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TECHNICAL NOTE

Bleeding characteristics for viscous cement and cement–bentonite grouts

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KEYWORDS: consolidation; filters; grouting; laboratory tests; permeability

INTRODUCTION

Bleeding of cement-based grouts reduces the effectiveness of compensation grouting operations. Compensation grouting involves the injection of a grout to heave the soil and compensate for settlements resulting from ground loss during tunnelling with a TBM. A grout bleeds at the incipience of the injection pressure. Water is squeezed out from pores between cement particles, into the ground, in a similar process to water drainage in soil consolidation. Water loss through bleeding has several consequences.

(*a*) Higher grout viscosity, reduced mobility and therefore poorer pumpability (Warner, 1992). Furthermore, the pressure needed to fracture in the ground (fracture grouting) will be higher with use of a grout with higher viscosity (Mori *et al.*, 1990).

(*b*) Reduced grout efficiency. The ground volume raised is lower when bleeding is higher. This volume is equal to the injected grout volume (V_i), minus volume loss through bleeding of the grout (V_b) and consolidation of the ground (V_{co}). The efficiency of grouting (E) is defined (Komiya *et al.*, 2001) in terms of these volumes as

$$E = \frac{V_i - V_b - V_{co}}{V_i} \tag{1}$$

(*c*) There may be a risk of fractures in the ground owing to bleeding of water. According to Mori *et al.* (1990), injecting a low-viscosity material into the ground increases the chance of fractures in the ground. Because the viscosity of water is low in comparison with the viscosity of the grout, there may be an increased chance of fracture.

The amount (volume) of bleeding water, expressed via V_b in equation (1), is affected by several parameters.

The development of fractures is dependent on in situ ground stresses and on the pore water pressures generated from grouting (Greenwood, 1994). In order to determine the pore pressure during grouting, knowledge of the rate and volume of bleeding is essential. The amount of water released (from the grout) per unit of time in combination with the permeability (of the soil) will affect the excess pore pressures in the soil. To be able to take the velocity of bleeding (or loss of efficiency in time) into account, knowledge of the permeability of both the soil (k_s) and the grout (k_g) is essential. Other parameters that affect progress of the grouting process are injection pressure p and the water–solids ratio of the grout. In the case of grout material where the water–solids ratio is not readily available, or is difficult to determine, a rheological parameter such as the viscosity parameter (μ_p) would be a good alternative.

Research has been reported on the rheology and viscosity of some grouts (Wallevik & Wallevik, 1998; Rosquoët *et al.*, 2003), and on the consolidation characteristics of cement-based grouts, but not so much in correlation with bleeding. In McKinley (1993), Bolton & McKinley (1997) and McKinley & Bolton (1999), research is carried out on the consolidation characteristics of cement-based grouts in relation to the water–cement ratio and the pressure applied to the grout. McKinley does not consider a possible link with the viscosity of the grout. On the basis of a numerical analysis, the effect of the porous block used for the tests performed by McKinley is neglected.

In this paper an experimental study is conducted on the influence of the permeability of the ground in combination with the conduct of bleeding of a grout. Furthermore, this paper provides an addition to the results of previous research on the subject by accounting for the grout viscosity. In short, this research establishes the link between the behaviour of grout in the form of efficiency (E) as defined in equation (1), the velocity of bleeding (S_b) (definition of bleeding as given later in equation (7)), the plastic viscosity of the grout, the grout (injection) pressure, and the permeability of the ground.

Plastic viscosity, permeability, injection pressure and efficiency are related by means of two separate laboratory test series. The first is a series of viscosity tests on grouts prepared at different solid–water ratios in order to relate plastic viscosity to void ratio (or water content) of the grouts. The second series of tests that followed are consolidation tests on grouts prepared at void ratios similar to those in the first test series. These tests relate the grout void ratio e (or water content) to the volume of bleeding water V_b. Only the bleeding and compression of the grout at the onset of injection are taken into account prior to soil consolidation (i.e. V_{co} is assumed = 0). The results of these two test series can be combined for research and practical use, and translate into efficiency measures for bleeding grouts with different viscosities or solid–water (or void) ratios.

GROUT MATERIALS

Water–cement and water–cement–bentonite mixtures are used in this research. Characteristics given by the manufacturers and laboratory tests of the cement (type: Portland, CEM II/B-M/V-L; ENCI, private communication, 2004) and bentonite (type: CEBOGEL CSR; CEBO, private communication, 2004) are given in Tables 1 and 2. The grain size distributions of the two materials are given in Fig. 1. The mixtures bentonite and bentonite–cement powders are prepared in a similar manner with a Hobart mixer using de-aired water.

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Table 1. Specific surface and specific weight (cement and bentonite)

	Specific surface: m^2/kg	Specific weight: kg/m^3
Cement	410	2950
Bentonite	130	2750

Table 2. Chemical components (cement and bentonite)

Component	Cement: %	Bentonite: %
SiO_2	28·1	52·9
Al_2O_3	9·0	17·7
Na_2O	0·3	3·5
K_2O	0·8	0·8
MgO	1·9	3·5
CaO	49·2	4·9
Fe_2O_3	3·6	4·6
P_2O_5	0·0	0·2
SO_3	2·5	2·0
TiO_2	0·5	0·8
Mn_2O_4	0·0	0·1
Rest	4·1	9·8

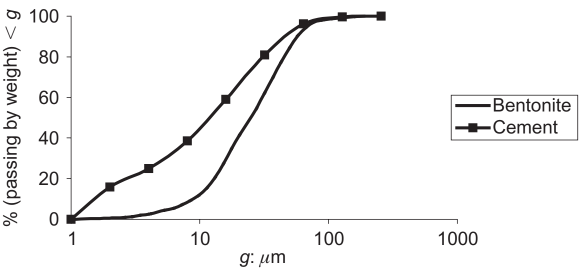

Fig. 1. Grain size distribution (cement and bentonite)

Adding bentonite to grout admixtures leads to significant increase in plastic viscosity and decrease in bleeding of cement-based grouts. Bentonite, totalling 5% of the weight of water, is added as is typical in compensation grouting practice.

These grouts are prepared at several void ratios ranging from 1·48 to 4·99 (for the viscosity tests) and 1·48, 2·07 and 2·66 (for the bleeding tests). The void ratios used for the mixtures without bentonite were the same as for the mixtures with bentonite. The measured plastic viscosity varied between 20 and 64 mPa.s and 17–100 mPa.s for, respectively, cement and cement–bentonite grouts.

VISCOSITY TESTS

The viscosity tests are performed with a Haake Rotovisco viscometer, type RV20-M5, incorporating a container, type MV2P, with a ribbed exterior to prevent 'slipping' of the slurry during testing (Gustin, 2004). Shear rates from 0·44 to 264 s^{-1} are used during the tests. The results with these shear rates were fitted with the Herschel–Bulkley model (equation (2); Ferraris *et al.*, 2001). A modified Bingham model is used (equation (3); Ferraris *et al.*, 2001; Banfill, 2003), to determine the plastic viscosity μ_p.

$$s = s_y + ax^b \tag{2}$$

$$\mu_p = \frac{3a}{b+2} x_{max}^{b-1} \tag{3}$$

The determined plastic viscosity is plotted against relative void ratio in Fig. 2. Use of the grout void ratio is preferred to water content (or water–solids ratio), for consistency with the convention in soil consolidation. The relative void ratio is defined as

$$e_{g,r} = \frac{V_w}{V_{ben} + V_{cem} + V_w} = \frac{e_g}{e_g + 1} \tag{4}$$

where V_{ben} and V_{cem} represent the volumes of bentonite and cement respectively. Use of equation (4) permits normalisation leading to $e_{g,r} = 1$, when the grout consists of only water. This point is also added in the plot.

Through the measured points a line can be fitted using the least square root method. A line represented by a power equation (equations (5) and (6) below) gives a good fit (R^2 is 0·94 and 0·97) for grouts without and with bentonite respectively. The measured points and the fitted lines are shown in Fig. 2.

Mixtures without bentonite:

$$\mu_p = e_{g,r}^{-8\cdot84} \quad \text{(in mPa.s)} \tag{5}$$

Mixtures with bentonite:

$$\mu_p = e_{g,r}^{-12\cdot41} \quad \text{(in MPa.s.)} \tag{6}$$

This plot and the accompanying equations establish the relationship between plastic viscosity and void ratio for the two grouts.

Bleeding testing, as outlined below, leads to relationships between void ratio and filtration/consolidation, which consequently provides the relationships between grout efficiency and viscosity based on equation (1).

BLEEDING TESTS

Grout samples with a thickness of 17·1 mm and a surface of 4·42 × 10^3 mm^2 are tested using a modified consolidation cell (Fig. 3). The top of the sample is made watertight with a rubber disc, which can slide friction-free. The bottom end of the grout sample is covered with a filter of predetermined

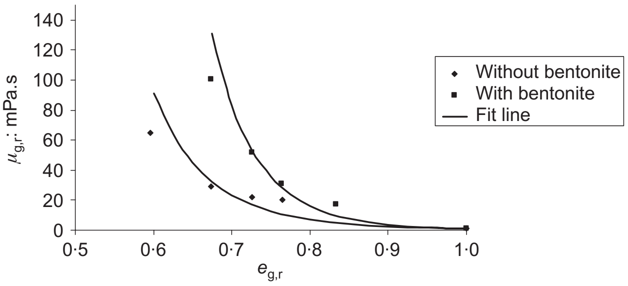

Fig. 2. Plastic viscosity–void ratio curves (cement and cement–5% bentonite grouts): viscosity tests

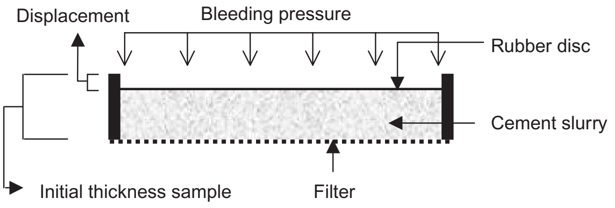

Fig. 3. Modified consolidation (bleeding) test cell

permeability coefficient. This ensures one-way drainage through this filter. Four filters are used with permeability coefficients comparable to different soils: k_s 4·9 × 10^{-7} m/s (filter 1), 4·3 × 10^{-8} m/s (filter 2), 1·9 × 10^{-9} m/s (filter 3) and 3·7 × 10^{-10} m/s (filter 4). The thickness of the filters is respectively 150 μm, 115 μm, 105 μm and 105 μm. Three filtration/consolidation stages were performed using 11·1 kN/m^2 pressure increments. Full consolidation is ensured at each pressure stage of 11·1, 22·2 and 33·3 kN/m^2, irrespective of the time it takes. The time for full consolidation was generally short (less than 20 min), increasing with each stage, with no time lapse between the end of consolidation and the beginning of loading. The short consolidation time required recording with a digital dial-gauge of vertical displacements and data-logging.

Test results are found to be consistent and repeatable. Verifiable assumptions are made to enable the processing of test data on the basis of soil's one-dimensional consolidation theory, namely:

(*a*) full saturation, ensured by the mixing method and de-aired water
(*b*) minimal bonding and chemical reaction between water, cement and bentonite, evident from observed short test durations
(*c*) negligible filtration of grout particles or change in filter's permeability during a test, as ensured by using a new filter per test.

Consolidation (void ratio–time) and grout (pressure–void ratio) plots provided the basis from which bleeding characteristics of the two grouts are produced. Gustin (2004) gives a full account of the consolidation results, covering the fundamental variables that could affect bleeding behaviour, including injection pressure, grout phase and rheological parameters (water–solid ratio and viscosity), and soil drainage quality (soil permeability).

In Figs 4 to 7 examples are given of plots of relative volume change against time. For Figs 4 and 5 time is presented as the square root of time, while for Figs 6 and 7 linear time is plotted. The relative volume change represents the percentage of volume change, at a given time, in relation to the total volume change at the end of the last pressure increment. Figs 4 and 5 show the results of the test, respectively with and without bentonite, using the filter with the highest permeability (filter 1), while Figs 6 and 7 show the results, respectively with and without bentonite, using the filter with the lowest permeability (filter 4). For each presented line the void ratio at the start of the test ($e_{g;start}$) and at the end of the third pressure increment ($e_{g;end}$) is given. The plots, as shown in Figs 4 and 5, show a good comparison with the plots provided by McKinley. The amount of water filtered is proportional to the square root of time, whereas the amount of water filtered as shown in Figs 6 and 7 is linear in time.

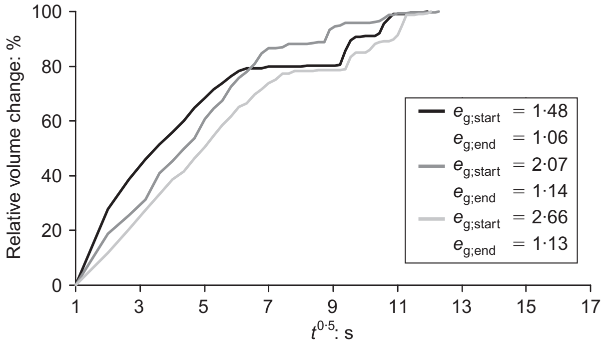

Fig. 4. Relative volume change, filter 1, without bentonite

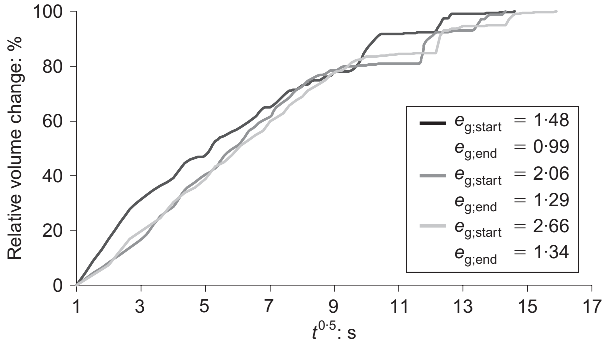

Fig. 5. Relative volume change, filter 1, with bentonite

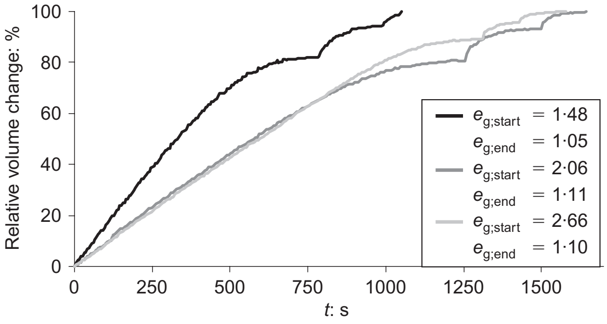

Fig. 6. Relative volume change, filter 4, without bentonite

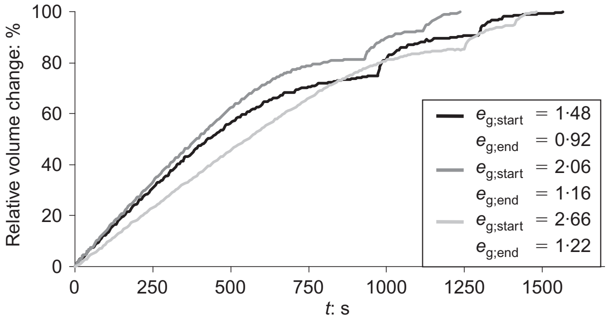

Fig. 7. Relative volume change, filter 4, with bentonite

In equation (7), a definition is given for the velocity of bleeding (S_b) in relation to the total volume of the grout sample, V_t.

$$S_b = \frac{V_b}{V_t \Delta t} \tag{7}$$

Because pore pressure was not measured, the end of consolidation is determined by examining the plots (volume change against time). In Fig. 8, the velocity of bleeding, as defined in equation (7), is plotted against plastic viscosity.

Figures 9 and 10 show the relationship between efficiency as given in equation (1) and the plastic viscosity as given by equations (5) and (6).

DISCUSSION

Because bentonite is a coarser material than cement, as can be seen in Fig. 1 and Table 1 (bentonite has a lower specific surface than cement), adding bentonite does not lead to a lower permeability of the grout. Therefore the decrease of velocity of bleeding when adding bentonite cannot be accounted for by a decreasing permeability of the grout.

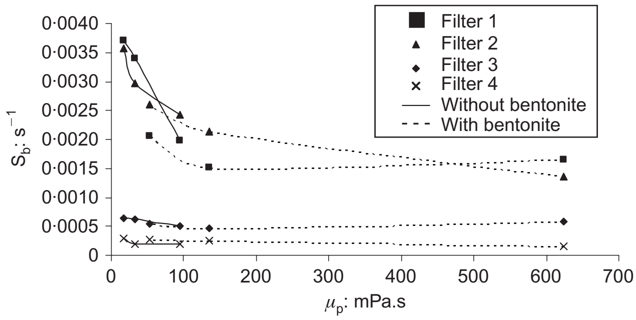

Fig. 8. Velocity of bleeding

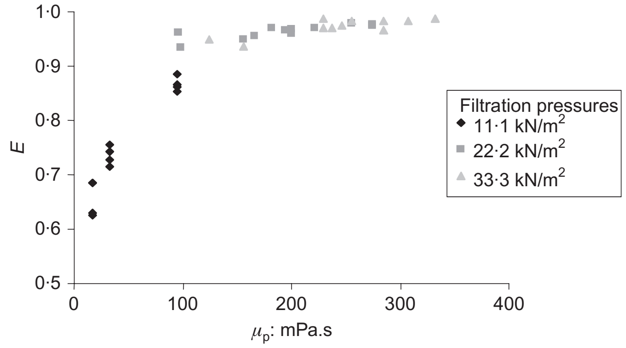

Fig. 9. Efficiency of cement grouts: bleeding tests

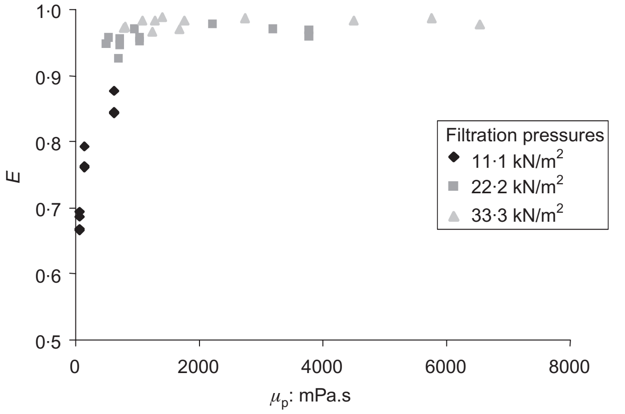

Fig. 10. Efficiency of cement–5% bentonite grouts: bleeding tests

Because the void ratios used for samples with and without bentonite are the same, Fig. 6 shows that the velocity of bleeding is not directly linked to the amount of water used in the sample. Plastic viscosity seems to be a well-suited variable to make an estimation of the velocity of bleeding. When the permeability of the used filter is below $4{\cdot}3 \times 10^{-8}$ m/s, the velocity of bleeding is no longer dependent on the plastic viscosity of the sample but depends on the permeability of the filter. This can be partially confirmed by the research done by McKinley, who concluded that the influence of permeability of the used porous block can be neglected in comparison with the permeability of the grout itself.

Efficiency loss due to bleeding of grouts can be interpolated using Figs 9 and 10 for other grouts from knowledge of the viscosity (or water–solid ratio, or void ratio, using equations (5) and (6)), and the applied grouting pressures. These results demonstrate a rapid non-linear decrease in efficiency (increased bleeding) with decreasing viscosity and grouting pressure. At high pressures grouts become highly consolidated, bleeding reduces significantly, and efficiency approaches 1. This also leads to the conclusion that most bleeding takes place shortly after injection at low effective stress. Comparing the two curves for the two grout materials shows that the addition of bentonite greatly enhances the efficiency, owing to sharp increases in viscosity. A maximum viscosity with bentonite is almost 20 times higher than that measured for the same solid–water ratio without bentonite.

No significance in the coefficient of permeability of the ground (filters) on grout efficiency could be clearly identified in this test series. A comparison with the findings of McKinley, who conducted consolidation tests on cement grouts without varying the permeability of the filters, cannot be made.

Because of the rapid changes of the relative grout permeability in comparison with filter permeability, making some samples less permeable than the filters even at the initial bleeding stage, bleeding becomes the more correct term to use, at low pressures and high water content (suspension state), than time-dependent consolidation. Filters do affect the results to a maximum recorded <15% at the lowest pressure and highest permeability range for the low-viscosity cement grouts. Bentonite reduces this effect to almost 5%. This spread could, however, also be influenced by experimental errors.

CONCLUSIONS

Extensive viscosity and consolidation test results are reported and coupled in Figs 9 and 10 to provide relationships of efficiency with viscosity for cement-based grouts. This is done using the change of relative void ratio in cement and cement–bentonite grouts (derived in equations (5) and (6)) as a common variable in both tests. This novel method and the test results are reported for the first time and are of practical value in correcting for reduction in grout efficiency due to bleeding. Plastic viscosity and void ratio correlations (Fig. 2, and equations (5) and (6)) derived for the first time are also of practical value when viscosity measures are not readily available. In order to determine overburden stresses, and thereby determine the chance of fractures in the ground, during the grouting process the velocity of bleeding is related to the plastic viscosity or void ratio of the grout.

NOTATION

a	correlation constant: Herschel–Bulkley model
b	correlation constant: Herschel–Bulkley model
E	grout efficiency
e_g	void ratio (grout)
$e_{g;start}$	void ratio at start of test
$e_{g;end}$	void ratio at end of third pressure increment
$e_{g,r}$	relative void ratio
g	percentage passing by weight
k_s	permeability coefficient of soil (filter)
k_g	permeability coefficient of grout
p	grout (injection) pressure
S_b	velocity of bleeding
s	shear stress
s_y	yield stress
V_i	injected grout volume
V_b	bleeding water volume (grout)
V_{ben}	volume of bentonite
V_{cem}	volume of cement
V_{co}	consolidation volume (soil)
V_t	total volume of grout sample
V_w	water volume (grout)
x	shear rate

$x_{\max}$	maximum tested shear rate
μ_p	plastic viscosity (grout)

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