Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)
 ISBN 978-0-415-68367-8

Review of Newtonian and non-Newtonian fluids behaviour in the context of grouts

Sina Kazemian
University Putra Malaysia, Serdang, Malaysia

Arun Prasad
Banaras Hindu University, Varanasi, India

Bujang B. K. Huat
University Putra Malaysia, Serdang, Malaysia

ABSTRACT: The objective of this review is to elucidate the rheological behavior of cement based grout. Rheology of grouts is a way of describing its properties without paying any attention to whether it is a homogenous grout or a mixture of grains in a grout. Cement grout based rheology is characterized by at least two parameters; yield stress and plastic viscosity. The rheological models are used to describe the relationship between shear stress and shear rate. The Newtonian fluids are true fluids that tend to exhibit constant viscosity at all shear rates. A non-Newtonian fluid is a fluid for which the relationship τ/γ' is not a constant. Pseudo-plasticity or shear thinning is the most common type of time-independent and non-Newtonian fluid behavior observed. It is characterized by an apparent viscosity which decreases with an increasing shear rate. Many mathematical models for fluids behavior have been proposed to model the shear thinning characteristics. These models are based on curve fitting method that gives empirical relationships for the shear stress vs. shear rate curves. Some models are based on the statistical mechanics. The Bingham model does not give an exact description of the behavior of a cement based grout even if the geometry is defined, but there are other models and the selection of model should be done carefully based on the requirement.

1 INTRODUCTION

1.1 *Rheology and viscosity of fluids*

Rheology can be defined as the study of the change in the form and flow of the matter. The scope of rheology includes elasticity, viscosity, and plasticity. Rheology of grouts is a way of describing its properties without paying any attention to whether it is a homogenous grout or a mixture of grains in a grout (Eklund, 2005). It is normally applied to fluid materials (or materials that exhibit a time dependent response to stress). It can also be defined as the study of the flow of the grout flows, before the setting point is reached. This is crucial due to the fact that the grout must be placed by some kind of mechanical process like, pumping into the prepared forms. Cement grout based rheology is characterized by at least two parameters: yield stress and plastic viscosity. In a similar way, an elastic solid is characterized by two parameters: Young's modulus and Poisson's ratio (Bentz *et al.*, 2006).

Brookfield Engineering Labs Inc. (2010a) emphasized that by measuring the rheology parameters of fluids much useful behavioral and predictive information can be obtained. These include quality control, chemical, mechanical, and thermal treatments, effects of additives on the curing reaction, and direct assessment of the process ability. Furthermore, the rheological measurements may also be used as an indicator of micro structural changes occurring in hydration of the cement-based grout or the investigation of the effect of admixtures, and the development of cementitious systems that are easily pumped or placed (Struble and Ji, 2001).

Hånsson (1993) stated that the rheological behavior of a cement-based grout is difficult to define because of the concentration and characteristics of the particles as well as the suspension medium. The rheological behavior is influenced by the chemical reactions in progress during the hydration of the cement and the thixotropy is dominant at short cycle times. The rheological models are used to describe the relationship between shear stress and shear rate. Syrjålå (1996) stated that there was no general rheological constitutive model available that time for non-newtonian fluids. Most commonly used time independent models in suspension rheology are: Newton model, Bingham model, power law model, modified power law model, and Casson model.

Brookfield engineering labs inc. (2010a) defined that the viscosity is the measure of the internal friction of a fluid. This friction becomes apparent when a layer of fluid moves in relation to another. By increasing the friction, a greater amount of force is required to for this movement, which is called shear. The shearing occurs whenever the fluid is physically moved or distributed, as in pouring, spreading, spraying, mixing, etc. It should be mentioned that highly viscous fluids, therefore, require more force to move than less viscous materials.

Consider two parallel flat areas of fluid of the same size A which are separated by a distance dx (Fig. 1). If the plates are moving in the same direction at different velocities V_1 and V_2, then the force required to maintain the speed is proportional to the difference in speed through the liquid, or the velocity gradient (Equation 1).

$$F/A = \eta \, dy/dx \tag{1}$$

where η is the viscosity of the fluid.

The shear rate describes the shearing which the liquid experiences. In other words, the velocity gradient, dy/dx, which is a measure of the change in speed at which the intermediate layers move with respect to each other is called the shear rate ($\dot{\gamma}$) and its unit of measure is the reciprocal second (s^{-1}). The term F/A indicates the force per unit area and is the shearing action or shear stress (τ). The unit of measurement of shear stress is dynes per square centimeter (dynes/cm^2) or Newton per square meter (N/m^2). According to the above statement, viscosity can be defined as shear stress over shear rate:

$$\eta = \tau / \dot{\gamma} \tag{2}$$

The most commonly used unit for viscosity is poise. A fluid with a shear stress of 1 dyne/cm^2 which produces a shear rate of 1 s^{-1}, has viscosity of 1 poise or 100 centi-poise. In the SI system, the unit of measurement of viscosity is Pa·s or mPa·s. One Pa·s is equal to 10 poise, and the smaller unit is one mPa·s which is equal to 1 cpoise.

2 NEWTONIAN AND NON-NEWTONIAN FLUIDS

The Newtonian fluids are true fluids that tend to exhibit constant viscosity at all shear rates (Karol, 2003; Krizek and Pepper, 2004). The relationship between the shear stress (τ) and the shear rate ($\dot{\gamma}$) is a straight line for the Newtonian fluids, and the viscosity of the fluid remains constant as the shear rate is varied (Fig. 2). Taylor (1997) showed that the fluids of simple and stable molecular structure generally obey the Newtonian law, like water and thin motor oils.

In practice, at a given temperature, the viscosity of a Newtonian fluid will remain constant regardless of which viscometer model, spindle or speed is used to measure it (Brookfield Engineering Labs Inc., 2010a).

A non-Newtonian fluid is a fluid for which the relationship $\tau/\dot{\gamma}$ is not a constant. In other words, when the shear rate is varied, the shear stress doesn't vary in the same proportion (or even necessarily in the same direction). Thus, the variation of shear strength causes to change the viscosity of such fluids. This is also called the "apparent viscosity" of the fluid. It is accurate only when the experimental parameters are provided and are also adhered to. Non-Newtonian fluids can be explained as fluids consisting of a mixture of molecules with different shapes and sizes. As they pass by each other, as happens during a flow, their size, shape, and cohesiveness will determine how much force is required to move them (Brookfield Engineering Labs Inc., 2010a).

Chhabra and Richardson (2008) defined the non-Newtonian fluid as one whose flow curve (shear stress versus shear rate) is either nonlinear or does not pass through the origin, i.e. where the apparent viscosity (ratio of shear stress to shear rate) is not constant at a given temperature and pressure but is dependent on the flow conditions such as flow geometry, shear rate, etc. Such materi-

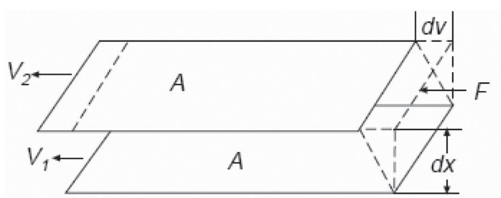

Figure 1. The definition of viscosity (after Brookfield Engineering Labs Inc., 2010a).

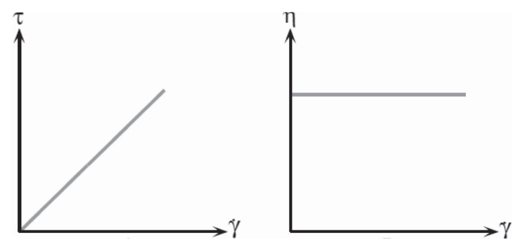

Figure 2. Newtonian fluids behaviour.

als can be conveniently categorized into three general classes:

1. Fluids, for which the rate of shear at any point can be determined only by the value of the shear stress at that point at that instant. These fluids are also known as purely viscous, time independent, inelastic or generalized Newtonian fluids.
2. Fluids, for which the relation between shear stress and shear rate depends on the duration of shearing and their kinematic history, in addition to the above conditions. These fluids are called time-dependent fluids.
3. Substances showing the characteristics of both, ideal fluids and elastic solids, and also showing partial elastic recovery after deformation are classified as visco-elastic fluids.

2.1 *Psedo-plastic fluids*

Pseudo-plasticity or shear-thinning is the most common type of time-independent and non-Newtonian fluid behavior observed. This is also characterized by an apparent viscosity that decreases with an increasing shear rate (Figure 3). Examples of the pseudo-plastic fluids are paints and emulsions.

Brookfield Engineering Labs Inc. (2010a) emphasized that in pseudo plastic fluids, the moment the spindle is turned, the structure of molecules of the fluid will be temporarily changed. This will lead to the molecule formation orientated more parallel to the spindle surface. Hence, the slowing down of the spindle rotation will decrease the change in the structure of the molecule. Faster the rotation of the spindle, the more the structure is destroyed; and the lesser of the structure of molecules will slide in together. Hence, the lower the viscosity will be.

2.2 *Dilatant fluids*

Dilatant fluids are similar to pseudo-plastic systems in that their apparent viscosity increases with increasing shear rate and they are time-independent fluids; thus these fluids are also called shear-thickening fluids (Figure 4).

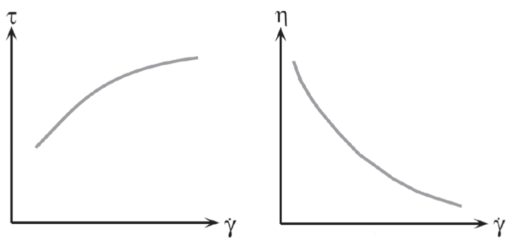

Figure 3. Pseudo-plastic fluids behaviour.

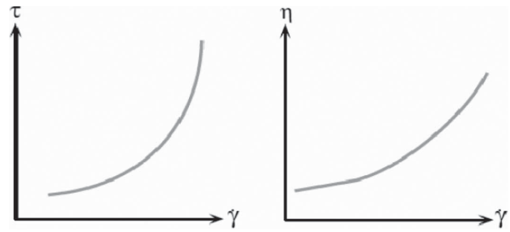

Figure 4. Dilatant fluids behavior.

This type of fluid behavior is normally observed in concentrated suspensions; such as sand/water mixtures, slurries of clay, compounds of candy, china clay, titanium dioxide, and corn flour in water (Griskey *et al.*, 1985; Metzner and Whitlock, 1958). Chhabra and Richardson (2008), and Goddard and Bashir (1990) explained this kind of fluid behavior as follows: the voids are minimum at rest and the liquid present in the suspension is sufficient to fill all the voids. At low shear rates, the liquid is able to lubricate the movement of each particle. Thus, the resulting stresses are therefore small. On the other hand, the material expands or dilates slightly at high shear rates so that there is no longer sufficient liquid to fill the increased voids. This prevents the direct solid–solid contacts resulting in increased friction and higher shear stresses (as shown schematically in Figure 5).

2.3 *Viscoplastic (plastic fluids)*

This type of fluid (which is time-independent) behaves as a solid under static conditions. As shown in Figure 6, a certain amount of stress must be applied to the fluid before any flow is induced, known as the yield stress (f′). Conversely, when the externally applied stress is smaller than the yield stress, such a material will deform elastically. Once the magnitude of the external stress has exceeded the value of the yield stress, the flow curve may be linear or non-linear but will not pass through the origin (Chhabra and Richardson, 2008; Uhlherr *et al.*, 2005).

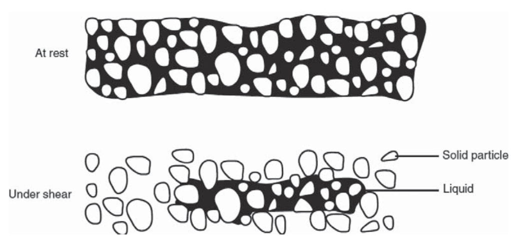

Figure 5. Schematic representation of dilatant behavior (after, Chhabra and Richardson, 2008).

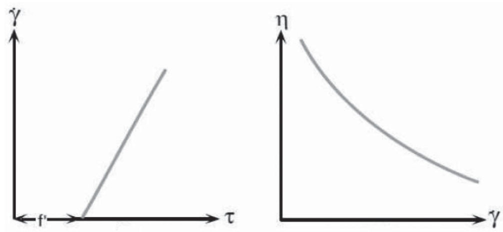

Figure 6. Plastic fluids behaviour.

However, the structure breaks down, at a stress level higher than f′, and the substance behaves like a viscous material, like Tomato ketchup.

2.4 *Thixotropic fluids*

In practice, apparent viscosity in some fluids may depend on the rate of shear and also the time for which the fluid has been subjected to shearing (Chhabra, 2010). The viscosities of time dependent fluids gradually decrease/increase as the internal structures present are progressively broken down or linked up. The rate of change of viscosity with time approaches zero or increases as the number of such structural linkages, capable of being broken down, reduce or increase; like bentonite-water suspensions, red mud suspensions (waste stream from aluminum industry), cement paste, and crude oils (Chhabra, 2010; Chhabra and Richardson, 2008; Nguyen and Uhlherr, 1983).

Thixotropic fluid is a category of time-depended fluid. Nguyen and Uhlherr (1983) explained thixotropic fluids as materials when sheared at a constant rate, their apparent viscosity (or the corresponding shear stress) decreases with the time of shearing (Figure 7 (a)), such as red mud suspension containing solids.

Figures 7 (b) and (c) show the hysteresis loops of thixotropic fluids. A hysteresis loop of thixotropic fluid can be defined as the flow curve obtained from an experiment in which if the shear rate is gradually increased at a constant rate from zero to some maximum value and then decreased at the same rate to zero again. Chhabra (2010) concluded that the rate of increase or decrease of shear rate, the duration of shearing, and the past kinematic history of the sample will decide the shape, height, and the enclosed area of the hysteresis loop. The larger the enclosed area, stronger is the time-dependent behavior of the materials. Thus, no hysteresis loop is observed for time-independent fluids, *i.e.* the enclosed area of the loop is zero. Struble and Ji (2001) observed the behavior of cement grout to be similar to thixotropic fluids and it is shown in Figure 8. The rheological parameters of

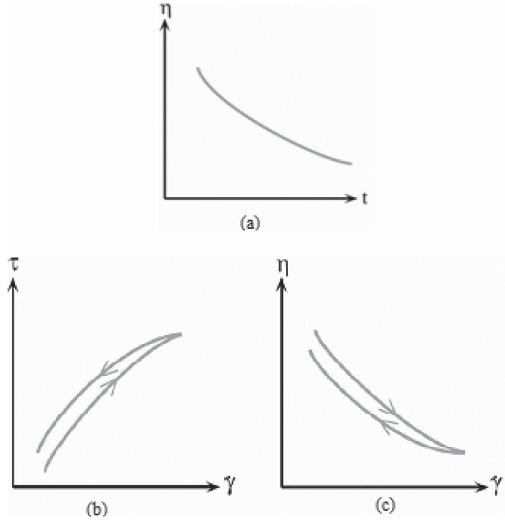

Figure 7. Thixotropic fluids behaviour.

grouts influence the course of the grouting. Eriksson (1998) illustrated different examples showing how the viscosity and yield value changed the spreading of the grout in a defined geometry. Håkansson (1993) stated that the rheology changes in grouts depend on the w/c ratio and the specific surface of the grout.

2.5 *Rheopexy or negative thixotropy fluids*

The second category of time-depended fluids is rheopexy or negative thixotropy fluids. The fluids for which their apparent viscosities increase with time of shearing are said to display rheopexy or negative thixotropy (Figure 9). Figures 9 (b) and (c) show the hysteresis loops of rheopexy fluids. In these cases, they are inverted, as compared with thixotropic fluids. In this type of fluid, the structure builds up by shear is applied and will break down when the material is at rest. In other words, in contrast to thixotropic fluids, the external shear encourages the build-up of structure in this case (Chhabra, 2010; Chhabra and Richardson, 2008). Both thixotropy and rheopexy behavior, Brookfield Engineering Labs Inc. (2010a) emphasized, can occur together with any of the previously mentioned flow behaviors.

Freundlich and Juliusburger (1935), Keller and Keller Jr (1990), Pradipasena and Rha (1977), Steg and Katz (1965), and Tanner (2000) have reported similar behavior of rheopexy fluids with suspensions of aqueous gypsum paste, saturated polyester, protein solutions, coal-water slurries, and ammonium oleate and colloidal suspensions of vanadium pentoxide.

3 MATHEMATICAL MODELS FOR FLUID BEHAVIOR

A review of the literature shows a number of mathematical models have been proposed for the behavior of the fluid to model the shear-thinning characteristics. Many of these methods attempt at curve fitting, giving empirical relationships for the shear stress or apparent viscosity-shear rate curves; while, other methods are based on the theory in the statistical mechanics (Bird *et al.*, 1987; Chhabra and Richardson, 2008).

As mentioned earlier, non-Newtonian fluids show a nonlinear stress-rate relationship which can be represented using an equation. However, the coefficients of a model, in some cases, can be used to predict the behavior of a fluid under the conditions of use. On the other hand, linear relationship is shown by Newtonian fluids which can be defined by a proportional response in the shear stress for a corresponding change in the shear rate (Brookfield Engineering Labs Inc., 2010a). Some of the more widely used models include Newton, Bingham, Casson, NCA/CMA Casson, Power Law, and Herschel Bulkley and their descriptions are shown in Table 1.

The grouts behavior has been modeled with Bingham model by Wallner (1976), Håkansson (1993), and Amadei and Savage (2001). Håkansson (1993) stated, "The Bingham model does not give an exact description of the behavior of a cement based grout even if the geometry is defined but laboratory tests show that the deviation is small".

4 CONCLUSIONS

Cement grout based rheology is characterized by at least two parameters: yield stress and plastic viscosity. The rheological measurements may be used as an indicator of micro structural changes occurring in hydration of the cement-based grout or the investigation of the effect of admixtures, and the development of cementitious systems. The rheological models are used to describe the relationship between shear stress and shear rate. The behavior of cement-sodium silicate system grout with kaolinite was investigated with the Bingham model using Brookfield viscometer. The Bingham model does not give an exact description of the behavior of a cement based grout even if the geometry is defined. However, careful consideration should be taken by any perspective researcher to choose the rheometric model to characterize the cement grout.

Table 1. Mathematical models for fluids behaviour

Model	Equation	Description
Newton	$\tau = \dot{\gamma}$	Linear (water)
Bingham	$\tau = \tau_0 + \eta\dot{\gamma}$	Yield linear
Casson	$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta\dot{\gamma}}$	Linear between the square root of shear stress and the square root of the shear rate
NCA/CMA Casson	$(1+a)\sqrt{\tau} = 2\sqrt{\tau_0} + (1+a)\sqrt{\eta\dot{\gamma}}$	
Power law	$\tau = k\dot{\gamma}^n$	Pseudoplastic
Herschel Bulkley	$\tau = \tau_0 + k\dot{\gamma}^n$	

REFERENCES

Ajlouni, M.A. 2000. Geotechnical Properties of Peat and Related Engineering Problems. *PhD Thesis*, University of Illinois at Urbana-Champaign, USA

Alwi, A. 2007. Ground Improvement on Malaysian Peat Soils Using Stabilized Peat-Column Techniques. *PhD Thesis*, University of Malaya, Kuala Lumpur, Malaysia.

Amadei, B. & Savage, W.Z. 2001. An Analytical Solution for Transient Flow of Bingham Viscoplastic Materials in Rock Fractures. *Int. J. Rock Mech, & Min. Sci.,* Vol. 38, pp 285–296.

Bentz, D.P., Garboczi, E.J., Bullard, J.W., Ferraris, C., Martys, N. & Stutzman, P.E. 2006. *Virtual Testing of Cement and Concrete*. In Significance of Tests and Properties of Concrete and Concrete-Making Material. (Lamond J.F. and Pielert, J.H. (ed.)), ASTM International, West Conshohocken, PA, USA.

Bird, R.B., Armstrong, R.C. & Hassager, O. 1987. *Dynamics of Polymeric Liquids. Fluid Dynamics*. 2nd ed., Vol. 1, *Wiley Interscience*, New York, USA.

Brookfield Engineering Labs Inc. 2008. Viscometers, Rheometers & Texture Analyzers for Laboratory and Process Applications. *Brookfield Eng. Labs*, pp 4–35.

Brookfield Engineering Labs Inc. 2010a. More Solutions to Sticky Problems: A Guide to Getting More from Your Brookfield Viscometer. *Bull. Brookfield Eng. Labs,* pp 1–53.

Brookfield Engineering Labs Inc. 2010b. Brookfield DV–II+ Pro. *Brookfield Eng. Labs,* Manual No. M/03-165-C0508, pp 3–71.

Chhabra, R.P. & Richardson, J.F. 2008). *Non-Newtonian Flow and Applied Rheology*. 2nd ed., *Butterworth-Heinemann*, Oxford, UK.

Edil, T.B. 2003. Recent Advanced in Geotechnical Characterization and Construction over Peat and Organic Soils. *In Proceeding of 2nd Int. Conf. on Advances in Soft Soil Eng. and Tech*., ed. Huat et al., Putrajaya, Malaysia.

Edil, T.B. & Wang, X. 2000. Shear Strength and K0 of Peats and Organic Soils. *Geotechnics of high water content materials, ASTM STP 1374*, West Conshohocken, Pa., USA, pp 209–225.

Eklund, T. 2005. Penetrability Due To Filtration Tendency of Cement Based Grouts. *PhD Thesis*, Dept. of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm.

Eriksson, M. 1998. Mechanisms that Control the Spreading of Grout in Jointed Rock. *ARD-98-15, SKB*, Stockholm, Sweden.

Freundlich, H. & Juliusburger, F. 1935. Thixotropy, Influenced by the Orientation of Anisometric Particles in Sols and Suspensions. *Trans. Faraday Soc.,* Vol. 31, pp 920–921.

Goddard, J.D. & Bashir, Y. 1990. *Recent Developments in Structured Continua II*. Longman, London, UK.

Griskey, R.G., Nechrebecki, D.G., Notheis, P.J. & Balmer, R.T. 1985. Rheological and Pipeline Flow Behaviour of Corn Starch Dispersions. *J. Rheology,* Vol. 29, pp 349–360.

Håkansson, U. 1993. Rheology of Fresh Cement-Based Grouts. *PhD Thesis*, Dept. of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm.

Karol, R. H. 2003. *Chemical Grouting and Soil Stabilization*. 3rd ed., Marcel Dekker Inc., New Jersy, USA.

Keller, D.S. & Keller, Jr, D.V. 1990. An Investigation of the Shear Thickening and Behavior of Concentrated Coal-Water Dispersions. *J. Rheol.,* Vol. 34, pp 1267–1291.

Krizek, R.J. & Pepper, S.F. 2004. Slurries in Geotechnical Engineering. *Texas A&M University, Texas*, USA.

Metzner, A.B. & Whitlock, M. 1958. Flow Behavior of Concentrated (Dilatant) Suspensions. *Trans. Soc. Rheology*, Vol. 2, pp 239–254.

Nguyen, Q.D. & Uhlherr, P.H.T. 1983. Thixotropic Behavior of Concentrated Red Mud Suspensions. *Proc. 3rd Nat. Conf. on Rheol,* Melbourne, Australia, pp 63.

Pradipasena, P. & Rha, C. 1977. Pseudo plastic and Rheopectic Properties of Globular Protein (β Lacto globulin) Solution. *J. Texture Studies,* Vol. 8, pp 311–325.

Puppala, A.J., Pokala, S.P., Intharasombat, N. & Williammee, R. 2007. Effects of Organic Matter on Physical, Strength, and Volume Change Properties of Compost Amended Expansive Clay. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, U.S.A., Vol. 133, No. 11, pp 1449–1461.

Steg, I. & Katz, D. 1965. Rheopexy in Some Polar Fluids and in Their Concentrated Solutions in Slightly Polar Solvents. *J. Appl Polym Sci,* Vol. 9, pp 3177–3193.

Struble, L.J. & Ji, X. 2001. Rheology – In Handbook of Analytical Techniques in Concrete Science and Technology. Ramachandran V.S. and Beaudoin J.J. (ed.), *William Andrew Publishing*, New York, USA.

Syrjålå, S. 1996. Numerical Study of Heat Transfer Behaviour of Power-law Non-Newtonian Fluids in Rectangular Channels. *PhD Thesis*, Technical Research Centre of Finland, VTT Chemical Technology, Espoo, Finland. ISBN 951-38-4950-3.

Tanner, R.I. 2000. *Engineering Rheology*. 2nd ed. Oxford University Press, London, UK.

Taylor, H.F.W. 1997. *Cement Chemistry*. 2nd ed., Thomas Telford Publishing, London, UK.

Uhlherr, P.H.T., Guo, J., Zhang, X-M., Zhou, J.Z.Q. & Tiu, C. 2005. The Shear-Induced Solid-Liquid Transition in Yield Stress Materials. *J.* Non-Newtonian *Fluid Mech.* Vol. 125, pp 101–119.

Wallner, M. 1976. Propagation of Sedimentation Stable Cement Pastes in Jointed Rock. *Rock Mechanics and Waterways Construction*, University of Aachen, Germany.