Rheological Properties of PHPA Polymer Support Fluids

Carlos Lam1; Peter J. Martin2; and Stephan A. Jefferis3

Abstract: Synthetic polymer fluids are becoming a popular replacement for bentonite slurries to support excavations for deep foundation elements. However, the rheological properties of the polymer fluids used in excavation support have not been studied in detail, and there is currently confusion about the choice of mathematical models for this type of fluid. To advance the current state of knowledge, a laboratory study has been performed to investigate the steady-shear viscosity and transient viscoelasticity of a polymer support fluid. It is found that over the shear-rate range measurable with the Fann viscometer, an industry standard instrument, the power-law model can be used to represent the results, whereas the Bingham plastic model will significantly overestimate the viscosity at low shear. When evaluated over a much wider shear-rate range with a cone-and-plate rheometer, the polymer fluids show signs of approaching limiting viscosities at the very low and high shear rates, and for this behavior the Carreau model is more appropriate. From a series of oscillatory tests, the viscoelastic properties of the polymer fluid have been shown to be very different from those reported for their bentonite counterparts. The key engineering implications of the rheological results have been discussed. DOI: 10.1061/(ASCE)MT.1943-5533.0001252. This work is made available under the terms of the Creative Commons Attribution 4.0 International license, http://creativecommons.org/licenses/by/4.0/.

Author keywords: Bored piles; Excavation; Polymer; Rheology; Viscosity; Viscoelasticity.

Introduction

Since the pioneering work of Veder (1953), bentonite slurries have been in continuous use for the construction of drilled shafts (bored piles) and diaphragm walls around the world. Bentonite slurries are thixotropic clay suspensions with a yield stress which enables the slurry to hold soil particles in suspension during excavation, so increasing the slurry density and excavation stabilizing pressure. Since the early 1990s, aqueous solutions of partially hydrolyzed polyacrylamides (PHPA) also have been used for the construction of deep foundations in many different countries (e.g., Ata and O’Neill 1997; Lam and Jefferis 2014b). PHPA is a synthetic polymer comprising repeating units of acrylamides and acrylates. Fig. 1 shows the chemical structure of PHPA.

In the oil and gas industry, PHPAs have a long history of use as bentonite additives to inhibit the swelling of water-sensitive shales and to reduce fluid loss in permeable formations (Liao and Siems 1990; Kadaster et al. 1992; Kelessidis et al. 2013). In civil engineering, PHPA fluids are increasingly being used as a complete replacement for bentonite slurries, as these synthetic fluids require a much-reduced site footprint for fluid-management equipment and offer potentially drier and therefore more readily reused excavated soil. They also offer opportunities to manage interactions with in situ soils through the exploitation of polymer chemistry. According to O’Neill and Reese (1999), the commercial PHPAs used in civil engineering typically have a molecular weight ranging from 14 to 17 million g/mol and a surface charge density (degree of hydrolysis) from 30 to 45%. A general introduction to the use of polymer fluids in geotechnical construction has been given in Jefferis and Lam (2013). In this paper, polymer is taken to mean PHPA unless otherwise specified.

Although both bentonite and polymer support fluids work by exerting a stabilizing pressure against the side walls and base of an excavation, their effects on the excavation and the completed foundation element can be quite different, in part, due to their distinct rheological behaviors. Unlike bentonite slurries, polymer fluids do not form a layer of filter cake on the exposed soil surface, so during excavation the fluids will continue to flow into the surrounding soil formations due to the pressure head difference (typ. >15 kPa) between the support fluid and groundwater. The shear viscosity of a polymer support fluid is known to be a controlling parameter for the rate of fluid flow into the ground (Lesemann and Vogt 2012). The viscous and elastic properties of a fluid also affect the settling velocity of soil particles in the fluid, and thus the amount of detritus accumulated at the base of the excavation or at the top of the fresh concrete as it is tremied into the hole (Kheng et al. 1991; Majano and O’Neill 1993; Lam et al. 2014a).

Sedimentation of small soil particles is likely to be in the creeping flow regime (Reynolds number, Re < 1) where the elasticity of the fluid does not come into play. McKinley (2002) also mentions that, when the Deborah number (De) is less than 0.1, the elasticity of a fluid has no effect on particle drag (the Deborah number is the ratio of the characteristic time of fluid to the characteristic time of process and is equal to zero for steady-state flows). Larger particles of size perhaps several millimeters will settle with a higher Reynolds and Deborah numbers so that the elasticity of a fluid will have an effect on the drag force tending to increase it. However, large particle settlement is a rapid process and the sediment easily can be removed prior to concrete placement. Thus as regards soil sedimentation, the transient viscoelasticity of a polymer fluid will be less important than the steady-state viscosity.
Although the rheological properties of bentonite drilling and support fluids have been widely studied (Hutchinson et al. 1975; Speers et al. 1987; Alderman et al. 1991; Santagata et al. 2008), to date rather little has been published on their polymer counterparts especially in the civil engineering literature (some of the available work will be discussed in the following section). This in part makes it currently not possible for the construction industry to develop specifications for polymer fluids as they have done so for bentonite (Institution of Civil Engineers 2007). Although polymer rheology has been studied extensively by polymer scientists (e.g., Ferry 1980), the findings are of limited application to support fluids as the materials studied and the applications are very different. However, the underlying rheological principles are applicable regardless of the fluid in question and some of them will be applied to interpret the results of this study of the rheological properties of PHPA fluids prepared at typical concentrations for excavation work. Before the experimental details and the results are presented, the current construction industry practice in terms of the choice of mathematical models to represent viscometer results is set out.

### Choice of Mathematical Models

As bentonite fluids possess a yield stress, the Bingham plastic model is commonly used to represent their flow behavior (Hutchinson et al. 1975). The equation for this model is

\[ \tau = \tau_0 + \eta_p \dot{\gamma}, \]

where \( \tau \) is the shear stress, \( \dot{\gamma} \) is the shear rate, \( \tau_0 \) is the yield stress, and \( \eta_p \) is the plastic viscosity. Note that in the oil industry and in some of the civil engineering literature, the parameters \( \tau_0 \) and \( \eta_p \) are denoted as YP and PV respectively, and the apparent viscosity of the fluid is referred to as AV (Ata and O’Neill 1997; Brown et al. 2010).

There is no consensus as to the appropriate mathematical models for the flow behavior of polymer support fluids, as no detailed studies have been reported in the construction literature, for this type of non-Newtonian fluid. Early researchers, such as Kheng et al. (1991), probably due to the influence of the previous bentonite research, used only the Bingham plastic model to interpret their results. In contrast, authors such as Beresford et al. (1989) and Howsam and Hollamby (1990) believed that the power-law model should be used, which has the form \( \tau = K \gamma^n \), where \( K \) is the flow consistency index and \( n \) is the flow behavior index. The research group led by the late Professor Michael O’Neill at the University of Houston took the middle ground and interpreted their viscometric data using both Bingham plastic and the power-law models (Majano et al. 1994; Ata and O’Neill 1997), although it is apparent that they preferred the Bingham plastic model when it came to the presentation of results in technical papers (Majano et al. 1994; Ata and O’Neill 2000). The approach of these two papers seems to have been carried through to the latest two editions of the U.S. Federal Highway Administration (FHWA) drilled shaft manual (O’Neill and Reese 1999; Brown et al. 2010). From the manual, it would appear that the FHWA regard the Bingham plastic model as an appropriate model for polymer excavation fluids even though the example flow curve given in the manual clearly shows strong shear-thinning (power-law type) behavior and a negligible yield stress.

When selecting an appropriate mathematical model, it is necessary to relate the model used to the shear rates of the process of concern. In Table 1, indicative shear rates for processes involved in fluid-supported excavations are presented. Where necessary for the shear-rate estimates, a Newtonian fluid of viscosity 20 mPa · s has been assumed. Polymer fluids used in practice may have higher non-Newtonian viscosity and thus the shear-rate figures given in Table 1 tend to be upper bounds. A brief discussion of other assumptions is set out in the table. It can be seen that the indicative shear rates range from 0.005 s⁻¹ for fluid flow above rising concrete to 10,000 s⁻¹ for fluid–solid separation in a hydrocyclone. It is therefore important to consider the process of concern when selecting a mathematical model and indeed the test instrument for viscosity measurements in the field. Table 2 lists three viscosity measurement tools that may be used for the control of fluid quality in the field. These are the Marsh funnel, the

### Table 1. Typical Fluid Shear Rates for Processes Relevant to Fluid-Supported Excavations

| Process                                      | Approximate shear rate (s⁻¹) | Assumptions¹ |
|----------------------------------------------|-------------------------------|---------------|
| Flow from excavation into adjacent soil      | 0.8–800                      | \( D_{10} \) range from 63 \( \mu \)m to 6 mm with hydraulic gradient from 0.1 to 10 m⁻¹ |
| Extraction—grab/auger insertion and removal  | 1–100                        | Assumes Hazen’s coefficient to be 0.01 for \( D_{10} \) in mm, Beresford et al. (1989) |
| Particle settlement                          | 8–130                        | 63 \( \mu \)m to 6 mm soil particles falling through a 20-mPa · s Newtonian fluid (calculated as \( 3 \times \) settling velocity/particle diameter) |
| Pipe flow                                    | 50–400                       | Pipe velocity 1 to 5 m/s; pipe diameter 0.1 to 0.15 m (calculated using the standard result: \( 8 \times \) pipe velocity/pipe diameter) |
| Fluid cleaning                               | 2,000–10,000                 | Flow likely to be turbulent and thus viscosity of limited significance |
| Support fluid above rising concrete during  | 0.005 to 0.01                | Flow likely to be turbulent and thus viscosity of limited significance |

¹A Newtonian fluid of viscosity 20 mPa · s has been assumed for all situations where a fluid viscosity is required for the shear rate estimation. Since the viscosity of polymer fluids can be higher, the given shear rates tend to be upper bounds.
Table 2. Three Viscosity Measurement Tools Suitable for Site Use

| Instrument       | Approximate shear rate (s⁻¹) | Assumptions⁴ |
|------------------|-----------------------------|---------------|
| Brookfield viscometer | 0.1–100                     | Low shear rates achievable with a low-viscosity adaptor |
| Fann viscometer  | 5–1,022                     | Standard rotor-bob combination: R1-B1 |
| Marsh funnel     | 1,350–3,100                  | Average shear rates for funnel time of 30–70 s |

⁴Advanced rheometers are not included here as they are laboratory bound.

Brookfield viscometer, and the Fann (direct-indicating) viscometer. Examples of their use can be found in Lam et al. (2010), Lam et al. (2014b), and Lam and Jefferis (2014a).

Experimental Details

Materials Used

A commercially partially hydrolyzed polyacrylamide (PHPA) known as Shore Pac was used to prepare the test fluids. It was supplied in dry granular form by CETCO Drilling Products. The molecular weight and the degree of hydrolysis of this material have been determined to be 20 × 10⁶ g/mol and 39% respectively. These results show that the polymer has a high molecular weight and is also highly charged. High-molecular-weight PHPAs are by far the most popular type of polymer used in foundation drilling (O’Neill and Reese 1999), so the CETCO product was chosen as a representative of the class of products used in practice. The results of this work also should be of relevance to projects using other types of PHPA but with similar properties. According to the supplier, the recommended concentration for the product is from 0.4 kg/m³ for clay soils to 1.2 kg/m³ for open cobbles. At these concentrations, the density of the polymer fluid is essentially that of water as the polymer has a density similar to that of water.

Sample Preparation

To prepare the test fluid and to avoid clumping of the polymer grains, a laboratory mixer rotating at a speed of 500 r/min (rpm) was used to create a vortex in the mix water and the required quantity of polymer granules then sifted into the vortex. Once addition was complete, the mixing speed was reduced to 200 rpm so as not to apply unnecessary shear to the fluid. After about 45 min of mixing, a clear viscous solution had formed, and it was left to stand overnight before use. This procedure was used to ensure consistent laboratory test fluids, though in the field polymer fluids can be and are used immediately after mixing.

Microstructure of the PHPA Fluid

Since the rheological properties of a polymer fluid are highly dependent on its underlying microstructure, a droplet of the prepared fluid was examined in an environmental scanning electron microscope (ESEM). An ESEM was used because it does not require the specimen to be coated with a layer of conductive material as in a conventional SEM; the microstructure of the fluid is therefore more likely to be preserved. The ESEM used was a Carl Zeiss Evo LS15, and the micrograph was captured using a variable pressure secondary electron detector. The sample preparation procedures generally followed those employed by Feng et al. (2002), which are briefly described as follows: a small droplet of the polymer solution was freeze-dried on a specimen holder to −15°C using a Peltier cooling system before being moved into the ESEM chamber. To reveal the polymer microstructure, the frozen water had to be removed, and this was achieved by gradually reducing the chamber pressure to about 133 Pa (1 Torr) absolute. This allowed the ice within the specimen to sublime without damaging the microstructure of the polymer. An acceleration voltage of 15 kV and a working distance of 7.5 mm were used for the imaging work.

Fig. 2 shows a micrograph of the polymer fluid after the water had been removed by sublimation. The micrograph shows that the polymer is not in the form of individual and independent chains but as an intertwined and entangled three-dimensional molecular network structure. Note the length of a single polymer chain is estimated to be about 70 μm which is consistent with its high molecular weight. The micrograph also shows that the polymer chains, although entangled with one another, appear to be rather stiff and have not coiled up. This is important as coiling would reduce chain interactions and hence the solution properties. The inhibition of coiling is believed to be the result of the electrostatic repulsion between the anionic charged sites distributed along the polymer chains and indeed the PHPA chemistry can be designed to achieve this. Discussions of how the fluid microstructure influences the rheological properties will be given later.

Test Instruments

Two test instruments were used to characterize the rheological properties of the polymer fluid, a direct-indicating viscometer and a Bohlin Gemini rheometer. The direct-indicating viscometer, also known as the Fann viscometer, has been a popular instrument for measuring the viscosity of drilling fluids for many decades (Darley and Gray 1988; Howsam and Hollamby 1990). The instrument has been borrowed from the oil industry for use in civil engineering where it has been widely used for the quantitative assessment of support fluids (Hutchinson et al. 1975; Beresford et al. 1989). The instrument works on the concentric-cylinders principle and the common six-speed model can operate at 3, 6, 100, 200, 300, and 600 r/min. With the standard bob and rotor geometry combination (R1–B1), this speed range is equivalent to a shear-rate range of 5 to 1,022 s⁻¹ (1 rpm equating to a shear rate of 1.703 s⁻¹). The shear rate indicated on the instrument and the measured shear stress are then used to calculate the apparent or effective viscosity of the fluid.
using the Newtonian equation (μ = τ/γ). The operating principles of the Fann viscometer can be found in Darley and Gray (1988) and Lam and Jefferis (2014a).

The Bohlin Gemini rheometer is a more sophisticated instrument, which can be used in both controlled shear-stress and controlled shear-rate modes. It has an air bearing system for the application of torsional stress and a Peltier element for accurate temperature control. The Gemini model has a torque range from 0.05 μN · m to 200 mN · m so enabling viscosity measurements to be made at very low shear rates. The torque resolution is better than 1 nN · m and the angular position (strain) resolution is 50 nano-radians. It can be used to perform a wide range of rheological investigations including viscometry, oscillatory shear, creep, and relaxation although only the first two are discussed in this study. For the viscosity measurements, a cone-and-plate geometry was used to achieve a uniform shear rate across the sheared area and thus absolute viscosity results. The tests were performed by controlling the shear rate and using the so-called table of shear function, where the shear rate is increased automatically from the predetermined minimum to maximum values over a series of steps. To minimize the effect of fluid evaporation, several such tests had to be performed, each over a different range of shear rates typically spanning evenly over a log cycle. For example, a test that started at 1 s⁻¹ involved 10 steps and viscosity was measured at the following shear rates: 1, 1.26, 1.58, 2.00, 2.51, 3.16, 3.98, 5.01, 6.31, 7.94, and 10 s⁻¹. Within each step, a delay period was specified to allow the fluid to achieve steady flow (equilibrium) before the shear stress was measured. The required delay time depended on the sample and the shear rate, typically it was no more than 5 min. For each step, the stress integration time was typically 100 s, so the total duration for a log cycle of viscosity tests was about 70 min. For the oscillatory measurements, a parallel-plate geometry was used as the condition of uniform shear rate was not necessary and the gap between the plates could be, easily adjusted to suit the requirements of the tests. A small gap of 150 μm was used to minimize the inertia effect of the sample. A solvent trap was used in all experiments to minimize the amount of evaporation.

### Steady-State Flow Properties

#### Modeling of the Fann Viscometer Results

As previously noted, there is currently no consensus on the choice of mathematical model for interpreting the rheological data for polymer excavation fluids. To resolve this issue, this section presents an interpretation of a set of data obtained with a Fann (direct-indicating) viscometer, an instrument commonly used by previous investigators. The polymer fluid had a concentration of 0.8 kg/m³ and was prepared using the methodology previously described. For comparison, a bentonite (Berkbent 163 marketed by Tolsa, U.K.) fluid at a concentration of 40 kg/m³ was also tested (both fluids were prepared at concentrations typical of site practice).

Fig. 3(a) shows the test data plotted as a shear stress versus shear rate (τ = γ) plot, with Bingham plastic model fitted to bentonite results and the power-law model fitted to the polymer results. It can be seen that the Bingham plastic model can fit the viscosity results of the bentonite fluid reasonably well and that the power-law model is suitable for the polymer fluid. If the Bingham plastic model is used to fit the polymer test results, the goodness of fit will be lower due to the nonlinear (τ = γ) relationship as clearly shown in the figure. Fig. 3(b) shows the same test results on an apparent viscosity versus shear-rate (γ = γ) plot. Again, it can be seen that the Bingham plastic and the power-law models are suitable for the bentonite and polymer fluids respectively but not the other way round. Although only one set of results has been presented for the polymer, the observed shear-thinning behavior is typical for polymer fluids prepared at other concentrations over the same range of shear rates.

Fig. 3(b) also shows that the bentonite fluid has a higher apparent viscosity than its polymer counterpart especially at low shear rates. For example, at a shear rate of 5 s⁻¹, the viscosity of the polymer fluid is 140 mPa · s (numerically equivalent to centipoise, cP) whereas the bentonite has a viscosity of 550 mPa · s. The difference can be seen to increase as the shear rate decreases. The different flow behavior of the two types of fluid has important implications for their performance in excavations. For example, during excavation, soil particles are released into the support fluid. The yield stress of the bentonite fluid gives it the ability to hold small soil particles in suspension and the higher apparent viscosity reduces the rate of sedimentation of larger particles. In a pile bore or a diaphragm wall trench, this can delay or prevent the accumulation of soft sediment at the base of the excavation. This is desirable because the sediment, if not removed before concreting, can create what is known as a soft toe, which will adversely affect the end bearing resistance of the foundation element. The downside of this flow behavior is that in some ground conditions (e.g., silt and fine sand) a substantial amount of soil particles can accumulate in the fluid resulting in the fluid density and/or sand content exceeding specified project limits (Lam et al. 2010). In addition, due to their high apparent viscosity bentonite fluids also require specialist equipment such as shaker screens and hydrocyclones to remove
the suspended soil before they can be reused. In contrast, polymer fluids, due to their lower apparent viscosity [Fig. 3(b)], have been found to be able to self-clean by particle sedimentation under gravity. This eliminates the need for specialist soil-fluid separation equipment, and thus polymer fluids are often favored over bentonite for piling works on congested urban sites (Jefferis and Lam 2013; Lam et al. 2014a) where there is no space for separation plant. However, due to the lack of a yield stress and lower apparent viscosity of polymer fluids, soil particles will settle faster through the fluid column so that sediment will accumulate more readily at the base of an excavation. Cleaning of the excavation base and testing of used fluids thus become very important when polymer fluids are used. Particle settlement is only one of the relevant processes listed in Table 1. However, since the lowest shear rate achievable with the Fann direct-indicating viscometer is 5 s⁻¹ whereas the relevant shear rates for some of other processes are much below this value, the flow behavior of polymer fluids has been studied over a much wider range of shear rates and the results presented as follows.

**Shape of Viscosity Curves**

After the initial investigations with the Fann viscometer, further rheological tests were carried out to characterize the flow behavior of the polymer fluids over a wider range of shear rates, particularly lower shear rates, and for a range of polymer concentrations. The tests were conducted using the Bohlin rheometer for shear rates from 0.0006 to 100 s⁻¹ and the Fann viscometer for shear rates from 5 to 1,022 s⁻¹ following the procedures described above. Fig. 4 presents the results for concentrations ranging from 0.2 to 1.2 kg/m³ over a shear-rate range of 10⁻³ to 10³ s⁻¹. All the tests were conducted at a controlled temperature of 25°C. Compared to Fig. 3(b), Fig. 4 provides a bigger picture showing more about the overall flow behavior of the fluids. The first observation that can be made is that, at very high and very low shear rates, the fluids tend toward limiting viscosity values. The data points have been fitted with the Carreau model, which can accommodate these viscosity plateaus and is expressed as follows:

\[
\frac{\eta - \eta_{\infty}}{\eta_0 - \eta_{\infty}} = \left[1 + \left(\frac{\lambda \dot{\gamma}}{n}\right)^2\right]^{(n-1)/2} \tag{1}
\]

where \( \eta \) = viscosity at any shear rate; \( \eta_0 \) = zero-shear viscosity; \( \eta_{\infty} \) = infinite-shear viscosity; \( \lambda \) = time constant; and \( n \) (<1) = flow behavior index. The parameter \( \lambda \) is called a time constant because its reciprocal value, which is known as the critical shear rate, \( \dot{\gamma}_{\text{crit}} \), is the shear rate at the transition between the upper (low shear rate) Newtonian plateau and the shear-thinning region. The flow behavior index, \( n \), represents the degree of shear thinning, i.e., the slope of the middle portion of the viscosity curves. When \( n \) equals 1, the Carreau model reduces to Newtonian behavior (\( \eta = \eta_0 \)). Table 3 summarizes the fitted values of the Carreau parameters at each polymer concentration.

Before the effects of polymer concentration are discussed, it is useful to consider the shape of the flow curves using the molecular theory. At the foot of Fig. 4 is a schematic diagram showing the fluid microstructure in three viscosity regions, namely, zero-shear viscosity (\( \eta_0 \)), shear thinning, and infinite-shear viscosity (\( \eta_{\infty} \)). Note that the microstructure shown for the zero-shear viscosity region is a hand-drawn sketch of polymer system shown in the micrograph, Fig. 2. The influence of microstructure on viscosity is explained as follows. When the fluid is static or is under near static conditions, the long-chain molecules intertwine and entangle with each other. However, as a result of their incessant Brownian motion, the molecules continuously slide over each other, forming and disengaging from individual entanglements as they move (Barnes 2000). Since entanglements resist flow and viscosity represents the resistance to flow, under near static conditions, the viscosity is at its highest \( \eta_0 \), the upper Newtonian plateau. If the fluid is subjected to increasing shear, the number of entanglements reduces as the chains orient along the direction of flow. The fluid therefore shows a gradual reduction in viscosity over the middle shear-thinning region of the viscosity-shear rate plot. Finally, at very high shear rates, the entanglements are combed out by the flow, so the viscosity is at its lowest at the infinite shear rate (\( \eta_{\infty} \)) Newtonian plateau. At this stage, the viscosity of the polymer fluid depends only on the underlying viscosity of the solvent (water), the concentration of the nonentangled polymers, temperature, and the chemistry of the fluid.

**Table 3. Summary of Carreau Model Parameters for a PHPA Polymer Fluid**

| \( c_p \) (kg/m³) | Infinite-shear viscosity, \( \eta_{\infty} \) (mPa·s) | Zero-shear viscosity, \( \eta_0 \) (mPa·s) | Flow behavior index, \( n \) (--) | Time constant, \( \lambda \) (s) | Critical shear rate, \( \dot{\gamma}_{\text{crit}} \) (s⁻¹) |
|------------------|-----------------|---------------------|-----------------|----------------|------------------|
| 0.2              | 2.2             | 1,300               | 0.42            | 180            | 0.0056           |
| 0.4              | 4               | 10,100              | 0.32            | 360            | 0.0028           |
| 0.6              | 5               | 19,500              | 0.3             | 380            | 0.0026           |
| 0.8              | 7               | 47,000              | 0.26            | 520            | 0.0019           |
| 1.0              | 8               | 75,000              | 0.25            | 550            | 0.0018           |
| 1.2              | 9               | 135,000             | 0.24            | 580            | 0.0017           |

© ASCE 04015021-5 J. Mater. Civ. Eng.
water used to prepare the solution (hardness and salinity reduce polymer activity).

**Effect of Concentration**

The molecular model also explains the effect of polymer concentration. It can be seen that as the concentration increases, the apparent viscosity increases significantly at low shear rates but only marginally at high shear rates where the intermolecular interaction is limited (Table 3). This effect is shown more clearly in Fig. 5, where \( \eta_0 \) and \( \eta_\infty \) are plotted against polymer concentration on a log-log scale. It can be seen that both \( \eta_0 \) and \( \eta_\infty \) follow power-law relationships with polymer concentration \( (c_p) \). It also can be seen that the exponent for concentration dependence for \( \eta_0 \) (2.75) is greater than that for \( \eta_\infty \), which is close to unity (0.96). This is because, as noted earlier, at high shear rates the effect of chain entanglements becomes limited as they have been combed out (see the sketch for high shear in Fig. 4). However, at low shear rates, a higher concentration gives more chain entanglements thus increasing the strength of the molecular network. This is shown by the steeper slope of the \( \eta_0 \) versus \( c_p \) curve.

A final point to note about the effect of polymer concentration is that, as shown previously in Fig. 4, the critical shear rate, \( \dot{\gamma}_{\text{crit}} \), tends to decrease as the concentration increases from 0.2 to 1.2 kg/m\(^3\). This implies that the fluid becomes more sensitive to shear when more polymer molecules are present. This is probably due to the increased number of chain entanglements so there is a greater impact of combing out by the flow. The gradient of the middle portions of the viscosity curves also can be seen to become steeper with increasing polymer concentration. This shows that the fluid becomes more shear-thinning again probably due to the greater impact of ‘combing out’ by the flow. Numerically, the increase in the shear-thinning behavior is indicated by the decreasing value of the flow behavior index, \( n \), as shown in Table 3. Similar polymer fluid behavior was reported by Howsam and Hollamby (1990) using the more basic direct-indicating (Fann) viscometer and the power-law model.

**Transitory Viscoelastic Properties**

**Background**

Since many processes relevant to fluid-supported excavations occur under steady-state conditions (Table 1), the transient viscoelastic properties of the polymer fluid are potentially less important than the shear viscosity. However, during excavation as the digging tool (auger, grab) is moved up and down the hole it will generate transient pressure surges, which can promote liquefaction of the adjacent soil especially if this is loose and cohesionless. Soil liquefaction can lead to localized or progressive collapse of the hole, which is highly undesirable. During excavation, the support fluid will penetrate into the surrounding soil and due to their different viscoelastic properties bentonite and polymer fluids will have different responses to transient phenomena and thus potentially different impacts on trench stability. Authors such as El Mohtar et al. (2008) have investigated the effect of bentonite fluids on soil liquefaction behavior, but studies using polymer fluids cannot be found. To enable an assessment of the possible influence of the viscoelastic properties of polymer fluids, measurement procedures and the properties so determined are discussed below. Where appropriate, the results are compared with those obtained for bentonite fluids by other investigators. To aid the interpretation of the test results, a brief overview of viscoelasticity is given below.

In the classical theory of elasticity, Hooke’s law states that in a sheared body the stress, \( \tau \), is directly proportional to the strain, \( \gamma \), and hence \( \tau = G \gamma \), where \( G \) is the shear modulus of the material. If a perfectly elastic Hookean solid is subjected to an oscillatory shear stress, the deformation will be instant, i.e., the stress and the strain will be exactly in phase. However, for a perfectly viscous Newtonian liquid, the strain will be 90° out of phase. For a viscoelastic material, the phase angle, \( \delta \), will be >0° and <90°. For the interpretation of oscillatory test results, \( \delta \) is usually used to separate the measured stiffness, \( G' \), into two components

\[
G' = G' \cos(\delta) \tag{2}
\]

\[
G'' = G' \sin(\delta) \tag{3}
\]

where \( G' \) = complex modulus; \( G'' \) = storage (elastic) modulus; and \( G'' \) = loss (viscous) modulus. The relative values of \( G' \) and \( G'' \) can be used to assess the nature of the material. If \( G' > G'' \) the material is said to be solid-like, whereas if \( G' < G'' \) the material is liquid-like.

**Effects of Amplitude of Oscillation**

The viscoelasticity of the polymer fluid was first investigated over a range of shear strains at a single frequency. This type of test is known as the amplitude sweep test and is the standard rheological test to establish the linear viscoelastic region (LVR) of a material. Within the LVR, the specimen oscillates within the Hookean region so the modulus values are independent of the maximum amplitude or stress of the oscillation. An oscillation frequency of 0.5 Hz was used for the tests, although other frequencies could have been used (subject to rheometer limitations) because in most cases the strain at which nonlinearity occurs is independent of frequency (Barnes 2000).

Fig. 6 shows the amplitude sweep results for polymer concentrations ranging from 0.2 to 1.2 kg/m\(^3\) (the same range that was used for the shear viscosity tests). First, it can be seen that at small strains, \( G' \) is greater than \( G'' \) implying that the polymer fluids are actually more solid-like. As the strain increases, \( G' \) breaks down faster than \( G'' \). This is expected, as for most materials, \( G' \) is the more sensitive of the two moduli. For each polymer concentration, the limit of the LVR is denoted as the transition point, which is determined as the point where the \( G' \) value has dropped by 5% from its plateau value. With the LVR established, it can be seen that the polymer fluids leave the plateaus at a strain value of just below 1 (100% strain), which is much greater than the 1–2% strain
found for bentonite fluids (Santagata et al. 2008; El Mohtar et al. 2008).

As the strain increases beyond the transition point, \( G' \) falls faster than \( G'' \), and the fluid gradually becomes more liquid-like. The point where \( G'' \) crosses over \( G' \) is denoted as the flow point. After this point, viscous behavior dominates. It is interesting to see that the strain values at the transition and flow points increase slightly as the polymer concentration increases. This is opposite to the trend that Santagata et al. (2008) found for bentonite fluids. In fact, the \( G'' \) curves for bentonite fluids also have a different trend with shear strain than that shown by polymers. The \( G'' \) curves for bentonite fluids are characterized by an upward trend immediately before the crossover (flow) point and then a downward trend after (Santagata et al. 2008; El Mohtar et al. 2008). This type of behavior is typical of the soft jammed systems (Coussot 2005).

Recall that PHPA fluids are solutions of synthetic polymers not clay suspensions and thus they can be expected to display different behavior.

As regards the effect of polymer concentration, it can be seen from Fig. 6 that as the concentration increases, the values of both moduli also increase. This is as expected since the transient viscoelasticity and the steady-state viscosity are due to the network of chain entanglements in the fluid. As the number of entanglements increases, both \( G' \) and \( G'' \) can be expected to increase. To show this effect more clearly, Fig. 7 plots the values of \( G' \) and \( G'' \) within the LVR against concentration. It can be seen that the modulus values do not increase linearly with concentration but follow a quadratic upward trend. The nonlinear shape of these curves is due to the fact that each additional polymer molecule can form more than one additional chain entanglement with the existing molecules, and this ability increases as the number of existing molecules increases.

In terms of the possible effect on the dynamic resistance of soil, since polymer fluids remain solid-like over a much wider shear-strain range than bentonite (100% \( \gg \) 1%), a polymer-saturated soil may have better cyclic resistance than one saturated with bentonite and thus be less sensitive to the pressure pulsations induced by the digging process. In addition, since both the magnitude of \( G' \) and the crossover \( (G' = G'') \) strain of polymer fluids increase with polymer concentration (Fig. 6), the beneficial effect on soil could be maximized by increasing the polymer concentration—a benefit that might not be appreciated without a knowledge of the viscoelastic properties of the polymer fluid. However, since the \( G' \) value of a bentonite fluid within the LVR can be considerably greater than that of polymer fluid [7.5 Pa for a 4% bentonite from Santagata et al. (2008) compared to 1.1 Pa maximum from this study], the difference in the performance between the two fluids must be further elucidated perhaps by performing dynamic soil tests such as those conducted by El Mohtar et al. (2008).

**Effects of Frequency of Oscillation**

Based on the results of the amplitude sweep tests, further tests were run to characterize the response of the polymer fluids at different timescales. In these experiments, the test fluid was subjected to an oscillating strain of 0.1 (10%) over a range of frequencies. The strain value was determined with reference to the amplitude sweep results so that the fluids remained within their LVR. As this series of tests involved measurements at very low frequencies, the test period was over 4 h, and it was necessary to create a saturated atmosphere in the air next to the sample by lightly misting the underside of the solvent trap with water (the solvent). It was found that, if this step was not taken, the periphery of the specimen gradually dried out. A similar procedure is reported in Barnes (2000).

Fig. 8 shows the results of the frequency sweep tests. It can be seen that at low frequencies (<0.01 Hz) the viscous behavior is more pronounced \((G'' > G')\) but not by a substantial amount. As the frequency approaches about 0.01 Hz, the two modulus curves can be seen to cross over. The exact point of crossover, however, is dependent on the solution concentration. At higher
frequencies, the elastic behavior can be seen to become more pronounced. Chain entanglement theory once again can be used to explain this behavior. Recall that the polymer chains in the solution are entangled but constantly slide over each other. It follows that when a stress is applied to this transient molecular network, on a short time scale, it will behave more elastically as the chains are stretched. However, given longer time these will relax and the fluid will therefore show more viscous properties.

As the viscoelastic behavior of polymer fluids is frequency dependent, their effect on soil liquefaction during excavation will also be dependent on the frequency of the loading, but data on the dynamic effects of digging tools is not available. Further research on polymer-impregnated soil specimens is required. Finally, it may be noted that the frequency sweep results shown in Fig. 8 are very different from those previously reported for bentonite. Galindo-Rosales and Rubio-Hernández (2006) found that for a 10% bentonite fluid, elastic behavior dominates ($G' \gg G''$) across a wide range of frequencies from 0.01 to 10 Hz. This suggests that the behavior of bentonite fluids may be less sensitive to the frequency of the shear stress though it should be noted that a bentonite concentration of 10% (100 kg/m$^3$) is too high for use in excavation work.

Conclusions

The steady-state viscosity and transient viscoelastic properties of a polymer support fluid have been studied using the Fann viscometer (an instrument widely used on construction sites) and an advanced rheometer. From the results of the tests and the associated research, the following key conclusions can be drawn:

- The polymer fluid has a three-dimensional network structure of chain entanglements (see the electron micrograph in Fig. 2). This microstructure has a substantial influence on the rheological behavior of these fluids including the effects of shear rate, shear frequency and amplitude.

- For the polymer fluids tested and over the shear-rate range of the standard six-speed Fann viscometer (5 to 1,022 s$^{-1}$), the two-parameter power-law model has been found to be a suitable model to represent the experimental results. However, the two-parameter Bingham plastic model cannot be used to represent polymer flow behavior due to the nonlinear $\tau - \gamma$ relationship displayed. The Bingham plastic model has however been found suitable to represent the results for a bentonite fluid (Fig. 3).

- If prepared at the typical dosage for excavation works, the polymer fluid (at 0.8 kg/m$^3$) has been found to have a lower apparent viscosity than the bentonite slurry (at 40 kg/m$^3$) especially at lower shear rates. This explains why bentonite fluids can effectively hold any dislodged particles in suspension, but polymer fluids cannot.

- For the wider range of shear rates of the Bohlin Gemini rheometer (10$^{-3}$ to 10$^3$ s$^{-1}$), a range sufficiently wide to identify trends toward limiting viscosities at very low and very high shear rates, the four-parameter Carreau model can satisfactorily fit the experimental results (Fig. 4). The polymer fluid becomes more shear-thinning when concentration increases (Table 3).

- As shown by the series of amplitude sweep tests, the linear viscoelastic region (LVR) of the test fluids is up to a shear strain of about 100%. This may be compared to the 1–2% found for bentonite fluids by previous investigators. As the polymer concentration increases, the stiffness ($G'$ and $G''$) and the strain values of the transition and flow points also increase (Figs. 6 and 7).

- The frequency sweep tests show that at low frequencies (<0.01 Hz) the polymer fluids can be said to be more liquid-like. This is in contrast to the behavior of bentonite fluids for which the elastic properties are usually more dominant (Fig. 8).

The results presented in this paper confirm that polymer support fluids used in construction show non-Newtonian behavior at shear rates relevant to construction work. The results have implications for the study of related engineering problems such as particle sedimentation in fluids and possibly also the mitigation of soil liquefaction during excavation, the latter is a speculative concept but worthy of further research. The rheological properties of polymer fluids may also influence the fluid loss from an excavation and hence its stability. For example, the lack of a yield stress, as shown by the upper Newtonian plateaus of the viscosity curves in Fig. 4, means that the rheological blocking model (Jeffersis 2013), which is commonly used to explain how bentonite fluid can stabilize coarse soils, does not apply to polymer fluids. New theories, possibly based on the Carreau model for steady-state flow, are therefore required to explain the stabilizing mechanisms of polymer fluids.

Acknowledgments

The results presented in this paper form part of a research project funded by the Engineering and Physical Sciences Research Council (EPSRC) under grant reference EP/C537815/1. The rheometer used was provided by the EPSRC Engineering Instrument Pool.

References

Alderman, N. J., Meeten, G. H., and Sherwood, J. D. (1991). “Vane rheometry of bentonite gels.” J. Non-Newton. Fluid, 39(3), 291–310.

Ata, A., and O’Neill, M. (1997). Characterization of the effect of POLY-BOR© polymer on the construction and performance of drilled shaft foundations. Phase I: Field tests, Dept. of Civil and Environmental Engineering, Univ. of Houston, Houston.

Ata, A., and O’Neill, M. (2000). “The physicochemical interaction between PHPA polymer slurry and cement mortar.” Geotech. Test. J., 23(2), 225–235.

Barnes, H. A. (2000). A handbook of elementary rheology, Institute of Non-Newtonian Fluid Mechanics, Univ. of Wales, Aberystwyth, U.K.

Beresford, J. J., Cashman, P. M., and Hollamby, R. G. (1989). “The merits of polymeric fluids as support slurries.” Proc., 3rd Int. Conf. on Deep Foundations, Vol. 1, Balkema, Rotterdam, Netherlands, 3–10.

Brown, D. A., Turner, J. P., and Castelli, R. J. (2010). “Drilled shafts construction procedures and LRFD design methods.” Publ. No. FHWA NHI-10-016, National Highway Institute, Federal Highway Administration, U.S. Dept. of Transportation, Washington, DC.

Coussot, P. (2005). Rheometry of pastes, suspensions, and granular materials: Applications in industry and environment, Wiley, Hoboken, NJ.

Darley, H. C. H., and Gray, G. R. (1988). Composition and properties of drilling and completion fluids, Gulf Professional Publishing, Houston.

El Mohtar, C. S., Clarke, J., Bobet, A., Santagata, M., Drnevich, V., and Johnston, C. (2008). “Cyclic response of a sand with thixotropic pore fluid.” Proc., Geotechnical Earthquake Engineering and Soil Dynamics IV Congress 2008, GSP 181, ASCE, Reston, VA.

Feng, Y., Luo, P., Luo, C., and Yan, Q. (2002). “Direct visualization of microstructures in hydrophobically modified polyacrylamide aqueous solution by environmental scanning electron microscopy.” Polym. Int., 51(10), 931–938.

Ferry, J. D. (1980). Viscoelastic properties of polymers, 3rd Ed., Wiley, New York.
Galindo-Rosales, F. J., and Rubio-Hernández, F. J. (2006). “Structural breakdown and build-up in bentonite dispersions.” *Appl. Clay Sci.*, 33(2), 109–115.

Howsam, P., and Hollamby, R. (1990). “Drilling fluid invasion and permeability impairment in granular formations.” *Q. J. Eng. Geol. Hydrogeol.*, 23(2), 161–168.

Hutchinson, M. T., Daw, G. P., Shotton, P. G., and James, A. N. (1975). “The properties of bentonite slurries used in diaphragm walling and their control.” *Proc., Conf. on Diaphragm Walls and Anchorage*, Institution of Civil Engineers, London, 33–39.

Institution of Civil Engineers. (2007). *ICE specification for piling and embedded retaining walls*, Thomas Telford, London.

Jefferis, S. A. (2013). “Grouts and Slurries.” *Construction materials reference book*, 2nd Ed., D. Doran and B. Cather, eds., Routledge, Abingdon, U.K., 165–194.

Jefferis, S. A., and Lam, C. (2013). “Polymer support fluids: Use and misuse of innovative fluids in geotechnical works.” *Proc., 18th Int. Conf. on Soil Mechanics Geotechnical Engineering*, Vol. 4, Presses desPonts, Paris, 3219–3222.

Kadaster, A. G., Guild, G. J., Hanni, G. L., and Schmidt, D. D. (1992). “Field applications of PHPA muds.” *SPE Drill. Eng.*, 7(3), 191–199.

Kelessidis, V. C., Zografou, M., and Chatzistamou, V. (2013). “Optimization of drilling fluid rheological and fluid loss properties utilizing PHPA polymer.” *Proc., SPE Middle East Oil and Gas Show and Conf.*, Society of Petroleum Engineers, TX, 1–9.

Kheng, H., Bloomquist, D., Townsend, F. C., Thompson, P. Y., and Dobson, E. (1991). “Slurry performance in drilled shaft construction.” *Final Rep. to the Florida Dept. of Transportation*, Dept. of Civil Engineering, Univ. of Florida, Gainesville, FL.

Lam, C., and Jefferis, S. A. (2014a). “Interpretation of viscometer test results for polymer support fluids.” *Proc., Sessions of GeoShanghai 2014 Int. Conf., GSP 242*, ASCE, Reston, VA, 439–449.

Lam, C., and Jefferis, S. A. (2014b). “The use of polymer solutions for deep excavations: Lessons from Far Eastern experience.” *HKIE Trans.*, 21(4), 262–271.

Lam, C., Jefferis, S. A., and Goodhue, K. G., Jr. (2010). “Observations on viscosity reduction of PHPA polymer support fluids.” *Proc., Sessions of the GeoShanghai 2010 Int. Conf., GSP 205*, ASCE, Reston, VA, 184–191.

Lam, C., Jefferis, S. A., and Suckling, T. P. (2014a). “Construction techniques for bored piling in sand using polymer fluids.” *Proc. I. Civ. Eng.-Geotec.*, 167(6), 565–573.

Lam, C., Martin, P. J., Jefferis, S. A., and Goodhue, K. G., Jr. (2014b). “Determination of residual concentration of active polymer in a polymeric support fluid.” *Geotech. Test. J.*, 37(1), 46–59.

Lam, C., Troughton, V., Jefferis, S., and Suckling, T. (2010). “Effect of support fluids on pile performance—A field trial in east London.” *Ground Eng.*, 43(10), 28–31.

Lesemann, H., and Vogt, N. (2012). “Investigations into hydraulic support using polymeric solutions.” *Geotechnik*, 35(1), 11–21 (in German).

Liao, W. A., and Siems, D. R. (1990). “Adsorption characteristics of PHPA on formation solids.” *Proc., SPE/IDC Drill. Conf.*, Society of Petroleum Engineers, TX, 297–308.

Majano, R. E., and O’Neill, M. W. (1993). “Effect of mineral and polymer slurries on perimeter load transfer in drilled shafts.” *Rep. No. UHCE-93-1*, Dept. of Civil and Environmental Engineering, Univ. of Houston, Houston.

Majano, R. E., O’Neill, M. W., and Hassan, K. M. (1994). “Perimeter load transfer in model drilled shafts formed under slurry.” *J. Geotech. Eng.*, 10.1061/(ASCE)0733-9410(1994)120:12(2136), 2136–2154.

McKinley, G. H. (2002). “Steady and transient motion of spherical particles in viscoelastic liquids.” *Transport processes in bubbles, drops, and particles*, D. De Kee and R. P. Chhabra, eds., Taylor & Francis, New York, 338–375.

O’Neill, M. W., and Reese, L. C. (1999). “Drilled shafts: Construction procedures and design methods.” *Rep. No. FHWA-IF-99-025*, Federal Highway Administration, U.S. Dept. of Transportation, Washington, DC.

Reiner, M. (1969). *Deformation strain and flow*, 3rd Ed., H.K. Lewis, London.

Santagata, M., Dalmazzo, D., and Santagata, E. (2008). “Deformation behavior of clay-water suspensions from rheological tests.” *Proc., 4th Int. Symp. Deformation Characteristics of Geomaterials*, Vol. 1, IOS Press, Amsterdam, Netherlands, 453–459.

Speers, R. A., Holme, K. R., Tung, M. A., and Williamson, W. T. (1987). “Drilling fluid shear stress overshoot behavior.” *Rheol. Acta*, 26(5), 447–452.

Veder, C. (1953). “Method for the construction of impermeable diaphragms at great depth by means of thixotropic muds.” *Proc., 3rd Int. Conf. of Soil Mechanics and Foundation Engineering*, Vol. 2, Organizing Committee, Zurich, Switzerland, 91–94 (in French).