6 Q

THE INTERNATIONAL JOURNAL ON
HYDROPOWER & DAMS
Volume Four, Issue One, 1997
(pp. 71-76)

THE USE OF ADDITIVES IN CEMENT GROUTS

DR ENG. ROGER BREMEN
Lombardi Engineering Ltd., Minusio-Locarno (Switzerland)

The use of additives in cement grouts

R. Bremen, Lombardi Engineering Ltd, Switzerland

Superplasticizers can improve considerably the properties of cement grouts, in particular for the injection of rock fissures. The use of these additives significantly affects the design of the grout slurries compared with the widely used cement-bentonite mixes. The results of an experimental investigation programme are presented here, and some general recommendations are made concerning the design of cement grout mixes.

The purpose of any cement or chemical grouting is to improve one or a combination of physical properties of the material to be injected: permeability, deformability and strength. Therefore the selection and design of the grout mix will have to take into account not only the characteristics and geometry of the voids to be filled, but also the precise purposes of the grouting work. Regardless of this purpose and independently of the material to be injected, the trend today is towards the use of stable thick mixes with a minimum water content. Stable slurries, which have less than 5 per cent sedimentation (bleeding) after 90-120 minutes, are generally preferred to low concentration suspensions, mainly because of the properties of the grout after setting, and because of the unpredictable behaviour of unstable mixes at the time of grouting [Deere and Lombardi, 1985[1]; and, Lombardi and Deere, 1993[2]]. To achieve a better stability of the slurry, bentonite was and still is extensively added to the mix in grouting practice, for the injection of both soils and rocks. During the last decade, various new additives have appeared on the market; these were primarily developed to achieve high-strength concrete by controlling its workability. These products radically modify the properties, and thus the design, of grout mixes compared with slurries, in which the stability is obtained by adding bentonite.

The purpose of this paper is to present some of the main properties of superplasticizers and to illustrate their effects on the rheological properties of stable grout slurries. Based on the results of an experimental investigation, the definite advantages offered by superplasticizers as compared with bentonite in terms of grout workability are discussed. The effect of other admixtures (such as accelerators and retardants) or cement replacement materials (flyash, furnace slag, and silica fume) will not be discussed here, despite their proven suitability for given working conditions or requirements.

It should be mentioned that although several grouting methods (permeation, claquage, displacement) and various materials may be adopted in grouting practice, this paper primarily refers to cement permeation grouting in soils, rocks or cracked concrete. In fact cement grouts to fill voids or fractures are the most commonly used because of their relatively low cost and wide applicability.

1. Rheology of fresh cement grouts

Recent literature on cement grouts rheology has highlighted the complexity of the laws applying to grout flow [Barnes, Hutton and Walters, 1989[3]; Håkansson, 1993[4]; Håkansson, Hässler and Stille, 1992[5]; and, Lombardi, 1985[6]]. In view of the extensive and still on-going research on single-phase fluids, one should be aware of the complexity of time-dependent multi-phase suspensions, the properties of which depend not only on the water/cement (W/C) ratio of the mix, but also on the nature of the cement, the type of mixer, the mixing time and the temperature, to mention only the most important.

For the development of appropriate rheological models, it is thus of primary importance to identify the most relevant flow parameters. Over-elaborate rheological models will not lead to any improvement in grouting practice until the geometry of the voids to be grouted is better known.

Bingham already proposed in 1922 the linear relationship for visco-plastic fluids

$$\tau = \eta_p \cdot \upsilon + \tau_0 \qquad \ldots (1)$$

where τ is the shear stress, υ the shear rate, η_p the plastic viscosity and τ_0 the yield stress (also known as cohesion or yield point) [Bingham, 1922[7]]. The Bingham equation is qualitatively shown in Fig. 1a. For Newtonian fluids, τ_0 will be zero and η_p will be the Newtonian viscosity. Although other more elaborate models were proposed later, (Power-law, Casson, Herschel-Bulkley, and so on) only the Bingham model will be considered here because of its simplicity and effectiveness in relation to

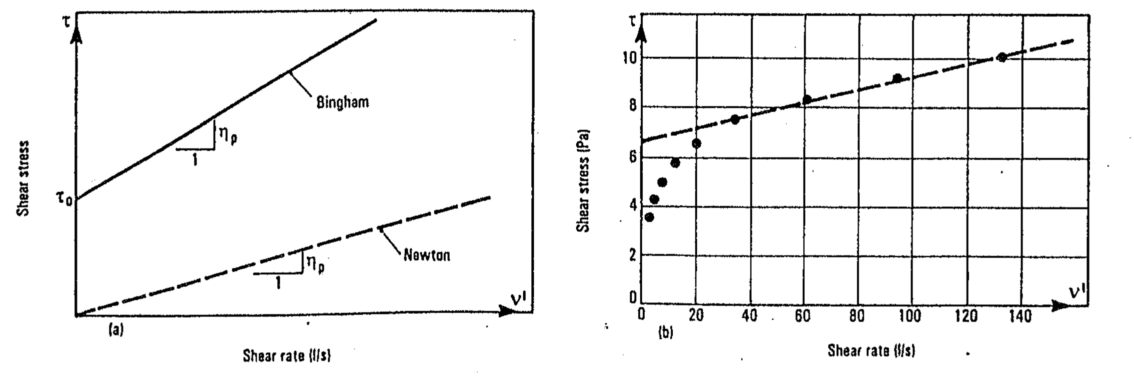


Fig. 1. Relationship between shear stress τ and shear rate υ according to (a) Bingham model, and (b) Experimental results of Håkansson [1993[4]] using a Brookfield concentric cylinder viscometer at variable angular velocities.

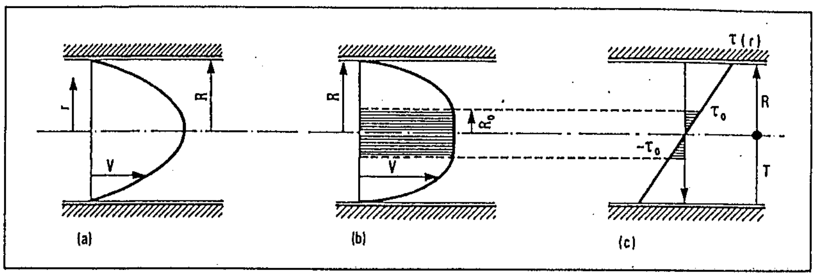


Fig. 2: Velocity profiles of viscous and visco-plastic fluids in a circular pipe [Lombardi, 1985[6]]. (a) Viscous flow (Newton), (b) Visco-plastic flow, and (c) Linear distribution of the shear stress and stiff kernel defined by cohesion according the Bingham law.

grouting practice, although it is recognized that the actual behaviour of the grout mix is more complex.

Experimental results using a rotational viscometer (Brookfield concentric cylinders), shown in Fig.1b, clearly indicate that the plastic viscosity η_p is not constant and no well defined yield stress value can be identified in using the adopted experimental technique.

The Bingham law may thus not be considered as a very accurate description of the rheological properties of a grout mix, but rather as a basic model to be used for the understanding of the grout propagation in fissured matter. As will be shown next, the accuracy of the Bingham model is usually well suited for requirements in practice, despite its theoretical limitations.

For a Bingham fluid flowing through a pipe or a smooth planar joint, two flow zones may be identified, as shown in Fig. 2. A stiff kernel will always form in the central zone of the pipe showing no shear rate (constant velocity profile) since the yield stress is not exceeded. Around it a shear flow will occur. In the case of a circular pipe, the kernel radius R_0, or the half thickness T_0, of a planar joint are expressed by equations:

$$R_0 = \frac{2 \cdot \tau_0}{\gamma \cdot J} \qquad \text{... (2a)}$$

$$T_0 = \frac{\tau_0}{\gamma \cdot J} \qquad \text{... (2b)}$$

where γ is the specific weight of the grout and J the pressure gradient. From the kernel the flow velocity decreases rapidly, reaching zero at the walls. According to the Bingham model, the discharge through a circular pipe or a planar joint can be expressed by the following equations [Lombardi, 1985[6]]:

Pipe:

$$Q_p = \gamma \cdot \frac{\pi J R^4}{8\eta} \cdot \left[1 - \frac{4}{3} \cdot \frac{R_0}{R} + \frac{1}{3} \cdot \left(\frac{R_0}{R}\right)^4\right] \qquad \text{...(3a)}$$

Joint:

$$q_c = \frac{2\gamma J T^3}{3\eta} \cdot \left[1 - \frac{3}{2} \cdot \frac{T_0}{T} + \frac{1}{2}\left(\frac{T_0}{T}\right)^3\right] \qquad \text{...(3b)}$$

For grouting purposes, the maximum penetration distance, or 'reach' L_{max} is of great practical significance. The grout process is theoretically stopped when the kernel radius R_0 or the half width T_0 of the stiff core becomes identical to the pipe radius R or to the half crack width T. The maximum theoretical penetration distance for viscoplastic flow in pipes and joints becomes the following:

$$L_{max} = \frac{\Delta P \cdot R}{2\tau_0} \text{ (Pipe)} \quad ; \quad L_{max} = \frac{\Delta P \cdot T}{\tau_0} \text{ (Joint)} \qquad \text{...(4)}$$

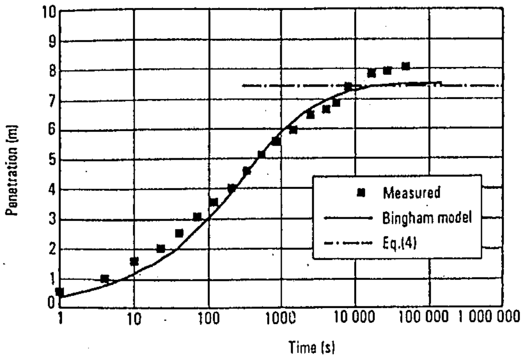


Fig. 3. Grout propagation in a 4 mm-diameter rough glass pipe using a water/silica fume grout mix (W/Sf = 0.67) and a grouting pressure of 50 kPa, according to Håkansson. τ_0 = 6.75 Pa, η_p = 2.92 MPa. (▪) Experimental data ; (—) Prediction of grout propagation according to Eq. (3a) (– · –) Maximum propagation distance according to Eq. (4).

where ΔP is the pressure drop along the distance L_{max}. The previous equations show the essential role of the yield stress τ_0 for the maximum grout propagation. Experiments carried out using a 4 mm-diameter pipe and a silica-fume/water mix (in place of cement) to avoid time-dependent effects, confirm the suitability of the Bingham model as shown in Fig. 3, provided the yield stress value is known [Håkansson, 1993[4]]. Furthermore the experiment has confirmed that the grout propagation stops at some distance as a result of the yield stress of the mix.

However, as shown in Fig. 3, the time duration required to attain the maximum penetration distance, according to Eq.(4), may become important, exceeding the workability time available of the cement grouts because of the decreasing shear stress at low velocity. Furthermore, considering the difficulties in experimentally determining the yield stress of grout slurries as well as the effective joint opening, which might vary as grouting progresses, any quantitative prediction of the grout propagation in fissured rocks or concrete becomes quite uncertain. The GIN (Grouting Intensity Number) is a practical approach to overcoming, at least partially, these difficulties [Lombardi and Deere, 1993[2]].

Despite these difficulties in predicting the grout propagation precisely, the yield stress, together with the joint opening and the cement particle size, become the determining factors affecting the grout propagation. The propagation of water, being a Newtonian fluid, in rock fissures thus differs significantly from the grout flow patterns, which raises questions concerning the use of any water pressure test (for example, Lugeon) to predict the grout take.

2. Effects of bentonite and superplasticizers on the rheology of grout mixes

2.1 General

Bentonite (sodium or calcium montmorillonite) is a volcanic clay, usually regarded as chemically inert, characterized by its great ability to absorb water, thus reducing the amount of water left for cement hydration. The effect of bentonite on the rheology of grout mixes was investigated first by Daxelhofer (in 1948) and subsequently by several other researchers.

According to the results of these studies, the addition of bentonite at a constant W/C ratio:

- reduces the bleeding;
- increases the yield stress;
- increases the viscosity; and,
- reduces the strength of the hardened grout.

For identical bleeding ratios of slurries, the addition of bentonite:

- allows an increased W/C ratio;
- increases the yield stress for bentonite/cement ratios larger than 1 per cent;
- affects, to varying degrees, the viscosity depending on the slurry characteristics; and,
- reduces the strength of the hardened grout.

Considering the significant role of the yield stress on the penetrability of the grout, the improved stability of the slurry achieved by the addition of bentonite is largely counterbalanced by the reduced reach of the grout at the same grouting pressures, because of the increased yield stress of the slurry.

The development of superplasticizers began in the 1960s with the objective of achieving a workable concrete while using low W/C ratios, to improve its final properties. Already widely used in structural grouts (offshore, precast elements, prestressing ducts), where the strength of the hardened grout is of primary importance, the use of superplasticizers in permeation grouting is still rather limited. Only in recent years, some authors [Lombardi and Deere, 1993[2]; Malhotra, 1989[8]; Saleh, Mirza, Baliry and Mnif, 1993[9]; and, Schulze, Kühling and Tax, 1992[10]] suggested replacing bentonite with superplasticizers, in particular when micro cements are used, mainly because of the relatively large size of the bentonite particles. As will be shown later, the use of superplasticizers for grout mixes reduces the yield stress (cohesion), thus improving the penetrability for given grouting pressures and joint openings.

Most of the superplasticizers currently available can be classified in one of the following categories:

- sulphonated melamine formaldehyde condensate;
- sulphonated naphtalene-formaldehyde condensate; and,
- modified lignosulphonates.

The action of superplasticizers is to charge electrically the cement particles, resulting in a mutual electrostatic repulsion. As a consequence, the agglomeration of cement particles, which usually occurs in water, is significantly reduced, resulting in an apparent decrease in the particle sizes, and also a reduction in the bleeding. Superplasticizers will usually not affect the hydration process of the cement, although some may have a retarding effect, especially when used at high dosage rates. The negative charge of the cement particles is progressively neutralized by metal ions produced during the hydration. As regards the characteristics of the settled grout, some superplasticizers may affect the hardening process of the mix by producing high strength grouts at early ages.

2.2 Experimental assessment of the yield stress

To evaluate the yield stress of cement mixes, both direct and indirect methods may be adopted. The most commonly used direct methods in laboratories are the shear-vane and stress-relaxation methods, while the raise-pipe and the plate cohesion meter are well suited for in-situ tests. Indirect methods consist of extrapolating the shear stress values measured with a viscometer (Brookfield or similar) to zero shear rate, as shown in Fig. 1.

More than any other rheological parameter of cement mixes, the experimental determination of the yield stress thus strongly depends on the adopted measuring technique and procedure. Details of the most commonly used techniques and procedures are given in the literature [Håkansson, 1993[4]; Lombardi, 1985[6]; Rixom and Mailvaganam, 1986[11]; and, Tattersall and Banfill, 1983[12]].

Because of this multitude of experimental procedures, and a lack of any standards, attempts to identify the 'true yield stress' and thus attribute variable accuracy levels to different measuring procedures will probably not result in any practical improvement in the near future.

As a consequence of the variety of experimental procedures adopted for the determination of the yield stress, the experimental results are characterized by significant discrepancies as reported by various authors [Tattersall and Banfill, 1983[12]]. In addition to the use of different measuring techniques, numerous factors can affect the rheological behaviour of the grout. The lack of reproducibility of experiments often results from the wide scatter in the adopted mixing procedure, the cement characteristics (chemical composition, particles size and shape), and the mix temperature. Furthermore the hydration process introduces a time dependency of the rheological properties of the grout mix which are not always duly taken into consideration.

The evaluation of experimental data from 13 different sources, as reported by Tattersall and Banfill [1983[12]]resulted in variations of the measured yield stress exceeding ten times for a constant W/C ratio, as shown in Fig. 4.

To demonstrate the essential role of the cement characteristics on the rheological parameters, the data provided by Tattersall and Banfill have been completed with yield stress measurements carried out by the present author, using a plate cohesion meter (PCM) suggested by Lombardi [1985[6]] and described next.

As shown in Fig. 4, part of the discrepancies of the experimental data may be attributed to the influence of the cement characteristics (gradation curve) on the properties of the grout mix. Obviously additional factors, including the adopted experimental procedure as well as the mixing method and time, have to be carefully considered when comparing experimental data of yield stresses from different sources.

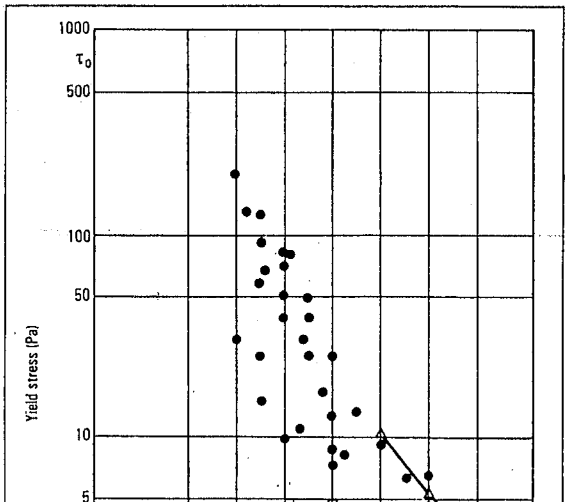
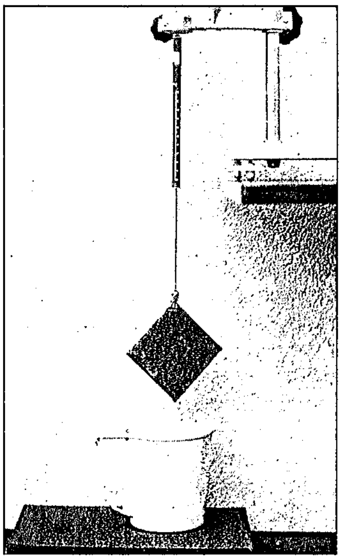


Fig. 4. Yield stress data of 13 different sources [Tattersall and Banfill, 1983[12]], completed with the data using a plate cohesion meter (PCM) for (o) Portland Cement Type I and (+) Portland Cement Type III.



Experimental layout of the plate cohesion meter (PCM) used for the measurement of the yield stress. The device hangs on a high precision dynamometer providing an accurate weighting of the grout sticking on the plate (± 0.25 g).

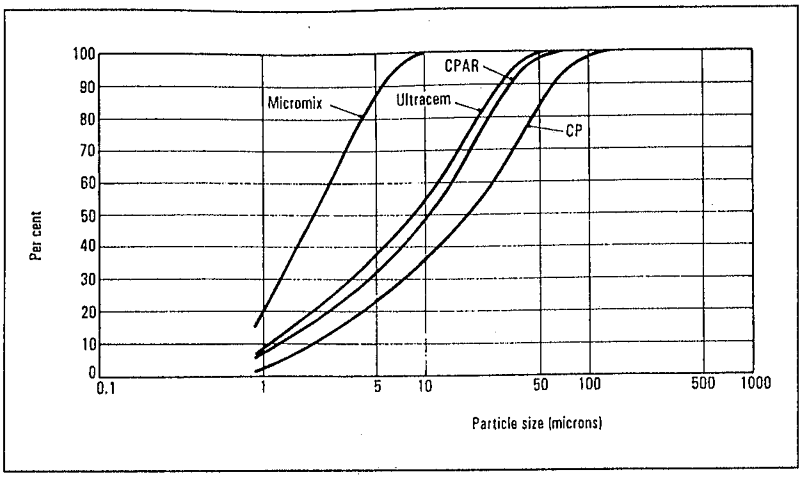


Fig. 5. Gradation curves of the cement types investigated: CP, Portland Cement Type I (3200 Blaines); CPAR, Portland Cement Type III (4200 Blaines); Ultracem (5200 Blaines); and, Micromix (12 000 Blaines).

2.3 Experimental investigation

As shown in the previous section, the yield stress is a basic factor for the grout penetration in fissured masses. With the main purpose of quantifying the influence of additives, in particular bentonite and superplasticizers, on the yield stress of cement mixes, a test programme was carried out using a plate cohesion meter (PCM). The photo shows the device which was used, consisting of a hard 10 cm^2 PVC plate with a well specified surface roughness, hanging on a dynamometer. Although originally stainless steel was used for the plate [Lombardi, 1985[6]], the lighter weight of PVC resulted in increased accuracy for the measurements. For the determination of the yield stress, the plate is immersed in the cement mix and then removed immediately. The weight of the grout sticking to the plate 15 seconds later is measured with the dynamometer, which has an accuracy of ± 0.25 g. Compared with other experimental devices, the PCM offers the advantage of directly providing the yield stress value without any combination of rheological parameters (viscosity, unit weight of the mix, and so on).

The yield stress is obtained dividing the measured weight by the surface of the plate (0.02 m^2). A direct scale of the yield stress value, expressed in Pascals, may be attached to the dynamometer, providing a direct measurement without the need for further calculations. As regards the accuracy level of the device, considering a maximum error in the weight measured of ± 0.25 g, the maximum deviation of the yield stress value is ± 0.12 Pa, corresponding indicatively to 3-4 per cent of the minimum yield stress of stable cement mixes.

A more precise definition of the test is under way, with a view to achieving the optimum layout of the plate and a standard test procedure.

For each grout mix investigated, the following measurements were made, and their rheological parameters determined:

- density;
- temperature;
- bleeding rate measured each 15 min up to 120 min;
- yield stress using a PCM measured 10 min and 45 min after mixing; and,
- Marsh-cone flow time.

Since the Marsh-cone is frequently used in practice, the flow time for 1 litre to flow out of an API standard Marsh-cone filled with 1.5 litres of slurry was also measured.

Four types of cements were selected for the test programe, to investigate the effect of the particle size on the rheological parameters. Fig. 5 shows the gradation curves of the cements used with Blaine values ranging from 3200 cm^2/g for the Portland Cement Type I, up to 12 000 cm^2/g for the micro cement used. The gradation curves of the cements used were determined using an optical particle size analyser.

All the experiments were carried out at slurry temperatures between 18°C and 22°C. A high velocity laboratory mixing device was used with a mixing time of 5 minutes.

Fig. 6a shows the yield stress measured with a PCM as a function of the W/C ratio for the cement types considered, without any additive. The figure also indicates the limit between stable and unstable grout slurries as a function of the W/C ratio. Using normal or fine Portland Cements with Blaine values not exceeding 5500 cm^2/g, stable grouts can only be obtained with W/C ratios of less than 0.85. Although not shown in the figure, stable grouts with significantly higher W/C rates (up to 1.6-1.8) may be achieved if microcements are used. Fig. 6b shows the same data as Fig. 6a, but the yield stress is plotted as a function of the Blaine value.

Apart from some minor discrepancies, a linear relationship seems to exist for a given W/C ratio between the measured yield stress and the Blaine value in the range between 3000 cm^2/g and 5500 cm^2/g. Therefore, especially for low W/C ratios, the yield stress depends significantly on the grain size of the cement used.

As regards the limit between stable and unstable slurries, it is interesting to note that the identified zone in Fig. 6 is horizontal, indicating that to be stable, grouts apparently require a minimum yield stress value of 3 ± 0.4 Pa, regardless of the cement particle size. In other words, measuring the yield stress using a PCM indicates the stability characteristics of the slurry in case of mixes without any additive. According to the results of the experimental study, it is not possible, however, to identify a clear line between stable and unstable grout slurries, mainly because of the effect of the temperature on the bleeding characteristics and the limited number of tests. According to the experimental conditions, the maximum W/C ratio for cement grouts to be stable without additives may be expressed as:

$$(W/C)_{max} = \frac{\text{Blaine value } (cm^2/g)}{9000} + 0.24 \quad \ldots (5)$$

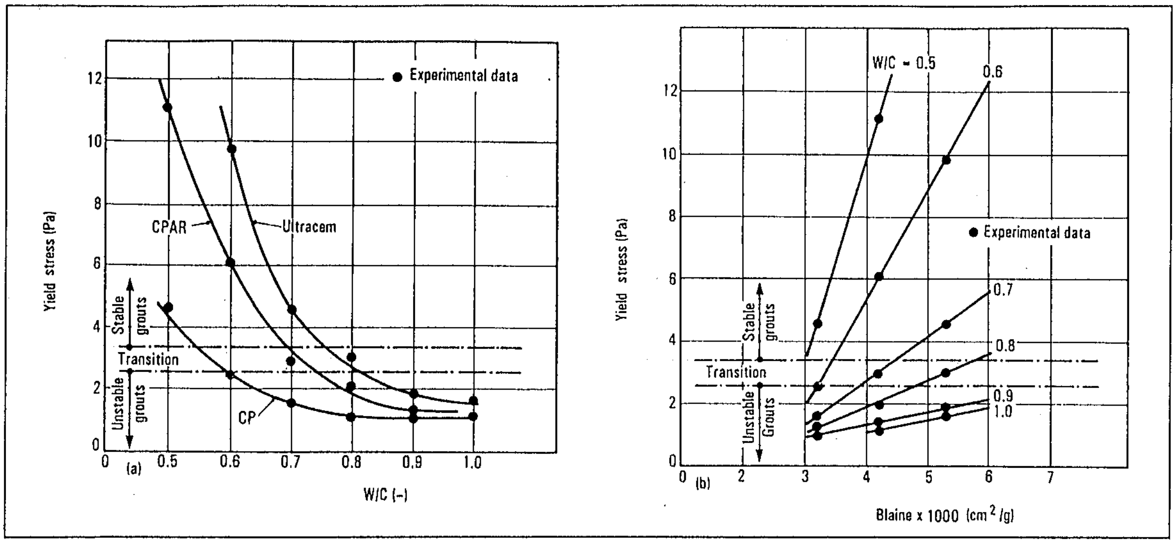


Fig. 6. Yield stress of grout mixes without the use of additives: (a) Yield stress as a function of the W/C ratio for different cement types; (b) Identical data plotted as a function of the cement Blaine value; (– · –) is the limit between stable and unstable grout mixes.

for Blaine values ranging from 3000 cm^2/g up to 12 000 cm^2/g. It should be mentioned that the previous equation is only indicative, and applies to the experimental conditions of the present investigation. The equation may however be used for preliminary design purposes for grout slurries prior to laboratory tests.

The influence of additives on the yield stress has been examined using a Portland Cement Type III (High Resistance Portland Cement). Fig. 7 indicates the influence of the addition of bentonite and of a naphtalene based-superplasticizer on the yield stress and on the Marsh flow time as a function of the W/C ratio.

As shown in Fig. 7a, for identical W/C ratios, the yield stress of a 2 per cent Cement-Bentonite slurry is 2.5 to 4 times higher than without bentonite. On the other hand, the addition of a superplasticizer reduces the yield stress value compared with mixes without additives. However, the influence of superplasticizers on the yield stress may vary significantly depending on the product used, and the result shown in Fig. 7b should not be generalized.

Because of the reduced agglomeration and the electric charge of the cement particles, superplasticizers improve the stability of the grout slurries equally. In other words, the minimum yield stress required for cement mixes to be stable (Fig. 5) is lower for slurries in which a superplasticizer is added, although the quantitative evaluation of this effect depends greatly on the superplasticizer used.

Concerning the time dependency of rheological parameters, the yield stress and the Marsh flow time were also measured one hour after mixing. However, as for site conditions, where the grout is constantly mixed before the measurements, the slurry was mixed again for 1 min. Although a systematic slight increase in the yield stress and the Marsh flow time were registered, no particular behaviour could be identified for mixes in which superplasticizers had been added. It can thus be assumed that the time dependency of the rheological parameters essentially relates to the cement hydration up to at least one hour after mixing, and temperatures of between 18°C and 22°C.

3. Implications for the design of cement grouts

Grouting works can be regarded as successful not only when the purposes of the grouting have been fulfilled, but also when the costs are kept as low as possible. For both aspects, control of the grout penetration during injection is of primary importance.

Depending on the purpose of the grouting and on the characteristics of the materials to be injected, the rheological properties of the grout mixes can thus be varied, to guarantee the filling of the voids in the vicinity of the grout holes while avoiding an uncontrolled propagation of the grout and an unnecessarily high grout take.

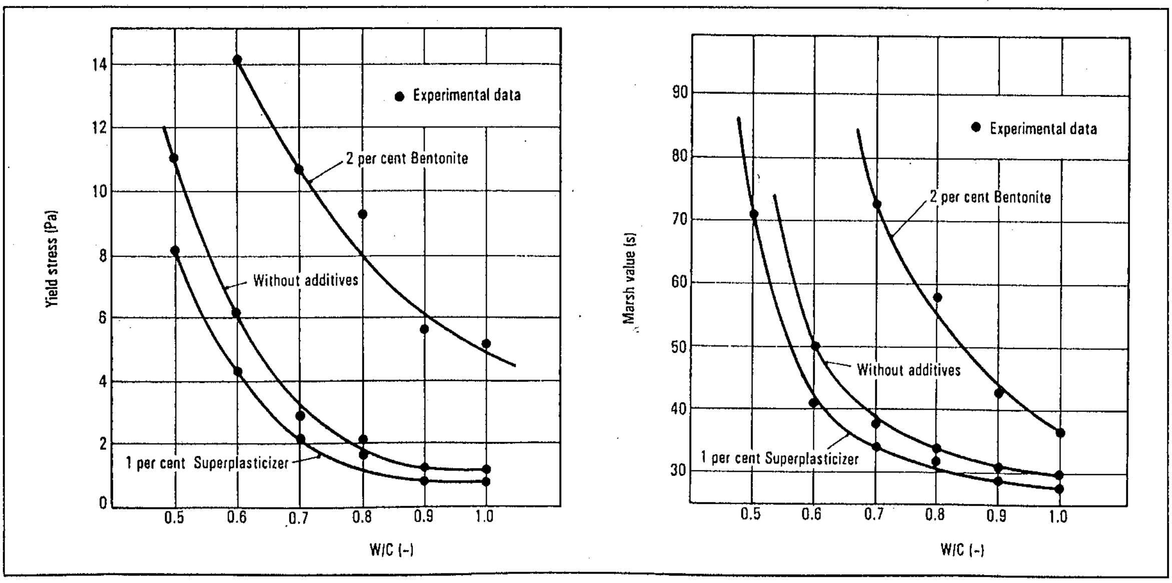


Fig. 7. Influence of bentonite and superplasticizer on the yield stress and the Marsh flow time: (a) Yield stress as a function of W/C ratio using Portland cement type III (CPAR) measured with a PCM; and, (b) Marsh flow time (Standard API funnel) of the same grout mixes.

To achieve adequate control of the grouting progress, the definition of precise grouting principles as well as correct design of the grout slurry are essential. As far as the selection of the slurry characteristics are concerned, the experimental results shown in the previous section lead to the following recommendations:

- For the injection of fine fissures, the yield stress of stable slurries should be kept as low as possible, to guarantee the optimum penetrability of the mix.
- The use of cement bentonite mixes is not recommended for the injection of the fine fissures in rocks and concrete because of the high yield stress values of this type of mix.
- Instead of using bentonite, stable grouts can easily be achieved with W/C ratios of between 0.6 and 0.9 and a 0.6-2 per cent addition of superplasticizers depending on the cement characteristics. Compared with cement-bentonite slurries, the yield stress of stable cement mixes with superplasticizers is significantly lower, thus improving the grout penetrability.
- To achieve the best possible penetration without using relatively expensive microcements, it is recommended to adopt fine-grained cements (typically Portland Cement Type III) with a Blaine value of not less than 4500 cm^2/g.
- The use of microcements should be considered for grouting very fine fissures in rock or concrete. Microcements with Blaine values exceeding 10 000 cm^2/g can be used to fill cracks down to a minimum width of 0.2 to 0.3 mm. Bentonite should never be added to microcements, since the advantages offered by the increased penetrability of the very fine cement particles are jeopardized by the increased yield stress resulting from the bentonite.

4. Conclusions

Although bentonite has been and still is extensively used as an additive for grouting to improve the stability of low concentration suspensions, one should be aware of its effects on the grout rheology and penetration characteristics. Although the prediction of the grout penetrability in fissured rock and concrete remains difficult, theoretical approaches as well as laboratory experiments have demonstrated the essential role of the yield stress on the upper limit of the penetration distance of cement grouts.

In particular, if high penetrability is of primary importance, the use of slurries with added bentonite should be avoided. High concentration suspensions of fine-grained cements combined with the use of superplasticizers offer the best penetrability mainly because of the low yield stress of the mix.

For the grouting of very fine fissures, microcement grouts may be suitable. However, to take full advantage of the properties of these cements, the addition of a superplasticizer is strongly recommended because of the reduced agglomeration of the cement particles and the lower yield stress of the mix. ◊

Acknowledgements

The author gratefully acknowledges Dr Eng. Giovanni Lombardi for the support and guidance provided throughout the present project. Special thanks are also due to Mr D. Martini who carried out the laboratory tests.

R. Bremen

Notations

J = pressure gradient
L_{max} = maximum penetration distance of grout
ΔP = pressure drop along L_{max}
R = pipe radius
R_0 = radius of the stiff kernel in pipes
T = half fissure width
T_0 = half width of the stiff kernel in fissure
γ = unit weight
τ = shear stress
τ_0 = yield stress
υ = shear rate
η = viscosity
η_p = plastic viscosity
W/C = water cement ratio by weight

References

1. **Deere, D.U. and Lombardi, G.**, "Grout Slurries - Thick or Thin?", Issues in Dam Grouting, ASCE, New York, USA; 1985.
2. **Lombardi, G. and Deere, D.**, "Grouting design and control using the GIN principle" *Water Power & Dam Construction*, June 1993.
3. **Barnes, H.A., Hutton, J.F. and Walters, K.**, "An Introduction to Rheology", Elsevier; 1989.
4. **Håkansson, U.**, "Rheology of Fresh Cement-Based Grouts", Doctoral thesis, Royal Institute of Technology, Stockholm, Sweden; 1993.
5. **Håkansson, U., Hässler, L. and Stille, H.**, "Rheological Properties of Microfine Cement Grouts with Additives", ASCE, Specialty Conference on Grouting, Soil Improvement and Geosynthetics, New Orleans, USA; 1992.
6. **Lombardi, G.**, "The Role of Cohesion in Cement Grouting of Rock", R13, Q58, 15th ICOLD Congress, Lausanne, Switzerland; 1985.
7. **Bingham, E.C.**, "Fluidity and Plasticity", McGraw-Hill, New York, USA; 1992.
8. **Malhotra, U.M.**, "Superplacticizers: a global review with emphasis on durability and innovative concretes", ACI Special Publication, SP-119, Ottawa, Canada; 1989.
9. **Salch, K., Mirza, J., Ballivy, G. and Mnif, T.**, "Selection criteria for Portland and microfine cement-based injection grouts", *Proceedings*, International Conference on Grouting in Rock and Concrete, Salzburg, Austria; 1993.
10. **Schulze, B., Kühling, G. and Tax, M.**, "Neue Zusatzmittel für feststoffreiche Feinstzement-Suspensionen", *Bauingenieur*, No.11, 1992.
11. **Rixom, M.R. and Mailvaganam, N.P.**, "Chemical admixtures for concrete", Spon, London, UK; 1986.
12. **Tattersall, G.H. and Banfill, P.F.G.**, "The rheology of fresh concrete", Pitman; UK; 1983.

Bibliography

Banfill, P.F.G., "Rheology of Fresh Cement and Concrete", E. & F.N. Spon, London, UK; 1990.

Domone, P.L.J. and Jefferis, S.A., "Structural Grouts", Blackie Academic & Professionals, London, UK; 1994.

Krizek, R.J., "Bleed and rheology of cement grouts", *Proceedings*, International Conference on Grouting in Rock and Concrete, Salzburg, Austria; 1993.

Roger Bremen was awarded an MSc in Civil Engineering at the Swiss Federal Institute of Technology Lausanne, Switzerland, in 1987. In 1990 he obtained a PhD in Civil Engineering from the same Institute. Since 1990 he has been working at Lombardi Engineering Ltd in Minusio, Switzerland, He is involved in the design and rehabilitation of dams and hydroelectric plants in Europe and Central and South America.

Lombardi Engineering Ltd, CH-6648 Minusio-Locarno, Via R. Simen 19, PO Box 1535, Switzerland.