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INTRODUCTION

A concise review of the literature and new experimental results are given in the attached manuscript (Tsai et al, 1992) concerning the effects of particle shape, density, size, and surface charge on the rheology of concentrated suspensions of noncolloidal particles in Newtonian liquids at shear rates ranging from 1 to 2000 s^{-1}. The measured relative viscosity of a Newtonian suspension as a function of particle volume fraction was found to agree well with the predictions of both the Krieger-Dougherty (K/D) and the Maron-Pierce-Kitano equations for both spherical and irregularly shaped particles. The former equation is preferable because its sole parameter, maximum packing fraction, was found to be in much better agreement with that determined from sedimentation than that of the latter equation. While the maximum packing fraction was found to adequately account for the effects of particle shape and size distribution, particle size and density were found to have no effect on the relative viscosity of a concentrated Newtonian suspension (Metzner, 1985; Tsai et al, 1992). How well the relative viscosity of a Newtonian coal water slurry (CWS) can be predicted by the K/D equation is described in this report. The Newtonian CWS was obtained in this study by the use of an anionic dispersant in such a quantity that the resulting interparticle electrostatic repulsion counter-balances the interparticle van der Waals attraction.

RESULTS AND DISCUSSION

The coals used are Upper Freeport and Pittsburgh Seam #8, both of high volatile bituminous rank. The coal analyses are given in Table I, and the coal particle size distributions are shown in Figure 1. An anionic dispersant, Coal Master A23M from Henkel Corp., was first dissolved in deionized water, and then mixed in a mixer with coal particles. The resulting mixture was stirred at 500 rpm for one hour to ensure macroscopic slurry homogeneity. The anionic dispersant used was an ammonium salt of naphthalene sulfonic acid formaldehyde polymer with a molecular weight of approximately 10,000.

As shown in Table II, the relative viscosities of Newtonian CWSs using both Upper

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Freeport and Pittsburgh Seam coals and anionic dispersant A23M are an order of magnitude higher than those predicted by the K/D equation with the intrinsic viscosity $[\eta]$ equaling 2.67 and the maximum packing fraction determined from sedimentation. It should be noted that the same value was used for colloidal (Krieger, 1972) and noncolloidal suspensions (Tsai and Viers, 1987) of polystyrene spheres as well as for noncolloidal suspensions of irregularly shaped sand (Tsai et al, 1992). The intrinsic viscosity was also found to be 2.67 for latexes of uniform spheres by Maron and Pierce (1956) using the Ree-Eyring generalized flow theory.

In order to fit the K/D equation to the experimental CWS data, a greater intrinsic viscosity was used. The relative viscosity predicted by the K/D equation with $[\eta]$ equaling 5.86 is shown in Figure 2 to agree well with the experimental data for Pittsburgh Seam coal. However, poor agreement is seen in this figure for the Upper Freeport Coal. Also shown in Figure 2 for comparison are the relative viscosities of Newtonian suspensions of irregularly shaped unsieved sand (triangles) and polystyrene spheres (circles) with particle size distributions also shown in Figure 1. Possible mechanisms that account for the excess energy dissipation of these CWSs under shear are under investigation. Understanding these mechanisms is imperative to achieving the minimum relative viscosity and, thus, the maximum coal loading of a CWS.

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TABLE I

Coal Analyses

Analysis Dry Basis	Upper Freeport Coal Up2	Up3	Up1	Pittsburgh Seam Pgh
Volatile, %	23.1	25.2	28.4	42.4
Ash, %	16.7	9.1	5.4	3.9
Carbon, %	72.1	81.1	82.8	78.4
Hydrogen, %	4.5	5.1	5.1	5.4
Nitrogen, %	1.3	1.4	0.7	1.4
Oxygen, %	5.5	3.3	4.8	7.9
Sulfur, %	0.7	0.6	1.2	3.1
Particle size				
MMD, μm	10	12.5	4.0	9.2
VMD, μm	15.8	17.8	4.9	12.9

TABLE II

Newtonian Coal Water Slurries Using Anionic Dispersant A23M

A23M Concentration wt% of Coal	Coal Loading Volume Fraction		wt%	Shear Rate s^{-1}	Relative Viscosity Measured	Predicted[a]	w/ φ_M[b]
1.15	0.48	UP1	54	250-1500	1150	162	0.49
1.15	0.45	UP1	52	250-5000	450	27	0.49
1.15	0.45	UP1	52	100-750[c]	450	27	0.49
1.20	0.43	UP1	50	500-5000	300	16	0.49
1.73	0.50	UP2	57	700-6000	160	17.6	0.60
0.75	0.55	UP3	62	500-6000	200	32	0.63
0.36	0.55	UP3	62	500-8000	205	32	0.63
1.35	0.55	UP3	62	500-8000	215	32	0.63
0.38	0.40	Pgh	48	150-440[d]	43	6	0.59
0.36	0.45	Pgh	53	4000-8000	145	9.7	0.59
0.61	0.45	Pgh	53	25-440[d]	165	9.7	0.59
0.38	0.49	Pgh	57	200-1300	520	16.5	0.59
0.37	0.52	Pgh	60	1000-4500	1520	29	0.59

a) Predicted by the Krieger-Dougherty Equation with intrinsic viscosity $[\eta]$ equaling 2.67.
b) Determined from sedimentation except 0.59 estimated for Pittsburgh #8 coal (Pgh).
c) The aqueous solution contains 35 wt% glycerol.
d) Measured with Haake rotational rheometer RV2.

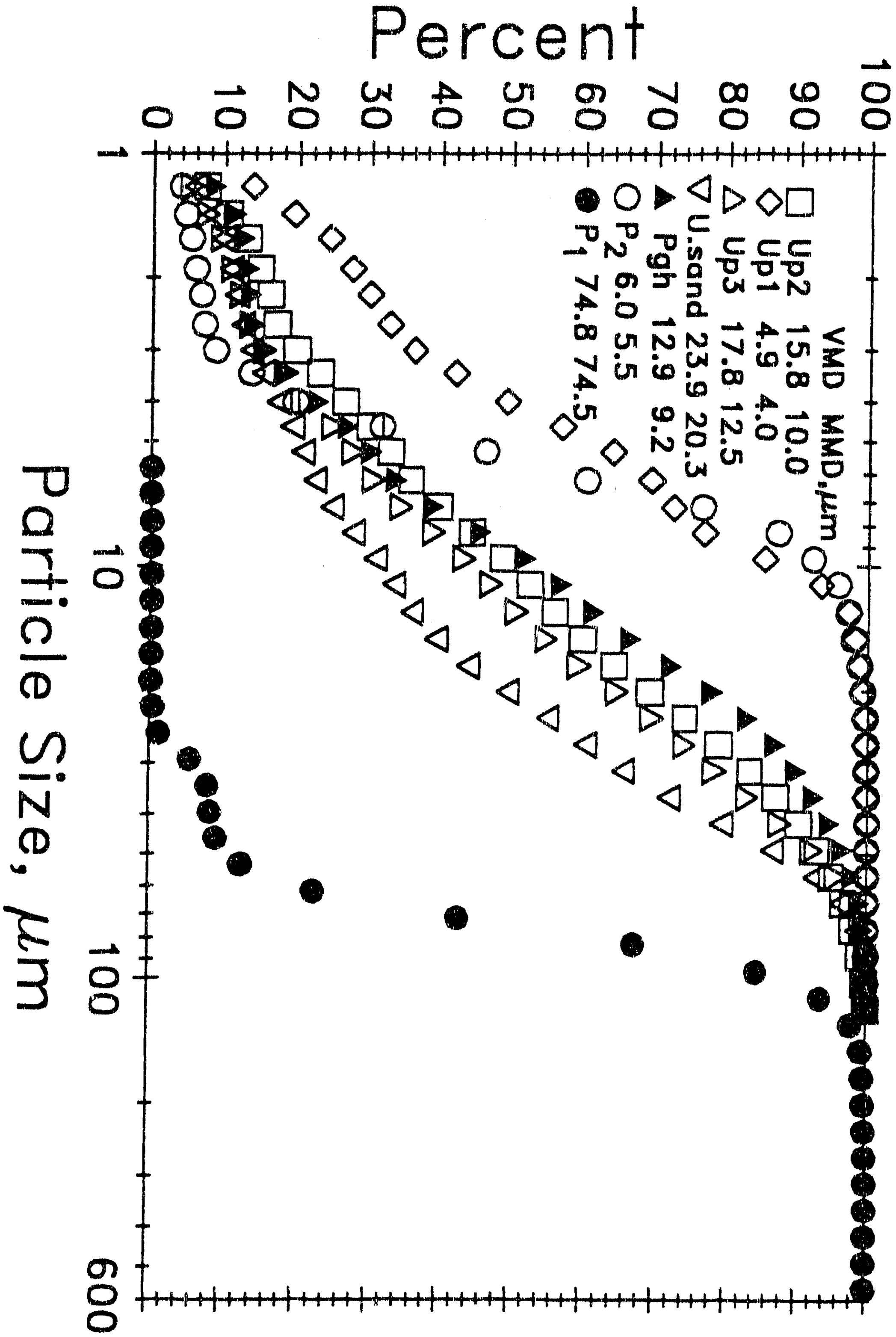

Fig. 1 Particle size distributions of polystyrene spheres P1 and P2, unsieved sand, Upper Freeport coal (UP1, UP2, and UP3), and Pittsburgh Seam coal #8 (Pgh).

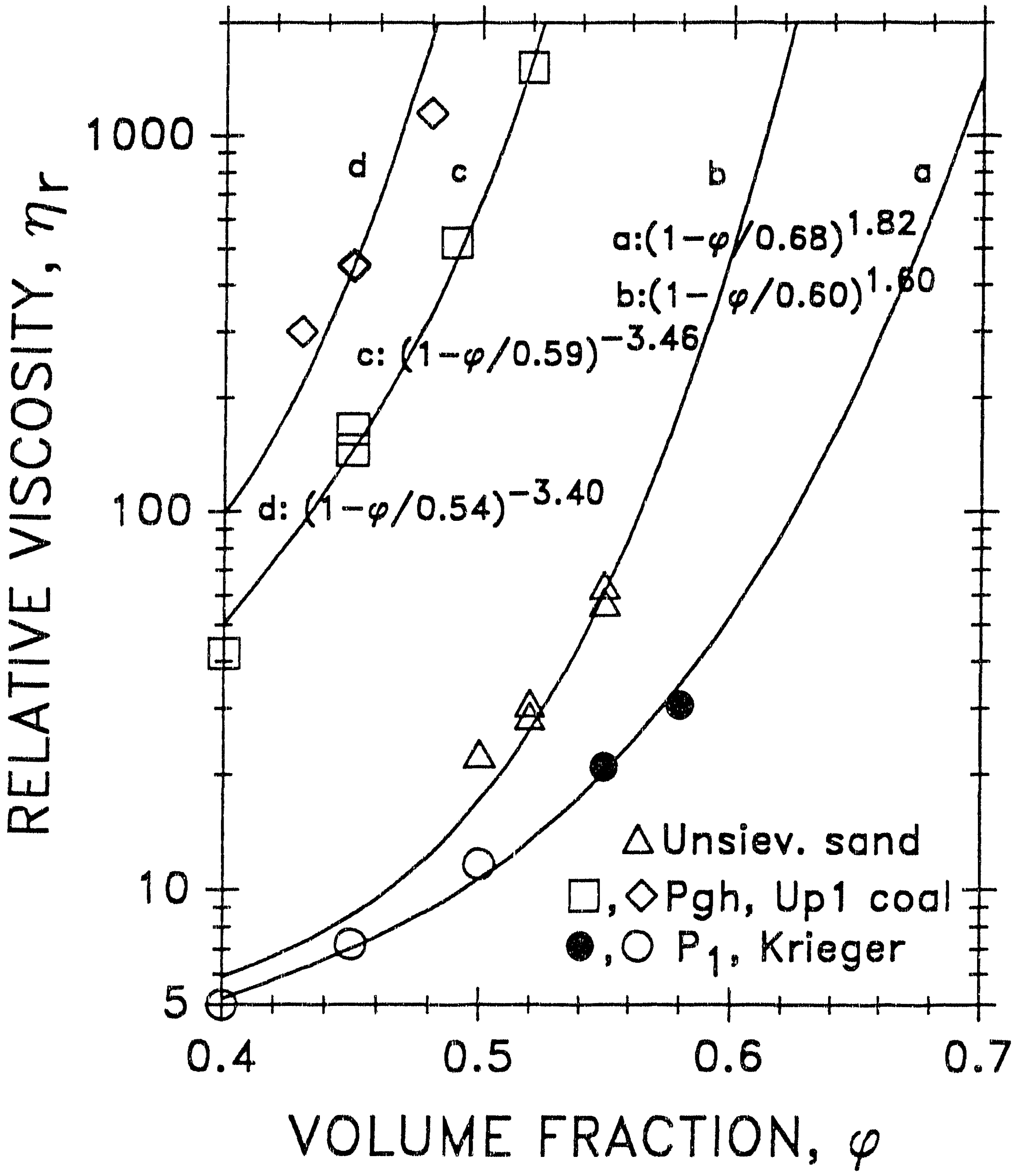

Fig. 2 Comparision of the experimental relative viscosities of the concentrated Newtonian suspensions of polystyrene spheres (circles), irregularly shaped unsieved sand (triangles). Upper Freeport Coal UP1 (diamonds), and Pittsburgh Seam #8 coal Pgh (squares).

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EFFECTS OF PARTICLE PROPERTIES ON THE RHEOLOGY OF CONCENTRATED NONCOLLOIDAL SUSPENSIONS

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ABSTRACT

A concise review of the literature and new experimental results are given concerning the effects of particle shape, density, size, and surface charge on the rheology of concentrated suspensions of noncolloidal particles in Newtonian liquids at shear rates ranging from 1 to 2000 s^{-1}. The measured relative viscosity of a Newtonian suspension as a function of particle volume fraction was found to agree well with the predictions of both the Krieger-Dougherty and the Maron-Pierce-Kitano equations. Also, the sole parameter of the former equation, maximum packing fraction, was found to be in much better agreement with that determined from sedimentation than that of the latter equation. In addition, we found that the relative viscosity of a pseudoplastic suspension correlates well with the particle Peclet number for both spherical and irregularly shaped particles. Specifically, since particle diffusional relaxation time increases with particle radius cubed, larger particles in an aggregated system diffuse to a lesser extent than smaller particles within the same time scale of shear, and less energy is dissipated as a result. Particle density, ranging from 1 to 2.5 g/cc, was found to have no effect on the relative viscosity.

INTRODUCTION

Concentrated suspensions have been used extensively in industry. Examples are colloidal latex paints (Krieger, 1972), ceramics (Sacks, 1986), and noncolloidal coal water slurry (Tsai and Knell, 1986; Tsai and Vu, 1987). In earlier publications, it was shown that the pseudoplastic behavior of a concentrated suspension of noncolloidal particles (Gadala-Maria and Acrivos, 1980) can be attributed to particle aggregation as a result of the interparticle van der Waals attraction (Tsai and Viers, 1987; Tsai and Zammouri, 1988; Tsai and Ghazimorad, 1990). Particle aggregation, which breaks down at high shear rates, effectively increases particle volume fraction because of entrapment or occlusion of liquid in the aggregates (Lewis and Nielsen, 1968; Castillo and Williams, 1979; van Diemen and Stein, 1982; Wildemuth and Williams, 1984; Tsenoglou, 1990). The suspension viscosity increases as a result. How the rheology of noncolloidal suspensions, at shear rates from 1 to 2000 s^{-1}, is affected by particle properties such as shape, density, size, and surface charge is examined in this paper. Since it is well known that the maximum particle packing fraction increases and the suspension viscosity decreases as the particle size distribution broadens (Brodnyan, 1968; Lee, 1970; Chong et al, 1971; Metzner, 1985; Poslinski et al, 1988), size distributions of the particles used in this study are examined in order to evaluate the effects of other particle properties.

The solid particles used in this study were: dry polystyrene spheres prepared by the Dow Chemical Company, Midland, MI, glass bead #4000 (GL1) and #2740 (GL2) from Ferro Corp., Cataphore Division, glass bead #5000 (GL4) from Potter Industry, silica sand from Fisher Scientific, and micronized Upper Freeport coal (Up1) from the Department of Energy, Pittsburgh Energy Technology Center. The Upper Freeport coal ranked high volatile bituminous A, and contained 28 % volatile and 5.4 % ash on dry basis. Coal and sand particles were irregularly shaped; the polystyrene P_1 and P_2 were spherical with respective volume mean diameters of 75 μm and 6 μm. All glass beads were at least 85% spherical according to the manufacturers' specifications. Batches of the glass bead #5000 and sand were screened to 20-40 μm (GL5 for glass bead) using an Alpine air-jet sieve. The particle size distributions were measured using a Malvern particle size analyzer 2600C, and the results are given in Fig. 1. Also shown in this figure are the mass median diameter (MMD) and the mean diameter based on volume (VMD). The smaller the difference between MMD and VMD, the narrower the particle size distribution. As shown in Fig. 1, while the polystyrene P_1 and P_2, and glass bead GL1 are rather monodispersed, glass beads GL4 and GL5, the Upper Freeport coal and sand, both unsieved and sieved to 20-40 μm (open diamond and open square in Fig. 1, respectively), have much broader size distributions. Glass bead GL2, not shown in this figure, is also monodispersed with 44.7 μm VMD and 44.6 μm MMD. The size distriibution of the Up1 coal is similar to those of GL4 and the sand sieved to 20-40 μm. The sieved sand has a much narrower size distribution than the unsieved sand. Specifically, less than 5% of the sieved sand but about 20% of the unsieved sand particles are larger than 40 μm. The sieved sand contains only 5% more of the <10 μm sizes than the unsieved sand.

Dry polystyrene spheres were dispersed in ethylene glycol while glass beads and silica sand particles were dispersed in silicone oils, ethylene glycol, a 80/20 wt/wt mixture of ethylene glycol and glycerol as well as aqueous solutions containing 72-74 wt% glycerol. Coal was dispersed in aqueous solutions containing 42 wt% ethylene glycol and 72 wt% glycerol. All nonaqueous liquids were reagent grade. The viscosities of all aqueous and nonaqueous solutions used are given in Table I.

The zeta potentials of the polystyrene spheres and the Upper Freeport coal particles dispersed in deionized water measured 4 mV and 11 mV, respectively, using a Malvern Zeta Sizer IIc. Therefore, we believe that the interparticle electrostatic repulsion is negligible in the nonaqueous suspensions of polystyrene spheres, and the interparticle van der Waals attraction predominates in the aqueous suspensions of the Upper Freeport coal. Although the zeta potentials of glass bead and sand could not be measured because the particles settled in the cell, the zeta potentials of colloidal silica dispersions in water at pH 3, 7, and 11 were found to be zero, -50 mV, and -75 mV, respectively (Sacks, 1986). The role which the interparticle electrostatic repulsion may play in the rheology of glass bead suspenions in aqueous glycerol solutions was examined at pH ranging from 1 to 11. Reagent grade hydrogen chloride and sodium hydroxide were added to deionized water to control the pH of the aqueous solutions. We found that the relative viscosity of a pseudoplastic suspension ($n= 0.85\pm0.02$) of glass bead GL1 at 0.55 volume fraction in an aqueous solution containing 74 wt% glycerol (viscosity of 0.31 P) is independent of pH. It should be noted that the conductivities of the water at pH 3, 7.5, and 11 were 940, 100, and 2700 μmho/cm, respectively, as measured with a Cole-Parmer digital conductivity meter Model 1481-60. These conductivities are equivalent to KCl concentrations of 0.0065 N, 0.0007 N, and 0.02 N. Addition of 74 wt% glycerol resulted in reduction of conductivity to 11, 3, and 44 μmho/cm, respectively.

Sedimentation was carried out in a covered, calibrated, precision graduated cylinder for two to five weeks or until no further settling was observed. The viscosity of the suspension was measured using a Burrell-Severs capillary rheometer A120, and corrected for the non-Newtonian behavior (Skelland, 1965; Tsai and Knell, 1986). Two capillaries were used: capillary C of 1.58-mm diameter and 5.00-cm length and capillary D of 3.20-mm diameter and 25.45-cm length. The viscosities measured using both capillaries show very good agreement. This indicates that no slip took place at the wall of either capillary (Skelland, 1965), and the wall effect expected in capillary C was compensated by the entrance effect (Tsai and Knell, 1986). The liquid viscosities were measured using a rotational viscometer Haake RV2. Detailed experimental procedures for suspension preparation and the methods of measuring viscosity and volume fraction have been described previously (Tsai and Viers, 1987; Tsai and Zammouri, 1988).

RESULTS AND DISCUSSION

Suspension rheology is characterized by the Ostwald-de Waele power law which describes shear stress and shear rate in terms of flow behavior index n and flow consistency index K in a power form $\tau = K\dot{\gamma}^n$. All suspensions studied have been shown to follow this power law.

1. Newtonian Suspensions

As reported in earlier publications (Tsai and Viers, 1987; Tsai and Zammouri, 1988; Tsai and Ghazimorad, 1990), the interparticle van der Waals attraction for silica, such as glass beads and sand particles, suspended in silicone oil is negligible because silicone oil is nonpolar and its refractive index is very close to that of silica. As a result, the suspensions of glass beads GL1 (glass beads #4000 with a volume mean diameter of 28 μm) in silicone oil at volume fractions as high as 0.60 are still Newtonian within the studied shear rate range from 10 to 2000 s^{-1}. Likewise, the suspensions of irregularly shaped silica sand (24 μm VMD) in silicone oils were found in this study to be Newtonian at shear rates ranging from 10 to 1500 s^{-1}. We also found that the relative viscosities of these non-colloidal Newtonian suspensions are in very good agreement with the predictions of the Krieger- Dougherty Eq. (1) (Krieger and Dougherty, 1959; Krieger, 1972; Castillo and Williams, 1979) and the

Maron-Pierce-Kitano Eq. (2) (Maron and Pierce, 1956; Kitano et al, 1981; Metzner, 1985; Poslinski et al, 1988):

$$\eta_r = \left(1 - \frac{\varphi}{\varphi_M}\right)^{-[\eta]\varphi_M} \tag{1}$$

$$\eta_r = \left(1 - \frac{\varphi}{\varphi_M}\right)^{-2} \tag{2}$$

where φ, φ_M, and $[\eta]$ designate the particle volume fraction, the maximum particle packing fraction, and the intrinsic relative viscosity of the suspension. $[\eta]$ is taken in this study as 2.67, as in the rigid sphere model for colloidal suspensions of polystyrene latex (Krieger, 1972) which is slightly higher than the Einstein value (2.5) for uncharged spheres (Happel and Brenner, 1983). Interestingly, this value was found to be 2.60 and 2.67 for latexes of uniform spheres by Maron and Pierce (1956) and by Maron and Sisko (1957) using the Ree-Eyring generalized flow theory. The sole parameter φ_M in either Eq. (1) or Eq. (2) was determined by fitting each equation to the experimental data. The results are given in Table II.

As shown in Fig. 2, the relative viscosities of the silicone oil suspensions of unsieved sand (open triangles) are in excellent agreement with the η_r (curve c) predicted by the Krieger-Dougherty equation with the maximum packing fraction equaling 0.60. This maximum packing fraction was found to be in excellent agreement with the maximum volume fraction (0.61) of the sedimented suspension of unsieved sand (see Table II). Likewise, substituting the maximum volume fraction (0.50) of the sedimented sieved sand suspension to Eq. (1) yields a relative viscosity (22), at 0.45 volume fraction, in excellent agreement with the measured value (solid triangle in Fig. 2). Very good agreement between φ_M determined by model-fitting of Eq. (1) and the experimental value determined by sedimentation is also seen in Table II for glass bead suspensions.

Eq. (2), first derived by Maron and Pierce (1956) for suspensions of spherical particles using the Ree-Eyring generalized flow theory and then developed by Kitano et al (1981) for polymer melts filled with various inorganic fillers, was found in this study to fit the experimental relative viscosities as well as the Krieger-Dougherty Eq. (1). As shown in Fig.2, Eq. (2) (dotted curve) is in better agreement than Eq. (1) with the averaged values (open circles) of the relative viscosities obtained by various researchers for Newtonian suspensions of uniform spheres (Thomas, 1965). However, as shown in Table II, a substantial difference exists between the maximum packing fraction determined by model-fitting of Eq. (2) and that determined by sedimentation. It should also be noted that a careful examination of some sources (Maron and Fox, 1955; Maron and Sisko, 1957) of the data used by Thomas (1965) reveals that the pseudoplastic latexes of uniform spheres at volume fractions above 0.50 did not reach their high shear Newtonian limits. This may account for the greater averaged relative viscosities (open circles) compared to those (open inverted triangles and solid circles) obtained by Krieger (1972) and by Tsai and Viers (1987).

A comparison between the data for the glass beads GL5 (85% spherical) and the irregularly shaped sieved sand particles reveals a significantly greater relative viscosity and a substantially smaller maximum packing fraction for irregularly shaped sand particles. Specifically, the relative viscosity of a silicone oil (viscosity of 0.52 P) suspension at 0.45 volume fraction of glass beads GL5 was found to be 8.9, while that of irregularly shaped sand particles was found to be 22 despite a broader sand particle size distribution (see Fig. 1). The maximum packing fractions were found to be 0.61 by model-fitting of the Krieger-Dourgherty equation and 0.58 by sedimentation for glass beads GL5, and only 0.50 by both the model fitting and sedimentation for sieved sand. In addition, Fig. 2 shows that the relative viscosities of all glass bead (85% spherical) suspensions are significantly smaller than those of unsieved sand suspensions at same volume fractions despite a much broader size distribution of the unsieved sand. Higher relative viscosity has also been reported (Kitano, 1981) for irregularly shaped talc suspensions than glassy sphere suspensions in polymeric liquids at volume fractions smaller than 0.40.

Our most recent results on Newtonian suspensions of glass beads with VMD ranging from 17 μm (GL5) to 45 μm (GL2) confirm that particle size has no effect on the relative viscosity of a concentrated Newtonian suspension (Metzner, 1985). It should be noted that the high shear Newtonian limits of relative viscosities of the polystyrene P_1 (75 μm) suspensions (solid circles in Fig. 2) were reported (Tsai and Viers, 1987) to agree well with the predictions of the Krieger-Dougherty equation (curve a) with the same maximum packing fraction (0.68) for latexes of polystyrene spheres smaller than 1 μm (open inverted triangles). In addition, the particle diameters of the uniform spheres used to obtain the averaged relative viscosities (open circles in Fig. 2) in Table I of Thomas (1965) ranged from 0.1 to 440 μm (Metzner, 1985). Thus, the effect of particle size on energy dissipation is negligible in a nonaggregated system and/or at high shear rates when hydrodynamic force predominates over interparticle attraction. In contrast, at low shear when interparticle attraction predominates over hydrodynamic force, microstructure-dependent phenomena such as non-zero storage modulus have been reported (Poslinski et al, 1988) for polybutene (65 P) composites at high volume fractions of glass spheres. In such a low shear rate elastic region, a substantial effect of particle size on the low shear rate (1 s^{-1}) Newtonian limit of relative viscosity has also been reported for injection molding model slurries in polybutene (Agarwala et al, 1992).

2. Pseudoplastic Suspensions

Significant interparticle van der Waals attraction is predicted by the Lifshitz equation (Israelachivili, 1985) for concentrated suspensions of polystyrene and glass beads in ethylene glycol, glycerol and its aqueous solution and for coal suspensions in water and aqueous glycerol or ethylene glycol solutions. Specifically, the dimensionless Hamaker constant A/kT ranges from 2.2 to 3.3 for the coal suspensions (Tsai and Ghazimorad, 1990) and from 0.6 to 1.2 for the polystyrene and glass bead suspensions (Tsai and Viers, 1987; Tsai and Zammouri, 1988), where k is the Boltzman constant and T is 300°K. These suspensions at volume fractions of 0.45 and 0.55 are pseudoplastic with flow behavior indices ranging from 0.89 to 0.58. Their flow behavior indices decrease with increased Hamaker constant (Tsai and Ghazimorad, 1990) and particle volume fraction (Gadala-Maria Acrivos, 1980).

The particle Peclet number, $Pe = \eta_o \bar{a}^3 \dot{\gamma}/kT$, rather than shear rate is used in Fig. 3 in order to compare particles of various sizes and densities, since it was found to give a satisfactory account for the effect of particle size on the relative viscosity of concentrated pseudoplastic suspensions of polystyrene spheres (Tsai and Zammouri, 1988). It should be noted that $6\pi\eta_o\bar{a}^3/kT$ is the diffusional relaxation time (Krieger, 1963; Russel, 1980; Russel et al, 1989), $2\bar{a}$ is the volume mean diameter of the particles, and η_o refers to the viscosity of the suspending liquid. The time required for a particle to diffuse a distance comparable to its radius in an aggregated system increases with particle radius cubed. Within the same time scale of shear (inverse shear rate), larger particles diffuse to a lesser extent than smaller particles, and less energy is dissipated as a result. Therefore, the relative viscosity of a pseudoplastic suspension decreases as the particle Peclet number increases for both spherical and irregularly shaped particles as shown in Fig. 3. It should be noted that kT is simply a convenient energy scale since Brownian motion is negligible for the particle sizes involved in this study.

Fig. 3 shows a substantial effect of particle shape on the relative viscosity of a pseudoplastic suspension. At the same volume fraction (0.45), the irregularly shaped sand suspension is considerably more viscous than the glass bead GL5 suspension despite its broader size distribution (Fig. 1). In fact, the relative viscosities of the sieved sand suspension at 0.45 volume fraction coincide with those of the glass bead GL5 suspension at 0.55 volume fraction. Like their Newtonian counterparts (silicone oil suspensions) mentioned earlier, sedimentation of these pseudoplastic suspensions shows a significantly smaller maximum packing fraction (0.53 vs 0.57) for irregularly shaped sand than for glass beads (see Table II).

More importantly, Fig. 3 shows that the relative viscosity as a function of particle Peclet number for the 0.45 volume fraction suspensions of sieved sand particles and the Upper Freeport (Up1) coal, in liquids of similar viscosities (0.35 P vs 0.28 P), falls nearly on the same line. Both the sieved sand and Up1 coal are irregularly shaped and have similar size distributions (see Fig. 1); but their respective densities are 1.33 g/cc and 2.50 g/cc. The same phenomenon is seen in this figure for the 0.55 volume fraction suspensions of glass beads and polystyrene suspensions despite a substantial difference between their particle densities (2.39 g/cc and 1.05 g/cc for glass bead and polystyrene, respectively) Therefore, we conclude that particle density ranging from 1.0 to 2.5 g/cc has no significant effect on the relative viscosity of a concentrated pseudoplastic suspension of noncolloidal particles. This is in contrast with the substantial effect of particle density ranging from 2.7 to 19.3 g/cc on the relative viscosity of injection molding model slurries in the low shear rate (1 s^{-1}) elastic region (Agarwala et al, 1992). It should be noted that the relative viscosity (solid triangle) of a silicone oil (0.96 P) suspension of polystyrene PS spheres 40-50 μm in diameter (Gadala-Maria and Acrivos, 1980) is also shown in Fig. 3 for comparison with our Polystyrene P_1 amd P_2 data (Tsai and Zammouri, 1988). The difference may be attributed to the effect of liquid viscosity (Tsai et al, 1989) which is also seen in this figure for Up1 coal suspensions.

CONCLUSIONS

Our experimental results clearly demonstrate that the shape of particles with aspect ratio close to unity dictates the relative suspension viscosity. Suspensions of irregularly shaped particles have higher relative viscosities than suspensions of spherical particles at same volume fractions, in agreement with the reported results at high shear conditions. The relative viscosity of a Newtonian suspension is in excellent agreement with that predicted by the Krieger/Dougherty rigid sphere model using the maximum packing fraction determined from sedimentation as the sole parameter.

The relative viscosity of a pseudoplastic suspension is independent of the particle density. It correlates well with the particle Peclet number. The extent of particle diffusion at high shear rates decreases considerably as the particle size increases, and less energy is dissipated as a result. The interparticle electrostatic repulsion plays no significant role in the rheology of pseudoplastic nonaqueous and aqueous glycerol suspensions of noncolloidal particles.

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NOTATIONS

a	Particle radius of rigid sphere, in cm
A	Hamaker constant
k	Boltzmann constant, 1.38×10^{-23} JK^{-1}
K	Consistency index
MMD	Mass median diameter, the particle diameter corresponding to the 50% point on the cumulative weight distribution curve
n	Flow behavior index, 1 for Newtonian fluid, < 1 for pseudoplastic fluid, and >1 for dilatant fluid
T	Temperature, in °K

Greek Letters

φ	Solid volume fraction
φ_M	Maximum packing fraction
η	Suspension viscosity, in P
η_o	Newtonian viscosity of suspending fluid, in P
η_r	Relative viscosity, η/η_o
$[\eta]$	Intrinsic relative viscosity of suspension
τ	Shear stress, in dyne/cm^2
$\dot{\gamma}$	Shear rates, in s^{-1}

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TABLE I

Viscosities of Various Liquid Solutions Used

Liquid Composition	Viscosity, P
Ethylene glycol	0.17
Glycerol	8.6-9.8
Silicone oils	0.52, 1.1, 9.05
Ethylene glycol/glycerol, 80/20 wt/wt	0.35
Aqueous solution, 42 wt% ethylene glycol	0.03
Aqueous solution, 72 wt% glycerol	0.28
Aqueous solution, 74 wt% glycerol	0.31

TABLE II

Maximum Volume Fractions, φ_M

Solid particles	Liquid viscosity	φ_M Sediment.	φ_M* model fitting Eq. (1)	Eq. (2)
Sieved Sand 20-40 μm	Silicone oil, 0.52P	0.50	0.50	0.57
Sieved Sand 20-40 μm	Glycol/glycerl, 0.35P	0.53	-----	-----
Unsieved Sand	Silicone oil, 0.52P	0.61	0.60	0.63
Glass bead 20-40 μm GL5	Silicone oil, 0.52P	0.58	0.61	0.68
Glass bead 20-40 μm GL5	Aqueous solution with 72 wt% glycerol,0.28P	0.57	-----	-----
Glass bead #5000 GL4	Silicone oil, 0.52P	0.62	0.62	0.65
Glass bead #4000 GL1	Silicone oil, 0.52P	0.61	0.63	0.65
Glass bead #4000 GL1	Silicone oil, 1.1P	0.61	0.63	0.65
Glass bead #4000 GL1	Aqueous solution with 72 wt% glycerol, 0.28P	0.60	-----	-----

* Obtained by fitting the Krieger-Dougherty model, Eq. (1), and the Maron-Pierce-Kitano model, Eq. (2), to the measured relative viscosity data of Newtonian suspensions

Fig. 1 Particle size distributions of polystyrene spheres P_1 and P_2, glass beads GL1 (#4000), GL4 (#5000), GL5 (#5000 sieved to 20-40 μm), and Upper Freeport Coal (Up1), sieved (20-40 μm) and unsieved sand.

Fig. 2 Comparison of the experimental relative viscosities of the concentrated Newtonian suspensions of 85% spherical glass beads #4000 and #5000 (GL1, GL4, and GL5: open diamond, solid diamond, and open square, respectively), and irregular shaped unsieved sand (open triangle) and sieved sand (solid triangle). Experimenatl values reported in the literature for uniform spheres are: open circle from Table I of Thomas, 1965, solid circle by Tsai and Viers, 1987, and open inverted triangle by Krieger, 1972.

Fig. 3 Effects of particle shape and particle density on the relative viscosity of a concentrated pseudoplastic suspension. (Solid triangles are for Polystyrene PS suspensions from Gadala-Maria and Acrivos, 1980.)

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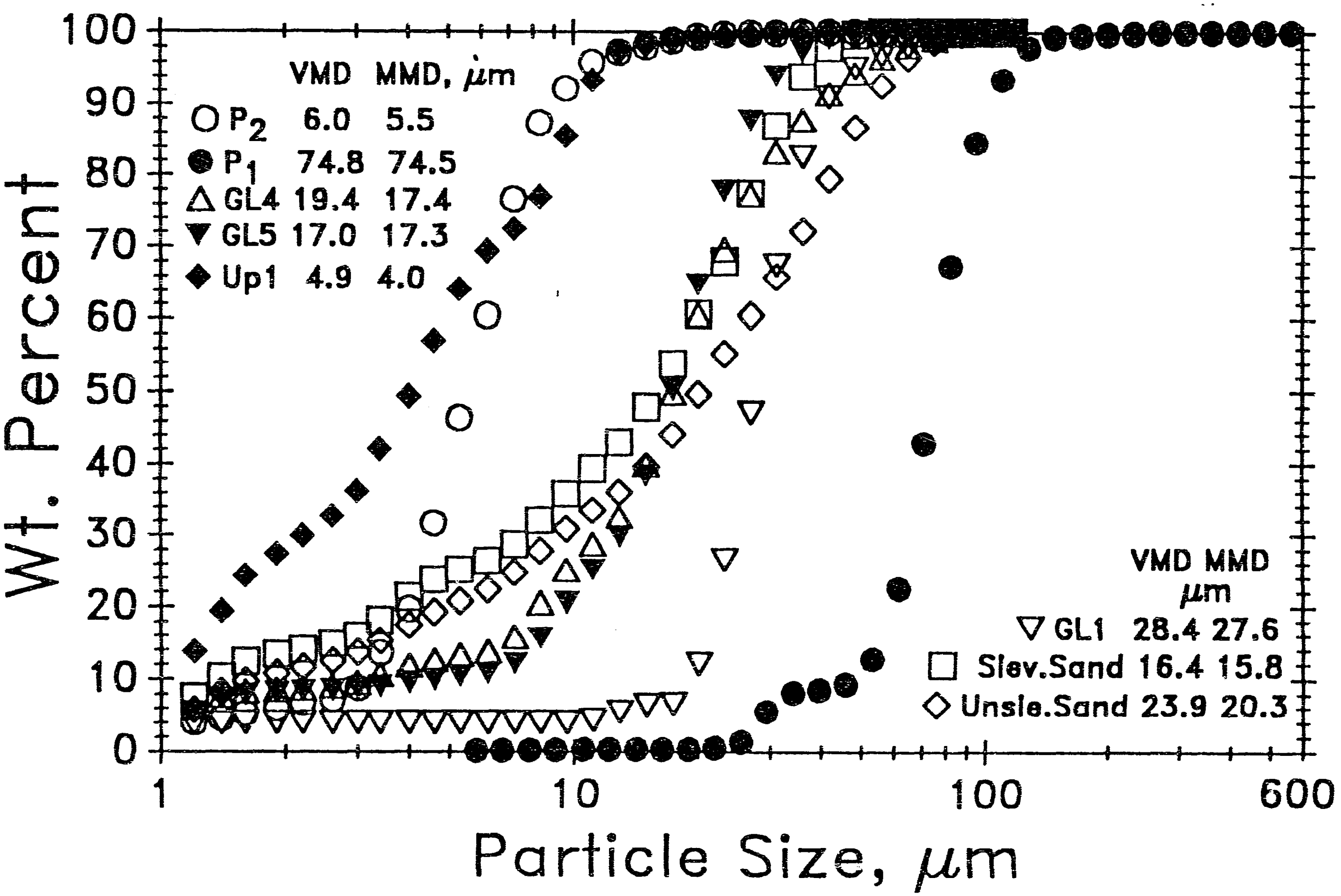
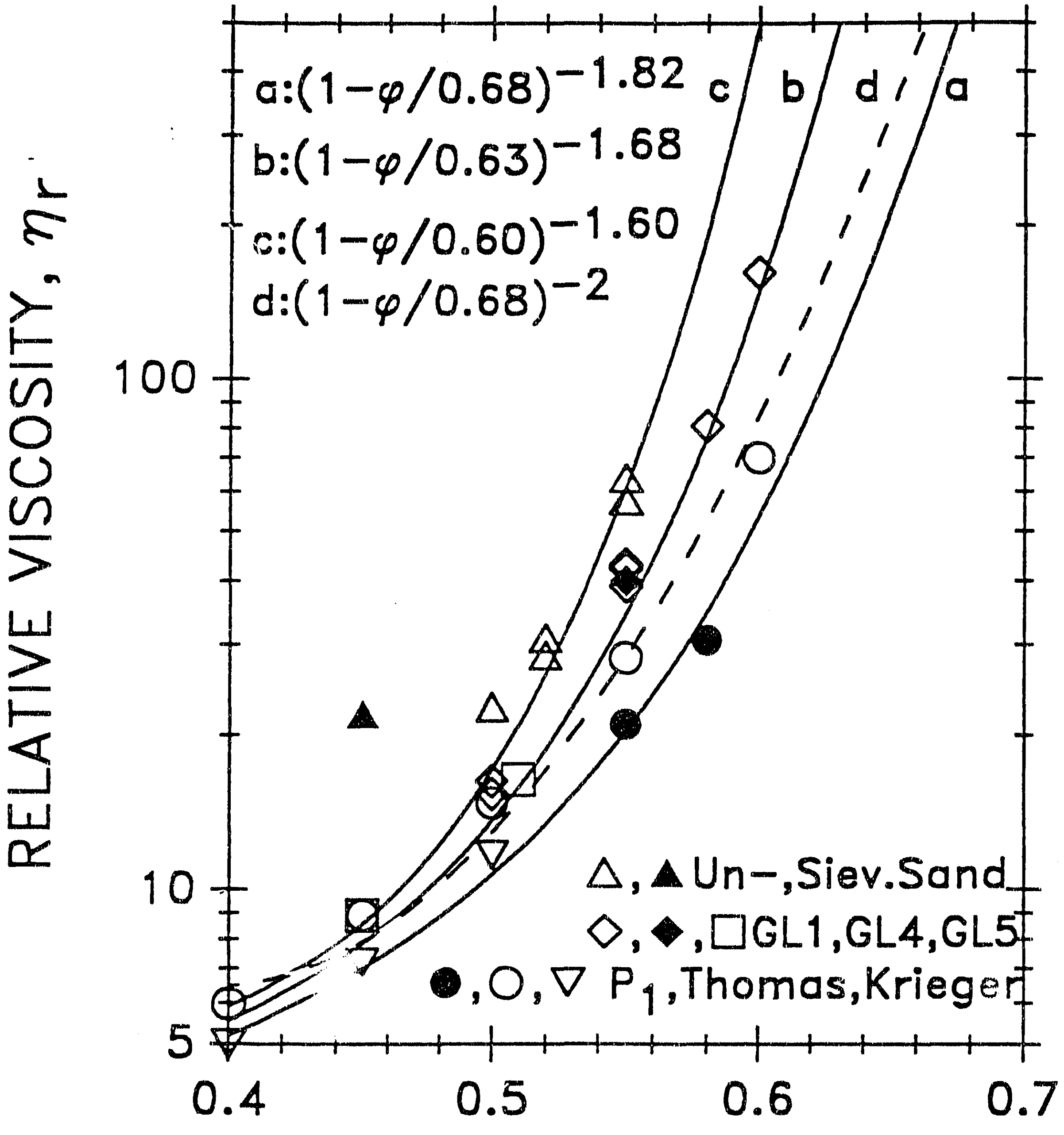

VMD MMD, µm
○ P₂ 6.0 5.5
● P₁ 74.8 74.5
△ GL4 19.4 17.4
▼ GL5 17.0 17.3
◆ Up1 4.9 4.0
VMD MMD
µm
▽ GL1 28.4 27.6
□ Siev.Sand 16.4 15.8
◇ Unsie.Sand 23.9 20.3
Wt. Percent
100
90
80
70
60
50
40
30
20
10
0
1
10
100
600
Particle Size, µm

KD.PAGT
KD.GRA
NEWVIS



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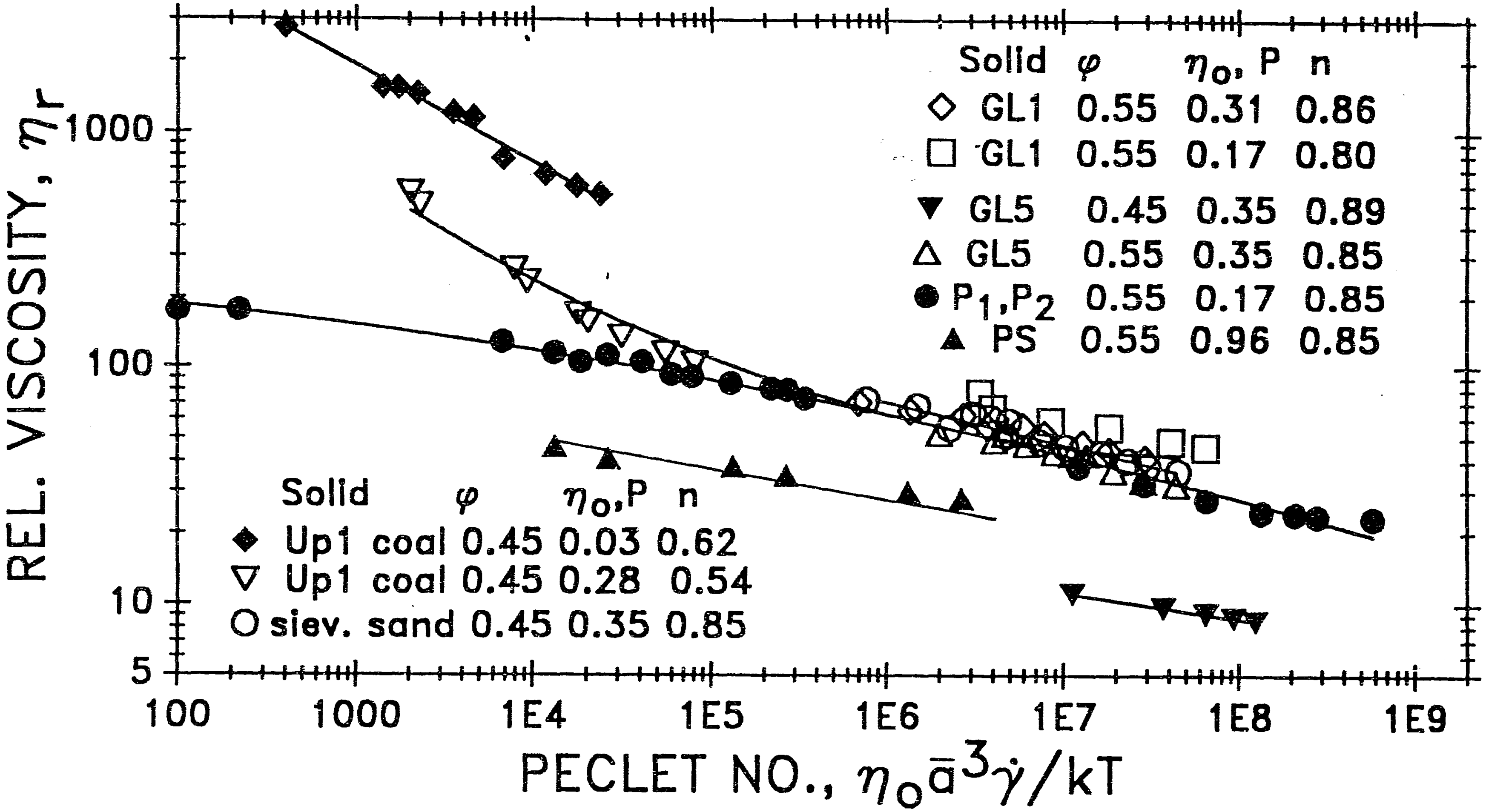
REL. VISCOSITY, η_r
1000
100
10
5
100
1000
1E4
1E5
1E6
1E7
1E8
1E9
PECLET NO., $\eta_o \bar{a}^3 \dot{\gamma}/kT$
Solid φ η_o, P n
◇ GL1 0.55 0.31 0.86
□ GL1 0.55 0.17 0.80
▼ GL5 0.45 0.35 0.89
△ GL5 0.55 0.35 0.85
● P_1,P_2 0.55 0.17 0.85
▲ PS 0.55 0.96 0.85
Solid φ η_o,P n
◆ Up1 coal 0.45 0.03 0.62
▽ Up1 coal 0.45 0.28 0.54
○ siev. sand 0.45 0.35 0.85

END

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