PENETRABILITY CONTROL OF GIN MIXES DURING FRACTURED ROCK GROUTING

Vafa Rombough, Golder Associates Ltd., Burnaby, British Columbia, Canada
Grant Bonin, Golder Associates Ltd., Burnaby, British Columbia, Canada
Dawn Shuttle, University of British Columbia, Vancouver, British Columbia, Canada

ABSTRACT
Modern fractured rock grouting commonly adopts the GIN principle as a means of controlling grout penetration. Assumptions of negligible fracture flow velocities within the method, however, are questionable. Theoretically, penetration length for a Bingham fluid (a common grout idealization) can be shown to be a function of the grout rheology, fracture geometry and the grout injection rate. This paper presents the material properties for three grouts, determined by rotational viscometry. The effects of fracture aperture and injection rate are then investigated for the "best" GIN grout using a 1-D fracture idealization. These preliminary results indicate that for realistic grout properties and injection rates the GIN approximation may over-estimate the achievable penetration.

RÉSUMÉ
Le grouting pour rocher fracturé moderne généralement adopte le principe GIN comme un moyen de contrôler la pénétration du grout. Les suppositions de vitesses de flux de fracture négligeables dans la méthode sont cependant questionnables. Théoriquement, la longueur de pénétration pour un fluide de Bingham (une idéalisation commune de grout) peut être vue comme une fonction de la rhéologie du grout, la géométrie de fracture et du taux d'injection du grout. Cet article présente les propriétés matérielles pour trois grouts, dérives par l'essai de viscomètre à grande échelle. Les effets du taux d'ouverture de fracture et d'injection sont alors étudies pour le "meilleur" grout GIN en utilisant une idéalisation de la rupture 1-D. Ces résultats préliminaires indiquent que pour des propriétés du grout et taux d'injection réalistes l'approximation GIN pour pénétration de grout peut surestimer significativement la pénétration possible.

1. INTRODUCTION

Grouting is used in fractured rocks as a means to reduce water flows within the subsurface, or to strengthen the foundation material. For this, a stable grout with low amounts of solid settling out of solution is desirable. A uniform, constant penetration is also optimal for sealing rock fractures. These objectives are often sought in modern practice through use of the Grouting Intensity Number (GIN) method of Lombardi and Deere (e.g. Aisiks et al. 1991, Turcotte et al. 1994, Gouvenot 1997). GIN (Lombardi and Deere 1993, Lombardi 1996, 1997, 2003) uses a single grout mix at a low water:cement ratio with the addition of superplasticizer to create a stable and effective grout. The main idea behind the method is the use of a constant grouting intensity, defined by the GIN = pV where p is grouting pressure and V is injected volume, to control grout penetration independently of fracture aperture.

The GIN method calls for grouts that possess low viscosity and low yield strength (Lombardi 2003), but only describes the importance of these attributes very generally. Furthermore, the GIN principle lacks a clear definition of the significance of velocity, or more specifically the injection rate, required to control grout penetration. Hence, there is a need to know what role grout rheology and injection velocity play within the GIN method.
The purpose of this paper is to investigate the suitability of typical GIN grouts for use in the GIN method; both in terms of the rheology of the grout and the penetration distance obtained as a function of the grout injection rate.

Details regarding the general principles behind grout rheology are presented and the theoretical limitations of the GIN method summarized. To obtain realistic grout properties, a series of laboratory tests have been carried out on a baseline grout mix and two grout mixes that might commonly be used with the GIN grouting method. The rheological parameters for all grouts were determined by rotational viscometry with both viscosity and yield strength derived from a plotted model of shear stress versus strain rate (Bingham model). Stability of the various grout mixes was determined by measuring the percent bleed, as well as the pressure filtration coefficient, while Marsh funnel testing was used in determining apparent viscosity.

The resulting mixes were numerically implemented in 1-D Bingham flow simulations to determine the significance of grout rheology on the approximations inherent in the GIN method; specifically whether for realistic grout viscosity and yield stress values, GIN accurately predicts the grout penetration length. Although simplified, the 1-D flow model is a reasonable approximation to channelled grout flow through rough fractures. Hence these Bingham flow simulations allow preliminary conclusions to be drawn on the reasonableness of the GIN method for different grout injection rates.

2. BINGHAM FLOW

In contrast to water which is represented by standard Newtonian fluid behaviour, i.e. $\tau_{yx} = \mu\dot{\gamma}_{yx}$, most fractured rock grouts exhibit a Bingham type behaviour. This relation between shear stress, τ_{yx}, and shear strain rate, $\dot{\gamma}_{yx}$, is characterized by a yield stress or cohesion, c', and a constant dynamic viscosity, μ, as illustrated in Figure 1. Rewriting mathematically:

$$\tau_{yx} = c' + \mu\left(\dot{\gamma}_{yx}\right) \qquad \text{for } |\tau_{yx}| > |c'| \qquad [1]$$

$$\tau_{yx} = 0 \qquad \text{for } |\tau_{yx}| < |c'| \qquad [2]$$

2.1 Bingham Idealization

The standard equation for flow of a Bingham fluid through a smooth parallel sided aperture of unit width is given in Chhabra and Richardson (1999):

$$q = \frac{b^2}{12\mu}\left(-\frac{dP}{dx}b\right)\left(1 - \frac{3}{2}\phi + \frac{1}{2}\phi^3\right) \qquad [3]$$

where $\phi = -\frac{2c'}{\frac{dP}{dx}b} \Leftrightarrow \frac{dP}{dx} = -\frac{2c'}{\phi\, b}$ [4]

q is the grout injection rate (per unit width), b is the fracture aperture, P is the pressure, and x is the grout penetration distance.

It can be seen from inspection that for the case *c'* = 0, the Bingham flow equation reverts to Newtonian flow, and Equation 3 becomes the cubic law.

The solution to Equation 3 for the grout penetration distance is given by:

$$\phi = 2\left(\frac{-\alpha}{3}\right)^{0.5}\cos\left(\tfrac{1}{3}\left(\theta + \pi\right)\right) \qquad [5]$$

where α is a local variable defined as:

$$\alpha = \left(-3 - \frac{12\mu\, q}{b^2 c'}\right) \qquad [6]$$

and where:

$$\theta = \cos^{-1}\left(\sqrt{27 / -\alpha^3}\right) \qquad [7]$$

2.2 GIN Idealization

The GIN method of Lombardi and Deere also assumes grout is a Bingham material, but only makes reference to the yield stress, c', of the grout to compute the penetration distance (e.g. Fransson 1999).

Force on the grout from pressure at the grout injection is:

Force = P*area = P.w.b [8]

This force is resisted by the yield stress, c', acting on the grout in contact with the fracture:

Resistance = 2*c'.w.L [9]

where L is the total grout penetration distance and the “2” arises because there is resistance along both top and bottom surfaces. Equating the force pushing on the grout with the resistance to movement:

L = (P.b) / (2c') [10]

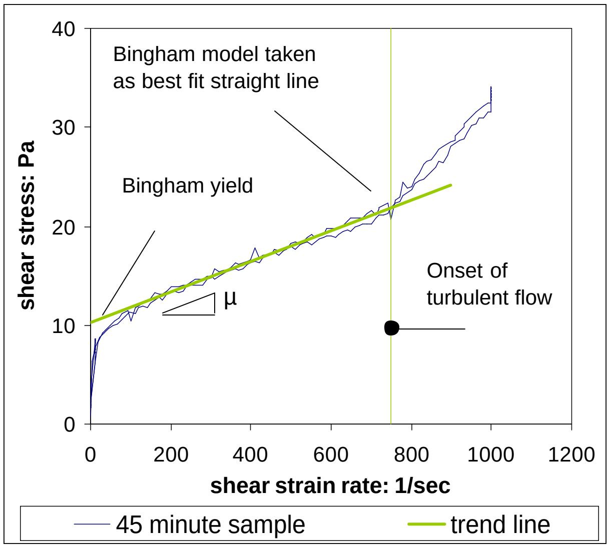

Figure 1. Determination of Bingham properties from rheometer testing.

The volume of grout injected when the grout has penetrated L into the fracture is:

$$V = w.L.b \;\text{›}\; b = V / (L.w) \qquad [11]$$

And by substituting Equation 11 into Equation 10 and rearranging:

$$L^2 = (P.V) / (2.c'.w) \qquad [12]$$

The product PV is the *Grouting Intensity Number* (GIN) as previously indicated. Equation 12 indicates a constant grout penetration will arise for any constant GIN, and that this grout penetration is independent of aperture. This is the basis of the GIN method. Equation 12 requires that injection be at a constant low-medium rate. However, this rate is never clearly defined within Lombardi and Deere's proposal, thereby making the procedure questionable. An issue then becomes to determine the effect of a finite velocity on grout penetration into an idealized fracture.

2.3 Importance of Rheology

Solution of the penetration length estimated using the GIN and Bingham equations require realistic material properties, particularly dynamic viscosity and yield stress (or cohesion). For this purpose rheological properties were obtained from a series of full scale grout mix tests performed, as described in Section 3.

Using the determined rheological parameters, the penetration length as a function GIN can be calculated by assuming a range of typical aperture and injection rates, while varying pressure over a specified range. This allows for a direct comparison of the Bingham idealization with the Lombardi and Deere equation for penetration.

3. EXPERIMENTAL METHODOLOGY

A series of full scale grout mix tests were carried out on a baseline mix, and two additional mixes which might commonly be used by the GIN grouting method (Rombough 2006). The rheological parameters for all grouts were determined by rotational viscometry, with both viscosity and yield strength derived from a plotted Bingham model. Standard field tests were also employed to evaluate and index the quality of each mix as a desirable GIN grout.

3.1 Mixing Equipment

The main focus during grout testing was to achieve a highly penetrating, stable GIN mix. As such, mixing was carried out using a 370 L capacity, high shear colloidal mixer operating at 1800 RPM. In the authors' experience, full scale grout mix testing carried out using colloidal mixers provides a more accurate representation of actual field conditions than laboratory scale testing carried out using commercial blenders following ASTM C938-02.

Each batch was mixed for three minutes, transferred to a 460 L capacity agitator and stirred for approximately two hours. Prolonged agitation allowed for sampling of grout at three separate testing times; nominally 5 minutes, 45 minutes and 2 hours. As grout rheology is temperature dependent, water was left out at room temperature for a minimum of 24 hours prior to use in a mix, and grout temperature was measured.

3.2 Grout Mixes Tested

Three mixes were performed at a water:cement ratio of 0.8:1 using Type III, high early strength, portland cement (ASTM C150). The grout mixes tested are summarized in Table 1.

The first mix contained no admixtures and was used as a baseline mix for direct comparison with later mixes utilizing superplasticizers. As a means of quality assessment, this baseline mix was repeated twice to test repeatability of mixing with respect to the determination of Bingham model parameters and other index properties.

The second and third mixes tested utilized high-range water-reducing admixtures (more commonly known as superplasticizing agents) supplied by Degussa Admixtures Inc. The second mix, repeated once to test for repeatability, utilized the polycarboxylate (PBX) based Glenium 3030 NS, dosed at 0.4% by weight of cement, while the third mix utilized the napthalene sulfonate (NSP) based Rheobuild 1000, dosed at 1.5% by weight of cement.

3.3 Evaluation of Grouts

The most straightforward method of obtaining the complete flow (or rheological) characterisation for a particular grout is rotational viscometry. A viscometer (or rheometer) with appropriate geometry can be rotated through a range of speeds to simulate the range of potential shear rates to which a grout will typically be subjected during a grouting program.

The stability of each mix can be determined by measuring bleed as well as propensity to pressure filtration. The determination of Marsh Funnel velocity aids to index apparent viscosity.

Table 1. Summary of test program

Mix	w:c	Superplasticizer (dosed by % weight cement)
A-1	0.8:1	None
A-2	0.8:1	None
A-3	0.8:1	None
B-1	0.8:1	0.4% Glenium 3030 NS (PBX)
B-2	0.8:1	0.4% Glenium 3030 NS (PBX)
C-1	0.8:1	1.5% Rheobuild 1000 (NSP)

3.3.1 Rheometer Testing

The rheological parameters for all grout mixes tested were determined using a HAAKE Viscotester VT550 fitted with an immersion sensor system, whose dimensions were specified according to the requirements of DIN 53019-2 for rotating coaxial cylindrical geometry (stationary outer sleeve and rotating inner bob). The viscometer was also equipped with a temperature probe.

The rotational speed, Ω (rpm), of the bob from the VT550 is software controlled. For each test, rotational speed was specified as a function of time; ramping up, holding at a constant rotational speed for a specified time and then ramping down. All tests used a common Ω – time function designed to illustrate the transition between laminar and turbulent flow of the grout mix (Jefferis et al. 2005), which was continuously monitored during the grout testing (see Figure 1).

Together, the computer and software package continuously monitor temperature, rotational speed and flow resistance of the sample (or the torque required to maintain the imposed rotational speed). In real-time this torque is reduced to a shear stress, τ (Pa), by application of instrument geometry factors and thus, data logged during each test is the shear stress at the bob surface and imposed on the grout.

3.3.2 Determination of Bingham Model Parameters

To display the Bingham-like behaviour of each grout, plots of shear stress vs. shear strain rate have been generated from the acquired data. Plots from rheometer testing display a clear transition to turbulent flow (change in slope) at the higher strain rates. Bingham properties are determined from the best-fit straight line through the measured data before the onset of turbulent flow, as illustrated on Figure 1. Results for the T_{45} testing time were chosen as best representing each grout at the midpoint of its workability and were therefore used in determining rheological parameters of each mix.

3.3.3 Additional Testing

The stability of each mix was evaluated by the determination of both the percent bleed and pressure filtration coefficient, K_{pf}, and comparison of this coefficient against its yield stress value as outlined in De Pauli et al. (1992). The apparent viscosity of each mix was indexed against its true viscosity at T_{45}.

Bleed capacity was determined by allowing a 500 mL sample (taken at the T_5 testing time) to sit undisturbed for four hours while particles settled out of solution. The amount of bleed water visible at the end of the testing period was recorded and calculated as a percentage of the original 500 mL sample.

Resistance to pressure filtration is characterized when bleed water is forced out, ahead of the grout, due to the pumping pressure imposed on it (Warner 2004). Injecting grouts into small apertures may result in the development of filter cakes at a borehole wall. With time, further injection may be limited due to the build-up of the filter cake (Chuaqui and Bruce 2003). Resistance to pressure filtration was carried out with an American Petroleum Institute (API) filter press in which a 400 mL reservoir of grout was pressurized until all the water was expelled from within it. From this, the pressure filtration coefficient K_{pf} is then calculated as:

$$K_{pf} = \frac{volume\,of\;\; filtrate}{volume\,of\;\; sample}\, x \,\frac{1}{\left(time\;\; in\;\; \min utes\right)^{1/2}} \qquad [13]$$

The Marsh time of each grout mix was measured as described in API Recommended Practice 13B-1. The Marsh time is determined by filling a Marsh cone to the base of its dump screen and measuring the time required for 946 mL of grout to flow through the funnel into a calibrated container.

4. EXPERIMENTAL RESULTS

The results of viscometer testing on all grouts, including temperature during mixing, yield stress and dynamic viscosity are summarized on Table 2; results of additional testing are summarized on Table 3.

An example plot of shear stress vs. shear strain rate used to determine rheological parameters at time T_{45} for mix A-1 is shown in Figure 1. In Figure 1 the slope of the trend line (i.e. viscosity) is 15.5 mPa.s and the y-intercept (i.e. yield stress) is 10.2 Pa. The Bingham behaviour of all grouts tested is shown in Figure 2.

Table 2. Results of viscometer testing

Mix	Temp (^{0}C)	Yield Stress (Pa)	Dynamic Viscosity (mPa.s)
A-1	26	10.2	15.5
A-2	21	8.2	15.5
A-3	18	6.5	14.5
B-1	15	1.0	11.0
B-2	16	0.9	11.5
C-1	18	7.0	16.5

Table 3. Results of additional testing

Mix	Bleed (%)	K_{pf} ($min^{-1/2}$)	Avg. Marsh Funnel Time (s)
A-1	1.8	0.08	42.35
A-2	1.6	0.1	39.57
A-3	1.8	0.1	40.90
B-1	12	0.07	36.69
B-2	10	0.08	36.00
C-1	1.4	0.09	41.42

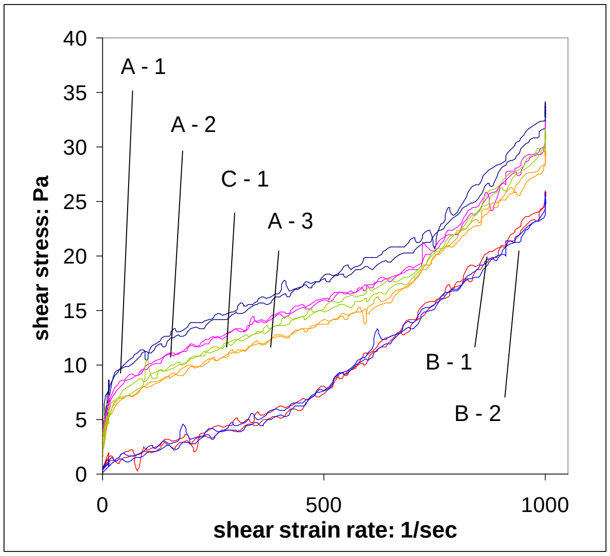

Figure 2. Viscometry results for all mixes

5. DISCUSSION

The discussion focuses on two distinct topics. First, the reliability and applicability of the grout properties obtained for GIN grouting. Second, the accuracy of the grout penetration length obtained using the GIN approximation.

5.1 Implications of grout properties

The results of the viscometer testing indicate rather good repeatability of the resulting grout properties, despite differences in the ambient temperature (see Figure 2 and Table 2). Table 2 indicates that of the two required material properties, yield stress and dynamic viscosity, the yield stress is markedly more temperature sensitive. A reduction in temperature of 8° for the baseline mix resulted in about 40% reduction of the yield stress, from 10.2 to 6.5 Pa. For the same 8° change in temperature for the Baseline mix, the dynamic viscosity is essentially unaffected.

An interesting aspect of the testing results is that the addition of different superplasticizers can have a variable effect. For the specified water:cement ratio of 0.8:1, Table 1 indicates that while addition of the polycarboxylate based superplasticizer showed a markedly lower yield stress, c', and a reduced dynamic viscosity, μ, the addition of the naphthalene sulfonate based superplasticizer produced properties very similar to those of the baseline grout mix.

The mixes utilizing the polycarboxylate based superplasticizer were also subject to high bleed, i.e. above the recommended limit of 5%. While, it is recognized that the bleed capacity of these grouts is in excess of the recommended practice for stable grout mixes, the basic premise of using the determined Bingham parameters within the context of the flow model remains unchanged. Additionally, it should be noted that the bleed capacity was obtained at 4 hours and that potentially these grouts would have fulfilled the 5% bleed requirement for stable grout mixes at the more usual measurement time of 2 hours. The mixes utilizing the naphthalene sulfonate based superplasticizer showed very low bleed.

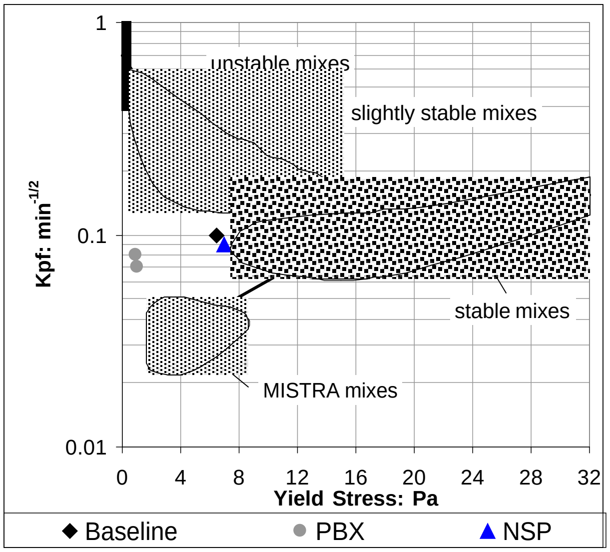

Figure 3. Relationship between resistance to pressure filtration and cohesion with mix results (after De Paoli et al. 1992)

Additional testing for pressure filtration shows little variability between mixes, indicating negligible effects with respect to the addition of superplasticizer. However, when plotted against cohesion, the pressure filtration coefficient aids in analyzing the stability of each mix. Figure 3 confirms that the mixes containing the polycarboxylate-based superplasticizer are furthest from the range of stable mixes.

The rheological properties for all of the grout mixes were strongly influenced by the chosen water:cement ratio and the ambient temperature of the grout mix. The water:cement ratio of 0.8 used in this work was chosen as near the centre of the recommended range for a typical GIN mix. However, during the testing program, the ambient temperature of the grout mix changed by as much as 11°C. This can be attributed to the fact that the mix testing program was carried out over several weeks. Therefore, it is strongly recommended that all grouts be tested prior to use, at a water:cement ratio suitable for the field ambient grout mix temperature.

5.2 Influence of grout properties on GIN penetration

The GIN approach idealizes grout as a Bingham material. Inspection of Figure 2 indicates that this approximation is reasonable for all of the grouts tested. To investigate the

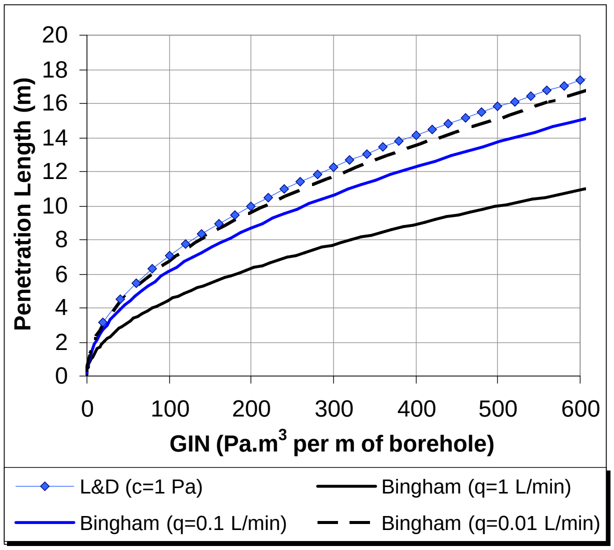

Figure 4. Penetration length versus GIN with varying injection rate

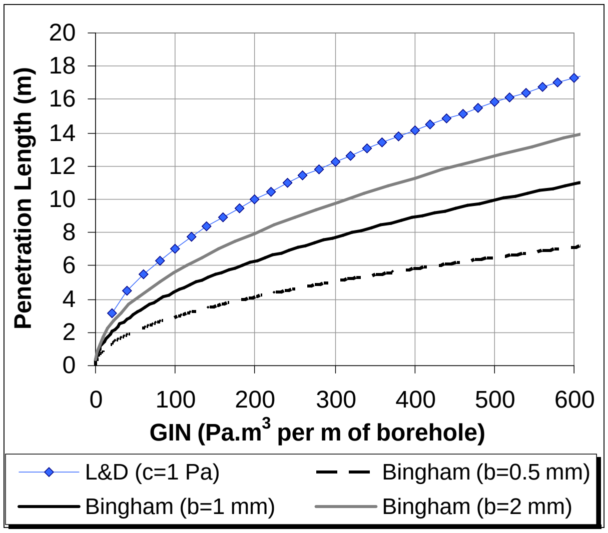

Figure 5. Penetration length versus GIN with varying aperture

applicability of the GIN estimate of grout penetration distance, the grout properties of the “best” GIN grout tested were used to determine penetration length. From our testing this was the grout that utilized the polycarboxylate-based superplasticizer, with a measured yield stress of 1 Pa. Comparison with the complete 1-D Bingham solution also requires the grout’s dynamic viscosity, which was assumed as 11.0 mPa.s in the subsequent simulations. Two other inputs are required in Equation 3, aperture and injection rate.

Comparison of the GIN and Bingham penetration lengths for differing GIN (=p.V) are shown in Figures 4 and 5. Figure 4 shows the effect of varying flow rate for a single 1mm aperture fracture. The results indicate that for the lowest injection rate of 0.01 L/min (velocity of 1 cm/min) the penetration predicted by GIN and the full Bingham equations is very similar. As the injection rate is increased to 0.1 L/min (velocity of 10 cm/min) GIN overestimates the penetration length by about 15%. For the largest injection rate of 1.0 L/min (velocity of 1 m/min) the GIN method typically overestimates the penetration length by over 60%.

The effect of aperture on grout penetrability is shown on Figure 5 assuming an injection rate of 1.0 L/min. The penetration length for any given GIN reduces as the aperture reduces (and velocity increases). The smallest aperture, 0.5 mm (velocity of 2m/min) predicts penetration less than half those from GIN. Even the largest aperture, 2mm (velocity of 50 cm/min) is a poor match for the GIN solution.

These preliminary results suggest that for grout velocities above about 10 cm/min the GIN method provides a poor estimate of penetration distance, and that since aperture affects the grout velocity this parameter may need to be considered if a uniformly penetrating grout curtain is required.

The results presented here are only for one set of grout properties, representing the “best” GIN properties from the three grouts tested. The grout yield stress is incorporated in GIN, but variability in the dynamic viscosity will affect Bingham behaviour independently of the GIN model. Therefore the effect of viscosity needs further consideration. In addition, these analyses considered 1-D flow associated with a constant flow area, and hence constant velocity. The idealization of radial flow away from the grout hole would reduce the velocity of flow with distance, and may provide a closer match between GIN and Bingham. Conversely, realistic injection rates may still lead to velocities that exceed the “very low rate” required by GIN. These issues require further investigation.

6. CONCLUSIONS

- Grout mixes, even with superplasticizers, may have non-negligible yield stress and dynamic viscosities, and thus may not always possess GIN-like characteristics.

- Mix testing whereby admixtures are batched at a range of dosages is highly recommended in order to satisfy requirements of both rheology as well as stability.

- Bingham and GIN idealizations are equal if q is near zero. For $q > 0$, rheology (viscosity, cohesion) have an effect on penetration distance.

- Unrealistically low injection rates are required in order for the penetration distance computed using the GIN grouting method to match that of a Bingham fluid. The magnitude of the difference between the GIN and Bingham solutions increases as the injection rate increases.

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