RHEOLOGY OF FRESH CONCRETE

Leslie Struble, Associate Professor
Richard Szecsy, Graduate Research Assistant
Guy Salinas, Graduate Research Assistant
Department of Civil Engineering, University of Illinois

ABSTRACT

Much is known about the rheology of particulate suspensions, including cement paste and concrete. Recent studies of cement paste using specialized rheological techniques have provided considerable information about the relationships between flow behavior and microstructure, including the effects of hydration on yield stress. Concrete workability is routinely characterized using the slump test, but rheometers are available that provide a more complete characterization of flow behavior. This paper presents some preliminary rheology results for concrete, both ordinary concrete and concrete designed as an airport pavement overlay, and discusses how rheological measurements might be used in concrete technology. Many technological advantages are provided by full characterization of flow behavior, particularly that it provides access to the large body of knowledge concerning the flow behavior of suspensions.

INTRODUCTION

The workability of concrete is usually and routinely assessed by measurement of slump. Much can be gained, however, from detailed studies of concrete flow behavior. This paper reviews the measurement of concrete flow behavior, presents some preliminary results measured in our laboratory on both ordinary concrete and concrete for pavement, and discusses some advantages of rheological measurements over the much simpler slump test. A related paper (*1*) was presented recently at an ASCE conference and some results from that paper are included here. Additional experimental details are provided elsewhere (*2*).

BACKGROUND ON RHEOLOGY

The principal rheological parameters are shear stress (τ) and strain rate ($\dot{\gamma}$), which are calculated from measurements of torque and flow rate. Viscosity (η) is defined as $\eta = \tau / \dot{\gamma}$. Several types of flow behavior are recognized (Figure 1). Newtonian behavior has a linear relationship between stress and strain rate with zero stress at zero strain rate. In plastic behavior (also called Bingham), a certain level of stress (called the yield stress) is required to initiate flow, while the relationship is linear above the yield stress. In pseudoplastic (or shear thinning) fluids the viscosity decreases as strain rate increases, while in shear thickening fluids the viscosity increases as strain rate increases.

The principal factors controlling the flow behavior of particulate suspensions are the volume fraction of solid particles and the extent to which the particles are flocculated. A dilute suspension typically shows Newtonian flow behavior. Increasing the volume fraction of solids causes a considerable increase in viscosity and the development of modest plastic or pseudoplastic behavior. Flocculated particles either form discrete aggregates or a gel, a continuous three-dimensional network; and flocculation (especially gelation) increases the yield stress considerably. If the forces responsible for flocculation are weak, the yield stress provides sufficient disruption of the flocculated network that the suspension flows with a fairly constant viscosity, producing plastic behavior. If the forces are stronger, the breakdown is not complete and the remaining flocculation is progressively disrupted as the strain rate is increased further, producing pseudoplastic behavior. Rheometers for measuring flow behavior must provide simple shear flow and a simple stress field in order to calculate stress and strain rate. Often some type of rotational rheometer is used, employing coaxial cylinders or parallel plates. The sample sits between the cylinders or plates, one of which rotates, and torque and rotational speed are measured. In order to provide a uniform strain rate, the gap must be narrow compared to the cylinder diameter. The gap in a typical laboratory rheometer designed for use with liquids or colloidal suspensions is 1 mm or smaller. On the other hand, it is necessary that the gap be considerably wider than the diameter of the largest particles in a suspension. With a wide gap, calculation of stress and strain rate require assumptions concerning these parameters over the range of shear across the gap. These factors make the design of a concrete rheometer rather complicated.

CEMENT PASTE

The flow behavior of cement paste can be studied in considerable detail using sensitive, precise, narrow-gap laboratory rheometers. Paste behavior has been studied in this way for several years, including work in our laboratory. Two highly specialized techniques developed for viscoelastic materials, creep/recovery and oscillatory shear, have provided considerable insight into the microstructure of cement paste and how this microstructure changes due to hydration reactions. Some of these results were reviewed recently (*3*). These studies show that the flow behavior of cement paste is controlled by the same factors that control any other suspension: the concentration of particles and the extent to which particles are flocculated. Cement paste shows modest pseudoplastic flow behavior at low water-to-cement ratio (w/c) and Newtonian behavior at high w/c. Reducing the w/c increases both viscosity and yield stress. Cement paste is flocculated unless a water reducer or superplasticizer is added to disperse it; flocculated paste shows pseudoplastic behavior, while dispersed paste is Newtonian (unless its w/c is low). The unique factor affecting flow behavior of cement paste is hydration, which causes a considerable increase in yield stress, until (at the end of the dormant period) the paste begins to lose its fluid properties.

CONCRETE RHEOMETERS

As already noted, it is difficult to design a rheometer for use with concrete. The particles range from submicron to centimeter, and the size of the largest particles necessitates a wide gap and therefore an extremely wide cylinder diameter (to maintain a small relative gap). Because these conditions are impossible to meet, the calculation of stress and strain rate are usually uncertain. In a wide-gap rheometer the stress is not uniform, so a plastic material such as concrete is likely to yield first at the wall of the moving cylinder. This condition is known as slip and is a major source of error in rheology of concrete and other suspensions. Ribs or grooves are often used on the cylinder wall to minimize slip, but these modifications complicate the flow making the calculation of stress and strain rate suspect.

Another challenge in designing a concrete rheometer is to prevent segregation during the test. A plastic material has a lower viscosity at high strain rates, so flowing concrete provides less resistance to settling of coarse aggregate under gravity. Rheometers are often designed to prevent settling, but these specialized designs also give rise to complicated flow fields.

Several rheometers are commercially available for concrete studies. The oldest is the Tattersall rheometer, described in some detail by Tattersall and Banfill (*4*) and manufactured by Wykeham Farrance in the UK. It is basically a coaxial cylinder design with a large gap and utilizes simple technology to measure torque and mixing speed. The inner cylinder has an interrupted helical design to reduce segregation. The rheometer is designed to measure torque and mixing speed, though an empirical calibration has been described (*4*, pp. 104-111) for computing stress and strain rate. A more recently developed rheometer is the BML, developed by Wallevik and Gjørv (*5*) and manufactured by the Con Tec Group in Iceland. It is computer-controlled and also utilizes a coaxial cylinder design. To prevent slip, ribs have been added to the inner and outer cylinder, or a bladed impeller may be used in place of the ribbed inner cylinder. Another computer-controlled, coaxial cylinder rheometer was developed by Beaupré and Mindess (*6*) and is available from the University of British Columbia in Canada. In this rheometer the inner cylinder is replaced by a planetary impeller, presumably also giving rise to a complex flow field. A somewhat different rheometer, the BTRHEOM, was developed by de Larrard and colleagues (*7*) and is available from the Laboratoire Central des Ponts et Chaussées in France. This computer-controlled rheometer utilizes a parallel plate geometry in which each plate consists of rather widely spaced vanes to prevent slip. Of these four rheometers, only the BTRHEOM claims to provide a geometry suitable for computing stress and strain rate.

MATERIALS

We have measured the flow behavior of several concrete mixes, all falling in the range of ordinary concrete. In this work we explored the effect of changing sand content (while keeping the total aggregate amount constant) and changing the type of coarse aggregate (natural river gravel versus crushed stone). We have also measured the flow behavior of concrete designed as an overlay for an airport pavement.

The materials used in these mixes were a Type I portland cement, a typical concrete sand (fineness modulus), and a typical concrete coarse aggregate. Most mixes utilized a 25 mm maximum coarse aggregate (No. 57), either a river gravel or a crushed limestone; the concrete overlay utilized a finer sized aggregate (No. 8). The concrete overlay also contained a Class F fly ash, a densified silica fume, and a naphthalene formaldehyde-based superplasticizer. The mixes fall into three general categories:

- A, varied the relative amounts of sand and coarse aggregate, all with river gravel as the coarse aggregate, with the same amount of total aggregate, and with the same w/c, 0.45,
- B, varied the type of coarse aggregate, all with the same amount of total aggregate, with the same relative amount of sand (40% of the total aggregate) and with the same w/c, 0.45,
- C, overlay mix, w/s 0.26, superplasticizer (2% by weight of cement), smaller sized coarse aggregate, and partial replacement of cement by fly ash and silica fume.

The concrete mixes are described in Table 1.

PROCEDURE

Our laboratory is equipped with a Tattersall rheometer that has been modified to utilize the geometry of the BTRHEOM instrument. Our procedure is to mix concrete in a pan mixer, transfer it to the rheometer, then mix at a series of speeds (from high to low) while measuring torque. Stress and strain rate are computed from measured torque and mixing speed using the equations developed by Hu et al. (8). The vaned plates make it possible to examine the concrete after testing for evidence that aggregate has settled; we have observed no segregation in the concretes we have tested, which are typical of concretes used in construction.

RESULTS

Typical flow curves for concrete and cement paste are shown in Figure 2. The concrete is from Category B with limestone as the coarse aggregate. The paste has the same w/c as the concrete. Both show plastic behavior. It is interesting to note that the strain rate is quite low compared to the strain rate typically employed to study colloidal suspensions (including cement paste) in a narrow-gap coaxial cylinder rheometer, the strain rate in the concrete rheometer is only a few inverse seconds, compared to several hundred inverse seconds for typical paste studies. In the concrete rheometer the plastic viscosity was around 90 Pa·s for concrete and around 20 Pa·s for cement paste. The paste value was much higher than what was obtained for the same paste using a laboratory rheometer (coaxial cylinder, 0.7 mm gap), which was around 0.8 Pa·s at 4 s^{-1} (2). The yield stress was 500 Pa for concrete and 225 Pa for paste. Again, the paste value was higher than values for similar paste using a laboratory rheometer, where the yield stress was around 20 Pa.

Aggregate has a major effect on concrete rheology. Concrete has a much higher viscosity and yield stress compared to paste (Figure 2), and these values increase as more aggregate is added. Both yield stress and viscosity are reduced by making the aggregate grading more dense, so both parameters reached a minimum value at an intermediate sand content (Figure 3) where the aggregate packs most densely. Aggregate shape is also important; crushed stone gave somewhat higher yield stress and slightly higher plastic viscosity than smooth gravel (Figure 4). Other parameters affect concrete behavior in the same way they affect paste behavior: a higher water content reduced both yield stress and viscosity, and water-reducing admixtures reduced the yield stress.

We have just begun to study the rheology of airport pavement overlays. Preliminary rheological measurements have been carried out on concrete suitable for use as an overlay. These results are shown in Figure 5. The overlay concrete had a yield stress of 550 Pa and a plastic viscosity of 105 Pa·s. Future research is planned to provide mix designs for high performance concrete that produce suitable rheological behavior for use as overlays.

DISCUSSION - WHY MEASURE CONCRETE RHEOLOGY?

It has been recognized for some time that concrete is not a Newtonian fluid and it is therefore necessary to characterize its flow behavior at various strain rates. It is widely accepted that concrete shows plastic behavior, so two parameters (i.e., yield stress and plastic viscosity) are required to characterize its flow. The yield stress measures how hard it is to start the concrete flowing and the viscosity measures how fluid is the concrete once it is flowing. Slump, on the other hand, provides only one parameter and therefore does not provide a complete characterization of the flow behavior. We have found, as have many before us, that slump correlates well with yield stress, but provides no information concerning viscosity at high strain rate. In fact, concretes with the same slump often have quite different viscosities.

Another consideration is that rheology provides a more precise characterization of rheology. Slump is a rather ambiguous test and its value is easily altered by minor changes in the procedure.
The most important consideration, in our view, is that rheology provides access to the large body of knowledge concerning the flow behavior of suspensions. Only by measuring rheological parameters (stress and strain rate) can we take advantage of this knowledge. The use of empirical measures such as slump prevent us from understanding concrete as a reactive particulate suspension. Thus a full characterization of concrete rheology offers many advantages over the slump test.
Links, if they exist, between concrete and cement paste flow behavior are particularly important because the behavior of cement paste can be measured with considerably greater accuracy and precision. We are actively exploring these links through experiments and mathematical models. If such links can be established, it may be possible to predict concrete behavior using the much more detailed and specialized measurements that are possible for paste. Our studies of paste rheology have demonstrated tests to measure evolution in yield stress during setting, but such tests cannot be applied to concrete. So linking concrete and paste would allow use of paste data to predict concrete behavior as a function of time. This approach could also be used to study chemical and mineral admixtures in concrete, which affect only the paste portion. This is the focus of much of our research on concrete rheology.

A general understanding of concrete rheology would allow certain broader rheological principles to be incorporated into concrete technology. For example, it would be possible to establish a criterion for set based on some meaningful stress level. It would also be possible to establish a minimum yield stress to prevent aggregate segregation. Finally, concrete can be designed to provide specific rheological values.

In order to utilize rheological measurements, it is important to understand what levels of yield stress and viscosity provide suitable performance in the field. If the strain rates associated with various processing operations (mixing, pumping, vibration, finishing) were known, then the constitutive behavior of concrete could be used to predict performance. Such prediction is not possible with slump, because slump describes behavior only at a low strain rate.

Many examples can be cited of how concrete rheology relates to field performance. For example, low yield stress means that concrete tends to segregate. High yield stress means that more power is required to start the mixer. Concrete with a very high yield stress may even not become fluid in an ordinary mixer. Vibration overcomes a high yield stress and causes a mix to flow. Even with vibration, ease of consolidation depends on viscosity; concrete with too high a viscosity does not flow and is difficult to pump, and concrete with too low a viscosity tends to segregate during vibration. The challenge, of course, is to determine the target values for these parameters.

List of Figures and Tables

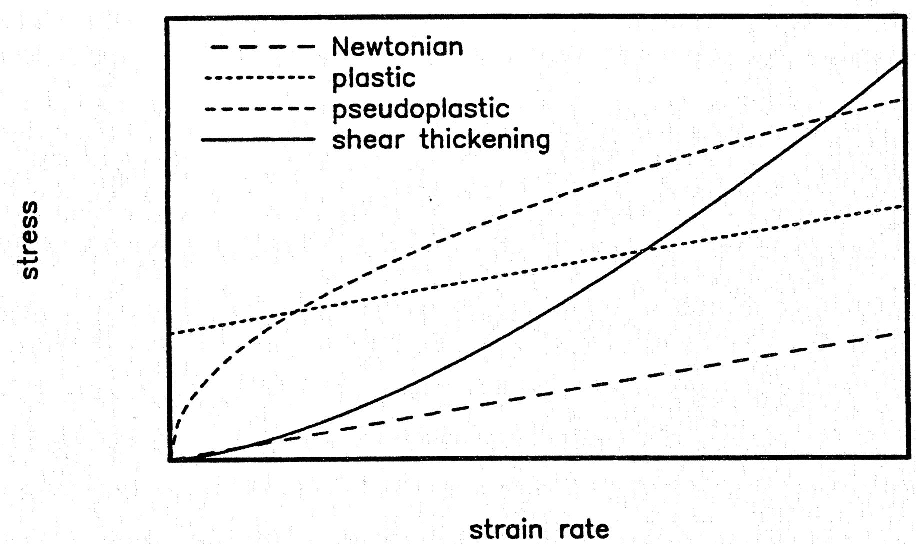

Figure 1. Types of flow behavior.

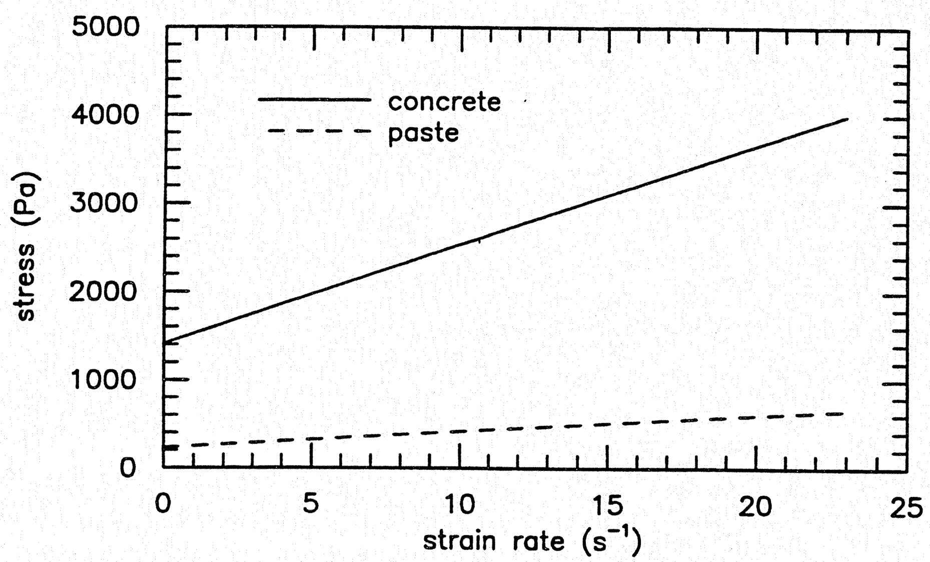

Figure 2. Flow curves for concrete and cement paste using concrete rheomete

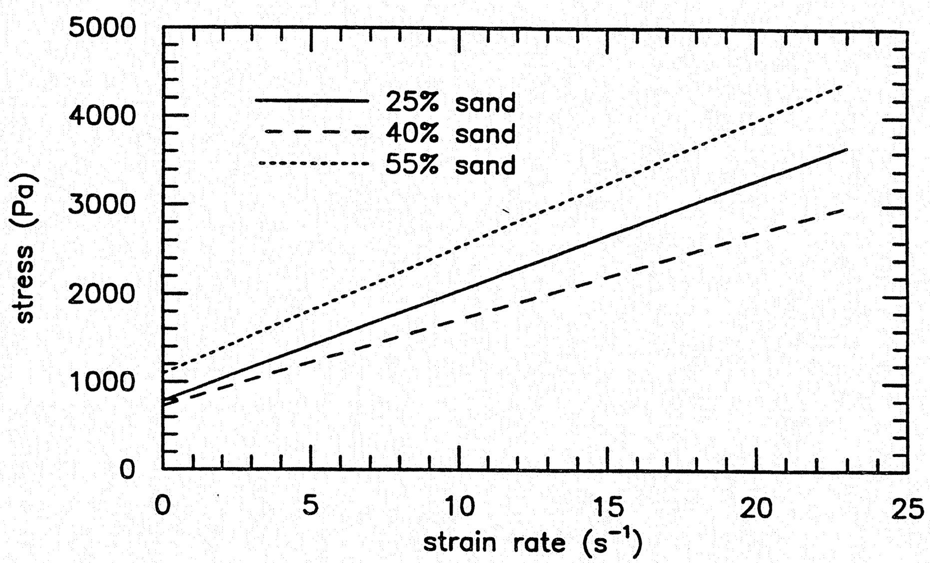

Figure 3. Flow curves for concretes with different sand contents.

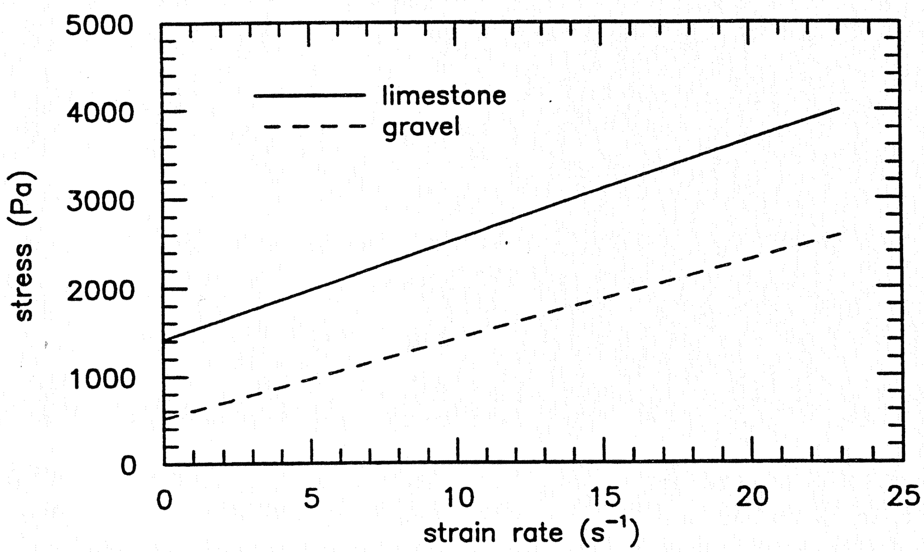

Figure 4. Flow curves for otherwise similar concretes with different aggregate types.

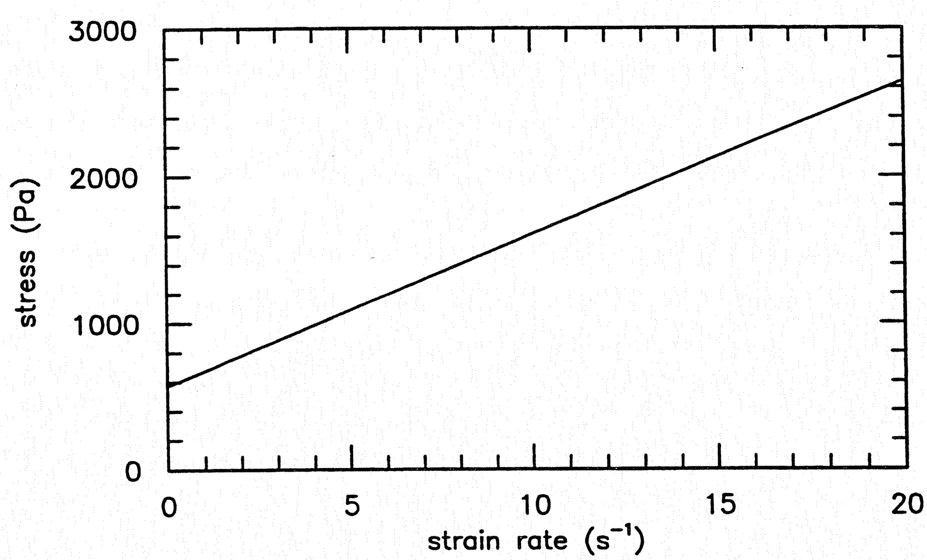

Figure 5. Flow curve for concrete designed as a pavement overlay.

Table 1. Concrete mix proportions

	A			B		C
	20% sand	35% sand	55% sand	gravel	stone	overlay
water (% by weight)	10	10	10	10	9	8
cement (% by weight)	21	21	21	21	21	23
fly ash (% by weight)	0	0	0	0	0	3
silica fume (% by weight)	0	0	0	0	0	5
fine aggregate (% by weight)	14	24	38	28	28	24
coarse aggregate (% by weight)	55	45	31	42	42	38
air (% by volume)	nd	nd	nd	nd	nd	5.0
slump (mm)	240	230	105	175	110	65

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