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Connection between the Rheology of Concrete and Rheology of Cement Paste


by Chiara F. Ferraris and James M. Gaidis

Although the workability of concrete is one of the concerns in any application of the material, many research investigations are directed toward examination of only the paste fraction. This paper presents a step toward connecting concrete rheology and cement paste rheology by introducing a new parameter, the "gap," which is related to the spacing between aggregates present in concrete. This is in addition to the more usual parameters, such as yield stress, shear rate, and viscosity.

Data obtained on cement pastes using a parallel plate rheometer are presented and discussed. The main conclusions are:

1. Maintaining constant rotation speed of the rheometer plates (which represent aggregate in concrete) requires more force as the plates are brought closer together. At small separations, a yield strength can be developed in cement paste, in contrast to Newtonian fluids.

2. Addition of dispersing agents (e.g., superplasticizers) has an unusually large effect at small separations.

3. The measurement of paste rheology as a function of the gap between parallel plates (simulating aggregate) is a more refined approach to predicting concrete flow because it combines observations on the properties of paste with attention to the volume fraction of paste. Neither the properties of paste nor its volume fraction alone give alone a reliable indication of concrete flow.

Keywords: aggregates; **cement pastes; concretes;** plasticizers; **rheological properties;** workability.

The cost of placing concrete is critically dependent on its workability, and uniformly good properties in the hardened structure are possible only with adequate flow and without segregation. The importance of workability of concrete has been universally recognized,[1] and is well known to be affected by variables including water-cement ratio (*w/c*), aggregate gradation, and admixture type and dosage, among others. Good mix design[2] takes into account the aggregate, water, and air fractions; however, it is almost always necessary to test flow in trial batches. This is because concrete flow is very sensitive to the volume fraction of paste,[2] and higher paste volume fractions can lead to segregation. Slump is the usual test method for measuring workability or consistency.[3] The slump test has been criticized for many years, but it will endure until a practical replacement is found.

There have been many investigations of the slump test and its parameters, as well as many attempts to circumvent its difficulties.[4] Paste has been the subject of most of the rheological examinations because it seems to be the most important rheological factor in concrete.[5,6] Even so, there is a broad feeling that establishing a connection between concrete rheology and cement paste rheology is far beyond our abilities.[1] Although paste tests can be set up to imitate slump on a smaller scale (e.g., the mini-slump test[7]), results are of limited usefulness because concrete slump depends on more than just the rheology of the paste fraction. This can be observed in a qualitative way by squeezing a drop of cement paste between microscope slides or other flat plates. At first the paste will act like a lubricant, but as the drop is squeezed thinner and thinner, the graininess of the suspension becomes evident and finally the surfaces lock up and will not slide with finger pressure. We suggest that this friction effect in thin layers (a particle-wall interaction, or "dry" friction, rather than viscosity, or "liquid" friction) is the major source of high yield strength (low slump) in concrete.

We have investigated cement paste flow in thin specimens representing the paste fractions in concrete to describe the behavior of paste in field concrete and ultimately to predict the behavior of the concrete from the behavior of the paste. This represents an abandonment of the usual requirement to make measurements on a thickness of fluid much greater than the largest particle contained in it. The fluid thickness, which we call the "gap," is related to the spacing between aggregates. The gap may be the parameter which permits shear stress and viscosity measurements at various shear rates on paste to be applied to prediction of concrete

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*ACI member **Chiara F. Ferraris** has been a research physicist for W. R. Grace & Co.-Conn., Columbia, MD, since 1987. She recieved her PhD from Ecole Polytechnique Federale de Lausanne, Switzerland, in 1986. Her interests are in shrinkage, rheology of concrete, and test-method development for mortar and cement paste.*

***James M. Gaidis** is a research associate with W. R. Grace & Co.-Conn., Columbia, MD, with interests in product development for the construction specialties area. More than three dozen patents and publications in cement, concrete, admixture, and waterproofing technologies have resulted.*

flow. In this work, we describe the rheological behavior of paste to establish the effects of thickness, admixtures, and shear rate.

RESEARCH SIGNIFICANCE

The rheological properties of fresh concrete and cement paste are complex in different ways, and measurements on paste are not always predictive for the corresponding concretes. We have found that conditions (small gap) can be established that are not typical of rheological measurements on cement paste, but which are defensible on the grounds of better representing the environment of paste in concrete. This approach should permit a better understanding of the factors controlling the rheology of cement paste and fresh concrete.

Brief theoretical background

Newton's equation [Eq. (1)] does not adequately describe the behavior of fresh concrete. A better approximation is Bingham's equation [Eq. (2)], which introduces the concept of yield stress. Neither equation suggests how the flow of concrete may be related to the flow of paste, especially when the paste may show no yield strength while the concrete shows a most definite yield strength. We should remember that concrete is quite complex, consisting of a concentrated suspension of solid particles (aggregate) in a fluid (cement paste) which is itself composed of a concentrated suspension of solid particles (cement grains) in a fluid (water—either with or without admixtures). Fig. 1 gives an idea of the complexity of the system as seen by Cheng:[8] the reference to particle effects and characteristics is related to our investigation

$$\tau = \pi\gamma \qquad \text{(Newton)} \qquad (1)$$

$$\tau = \tau_0 + \pi\gamma \qquad \text{(Bingham)} \qquad (2)$$

where

τ = shear stress
π = viscosity
γ = shear rate
τ_0 = yield stress

The rheological description of concrete is complicated because it is not a dilute suspension where interaction between particles (and walls) is assumed negligible, nor is it a concentrated suspension that is homogeneous even on a small scale.[9,10] Some investigators have used fitting parameters without physical or chemical derivation,[11,12] but these must be experimentally established for every mix. Modeling by finite element techniques has been applied to the slump test,[13-15] but there is no direct relation to concrete composition.

A new parameter: The gap

Cement paste, the lubricant between aggregates in concrete, strongly affects concrete flow. Composition factors of cement paste, such as *w/c* and the presence of admixtures, are known to influence concrete workability strongly. It is also known that changing only the paste volume fraction in concrete can change the concrete flow, even when the paste composition remains the same. It occurred to us that the characteristics of the paste might be changing depending on the aggregate spacing, and this led us to investigate the response of the paste at thicknesses of paste ("gaps") comparable to those present in commercial concrete.

This concept is related to the practice of using the minimum cement paste volume needed to obtain the flow desired. The paste volume chosen results in a wide enough spacing between aggregates so that aggregate-aggregate interaction (friction leading to a yield stress in concrete) is reduced to the desirable level by the lubricating effect of the paste. One of our findings is that the paste does not exert a constant effect for all gaps, nor is it a smooth function of 1/gap, as might be expected for Newtonian fluids, but is rather more abrupt. The concept of gap has been until now an intuitive parameter that has not been investigated or measured. This paper reports the first systematic measurements of this parameter.

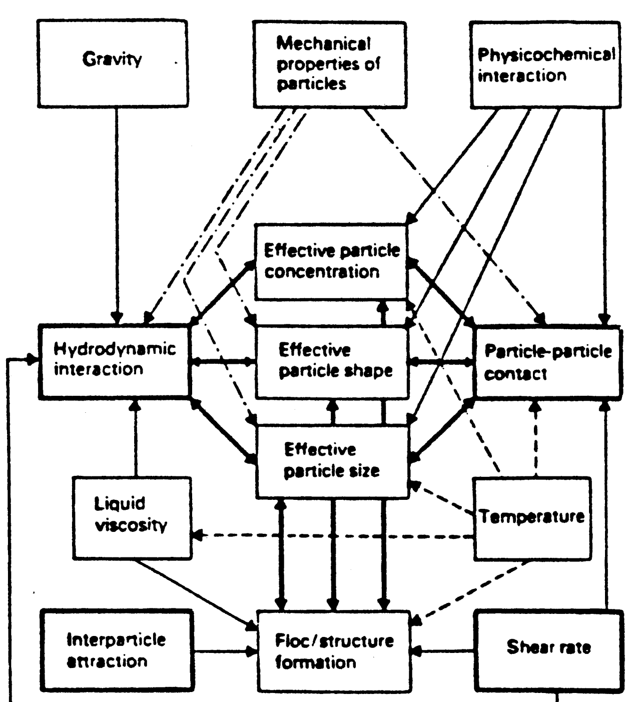

Fig. 1—Interplay of the three categories of interactions and factors affecting suspension viscosity[8]

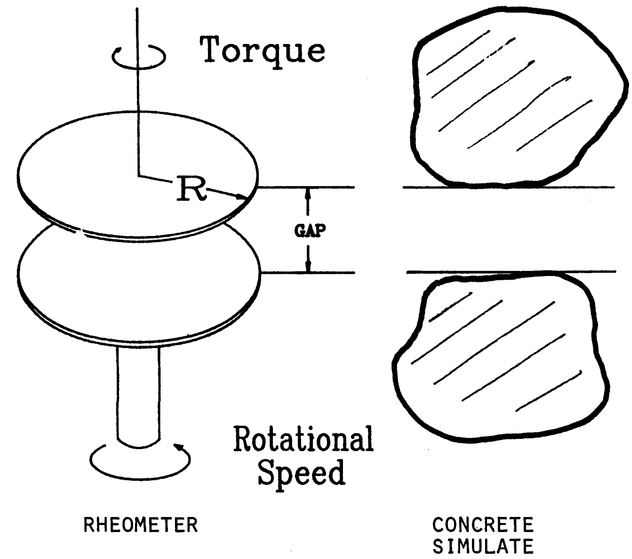

Fig. 2—Rheometer plate configuration compared to concrete

EXPERIMENTAL

Materials used

The cement used was ASTM Type I. Only one cement was used in this study. The *w/c* was varied between 0.40 and 0.55. These limits were selected because higher *w/c* led to bleeding, whereas lower ones led to mixing problems in pastes.

The admixtures used were:

- Naphthalene sulfonate formaldehyde condensate, sodium salt.
- Melamine sulfonate formaldehyde condensate, sodium salt.
- Sodium polyacrylate (mw 2000).

The admixture dosages were usually between 0.4 and 0.6 percent of solids based on cement weight. They were usually added predissolved in the mix water, but some tests were conducted with delayed addition.

Equipment

The instrument used was a fluids rheometer with flat parallel plates with 50-mm diameter. The distance between the titanium plates simulates the gap between aggregates in concrete. We used gaps varying from 0.07 to 0.6 mm. The average paste thickness in concrete is considered to be about 0.2 mm.[16]

Fig. 2 shows the plate configuration. The bottom plate is rotated at a controllable speed, and the gap between plates was measured by an integral micrometer. The torque induced on the upper plate by the material under shear was automatically recorded.

The experimental procedure used is as follows:

1. A measured volume of cement paste, corresponding to the exact volume between the plates for a given gap, was put on the lower plate while the upper one was in the raised position. This insured good reproducibility.

2. Special care was taken to remove the air entrapped during the transfer of cement paste onto the plate. This reduced the scatter of the data because the torque is strongly affected by the position of air bubbles. To obtain reproducible data it is important that the material be homogeneous. Bubbles act as inhomogeneities. The following mixing sequence led to a bubble-free cement paste mixture:

   0 min—Add water to cement in vacuum flask.
   1 min—Turn on vacuum to about 100 mm Hg.
   4 min—Mix at high speed with magnetic stir bar.
   6 min—Keep under vacuum; stop mixing.
   8 min—Mix at slow speed (under vacuum).
   9 min—Mix at high speed for 1 min (under vacuum).
   10 min—Admit air to flask and remove paste carefully with a syringe.

3. The upper plate was lowered very carefully to obtain the desired gap. Downward pressure was always applied, so the gap never increased. To achieve very small gaps, the lower plate was rotated while lowering the upper plate to help distribute the paste evenly between the plates.

4. A moistened cover over the two plates was used to prevent evaporation of water during the test procedure.

5. Shear was applied for 30 seconds (shear rate 10 s^{-1} at the perimeter of the plate) to evenly distribute the paste.

6. At a given time, the shear rate was scanned from 0.1 to 100 s^{-1} (with 15 measurement points) and the torque was measured. If a second curve was desired at a later time the paste was left in place. Typically, elapsed times were 20 and 40 min after adding water to cement.

7. All the measurements were repeated with identical samples four times and averaged. The curves of average points were compared to determine the influence of gap or composition on torque.

Measurements and data

Fig. 3 shows the effects of *w/c* on the minimum gap obtained in a Type I cement paste. The minimum gap was defined by a safety device which shut down the rheometer if torque exceeded 1.5×10^{-2} Nm (0.13 lb-in.). The points in Fig. 3 represent the smallest gap at which at least four series of shear rate scans could be made without exceeding the 1.5×10^{-2} Nm limit; although scans at smaller gaps were occasionally successful, the success rate for them was typically less than 50 percent. We observed that the addition of superplasticizer lowers the minimum gap at constant *w/c*.

Fig. 4 shows the effect on torque of changing the gap over the range from the minimum all the way up to 0.6 mm (0.024 in.) at one maximum shear rate (39 s^{-1} at the perimeter). A curve calculated for a Newtonian fluid of varying thickness (with torque = 0.05×10^{-2} Nm at 0.15 mm thickness) is also plotted for comparison. For a given gap, the same reduction in torque can be achieved either by the addition of water or by the addition of superplasticizer. At a constant *w/c*, the curves for a cement paste with superplasticizer are shifted from a curve without it.

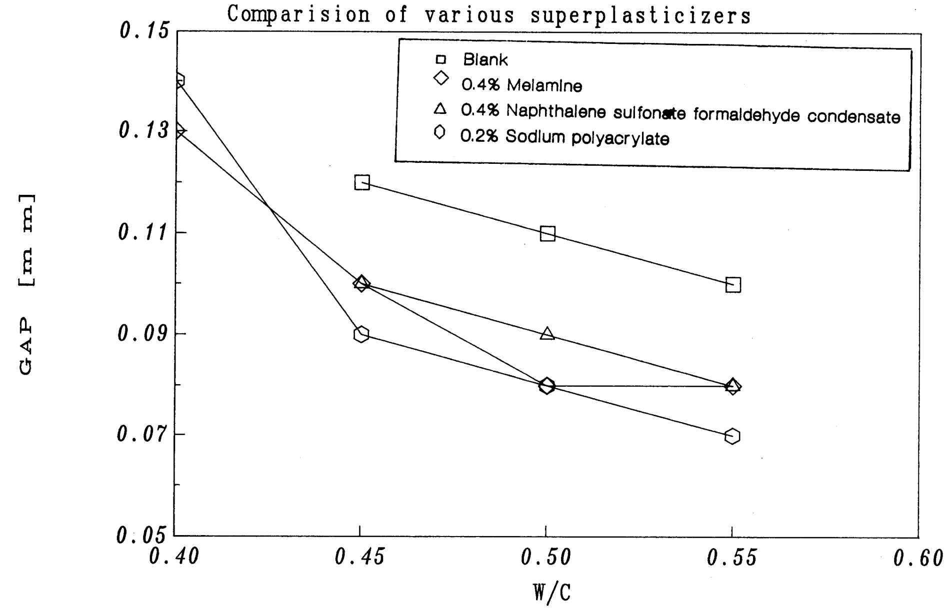

Fig. 3—Relation between minimum usable gap and w/c *for cement paste*

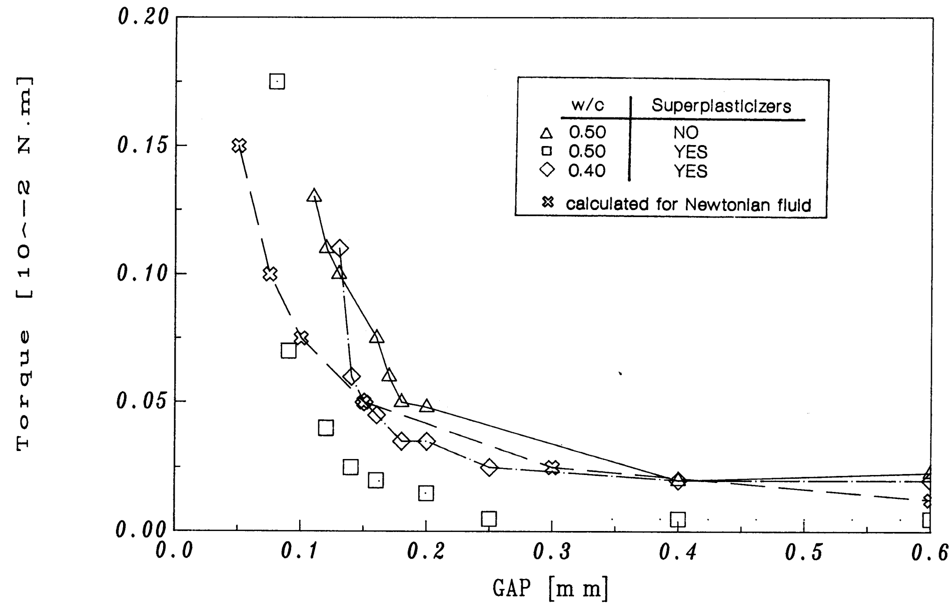

Fig. 4—Influence of gap; superplasticizer used is naphthalene sulfonate formaldehyde condensate

Fig. 5 shows the effect on torque of varying shear rate from 0.1 to 100 s^{-1}, using a Type I cement paste with various dosages of naphthalene sulfonate superplasticizer, at a gap of 0.4 mm. The lowest dosage tested (0.4 percent solid/cement by weight) shows a small torque reduction, but the full effect is not observed until at least 0.5 percent solid/cement is added. This response varies from cement to cement. Over the range from 1 to about 10 or 20s^{-1}, which is a typical shear rate experienced by the paste in concrete during placing, the torque increases with shear rate, but not as greatly with superplasticizer as without. The increased dosage of superplasticizer decreases the torque at a given shear rate. With this kind of measurement an appropriate dosage of superplasticizer can be found.

DISCUSSION

The direct rheological investigation of concrete is difficult not only because of the scale involved, requiring large amounts of materials, but also because measuring devices for such large scale operations are not generally very sophisticated and because the lack of reproducibility of raw materials (especially aggregate) leads to large scatter. We decided to investigate what is widely felt to be the most active rheological component of concrete, that is, the cement paste. The paste in concrete is not easily defined, for it usually contains some air and some of the finer sand [below 100 μm (0.004 in.) diameter]. A medium-sized sand grain might at one time be a lubricated aggregate particle and then, a short time later, become a grit in the lubricant phase, where

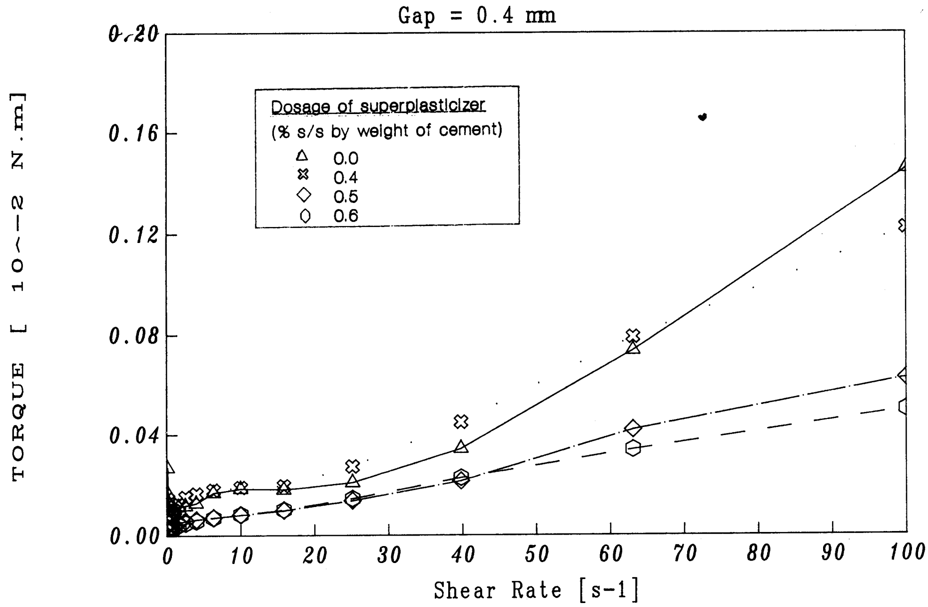

Fig. 5—Influence of superplasticizer dosage; superplasticizer used is naphthalene sulfonate formaldehyde condensate

it could reduce flow. In light of these complexities we focused on the properties of "pure" cement paste, because there seemed to be a great incongruity between its properties and its assumed action in concrete: how, for instance, could a fluid (paste) with little or no yield strength be the rheologically critical component in a concrete with low slump (high yield strength)?

It is not sufficient merely to fill the spaces between stones with a fluid to enable the stones to move, but the stones have to be separated, even if only ever so slightly. Water is a poor lubricant because it has so little cohesiveness in this situation; adding cement to the water increases cohesiveness, but at the cost of requiring a little more separation between stones, perhaps on the order of two or three cement-grain diameters. This kind of spacing [0.10 to 0.20 mm (0.004 to 0.008 in.)] is in fact observed between aggregate particles in hardened concrete.

The normal way to measure the rheological characteristics of a slurry is to establish a rheometer measurement surface spacing about 10 to 100 times as large as the largest particle in the slurry to reduce wall effects. In real concrete, however, wall effects (or aggregate interlock) are part of the rheology, and flow in actual concrete is sensitive to spacing, so we investigated rheometer spacing (gaps) on the order of a few grain diameters [down to 0.07 mm (0.003 in.)]. We found an abrupt increase in torque at small spacings. To extrapolate to concrete, it was as if the cement grains were being caught between larger aggregates and were thus providing a dry friction, rather than being excluded from these close-approach zones to leave only water and the smallest particles. Cement grain flocs (prevalent in nonadmixed cement paste) had an apparent size which was larger than the dispersed grains in superplasticizer-admixed pastes (Fig. 4), and therefore either the gap had to be larger for the same flow (i.e., higher *w/c* if the cement content remains the same) or else the fluidity would decrease because the resistance to movement (torque) is higher in the unadmixed paste.

Making an exact prediction of flow using the gap (or minimum gap) parameter is not yet possible, and more correlations between instrumental measurements on pastes and actual flow (e.g., slump) of concretes are necessary. This approach can be used, however, for screening admixtures and their dosages, and may be a more reliable indicator of concrete performance than large-gap methods such as the usual viscometers and mini-slump, because it forces a consideration of paste volume fraction to be made.

CONCLUSIONS

1. At a constant relative velocity between two plates, the maximum shear force that can be sustained by a cement paste increases more abruptly than the reciprocal of separation at small separation of the measurement surfaces.

2. When the thickness of the cement paste between the parallel-plate surfaces is larger than two to three times the diameter of an average particle, the bulk fluid forces are predominant; at smaller separations, particle-wall interactions predominate, if only because the proportion of bulk to surface decreases.

3. Addition of dispersing agents (like superplasticizers) reduces flocculation of cement grains and therefore has a large effect at small separations, by reducing effective particle size and particle-wall interactions.

4. The measurement of paste rheology as a function of paste thickness is a more refined approach to predicting concrete flow because it combines observations on the properties of paste with attention to the volume fraction of paste. Neither the properties of paste nor its volume fraction alone are able to indicate concrete flow reliably.

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