Pregrouting for Tunnels in Rock: The Case for New Thinking

Dr. Donald A. Bruce, Member, Geo-Institute[1]

Abstract

Pregrouting is an extremely important part of many rock tunneling projects. However, poor and unsatisfactory performances have been frequently recorded often with very severe consequences to one or more of the parties, both technically and financially. This paper provides recommendations with respect to specification drafting, drilling, water pressure testing, and grouting methodologies, and cementitious grout mix design principles. Even given that the logistical challenges facing tunnel pregrouting from underground will prevent all the sophistication and innovations of contemporary dam foundation grouting being practically implemented, there is still opportunity and need to change "traditional" approaches for the benefit of the tunneling industry.

1. Introduction

Rock pregrouting procedures have been used in tunnel and shaft construction for over a century in countless countries throughout the world. The most common applications have been to reduce water inflows into underground structures a) to facilitate and safeguard their construction, and b) to maintain piezometric levels in the surrounding rock mass at desired elevations. Where the groundwater may contain undesirable or dangerous chemicals or gases, grouting is intended to minimize safety hazards to personnel, and to reduce the volume of inflow water which must be collected, pumped out and disposed of, following chemical treatment as appropriate. In certain conditions, pregrouting is conducted to improve the mechanical properties of rock masses in order to enhance their stability during construction, and during subsequent service if required by the design. Pregrouting can also be a necessity when constructing tunnels with shotcrete as the permanent lining, in order to enhance its long-term performance and efficiency.

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[1] President, Geosystems, L.P., P.O. Box 237, Venetia, PA 15367, U.S.A., Phone: (724) 942-0570, Fax: (724) 942-1911, dabruce@geosystemsbruce.com.

Broadly, there are significant differences between the pretreatment of soil, and the pretreatment of rock, for tunneling purposes, as summarized in Table 1. This paper addresses only rock pregrouting and does not address other types and goals of tunnel grouting, such as the backfilling and contact grouting of precast segments.

Table 1. Differences between the pretreatment of soil and the pretreatment of rock for tunneling.

PRETREATMENT OF SOILS	PRETREATMENT OF ROCK
• Typically conducted from the surface, since depths rarely exceed 50 m.	• Typically conducted from the face, since tunnel depths are usually greater than 50 m.
• Typically requires sophisticated specialty construction methods and concepts such as jet grouting, permeation grouting, and deep mixing.	• Typically uses "traditional" drill and grout methods and concepts.
• May often require "exotic" materials, e.g., ultrafine cements, sodium silicate.	• Typically uses simple cement/water ± bentonite mixes. Accelerators are used in certain cases where artesian heads and/or "gulpers" are encountered.
• Usually conducted by specialty contractors.	• Often conducted by tunneling company's in-house resources, frequently with advice from outside consultants and suppliers/ manufacturers.
• Specifications are typically mainly "Performance" with well defined technical goals (e.g., strength, residual permeability) for the treated soil mass.	• Specifications are typically mainly "Prescriptive" with often poorly defined goals relating to the maximum allowable tunnel inflows or piezometric drawdowns.

Specifically, regarding the pretreatment of rock, it would be accurate to regard typical current North American practice as being "traditional," without denying that it has, in general, met the performance goals on many projects. The same traditionalist observation has been made about dam grouting practice, the historic weaknesses in which are progressively exposed when curtain efficiency deteriorates with time. Grout longevity in tunnel pregrouting works is rarely a concern beyond the construction phase. Nevertheless, there have been numerous rock tunneling projects which can be cited in recent years, for example in Ontario, Michigan, Wisconsin, and California, which have experienced major delays, cost overruns and even abandonment, as a result of rock grouting programs which proved ineffective in consistently and reliably meeting the project needs.

It is not the purpose of this paper to back-analyze such failures in detail, assuming even that the relevant details could in fact be discussed in open forum. Rather, the goal is to simply reaffirm a number of facts, conclusions and observations that constitute contemporary basic principles. For some readers there will be an element of novelty, and for others, a basis for disagreement. The latter group should be aware that similar reaction was also initially displayed by many dam engineers loath to change the ways of grouting specifications employed virtually unchanged since the 1930's: today North American dam grouting practice is as effective and sophisticated as any on the planet, and is routinely meeting even the most difficult challenges (Wilson and Dreese, 2003; Bruce, 2007).

2. Plans and Specifications

Grouting plans and specifications must be prepared by a grouting specialist. The success or failure of a project, from technical, schedule and/or cost perspectives, will depend directly on the quality and responsiveness of the grouting design and the associated project documents. These documents need not be voluminous — they can be less than 20 pages — but they should not be left to inexperienced personnel and/or "cut and paste" tactics to prepare. They must be based logically upon the results of the site investigation and the project constraints and requirements. They must be consistent with the foreseen construction details of the subsequent tunneling (and lining) activities and must not contain requirements which will inhibit progress while contributing little of practical importance.

Site investigations must provide an accurate representation of the rock mass structure, and spacial and statistical distributions of permeability (as well as the usual recital of regional and local geology and hydrogeology to give overall perspective). Knowledge of rock mass structure and the nature and characteristics of the discontinuities is critical in predicting the "groutability" of the rock mass, providing an accurate estimate of grouting quantities for bidding purposes, and determining a realistic and clear definition of an acceptable grouting goal. An evaluation of the susceptibility of the formation to short-term solutioning and/or erosion is also essential, especially in terrains known to contain gypsum and anhydrite beds or clay/sand-filled karstic features. It is essential that an appropriate Geotechnical Baseline Report (GBR) is prepared by the Engineer, and that this GBR is made available to the potential contractors at the bid stage. This GBR serves the project best when it provides a clear picture of what the Contractor can reasonably expect to encounter — <u>not</u> as a retrospective tool for a future claim, but as the basis for planning the strategies and tactics of his work in real time. The author has also found it beneficial to share with the Contractor the Geotechnical Design Report (GDR) to improve all parties' understanding of the design philosophy of the project. Of course, any cost estimates which may be contained in the GDR must be withheld.

To reiterate, the goal of the grouting, i.e., the "measurement of success" must be clearly and reasonably stated. Specifications can often be ambiguous and vague with respect to the obligations and responsibilities of the parties. For example, the Contractor is often instructed to satisfy a residual inflow criterion (per length of tunnel), or even to conduct the grouting to an intensity such that surrounding piezometric levels must vary during subsequent tunneling only within a certain interval. This is truly a "Performance" type specification which puts major technical responsibility on the Contractor to satisfy. However, it is also typical in such specifications to find that various key elements and processes are still very closely prescribed by the Engineer, or, somewhat softer, are required to be "proposed" by the Contractor for "acceptance" / "approval" by the Engineer.

Such contractual flabbiness in specification writing can prove the downfall of all parties and can lead to the failure of the project: the Contractor spots an obvious "bust" in the design or the quantities, and loads his bid, quite logically, accordingly; The Engineer is surprised and hurt when the amount of work necessary to achieve the design intent is far in excess of what he anticipated; The Owner is angered when the cost of the grouting escalates exponentially and the water is still flowing or dropping, depending on the project's performance goal.

Both the Engineer and the Contractor must adopt realistic and relevant stances. The Engineer should provide <u>a target residual permeability</u> of the treated rock mass that will satisfy the project's inflow limits or piezometric impact goals which he has — or should have —

previously calculated. He should bear in mind that the additional cost of reducing water ingress by 95% as opposed to 90% of some optimum target rate may be higher than the cost of sealing off the first 90% (Garshol, 2003). He should also be aware that the probing, drilling and pregrouting program may represent a very significant percentage (perhaps 20% or more) of the total tunneling costs, and furthermore, that using the cement quantity as the main or only unit for payment of the drilling and grouting work is wrong, and not only because materials are typically less than 10% of total pregrouting costs. The Contractor has to evolve a drilling and grouting scheme that will — in these specific ground conditions and with regard to logistical restrictions he knows he will face during the implementation of the work — satisfy the residual permeability criterion. He must not simply "shoe horn" his traditional means and methods to superficially satisfy the requirements in his Method Statement which, in turn, must be more than just a collection of equipment drawings or photographs.

The Specifications must clearly describe what is not acceptable in terms of means, methods and equipment, and must detail acceptable levels of quality control and process verification. The Contractor should engage specialty assistance when developing his methodology, either in the form of a specialty consultant or in a prebid alliance with a specialty contractor. If the Engineer's calculation of the required residual permeability is correct, and the Contractor can demonstrate he has provided it in the field, then the grouting will satisfy the project goals.

Post-bid, the Contractor must create a detailed Method Statement describing precisely how he will achieve the requisite residual permeability target (and the steps he will take in the event of "failure" or "unforeseen events"). This Statement, when approved by both the Contractor and the Engineer, will then become the document by which compliance is judged by the Owner's inspection team during construction. The grouting program should not commence until there is full and clear accord between the Contractor and the Engineer regarding details of the execution of the work. This Method Statement must then be recalibrated upon execution and critical analysis of the initial field test phase.

Of critical importance at this stage is the issue of exactly who is responsible for determining whether additional work has to be conducted to meet the project goals at any given juncture. This party will obviously be the one responsible for technically analyzing the drilling, water pressure testing and grouting data. It is typical that the Engineer (or Construction Manager) is best equipped and most closely engaged to carry this responsibility. Furthermore, to leave it solely to the Contractor will often raise doubts in the Owner's mind as to the "real" motives for any proposed quantity variations or major methodology modifications. At the same time, the Engineer must not shy away from always making "best for project" decisions: it will be a false economy to not instruct additional work (to thereby limit drilling and grouting costs) if the Contractor's subsequent advance through the incompletely treated ground is compromised. The Specifications must allow and encourage flexibility of response during construction to deal with the specific field conditions actually encountered — without recourse to professional defensiveness and contractual posturing.

3. Technological Aspects

It is natural that the efficiency of certain aspects of drilling operations will be impacted when working underground and especially from the face of the TBM. Regardless, the drill holes must be oriented to intersect the major rock mass structural discontinuities as effectively and frequently as possible, and must be spaced, or overlapped, such that no "windows" in the treatment zone will remain after grouting. In this regard, holes can be expected to deviate — even if accurately set up — by as much as 1 in 30 for inclined "umbrella" holes, even in the 15 to 25 m length range typically found in most pregrouting schemes.

The method of drilling is the subject of old debate. With respect to the potential effect on "groutability," there is no consistent or reliable experience to favor rotary over rotary percussion (which has a far higher productivity potential). In "classic" rock fissure drilling, water flush is preferred over air flush since the latter has been found to induce clogging in fissures which then prevents subsequent grout ingress. However, much pregrouting, being implemented from the tunnel face, is conducted against excess groundwater pressure. The natural tendency is therefore for fissure water to flow into drill holes and therefore naturally flush out any drill debris which have become lodged in fissures during drilling. Thus, in general terms, air flush drilling for pregrouting when conducted from a face below the water table is usually acceptable. If either party has doubts over the appropriateness of the drilling method and flushing medium, a full scale trial should be organized. Fissure cleanliness can be further enhanced by rigorous flushing prior to water pressure testing and grouting.

Every production hole that is drilled is, in itself, a source of information on the ground. This is the underlying concept behind "Measurement While Drilling" principles (MWD). Whether manually or electronically recorded, the drilling parameters can be used to provide a "drillability" profile of the ground. These parameters include penetration rate, thrust, torque, flush characteristics, "drill action" and so on (Bruce, 2003). Interpretation of these data in real time is an invaluable tool for geological interpretation and is a risk management tool of benefit to all parties. Alternatively, if manually recorded, relevant data can be logged every 2 minutes or 2 m of penetration. The use of automated monitoring removes the necessity to have skilled geologists at the face recording and interpreting data, and provides a continuous profile of the drilling "specific energy," or drillability of the rock mass ahead.

Water pressure testing (permeability testing) is an integral part of any rock grouting project. Every hole should be so tested prior to grouting, as a means of measuring the existing rock mass permeability, and as a basis for selecting the grout mixes to be used. Rock mass permeability is most appropriately expressed in terms of Lugeon Units (Lu), not cm/s which more correctly relates to soils. A Lugeon Unit is defined as a flow of 1 liter/minute/meter at an equivalent excess pressure of 10 bars. As a rough guide, 1 Lu $\approx 1.3 \times 10^{-5}$ cm/s. Such values can be calculated based on either outflow measurements or by pump-in (packer) testing, using pressures, obviously, higher than the static head acting on the hole.

Depending on the degree of "sophistication" of the grouting, various residual target permeabilities can reasonably be anticipated (Table 2 – Wilson and Dreese, 2003). Lugeon testing is most accurately conducted in discrete stages not more than 5 m long. However, any particular interval can be investigated if detected by the MWD records, or required for specific purposes. Pregrouting investigation holes, and postgrouting verification (demonstration) holes, should be subject to multipressure testing as first simply described by Houlsby (1976). Such testing gives information on the nature and performance of the fissure flow characteristics (i.e., Laminar, Turbulent, Washout, Infill, Hydrofracture) as well as the stage permeability itself. Water pressure tests for production grout holes are typically a shorter duration, single pressure event or in fact may just be a measurement of outflow rate and pressure. In either case, they are an invaluable source of information and merit serious and close attention to their execution and analysis.

Table 2. Recommended Design Permeability for Grout Curtains (Wilson and Dreese, 2003).

	Project Characteristics	Single Line Curtain	Triple Line Curtain
Level 1	Low bid contracting; inexperienced contractors Procedure specification – not engineer directed Payment provisions based on solids injected Thin neat cement grouts (thinner than 3:1) Minimal water pressure testing Final hole spacing on about 3 m centers Conservative, rule of thumb grouting pressures Dipstick & gage monitoring technology Holes not grouted to absolute refusal Inexperienced inspection staff Number of inspection staff inadequate to cover all operations full-time Non-existent understanding/analysis of results	Results Unpredictable Not Recommended	$1x10^{-5}$ m/s (80 Lugeons)
Level 2	Low bid contracting *with experience requirement for grouting contractors* Primarily procedure specification – *limited engineer direction* Payment provision based on solids injected *Neat Type I or Type II cement grouts with mixes not thinner than 3:1* *Limited* water pressure testing *Final hole spacing on about 1.5 m centers* Conservative, rule of thumb grouting pressures Dipstick & gage monitoring technology *Holes grouted to absolute refusal with holding period after refusal* *Inspection staff with limited experience* *Number of inspection staff adequate to cover most operations full-time* *Limited understanding/analysis of results*	$1x10^{-5}$ m/s (80 Lugeons)	$1x10^{-6}$ m/s (8 Lugeons)
Level 3	*Pre-qualification of specialty grouting contractors and equipment & advance commitment by General Contractor* *Payment provisions based on fluid injection time* *Balanced stable grout mixes* *Extensive* water pressure testing *Engineer directed program* Final hole spacing 1.5 m *maximum* *Higher grouting pressures determined in the field as safe for each geologic unit* *Monitoring based on pressure transducers, magnetic flowmeters, and real-time display of results* Holes grouted to absolute refusal *Experienced inspection staff* *Number of inspection staff adequate to cover all operations full-time* *Good understanding/analysis of results*	$1x10^{-6}$ m/s (8 Lugeons)	$4 x10^{-7}$ m/s (3 Lugeons)
Level 4	*Best Value Selection* or pre-qualification of specialty grouting contractors and equipment & advance commitment by General Contractor Payment provisions based on fluid injection time *Balanced stable grout mixes and special cements* Extensive water pressure testing Engineer directed program Final hole spacing 1.5 m maximum *and based on detailed closure analyses* *Highest grouting pressures determined in the field as safe for each geologic unit* Monitoring based on pressure transducers, magnetic flowmeters, real-time display of results, *and real-time analytical systems* Holes grouted to absolute refusal *Highly experienced inspection staff* Number of inspection staff adequate to cover all operations full-time *Comprehensive understanding/analysis of results*	$4 x10^{-7}$ m/s (3 Lugeons)	$1x10^{-8}$ m/s (0.1 Lugeon)

The grouting operations should reflect traditional practices with respect to sequencing (i.e., discrete Primary, Secondary, Tertiary, and higher phases if necessary) and staging (i.e., ideally ascending stages). The hole pattern and sequence should be designed so that acceptable residual permeability is attained after no less than three phases, to improve the tactical control and verification processes. Thus, for example, if the design anticipates a final interhole maximum spacing of 1.5 m, then Primaries should be first drilled and grouted at 6 m centers. The drilling of any hole, regardless of its target depth, should be suspended, and a downstage declared, when the MWD results indicate an extreme ground condition, e.g., a large void, a very unstable zone, a sudden loss of drill flush, or a sudden inflow of groundwater. To attempt to drill to a fixed target depth without separately treating such a feature will severely impact the practical execution and the resultant quality and effectiveness of the work. In general, the shorter the stage length the more intense and effective the treatment. However, if proper injection procedures and mix designs are adopted, longer stage lengths (including “one shot” grouting of the entire borehole length say up to 20 m) can prove adequate, subject to close monitoring of field performance.

When creating conical zones of treated rock in front of the tunnel face, careful consideration must be given to the degree of overlap between successive treated zones. If there is any suspicion in any given drive (i.e., face advancement) that the geological and hydrological conditions will defeat a “single cover” approach (Figure 1) given that drill hole locations are typically controlled by the mechanical arrangement of the tunneling equipment, then the tunnel drive length must be shortened to permit the suspect zone to be treated again to a verifiable and acceptable residual permeability. This requirement is valid even if the hole pattern for any particular drive involves holes in concentric inner and outer circles. It is furthermore prudent to leave at least a 5-m-long grouted “plug” in front of the face at any time, longer if a particularly poor or permeable zone has been encountered or has been suspected further out.

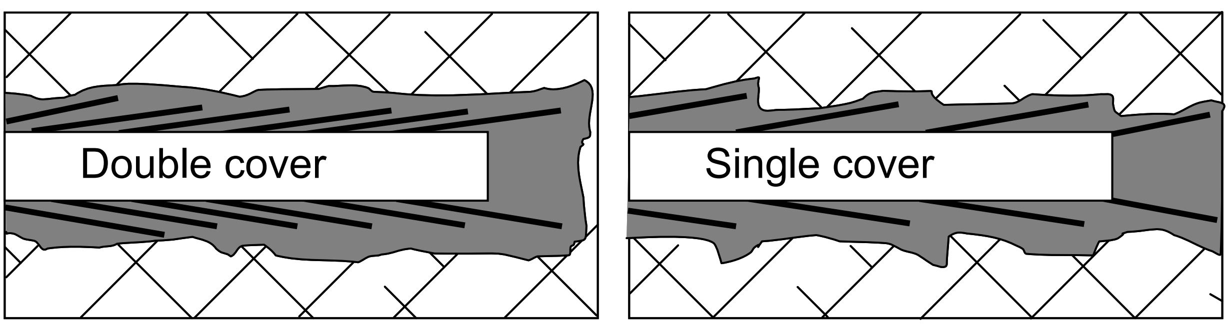

Figure 1. Double and single cover pregrouting (Garshol, 2003).

In dam grouting there is a growing trend towards the use of electronic grouting parameter recording, analysis and control instrumentation which permits the sophistication of multiple hole grouting to be fully exploited. Operational conditions at the tunnel face are typically inconsistent with the reliable deployment of highly technical instrumentation, and the use of relatively complex injection sequences and operations. However, contemporary equipment is available which is sufficiently robust and reliable that the “dipstick and gage” approach of Level 1 (Table 2) can be, and should be, abandoned. The use of more sophisticated grout delivery and parameter recording systems is a benefit to construction progress, and an enhancement to quality and reliability. In dam grouting projects it has been reported to reduce total grouting costs by as much as 15% with respect to "traditional" methods (Wilson and Dreese, 1998).

Many pregrouting schemes fail due to wholly inadequate stage refusal criteria or methods. For example, the use of grouts which are too viscous, or are rapidly accelerated may lead to an artificial refusal condition in which the fissure is prematurely "choked off" near the borehole. Alternatively, it is not uncommon to find stages which are accepting large volumes of grout being "rested" after a certain arbitrary volume has been injected with the prospect of resuming injection some hours later. This plan is rarely successful and again significant flow paths will remain incompletely treated. The key is to bring each stage to absolute refusal by progressively varying the rheology of the grout. This concept is in fact commonly followed in underground work, with any one stage being subjected to a progression of grout mixes of diminishing water cement ratio. However, as quantified in the following section, the proper design of the grout mixes is critical, and much of current practice still features inappropriate mixes. In short, however, a stable grout can be regarded as a hydraulic test medium during its injection: the goal of the progressive refusal process is to gradually reduce the Apparent Lugeon Value (calculated using grout) to zero at the target refusal pressure (i.e., zero grout flow, as measured over at least a 5-minute period).

The selection of maximum grouting pressures must be made on a project-specific basis. The effective grouting pressure must be greater than the in situ water pressure to cause grout flow into the fissures. In theory, higher pressures (when using stable grouts) will cause grout to travel further and so fill more fissure volume. In reality, however, pressures must be limited to prevent a) "blow back" to the face of the tunnel, where there is only atmospheric pressure, or b) unwanted hydrofracture and jacking of the rock mass permitting wasteful travel of grout long distances. Maximum anticipated gauge pressures should be stated in the Specifications, (since they will influence the Contractor's choice of the injection equipment), but must be verified in the field prior to full scale production. Such pressures may vary with the phase of the work, e.g., lower pressures with higher grout volumes in Primaries, but higher pressures with lower grout takes in Tertiaries. This concept is the basis of GIN (Grouting Intensity Number) Theory (Lombardi, 2003).

4. Grouting Materials and Mix Design

There are arguably more misconceptions and biases regarding the selection of grouting materials and mixes (and how to vary them during injection) than in any other aspect of rock grouting. These erroneous notions are maintained by practitioners with no awareness of, or interest in, the fundamental developments in grouting materials science of the last 15 years, and by certain operators who deliberately exploit their apparent naivety for commercial gain. Cement-based grouts remain the first choice for tunnel pregrouting due to low cost, availability, well-documented properties and experiences, and environmental acceptability. "Chemical" grouts are only used in extreme conditions and circumstances. The relative costs of grouting materials are shown in Figure 2.

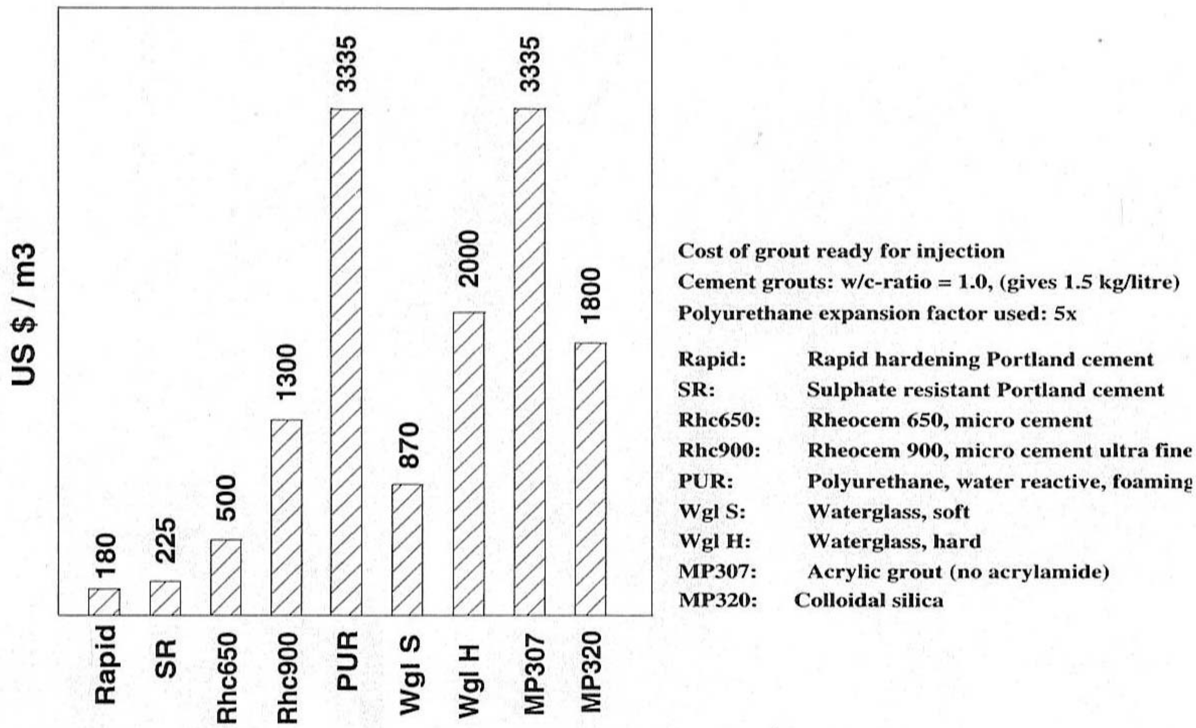

Figure 2. Relative material volume cost of various injection products (Garshol, 2003).

The ability of a cement-based grout to penetrate a certain fissure is governed, inter al., by its particle grain size distribution, its cohesion, and its pressure filtration stability. In general, the fissure must be three times wider than the D_{95} size of the cement (including the size of flocculates). The logic is, therefore, that following injection, fissures smaller than a certain size will remain ungrouted (and ungroutable) and will therefore permit a certain small, but finite, residual permeability to exist, even if the fissure in question has been intercepted by a drill hole and grouted to proper refusal. Depending on conditions, even an efficiently grouted formation may exhibit a residual permeability of several Lugeons, and even more. As noted above, the selection of an acceptable residual permeability is the responsibility of the Engineer as an integral part of his design to limit inflows and/or piezometric impact.

Grouts of low cohesion may be expected to penetrate further than grouts of higher cohesion, all other factors being equal. Traditionally, low cohesion has been achieved by preparing grouts with very high water cement ratios (i.e., "thin mixes"). However, as shown in Figure 3 these thin mixes also have extremely poor pressure filtration coefficients. This means that when the grout is pressurized to drive it into a fissure, the water will simply escape from the mix, leaving behind a low water content paste which will block off access to the fissure and so cause premature refusal. This is an indisputable and long-known phenomenon which, unfortunately, still is regarded as a technical irrelevancy in certain traditional circles. In this day and age, this ignorance defies logic and belief. Unstable, high water content mixes also have comparatively long setting times, low strength, and poor durability and longevity.

In short, the use of unstable (i.e., more than 5% bleed and with kpf factors in excess of 0.040 min -½) high water content mixes is poor practice and is not conducive to the effective and efficient filling of rock mass fissures and the attainment of low residual permeabilities.

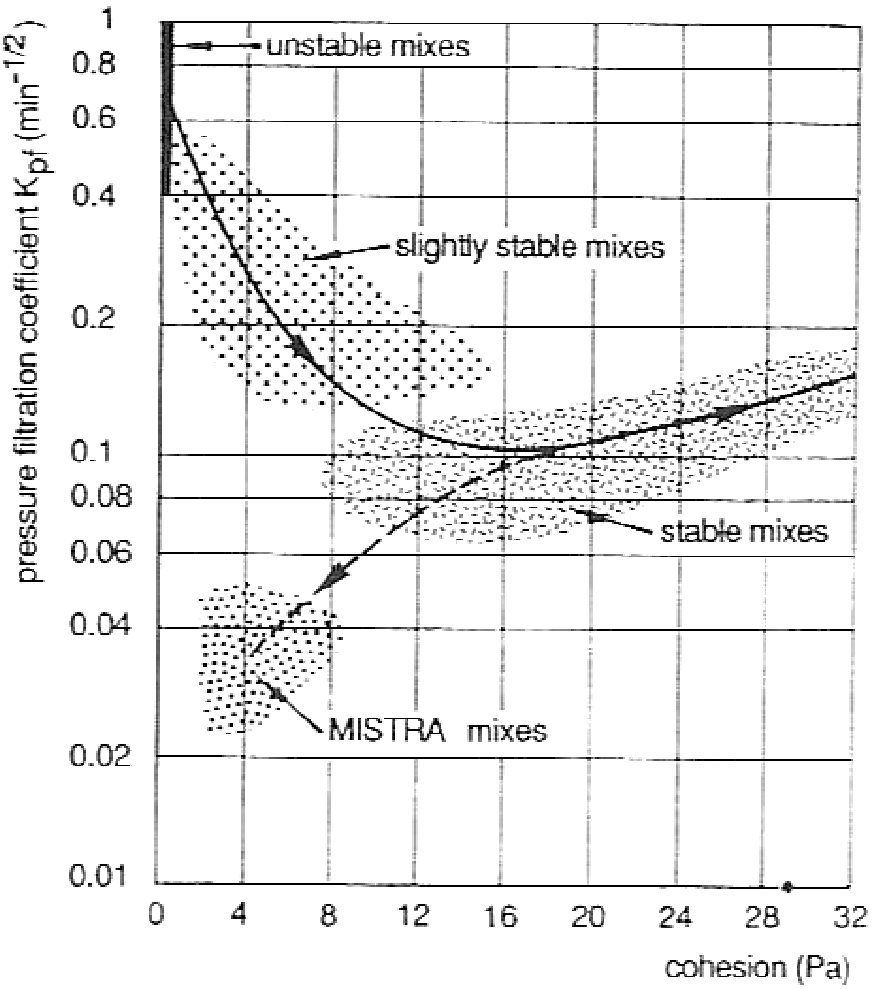

Figure 3. Relationship between stability under pressure and cohesion for the different types of mixes (DePaoli et al., 1992a).

Instead, multicomponent grout mixes are far superior products. In addition to cement, water and bentonite, such mixes can incorporate materials to enhance pressure filtration stability, durability, modify hydration and/or resist washout prior to setting (Chuaqui and Bruce, 2003), as directed by specific project requirements. As an absolute minimum, water-cement-bentonite mixes, with water cement ratios not more than 2 (by weight) and incorporating a chemical dispersant ("superplasticizer") and viscosifier will provide an adequate starting package in many conditions. As the injection of each stage progresses, the viscosity of the mix can be easily varied by changing the water cement ratio or altering the dispersant content. The fluid properties of all the grouts foreseen to be used must be proved in the field prior to production commencing. It is relatively easy — even in a tunnel — to produce a family of stable grouts with, successively, Marsh Flow Cone times of say 35-40 seconds ("very thin"); 50-60 seconds; and "no flow" (for "gulpers"). In extremely open conditions, sand can be added (at weight ratios of up to 1 with cementitious materials) to increase the grout's internal friction, but the operational impact on equipment and pipework must be closely evaluated. In passing, it may be noted that dispersants can be effective in reducing the actual particle size distribution of the grout (Figure 4). This will also greatly enhance the ability of the grout to penetrate finer fissures — in this case by a size factor of almost 2.

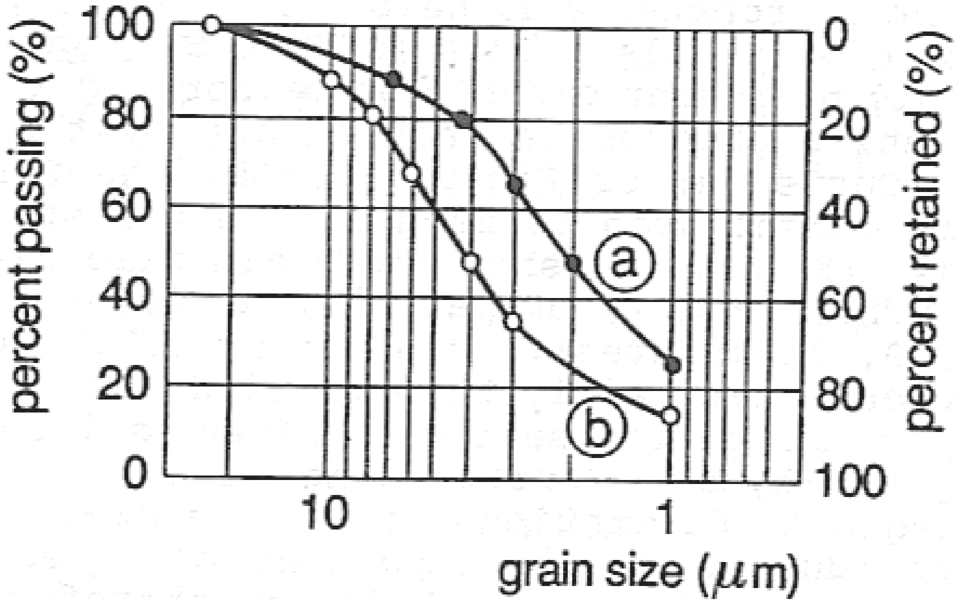

Figure 4. Grain size distribution curves of the same microfine cement in aqueous suspension (a) with and (b) without, dispersive agent (DePaoli et al., 1992b).

All the above comments refer to cement-based grouts accurately batched, and mixed in a high speed, high shear ("colloidal") mixer.

5. Final Remarks

Pregrouting activities for rock tunnels are extremely important in terms of the technical consequences of their performance, and their percentage of overall tunnel costs. Failure of the pregrouting to meet the project's goals may result in the severest consequences in terms of safety, performance, cost, and schedule. Remedial grouting attempts ("post-excavation" or "post-injection) are invariably more challenging technically — since dynamic water conditions are inevitably involved — and are correspondingly more costly. A review of certain Norwegian projects (Stenstad, 1998) concluded that "based on experience the cost of stopping water ingress by post-injection is 30 to 60 times higher than that of using pre-injection." It is recognized that the current wave of sophistication sweeping through the dam grouting industry simply cannot be replicated in underground grouting — there are too many logistical barriers, not to mention historical mindsets. Nevertheless, there is much that can be quickly, painlessly and profitably assimilated, provided that all parties are prepared to commit accordingly. There have been too many unhappy events in the last decade alone to warrant persevering with the status quo.

6. References

Bruce, D.A. (2003). "The Basics of Drilling for Specialty Geotechnical Construction Processes." *Grouting and Ground Treatment*, Proceedings of the Third International Conference, Geotechnical Special Publication No. 120. Edited by L.F. Johnsen, D.A. Bruce, and M.J. Byle, American Society of Civil Engineers, New Orleans, LA, February 10-12, pp. 752-771.

Bruce, D.A. (2007). "Managing the Design and Construction of Grouted Cut-Offs in Emergency Conditions," American Society of Civil Engineers, GeoDenver, February 18-21, Denver, CO.

Chuaqui, M. and D.A. Bruce. (2003). "Mix Design and Quality Control Procedures for High Mobility Cement Based Grouts." *Grouting and Ground Treatment*, Proceedings of the Third International Conference, Geotechnical Special Publication No. 120, Ed. L.F. Johnsen, D.A. Bruce, and M.J. Byle, American Society of Civil Engineers, pp. 1153-1168.

DePaoli, B., B. Bosco, R. Granata, and D.A. Bruce, (1992a). "Fundamental Observations on Cement Based Grouts (A): Traditional Materials." Proc. ASCE Conference, "*Grouting, Soil Improvement and Geosynthetics*." New Orleans, LA, Feb. 25-28, 2 Volumes, pp. 474-485.

DePaoli, B., B. Bosco, R. Granata, and D.A. Bruce. (1992b). "Fundamental Observations on Cement Based Grouts (B): Microfine Cements and the Cemill Process." Proc. ASCE Conference, "Grouting, Soil Improvement and Geosynthetics." New Orleans, LA,. Feb. 25-28, 2 Volumes, pp. 486-499.

Garshol, K.F., (2003). "Pre-Existing Grouting in Rock Tunneling." MBT International Underground Construction Group; 138pp.

Houlsby, A.C. (1976) "Routine Interpretation of the Lugeon Water-Test." *Quarterly Journal of Engineering Geology.* 9, 303-313.

Lombardi, G., (2003). "Grouting of Rock Masses." *Grouting and Ground Treatment*, Proceedings of the Third International Conference, Geotechnical Special Publication No. 120. Edited by L.F. Johnsen, D.A. Bruce, and M.J. Byle, American Society of Civil Engineers, New Orleans, LA, February 10-12, pp. 164-197.

Stenstad O., (1998). "Execution of Injection Works" (in Norwegian), Proceedings of Post Graduate Training Course sponsored by the Norwegian Chartered Engineer Association and the Norwegian Rock Mechanics Group, Fagernes, Norway.

Wilson, D. and T. Dreese. (1998) "Grouting Technologies for Dam Foundations", Proceedings of the 1998 Annual Conference Association of State Dam Safety Officials, October 11-14, Las Vegas, Nevada, Paper No. 68.

Wilson, D. and T. Dreese (2003) "Quantitatively Engineered Grout Curtains," *Grouting and Ground Treatment*, Proceedings of the Conference sponsored by the Geotechnical Engineering Division of the American Society of Civil Engineers, New Orleans, LA, February 10-12, pp. 881-892.