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Influence of the shape and roughness of inclusions on the rheological properties of a cementitious suspension

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Abstract

The influence of particle shape and surface roughness on the rheological properties of cementitious composites (cement paste plus coarse and fine particles) was investigated for mixtures of mortars and laboratory-made aggregates. The coarse particles were monosized spheres and cubes made from mortar, and monosized glass spheres, uncoated or roughened. The fine particles were uncoated or roughened monosized glass mini-spheres. The coarse particle mixtures were tested with a concrete rheometer to investigate separately the influence of overall particle shape and surface roughness on rheological properties as a function of aggregate concentration. The fine particle mixtures were tested with a paste rheometer to investigate the effect of surface roughness on flow at a smaller length scale using a different rheometer size and geometry. Results showed that shape had a large effect on plastic viscosity and, to a lesser degree, on Bingham yield stress. Surface roughness did not appear to have a significant effect on either property at the scale of roughness and particle volume fractions used. The tests were simulated using a validated computer model, which showed good agreement with the measured results.

Keywords: Experimental concrete rheology; Concrete rheology modeling; Aggregate shape; Aggregate surface texture; Bingham

1. Introduction

The uniformity and ease with which concrete or mortar can be transported, placed, consolidated, and finished is crucial for its use in a wide variety of building applications, such as pumping, placement in formwork congested with reinforcing bars, and underwater concreting. Such flow characteristics of concrete are usually identified with a property called workability. While the concept of workability is intuitive so that the experienced practitioner is quite able to identify "more workable" mix designs, it lacks a quantitative basis. In recent years, the quantitative basis has been taken to be the science of rheology.

Often, the rheological properties of concrete are identified with those of a Bingham fluid. A Bingham fluid has a linear relationship between shear stress, τ, and shear strain rate, $\dot{\gamma}$. This defines a plastic viscosity, μ, and a minimum stress, τ_0, called the yield stress, that is required to initiate flow (see Fig. 1):

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (1)$$

The slump cone test [1] has been shown to correlate with yield stress. However, it is a poor predictor of plastic viscosity [2].

Flatt et al. [3] found that for cementitious materials exhibiting Bingham behavior, plastic viscosity is the most relevant rheological parameter. Of course, concrete is not a perfect Bingham fluid as the relationship between shear stress and shear strain rate might not be linear for all shear stresses or shear rates, e.g., the viscosity may increase with shear rate (shear-thickening) or decrease with shear rate

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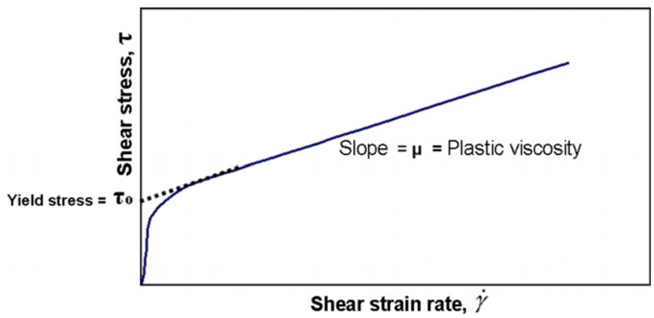

Fig. 1. A typical measured shear stress vs. applied shear strain curve for a Bingham fluid. The plastic viscosity is determined by the slope of the stress–strain rate curve at high strain rate. Yield stress is determined by extrapolating the shear stress–shear strain rate relationship to zero shear strain rate.

(shear-thinning). These properties can also change with time and flow history. Nonetheless, as a first approximation, ordinary fresh concrete is often assumed to behave like a Bingham fluid [4,5]. A variety of rheometers of various types and geometries that measure yield stress and viscosity have been proposed in recent years as an alternative to the slump cone test [6,7].

Aggregate (coarse and fine particle) content is an important factor affecting concrete rheology. Ferraris and Martys [7] reported that aggregate volume concentration mainly influences the relative plastic viscosity although other factors such as shape play a role. The 'relative viscosity' of a suspension, as used here, is defined as 'the ratio of the plastic viscosity of the whole suspension to the plastic viscosity of the embedding fluid matrix or medium' [8]. Similarly, we define the 'relative yield stress' of a suspension as 'the ratio of the yield stress of the whole suspension to the yield stress of the fluid matrix'.

Aggregates naturally occur, or are manufactured, in a wide variety of shapes and sizes. For example, aggregates produced in a quarry are usually derived from crushed rock and can be angular in shape, whereas riverbed aggregates are typically rounded. The morphological properties of aggregates have previously been described at different length scales with the terms shape (large-scale), angularity (intermediate-scale), and roughness or texture (fine-scale) [9–12]. Using different order spherical harmonic coefficients to describe increasingly finer particle shape detail [13–15] helps clarify this point. While the shape of inclusions present at such high amounts as in concrete (generally 45% by volume for coarse aggregates and 30% by volume for fine aggregates) will influence the rheological properties (yield stress, viscosity) of the mixture, the effect of varying degrees of surface texture on the rheological properties has not been ascertained. Conflicting findings are available [16,17]. One problem with determining the effect of texture on flow properties is that it is difficult to separate the effect of two different length scale shape properties like overall shape and surface texture on concrete flow. While natural aggregates tend to have more equal-dimensional and rounded shapes, and manufactured aggregates tend to have more elongated (and/or flat) and angular shapes, both types of aggregates may have smooth or rough surfaces.

In this paper, we present results of a study investigating the effect of aggregate concentration and shape properties on the rheological properties of various mixtures. Monosized coarse-aggregate particles having nominally identical roughness but different overall shape were made out of mortar, in the shape of spheres and cubes. The influence of surface roughness alone on viscosity and yield stress was also examined, by comparing rheological measurements using glass monosized spheres, as purchased and roughened by coating with a layer of epoxy and fine granite aggregate. Similarly, glass mini-spheres, uncoated or coated with a layer of epoxy and silica fume, were used as fine aggregate particles to investigate the influence of texture only on flow properties. Tests were performed with a concrete rheometer and a parallel-plate mortar rheometer using increasing amounts of aggregates. Results were compared with the results from a validated computer simulation describing similar systems. Table 1 summarizes the different cases tested.

2. Experimental

A recent round-robin test to compare concrete rheometers [6] found that absolute rheological parameters depended on the rheometers used. However, similar relative plastic viscosity values were obtained using most rheometers. Therefore, it was decided to select two rheometers – a portable, rotational rheometer for concrete and a fluid parallel-plate rheometer for paste and mortar – and measure the influence of aggregate content and properties relative to base (suspending fluid) cases.

2.1. Materials and sample preparation

Three different sizes of aggregate particles (two sets of particles in each) were prepared: (1) coarse spheres and

Table 1
Summary of the different test cases, showing the particles, the rheometer, and the suspending matrix used

Aggregate size	Coarse				Fine	
Material	Mortar particles		Glass particles		Glass mini-particles	
Shape/texture	Spheres	Cubes	Spheres/roughened	Spheres/smooth	Spheres/roughened	Spheres/smooth
Rheometer used	Concrete rheometer	Concrete rheometer	Concrete rheometer	Concrete rheometer	Mortar/paste rheometer	Mortar/paste rheometer
Suspending matrix	Mortar	Mortar	Mortar	Mortar	Cement paste	Cement paste

cubes made of mortar; (2) smooth and roughened glass coarse spheres (marbles); (3) smooth and roughened glass mini-spheres. Each experiment used one of these monosize particle sets to simplify the production. Spheres were chosen as the primary shape due to two main reasons. First, the model to which we wanted to compare was validated, at the time of this research, for spheres only. Second, spheres lend themselves well to experimental rheology in that particle interlocking is not likely and high-concentration monosized coarse particle mixtures can be tested without exceeding the maximum allowed torque on the rheometer. Cubes were chosen because this is a simple shape with high symmetry (therefore still easier to simulate than a random shape), sufficiently different from a sphere (having edges), and easy to manufacture.

2.2. Suspending matrix

The suspending matrix was a mortar for the tests made using the concrete rheometer and a cement paste for tests made using the paste/mortar rheometer. The mortar matrix was composed of an ASTM Type I cement, a siliceous sand, and water. The size of the cement and sand particles were sufficiently smaller than the size of the coarse particles so that the mortar matrix could be thought of as a continuum fluid. The proportions of the mortar matrix and the paste matrix are given in Table 2. The water-to-cement ratio (*W*/*C*) of the mixtures was chosen based on a series of mixtures [18] using the same sand and cement contents and types as in the mixtures shown but with varying water content, to locate a range over which the effect of small changes to the water content (such as due to variation in the moisture content of the added artificial particles) on the viscosity of the suspension would be minimal. The properties of the cement and sand are available [18]. The paste matrix also used a Type I cement.

2.3. Coarse spheres and cubes

The volume of the coarse particles was controlled by the mold available for the spheres. Table tennis balls served as molds for the spheres. A 5 mm hole was drilled in the surface of the balls through which the mortar was injected. The mortar was compacted using a narrow metal rod to achieve adequate compaction while avoiding fine aggregate segregation and maintaining homogeneity. The mortar was then allowed to set, which due to bleed water left a void near the mold opening. The resulting void was patched using a stiffer mortar with slightly smaller fine aggregate particles, and the original curvature of the sphere was regained. The spheres were visually checked for air pockets and inhomogeneity using a rolling test (in which the rotation of particles on a flat surface is checked for wobble) and by demolding randomly selected particles. The diameter of the spheres including the mold was 40 mm with an observed uncertainty of 1 mm. The volume of the cubes were made to equal the volume of the spheres. They were cast into wooden molds coated with two layers of polyurethane and mold grease that came apart at all four sides. The length of one side of the cubes was about 32 mm with an observed uncertainty of about 2 mm. The higher variability in the size of the cubes arose from the reuse of the wooden molds, which distorted slightly after each use. Excessively large or small cubes (with volumes differing from the mean sphere volume by more than about half the range of sphere volume values) were discarded. A similar mortar as for the spheres was used, to achieve similar specific gravity and thus buoyancy. The specific gravity of the particles was about 2.3. Trial mixtures showed that some of the spheres that had the plastic mold peeled off suffered surface damage during mixing, which reduced sphericity, so it was decided to keep the plastic mold on the spheres for durability. Fig. 2 shows the artificial coarse sphere and cube particles.

It was seen that the shape of the coarse spheres and cubes changed slightly due to particle collisions during

Fig. 2. Artificial coarse sphere and cube particles used in the experiments (Scale bar shows 10 mm).

Table 2
Mixture proportions of the concrete and mortars used

Inclusions		Matrix material			Rheometer used and test geometry
Aggregate type	Volume concentration (%)	Water/cement (mass ratio)	Sand/cement (mass ratio)	Fine aggregate type	
Spheres	0, 15, 25, 35, 45	0.36	1.50	Siliceous sand	Rotational (with 406 mm diameter container)
Cubes	0, 15, 25, 35, 45	0.36	1.50	Siliceous sand	Rotational (with 406 mm diameter container)
Uncoated marbles	0, 10, 20, 30, 40	0.38	1.50	Siliceous sand	Rotational (with 254 mm diameter container)
Coated marbles	0, 10, 20, 30, 40	0.38	1.50	Siliceous sand	Rotational (with 254 mm diameter container)
Uncoated mini-spheres	0, 40	0.40, 0.45	–	–	Parallel-plate
Coated mini-spheres	0, 40	0.40	–	–	Parallel-plate

the early stages of mixing. The cube edges became rounded, and the plastic surfaces of the spheres got rougher (see Fig. 2). This change was mostly achieved in trial mixtures prior to the tests whose results are presented here. It was assumed, for the purposes of comparing the influence of particle shape on flow properties, that the texture of the spheres and that of the cubes were essentially identical even though the roughness of each may have been of different scale. The tests that compared the influence of only particle surface texture on flow properties helped evaluate the correctness of this assumption.

2.4. Coated and uncoated coarse glass spheres

The diameter of the glass sphere coarse particles (marbles) was 16 ± 0.5 mm. The roughened particles were prepared by coating the glass marbles with a thin layer of fine aggregates. Marine-grade epoxy was used to adhere ASTM No. 100 sieve size (150–300 μm) granite particles to the glass surface with attention paid to keeping the layer of texture as thin as possible. The coating was then allowed to set, after which the particles were washed and mixed in a container to remove any excess fine particles. The coating thickness was between 0.2 and 0.4 mm (1/40–1/80 of the diameter). The change in volume of a particle due to the coating was less than 10%. Particles with thicker or imperfect coatings were discarded. The specific gravity of both the uncoated and coated marbles was found to be about 2.4. Figs. 3 and 4 show the coated and uncoated marbles, and a close-up of the fine aggregate coating and the cross section of the coating to indicate texture thickness, respectively.

2.5. Coated and uncoated fine spheres

The uncoated fine particles were 0.9–1.1 mm (diameter) glass mini-spheres. The roughened mini-spheres were prepared by coating with silica fume (passing a #400 (38 μm) sieve to minimize agglomerates) using a moisture-resistant epoxy spray. Similar to the marbles, the spheres were allowed to set and wet sieved through an ASTM #16 (1.18 mm) sieve. The coating was checked using a microscope under different lighting conditions. Fig. 5 shows optical microscope images of the uncoated and coated spheres.

The thickness of the layer of texture was not as uniform as that of the coarser marbles. However, the particles appeared to have a spherical shape and roughened surface. The coating was about 2–50 μm thick (1/500–1/20 of the diameter). The proportions of the matrix material and the composite (matrix plus inclusions) are given in Table 2 for the various material combinations used.

2.6. Tests

Rheology tests were done at three different size scales. A rotational, concrete rheometer [19] developed at the International Center for Aggregates Research (ICAR) was used with the mixtures made using the coarse spheres and cubes, and the coarse marbles. This is a portable, controlled-rate rheometer that utilizes a four bladed vane immersed in the concrete. The container that holds the concrete during testing can be changed to accommodate varying maximum aggregate sizes and mixture volumes. Fig. 6a shows the

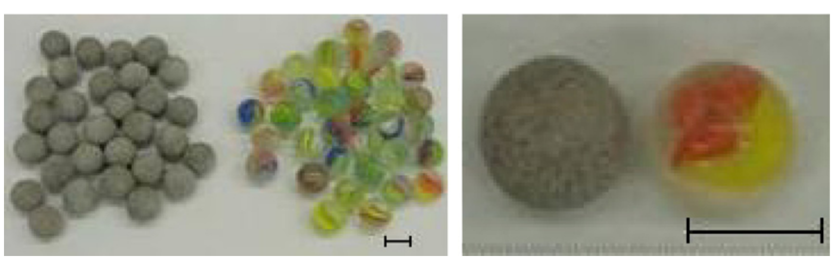

Fig. 3. Coated and uncoated glass sphere particles used in the experiments (Scale bars show 15 mm).

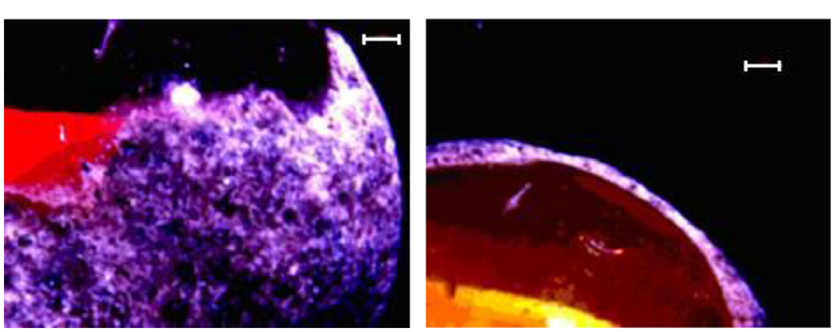

Fig. 4. A roughened glass sphere particle with the coating layer peeled to show detail of roughness layer [left], and cross-section of the coating showing thickness [right]. The cross section appears thicker on the sides of the image due to the presence of coating closer to the lens. Scale bars represent 1 mm.

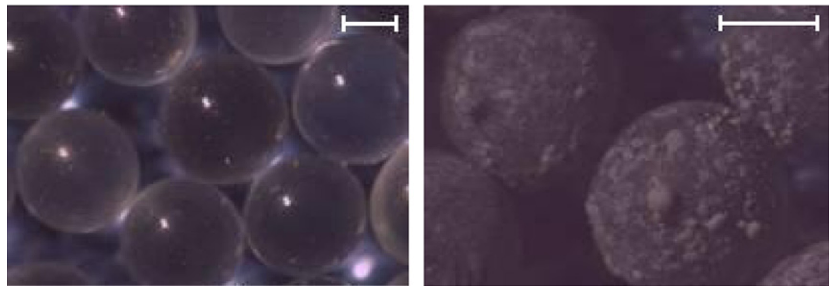

Fig. 5. Uncoated mini-spheres [left] and the coated mini-spheres [right] used in the experiments. The scale bars represent 0.5 mm.

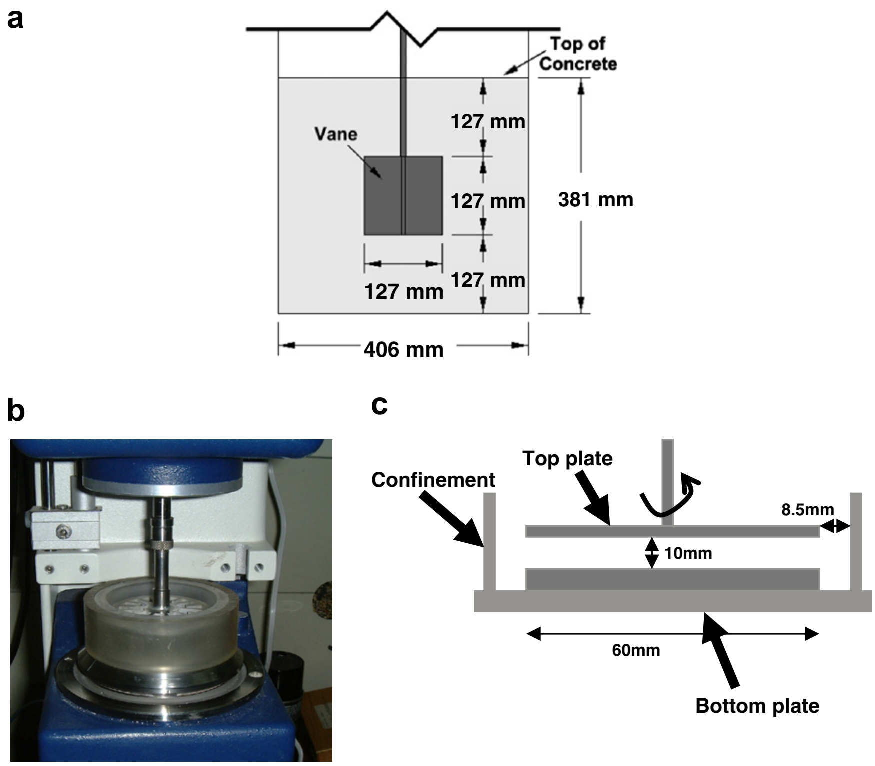

Fig. 6. (a) The dimensions of the container and the vane used with the coarse mortar particles [20]. (b) The parallel-plate rheometer used with the fine particles and its dimensions.

dimensions of the container and the vane used for the coarse mortar sphere and cube mixtures.

A smaller container than that shown in Fig. 6a (254 mm outer diameter, 381 mm height) was used with the same vane to test the marble mixtures. Each test used a breakdown period [20] (an initial period of mixing for the elimination of the effects of thixotropy, in which the vane turns to partially de-flocculate cement particles and realign aggregate particles, creating a repeatable, representative test state) of 15 s at 2π rad/s. Seven torque measurements were taken at equal intervals in descending order between a maximum speed of 6.28 rad/s (1.0 rev/s) and a minimum speed of 0.31 rad/s (0.05 rev/s), to measure the flow curve. Each measurement was averaged over a 5 s time period.

A fluid parallel-plate rheometer was used for the glass mini-sphere mixtures. The set-up was modified as shown in Fig. 6b from the standard parallel plate to accommodate larger particles. The shear rate was varied from $10\ s^{-1}$ to $1\ s^{-1}$ in 10 steps with an equilibrium period of 20 s at each step.

The mortar sphere and mortar cube particle and the marble tests were performed by measuring the flow curve for the matrix mortar only with the concrete rheometer (0% coarse particle volume concentration), adding enough particles to the mixture to reach a certain volume concentration, remixing, measuring the flow curve again with the rheometer, adding some more particles and repeating the process. The particles were then recovered by wet sieving to be used in future tests.

The mini-sphere tests were performed using the modified parallel-plate rheometer, by measuring the flow curve for the cement paste matrix only (0% particle volume concentration) followed by measurements of a mixture with an identical paste matrix and added smooth mini-spheres, and then a third mixture with an identical paste matrix and added rough mini-spheres.

2.7. Model description

As a check on the measurements, the experimental results were compared with a validated computational rheology model of suspensions [21]. The model is based on an approach called Dissipative Particle Dynamics (DPD). DPD is a mesoscopic model of complex fluids that blends together cellular automata ideas with molecular dynamics methods. It simulates the motion of arbitrary-shaped objects subject to hydrodynamic forces and interparticle interactions.

When modeling suspensions using DPD at any scale, the fluid phase is represented by particles corresponding to the mesoscopic regions of fluid. Interactions between the particles are incorporated so that their motion is consistent with the equations of hydrodynamics. To model the motion of solid bodies, a subset of DPD fluid particles are "frozen" together to present individual aggregates. Once the forces on each rigid body are determined, the particles move according to the Euler equations. Details of modeling suspensions with the DPD method are available [22,23].

Simulation of concrete rheology is computationally very expensive due to the very broad span of solid particles sizes (from micrometers to tens of millimeters). For this reason, the model uses a multi-scale approach in which phenomena are modeled at a characteristic length scale to determine an average property, which is then input into a simulation at a coarser scale. Thus, 'relative viscosity' is obtained, as described previously. For example, the viscosity of mortar can be determined through simulation or experimentation and can be used as the viscosity of the suspending fluid in a concrete simulation.

The simulation did not precisely model the geometry and size of the concrete rheometer but the particle size-to-system size ratio was chosen so that the bulk viscosity of the suspension could be calculated. This is possible when the size ratio is about 0.2 or smaller. The value of this ratio was ≈0.1 for the simulation results shown in this paper.

A point to be noted is that the model results were obtained by averaging results from several simulations for each case (a mixture with certain properties, e.g., 35% glass mini-spheres in a fixed *W*/*C* cement paste matrix), similar to the experimental results. This was necessary, particularly at high volume concentrations and since monosized particles were used, since different starting positions of the particles in the simulation can affect the computed viscosity values.

3. Results and discussion

3.1. Experiment

3.1.1. Concrete mixtures using the rotational concrete rheometer

Following the Bingham model, a linear fit was applied to the torque vs. rotation speed data. The slope is proportional to the viscosity value of the mixture, and the intercept is proportional to the yield value for the mixture. Yield stress and plastic viscosity were determined using the 'Effective Annulus Method' [20] to correct for the 'dead zone' (zone in which the concrete does not flow) in the container. By only considering relative values of yield stress and plastic viscosity, there was no need to evaluate the proportionality constants.

Fig. 7 shows the change in relative yield stress and relative viscosity for mixtures made using spheres or using cubes, with increasing particle concentration. The uncertainty bars in Fig. 7 represent the 90% confidence interval for the mean of the individual yield stress or plastic viscosity measurements at each particle concentration. The plastic viscosity of the mixtures is influenced more significantly by increasing coarse particle concentration than the yield stress. This appears reasonable as yield stress is based more on the static state of the mixture and relative distribution/position of particles whereas viscosity is measured in a dynamic state with more particle interaction. Particles in a monosized mixture may remain largely out of contact even at high concentrations. Therefore, yielding would occur in the mortar phase alone and this value dominates the yield stress for all particle concentrations tested. It is expected that if the experiments could be performed at high-enough concentrations, an increase could be observed in the relative yield stress, due to aggregate interlock. The

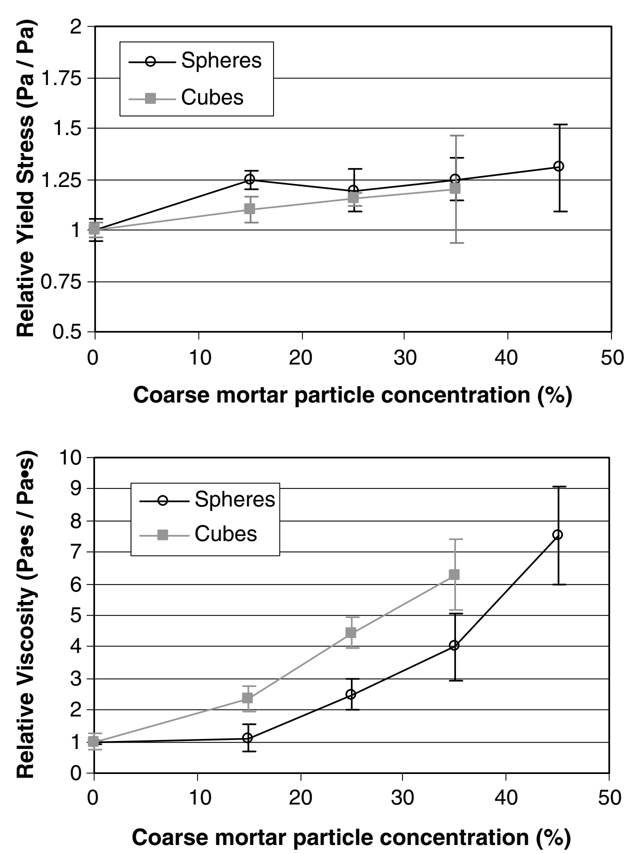

Fig. 7. Comparison of the change in relative yield stress (top) and relative viscosity (bottom) for mixtures using mortar spheres and cubes (coarse), with increasing particle concentration.

relative change in yield stress for the sphere and cube cases is essentially identical, within the experimental uncertainties. The relative viscosity of the cube mixture is higher than that of the sphere mixtures at all particle concentrations (Fig. 7 [bottom]). This is expected since the intrinsic viscosity of cubes is greater than the intrinsic viscosity of spheres [24].

Fig. 8 shows the change in relative yield stress and relative viscosity for mixtures made using uncoated and coated marbles, with increasing particle concentration. The uncertainty bars in Fig. 8 show the 90% confidence interval of the mean of the measurements. It is seen that, unlike overall shape, surface texture or roughness does not seem to noticeably influence the viscosity or the yield stress of the mixture. This could be due to fact that the magnitude of the surface roughness is smaller than the sand particles in the mortar matrix. The diameters of the sand particles were ≈0–1.1 mm, with the particle size median being ≈0.3 mm based on sieve analysis. The particle surface roughness of 0.2–0.4 mm was therefore comparable to or smaller than a large fraction of the sand particles. Another reason could be that the particle volumes tested were low enough so that particles remained distant from each other in the 3D system, which would support the argument that particle surface roughness affects concrete viscosity mainly through particle contacts or near-contacts, which occur much more frequently at high aggregate volumes. It is possible to estimate the average surface-to-surface separation of the coarse sphere particles using:

$$\frac{h}{a} \approx 2\left[\left(\frac{\phi_{\max}}{\phi}\right)^{1/3} - 1\right] \tag{2}$$

where h is the particle surface-to-particle surface separation, and a is the particle diameter [23]. Assuming $\phi_{\max} = 0.64$, h can be estimated as $0.58a$ and $0.34a$ at 30% and 40% sphere concentrations, respectively, confirming that the particles could be too separated, even at the relatively high concentrations tested, to noticeably affect the flow.

It should be pointed out that the particle diameter-to-vane width ratio for the coarse mortar sphere mixtures, ≈0.3, determined by the available spherical mold sizes, is rather high for ignoring system finite size effects. Nonetheless, the change in relative viscosity with increasing particle volume concentration for these mixtures was similar (within calculated uncertainties) to that for the glass sphere mixtures, for which the particle diameter-to-vane width ratio was ≈0.1.

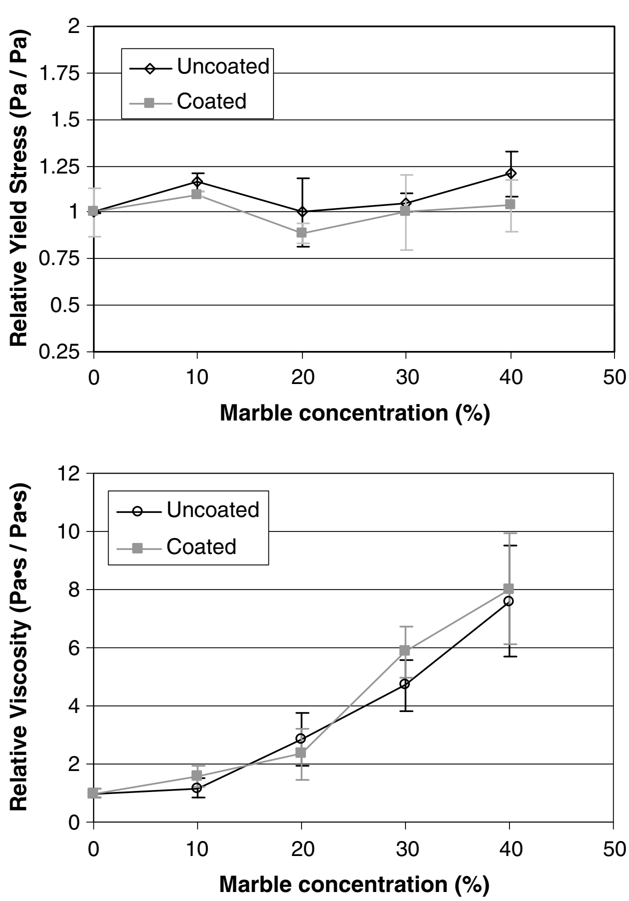

Fig. 8. Comparison of the change in relative yield stress (top) and relative plastic viscosity (bottom) for mixtures using uncoated and coated marbles (coarse), with increasing particle concentration.

3.1.2. Cement paste/mortar measurements using the modified parallel-plate rheometer

Tests were performed with a different matrix (see Table 1) to investigate the influence of roughness using another rheometer geometry and particle size. Fig. 9 shows the flow curves for the neat cement paste and the uncoated and coated mini-sphere mixtures at a volume concentration of 40%. The relative Bingham yield stress and plastic viscosity values calculated from the flow curves are given in Table 3.

The repeatability of measurements made with the parallel-plate rheometer was approximately 5%, determined in previous testing [25]. The difference between the relative yield stress and plastic viscosity for the uncoated and coated cases (compare A with B in column 4) values is less than 5%. The flow of the two mixtures was essentially identical for the degree of roughness tested. The negligible influence of roughness on our results may again be due to the fact that the magnitude of surface roughness was of a similar order or smaller than the size of the cement particles in the paste that served as an interstitial fluid in the experiments, since the surface roughness was approximated to be 2–50 μm based on microscopy imaging and the cement grains had an equivalent spherical diameter median of ≈15 μm. Fig. 9 also shows the influence of increasing the water-to-cement ratio of the fluid matrix (compare D with E in columns 5 and 7) for the purpose of comparison to the influence of the roughness alone (A vs. B). Note that these values are less than 1.0 because an increase in W/C at the same inclusion volume concentration reduces the paste viscosity and therefore the overall viscosity. A relatively small change in W/C had a noticeable effect on the measured yield stress and viscosity

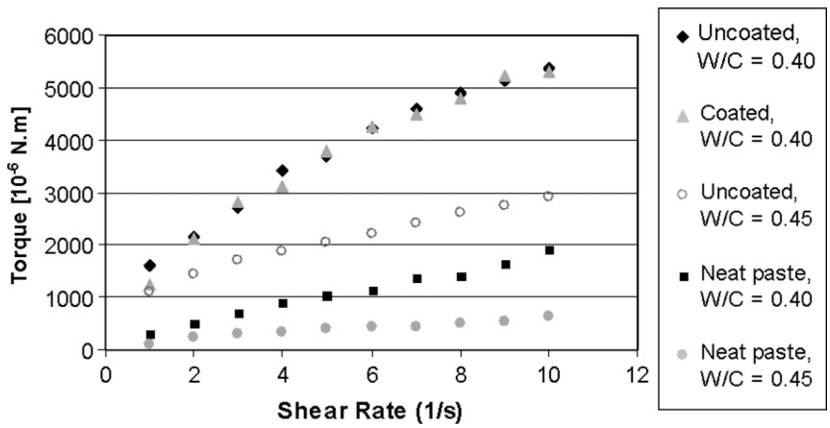

Fig. 9. Flow curves for the cement paste matrix, and matrix with uncoated and coated mini-spheres at 40% volume concentration.

Table 3
Results of the mortar rheology tests performed on uncoated and coated glass mini-spheres

ID	Inclusion type	Inclusion volume concentration (%)	*W*/*C*	Relative viscosity (relative to *W*/*C* = 0.40 paste, row E)	Relative viscosity (relative to *W*/*C* = 0.45 paste, row D)	Relative yield stress (relative to *W*/*C* = 0.40 paste, row E)	Relative yield stress (relative to *W*/*C* = 0.45 paste, row D)
A	Uncoated mini-spheres	40	0.40	2.64		8.02	
B	Coated mini-spheres	40	0.40	2.73		7.17	
C	Uncoated mini-spheres	40	0.45	2.04	3.88	9.19	8.56
D	None	0	0.45	0.31	1.00	0.89	1.00
E	None	0	0.40	1.00		1.00	

The values in column 6 and column 8 are the relative viscosity and relative yield stress with the $W/C = 0.45$ paste taken as the base fluid.

whereas a change in roughness alone at the scale used appears to have less of an effect. For the purpose of evaluating the influence of fine-scale particle surface roughness on flow, the results show an insignificant effect.

3.2. Comparison to model predictions

The change in the viscosity of a suspension as a function of the shape and volume fraction of the particle inclusions was determined using the DPD simulation model. As in the experiments, a series of simulations were carried out with suspensions composed of either mono size spheres or cubes for a set of volume fractions. Fig. 10 shows a snapshot from the simulation of a sheared suspension of cubes. The suspending fluid (equivalent to the mortar in the experiments) was given an inherent viscosity and the relative increase in the viscosity of the suspension was determined as solid inclusions were added to the system.

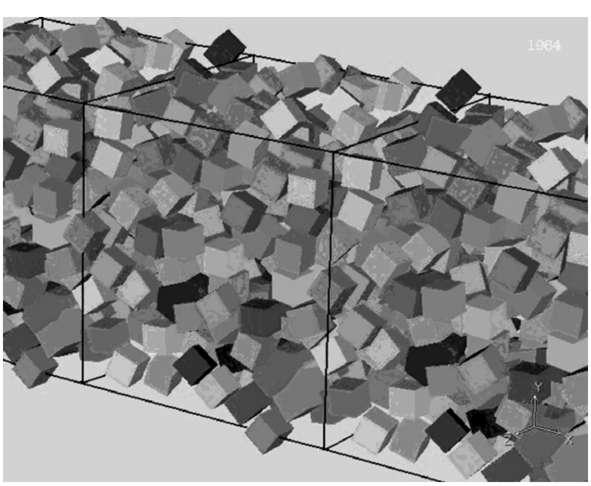

Fig. 10. Simulation of a sheared suspension of cube-shaped inclusions. The volume fraction is 0.3. The relative viscosity for this system was approximately twice that of an equivalent sphere suspension.

Fig. 11 compares the model predictions of the relative change in the viscosity to the empirical results. The uncertainty bars in Fig. 11 show the 90% confidence interval for the mean of measurements on the rheometer curve, and 10% relative uncertainty for the model-predicted data points. Uncertainty in the model data are due to differences in starting positions of the virtual particles as previously mentioned, and has been found to be generally less than 10%. The model results for the spheres were slightly lower than the empirical results, especially at higher particle concentrations. This could be due to the assumption made that the properties of the base fluid remain constant during the test. In reality, this normalizing viscosity increases with time, mainly due to ongoing hydration. The tests took ≈30 min from start to end. Other researchers have found that a noticeable increase in viscosity can be observed in the first 15–30 min after mixing ends [26,27].

The results for spherical particles using the Krieger–Dougherty equation [28] and for both the simulations and the experiments agree within the uncertainties. The

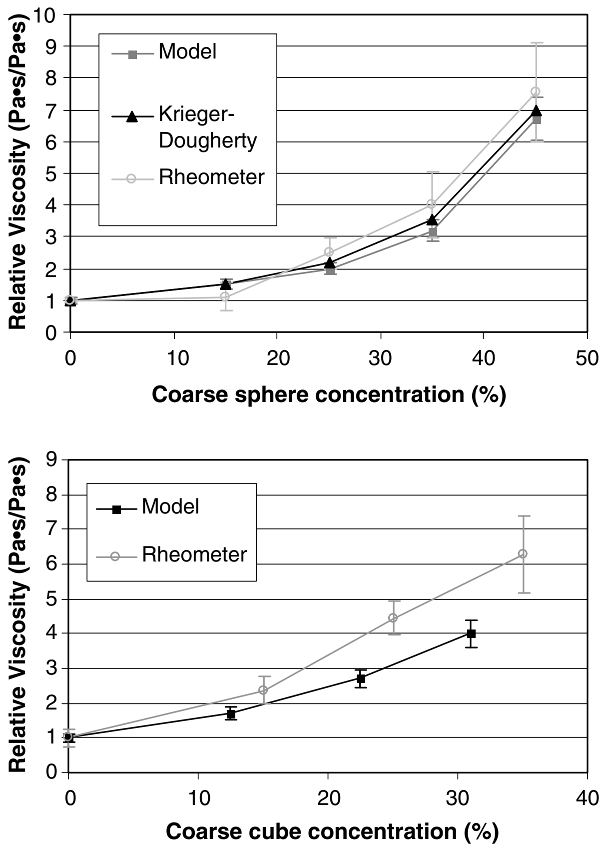

Fig. 11. Comparison of the change in the relative viscosity of a sphere-mixture (top) and a cube-mixture (bottom) for mixtures using spheres and cubes, with increasing particle concentration.

advantage of such a DPD model over predictive equations like the Krieger–Dougherty equation, of course, is that the effect of various shapes and size distributions can be investigated, making it more suitable for concrete. The Krieger–Dougherty equation works only for spheres, since one needs to analytically solve the change in viscosity due to a single particle, which is not possible except for spheres and ellipsoids. The agreement between the predicted and measured curves is better in the sphere mixture case than in the cube mixture case. This is probably due to the rotational independence of the sphere particles, which eliminates particle orientation from affecting the results. Cubes however, could be preferentially oriented at the initial state of the mixture prior to testing (in comparison, the particles in the model are well-distributed prior to the start of the simulated test). They can also jam temporarily due to the imperfect nature of the monosized test case, which is less likely to happen in the simulated flow, resulting in larger error in the measured data.

The relative viscosity values calculated for the 40% mini-sphere concentration mixtures are much lower than that predicted by the model at this concentration, whereas the relative yield stress is much higher than that measured using the coarse spheres (compare A in column 5 to Fig. 11 and A in column 7 to Fig. 8). This may be due to the flow of the paste and mini-sphere particle mixture not being as expected or assumed in the parallel-plate rheometer case due to settling or movement of the particles to one part of the rheometer. However, such an explanation would not help explain the significant increase in relative yield stress that was observed. The different relative viscosities measured for the two mixtures with different W/C ($W/C = 0.40$ and $W/C = 0.45$) but identical mini-sphere concentration may also indicate some problems with the measurements (compare A vs. E in column 4 to C vs. D in column 5). Note that W/C should not have an effect on changes in relative viscosity with particle addition, unless the W/C is high enough to promote segregation of the artificial inclusions.

4. Conclusions

Test cases were chosen to separately investigate the effect of overall coarse aggregate particle shape and that of particle surface texture on the flow of concrete mixtures, for monosized particles. An attempt was made to separate the influences of shape and surface texture by using laboratory-made aggregate particles. First, coarse spheres and cubes made of mortar (different shape, approximately same texture and size) were compared using a concrete rheometer of cylinder/vane type. The cube mixtures consistently had higher relative plastic viscosities than the sphere mixtures at each particle volume concentration tested. The difference increased with increasing coarse particle concentration as a result of increased particle interaction. The influence of coarse particle shape on relative yield stress was less pronounced, if at all, with the uncertainty in the rheometer measurements making it difficult to conclude that a difference in the effect of the two shapes was observed. It is possible that an effect of the shape on yield stress would be observed for mixtures using higher concentrations of coarse particles with a lower particle size-to-rheometer diameter ratio.

The surface roughness of the mortar cubes and spheres were assumed to be identical to be able to compare the effect of shape alone on flow properties. However, since the roughened mold was kept on the sphere particles, so that the texture may not have been exactly the same, it was decided to more carefully investigate the influence of just surface texture on relative viscosity and relative yield stress. Coarse glass spheres with smooth surfaces and surfaces roughened by coating with a layer of granite fine aggregate particles were used in increasing volume concentrations and a difference neither in relative viscosity, nor in relative yield stress, was observed. The increase in the relative viscosity of both mixtures was slightly higher than that predicted by the Krieger–Dougherty equation and a verified DPD model but the same within experimental uncertainty. Both models predicted a change in relative viscosity very similar to the change for the mortar coarse spheres mixture. The DPD model was also used to simulate the coarse cube mixture and underpredicted the increase in relative viscosity, although still within the calculated uncertainty range for the experimental results. This difference was attributed to a potential stiffening of the base mortar (the interstitial fluid) during the testing period.

The effect of surface roughness on viscosity was also investigated at a smaller scale using a parallel-plate mortar rheometer. Again, roughness did not have a noticeable effect at the scale used. Based on these results, it is concluded that overall (large-scale) coarse aggregate particle shape has a much greater influence on the relative viscosity of a mixture than does surface texture. This finding could be useful in the selection of aggregates to better control the workability of concrete mixtures.

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