport fresh concrete. Until recently, pumping engineering has been an empirical process. Now, a systematic scientific research is being carried out, which should lead eventually to optimization of concrete-pumping systems.

Practical Problems Dealing with Concrete Pumping

For placing large quantities of fresh concrete, piston pumps are generally used.[48] Concrete is pushed alternately by two pistons acting in cylinders. The first problem to be solved is filling the total length of the pumping network without creating a blockage. Blockage may occur due to leakage (generally at the joint between several pipes, where cement paste may flow out, provoking an accumulation of aggregate) or segregation. Also, after a stop in the pumping process, concrete setting may begin. To avoid blockage, a number of precautions must be taken:

- The network must be concrete tight.
- Fresh concrete should have a minimal susceptibility to segregation.
- A sufficient volume of cement grout has to be pumped before fresh concrete, so that the coarse aggregate particles that are expelled out of concrete by the pumping strokes remain in a suspending fluid.
- The time of practical use of the concrete, during which the consistency is soft enough, should be higher than the time necessary to pump and to place it.

However, even when these conditions are met, the pump may be unable to convey the concrete up to the end of the pumping network at the required flow rate. This emphasizes the need for a thorough understanding and application of rheological principles.

Tribology of the Steel/Concrete Interface

When concrete is pushed through a steel pipe of constant diameter, coarse aggregate particles tend to concentrate in the axis of the pipe, so that a slip motion happens in a thin layer of cement paste located at the steel/concrete interface (see Fig. 10). In general, all shear deformations are located in this zone with the rest of the concrete being transported as a plug. Thus, the study of the interface mechanical behavior, which is the purpose of tribology,[49] must be carried out. It is possible to reproduce the slip phenomenon in the laboratory, using a large-gap coaxial viscometer with a smooth inner cylinder. At low rotation speed, a linear relation is found between shear stress and slip rate, corresponding to the following equation:

$$\tau = \tau_{0,i} + k\,v$$

where τ is the shear stress, $\tau_{0,i}$ is the interface yield stress, v is the slip rate, and k is a viscous interface constant. At higher rotation speeds, the shear deformation tends to propagate into the bulk of concrete. Therefore, a rheometer test must be performed first in order to know the Bingham constants of the concrete considered. Then, a numerical analysis of the experimental relationship between torque and rotation speed in the coaxial viscometer leads to the determination of the two interface parameters. It is especially important to have a gap large enough in order to be able to keep the external concrete layer at rest in the viscometer.

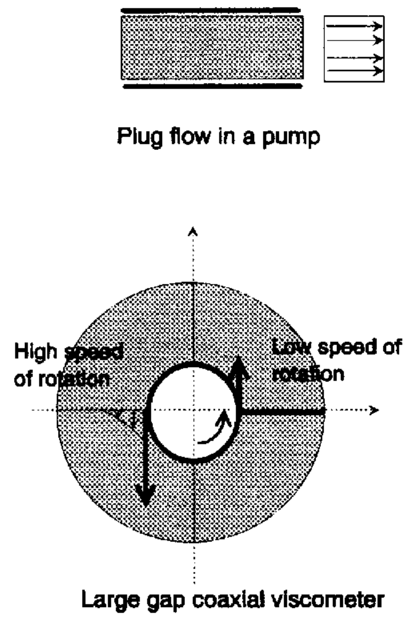

Figure 10. Flow of fresh concrete in a pump and in a large-gap coaxial viscometer. The arrows represent for the speed of particles.

The CALIBE Project

In the CALIBE national project carried out in France from 1995 to 1999, one of the goals was to develop special devices in order to better control concrete pumping. An experimental 150-m (500-ft) pumping network with 12 elbows was installed, in which more than 50 concrete compositions were pumped. The flow rate and the pressure in the concrete versus length were measured during each test. It was found that the pressure versus length patterns were always linear, which is experimental evidence of the validity of the equation in the previous section. Moreover, the rheological

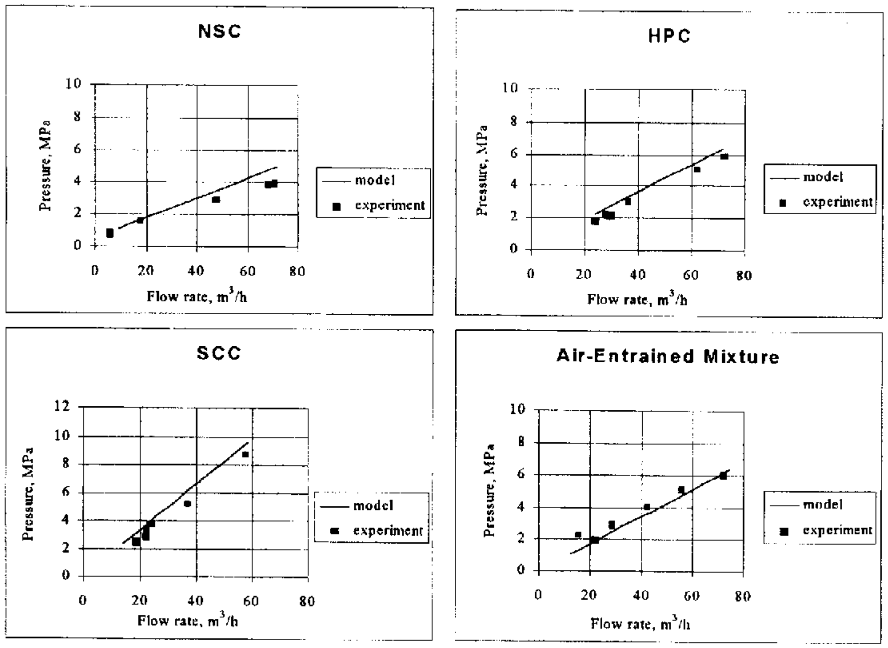

Figure 11. Comparison between experiments and theory from the CALIBE pumping tests.[49] NSC: normal-strength concrete (w/c = 0.53, slump = 190 mm); HPC: high-performance concrete (w/c = 0.33, slump = 240 mm); SCC: self-compacting concrete (w/c = 0.25, slump = 270 mm); air-entrained mixture: 10% air (w/c = 0.40, slump = 110 mm).

parameters measured with the BTRHEOM rheometer and the interface parameters assessed with a large-gap coaxial viscometer were used to predict the relationship between pressure and flow rate, accounting for the total length and diameter of the pipes. The agreement between a calculation and experiment was found to be very satisfactory (see Fig. 11). In addition, it was found that elbows play a negligible role in the pressure losses, but are important only to the extent to which they may facilitate blockage.

Self-Consolidating Concrete

Self-consolidating concrete (SCC) can be placed without vibration and flows easily in very narrow gaps. It is widely used in Japan and has recently been used in Europe, but is used very little in the United States. Nevertheless, it must be expected that SCC will be used more in the future because of its good performance, such as ease of placement. Due to its rheological properties, the expense of vibration can be eliminated while still obtaining good consolidation. Heavily reinforced structures can be designed and built using this material. According to Kim et al.[50] the major factors defining SCC are rheological properties of the cement paste, the volume ratio of paste to coarse aggregates, and the unit volume of the coarse aggregates. If we examine the rheological properties that characterize SCC, the yield stress must be zero or very low and the viscosity must be controlled. The range of viscosities needed to obtain good consolidation without vibration and without segregation has been the topic of various papers.[50–53] Most of them used semi-empirical tests such as the filling ability test to characterize concrete flow behavior. The properties of the cement paste or the mortar of SCC were found to be very important to avoid segregation. If the viscosity of the mortar is high enough, the coarse aggregates will be supported by the mortar, thus avoiding segregation. Often, viscosifiers such as welan gum or mineral admixtures are added to increase the viscosity of the paste, without significantly increasing the yield stress.[53,54] NIST research should provide a tool for use in linking cement paste rheology to the performance of SCC and lead to a full specification for SCC.

Conclusion

This review has presented recent developments in the rheology of concrete, including:

- Tests that are commonly used.
- Models and simulation of concrete flow.
- Factors that affect the rheological properties of concrete.
- Examination of two special applications: pumpable concrete and self-compacting concrete.

Concrete workability can be characterized in terms of the rheological parameters in either the Bingham or Herschel-Buckley equation. The theory exists but the measurements are not easy to obtain. The flow of a granular material such as concrete needs to be defined by at least two parameters, for instance, yield stress and plastic viscosity, as defined by the Bingham equation. While there are numerous tests to characterize the flow of concrete, few give results in fundamental units and therefore the measured rheological properties of concretes, using different tests, cannot be directly compared. Recently, new tests have attempted to characterize concrete using a more fundamental approach. While not all researchers agree on which test is the most suitable for the wide range of concretes in use today, all agree that tests that give results in fundamental units and that can be used on a construction site are needed.

Three different models allow the prediction of the flow of concrete from the mixture composition. The approaches of these models are based on:

- Packing density of all solids included in concrete, that is, cement, sand, and aggregates.
- Simulation of granular flow using dissipative particle dynamic methods.
- Application of the Krieger-Dougherty equation.

Factors affecting the flow of concrete extend beyond mixture composition, with processing and the environmental factors also affecting rheological behavior.

The application of rheological principles to pumpable concrete and SCC seems to be a particularly promising field of investigation. The prediction of the pressure/flow rate relationship in pumping networks is critical for today's construction industry. Such a calculation appears possible, based upon scientific measurements of the concrete flow, but of interaction at the steel/concrete interface, which can be readily performed with a large-gap coaxial viscometer. In the case of SCC, the properties are heavily based on the viscosity of the cement paste and of the concrete. These properties must be properly characterized to be able to design concrete mixtures with improved performance.

Progress in the areas discussed in this review will facilitate specification of concrete based on performance instead of prescriptive criteria. Research is being performed to validate the models and simulations that will provide new tools for use in optimization of day-to-day processing of concrete in ready-mixed concrete plants and other concreting operations.

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