SOME RECENT DEVELOPMENTS IN GROUND TREATMENT FOR TUNNELLING

by D.A. Bruce[+], R. Granata[*], M. Mauro[*],
and A. Perelli Cippo[*]

[+] Nicholson Construction, Bridgeville, PA

[*] Rodio & Co., S.p.A., Milano, Italy

ABSTRACT

During the last few years, significant advances continue to have been made in aspects of grouting technologies used for ground treatment in advance of tunnelling. In permeation grouting, fundamental researches have continued into improving the penetrability characteristics of cement-based grouts. The twin advantages of field regrinding normal grouts to reduce cement particle sizes, and incorporating special additives into stable grouts, are now being systematically exploited in major soft ground tunnelling projects in Europe. The methodologies of jet grouting continue to be developed with special attention being paid to qa/qc issues, reducing unit production costs, and improving predictive capabilities for subsequent settlements.

INTRODUCTION

One of the major applications for grouting techniques throughout the world is the treatment of ground in advance of tunnelling activities. Such treatment is conducted for many reasons including technical, environmental, safety and financial. A measure of the significance of this particular application is its direct link with innovation. This influence is impacting all aspects of soil grouting: compaction grouting (Baker, et al., 1983), permeation grouting (Mongilardi and Tornaghi, 1986), jet grouting (Ceppi, et al., 1989), compensation grouting (Essler and Linney, 1992), hydrofracture grouting (Bruce, 1987), mechanical mix-in-place (Taki and Yang, 1991) and in grouting materials research (De Paoli, et al., 1992a, b).

With reference to soil treatment by permeation grouting, a particularly innovative system is the CEMILL^R process which permits the industrial production of microfine grout mixes on site from grouts prepared from cements of conventional grain size. Depending on the desired properties of the treated soil, bentonite can be added to the grout. The properties of the CEMILL mixes have been closely established in laboratory tests, and have been confirmed in practice during several major projects.

The increasingly frequent use of jet grouting in sensitive applications has highlighted the importance of an efficient construction monitoring system. The recently developed PAPERJET^R system allows real time quality control, as well as offering new possibilities for reducing production costs, and improving predictive capabilities in terms of results and performance.

This paper outlines the recent developments in the production of microfine grouts using the CEMILL process, and in the quality assessment of jet grouting operations using the PAPERJET instrumentation.

MICROFINE GROUTS AND THE CEMILL PROCESS

Background

The greater attention being devoted to environmental concerns has led in recent years to a critical and conservative attitude towards the acceptability of chemical grouts of the type traditionally employed for grouting fine grained soils and microfissured rock or concrete. This situation has renewed the interest in cement based grouts and, in particular, those based on microfine cements (Clarke, 1984).

The fine grained cements commercially available are manufactured either by initial milling beyond the usual industrial limits, or by fractionating the commercially available cements, in order to separate out the finest portion. However, the efficient use of such materials is often hindered by certain key factors. For example, in dry form microfine cements tend to compact, due to their sensitivity to electrostatic phenomena and humidity. This creates transportation and storage problems. Furthermore, when mixed with water, they tend to flocculate, losing that extreme fineness of particle size which is their fundamental characteristic. This problem can be partially solved by using dispersive additives or anti-flocculation agents.

Conversely, grouts based on microfine cements can also be generated through the wet process, by exploiting the decantation principle under which particles of equal density fall, in a liquid, at a rate proportional to their diameter. In this way, once the grout has been prepared, the subdivision of the particles can be achieved: the upper portion, containing the finer fraction can be recovered and used for grouting, whilst the coarse, sedimented lower portion can be discarded. This may prove to be both wasteful and uneconomic.

The CEMILL^R Process

An alternative method for manufacturing microfine cementitious grouts is the CEMILL process, recently developed by the authors' company. The goals which led to the development of the system were:

a) to develop an on-site manufacturing process to provide microfine grouts;
b) to use, as the starting material, conventional cements, in order to be independent of the local market availability of microfine cements (at present only available in a limited number of industrialized countries);
c) to overcome the limits of pure decantation which permit only the manufacture of very diluted grouts and involve the potentially difficult disposal of the coarse, discarded portions;
d) to make possible the production of not only unstable grouts (water, cement, possibly dispersive agent), but also stable grouts using bentonite. This latter category is not possible using the decantation principle.

Achieving these goals involved the development of a special colloidal wet refiner, having a dual function:

a) it imparts a very strong dispersive action to the cement particles used in the grout. In this way the effectiveness of any microfine portion is safeguarded even if dispersive agents are not used;
b) it carries out a progressive refining process of the coarse portion, until the desired fineness is reached, and so does not require its elimination as in the case of decantation.

The CEMILL method makes possible, by using commercially available cements (2000-5000 cm^2/g), the manufacture of grouts capable of permeating by soffusion medium-fine sands. CEMILL grouts can be manufactured, with a variable

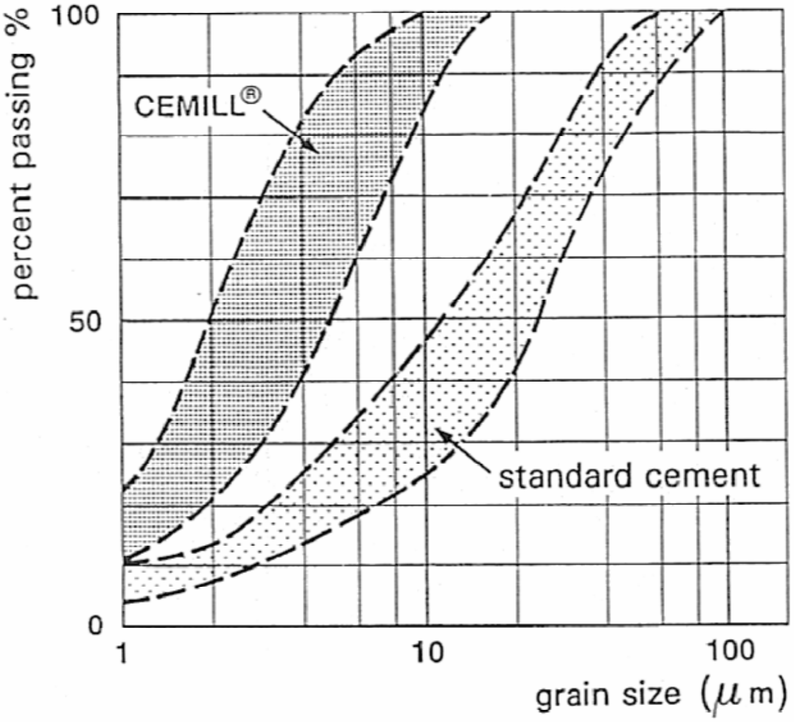

Figure 1. Grain size distribution curves of conventional and CEMILL cementitious grouts.

range of grain size distribution. Figure 1 shows the grain size distribution of traditional cements (used for the preparation of starting grouts) as compared to those in the various CEMILL mixes.

The production process is monitored in the grout by granulometric analysis, obtained with laser diffractometer. Therefore the grain size distribution curves refer not to anhydrous products but to the cement particles actually present in the grout and which have already undergone possible aggregation effects or swelling due to hydration.

According to the application intended, stable (CEMILL-S) or unstable (CEMILL-I) grouts can be manufactured by adding bentonite to the starting mix. The bentonite is itself further refined and does not alter the final fineness of the produced mix.

Characteristics of CEMILL Mixes

Laboratory tests were performed to evaluate the two groups of mixes (CEMILL-S and CEMILL-I) rheologically and with respect to stability, penetrability, strengthening and waterproofing potential. The testing methods were as described by De Paoli, et al. (1992a).

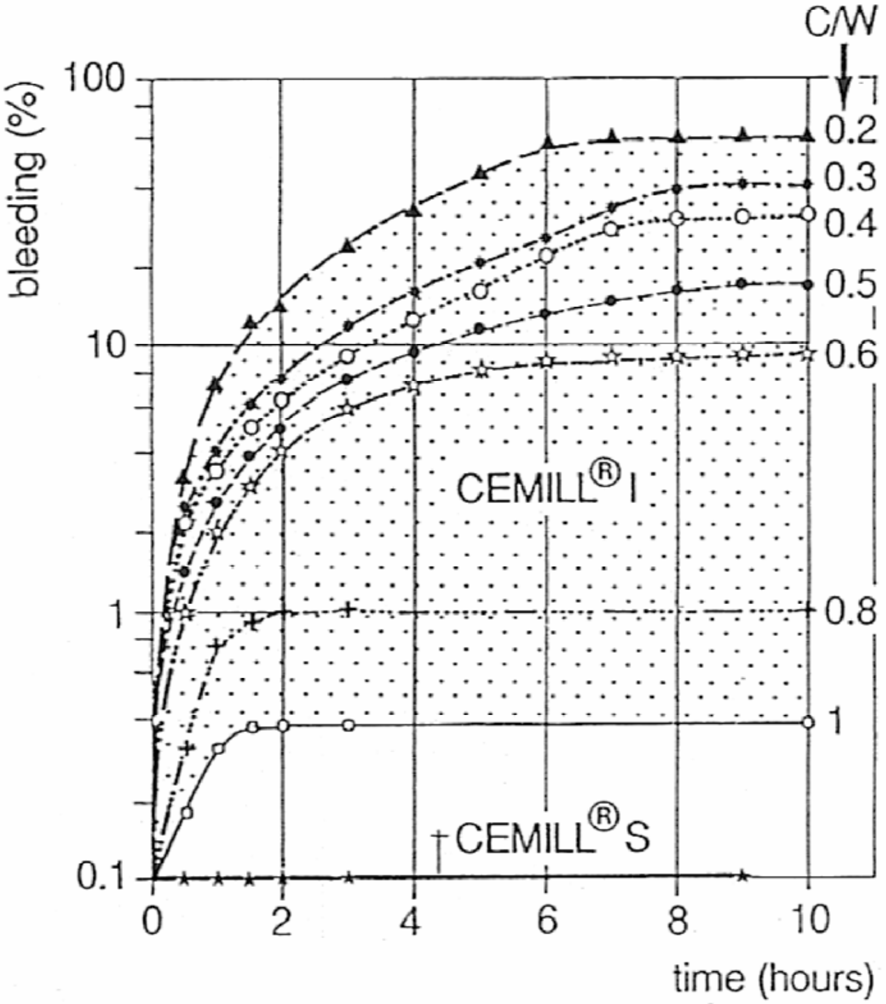

Figure 2. CEMILL grouts: stability as a function of time and cement content.

The bleed potential of the two groups of grouts is summarized in Figure 2. CEMILL-S mixes are stable, CEMILL-I mixes bleed at 8 hours, from 60 to 0.4% in relation to the cement-water ratio (C/W), ranging from 0.2 to 1.0. The CEMILL-I bleed potential is much lower than that of the corresponding mixes produced with traditional grain size cements. The improved stability to bleeding is attributable to the fineness and dispersion of the particles, which then settle singly and slowly.

The rheological characteristics of CEMILL mixes are illustrated in Figure 3. CEMILL-I mixes are close to the straight line VA = VP (characteristic of a Newtonian fluid), whilst the CEMILL-S mixes, having a slight cohesion, have the characteristics of a Binghamian fluid.

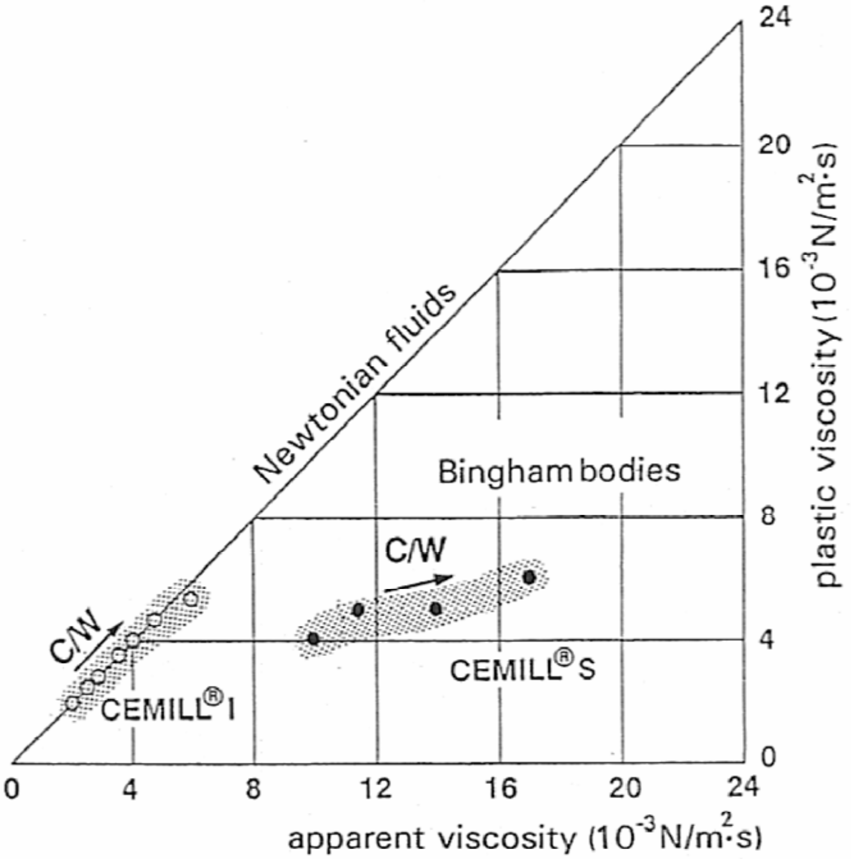

Figure 3. CEMILL grouts: relationship between plastic viscosity and apparent viscosity.

The considerable importance attributed by various authors including Deere and Lombardi (1985), to mix stability and initial cohesion is well known. The characteristics of stability to pressure filtration are correlated to cohesion (Figure 4), in terms of the pressure filtration coefficient (K_{pf}). The lower this coefficient, the higher the stability under pressure: the CEMILL-I mixes, by remaining in theory unstable suspensions, present pressure filtration coefficients comparable to those of ordinary mixes stabilized by the addition of bentonite; the CEMILL-S mixes are, on the other hand, in the field of the MISTRA^R mixes, which are stable mixes with low cohesion patented by Rodio (Tornaghi, 1985; DePaoli, et al., 1992a).

The experimental study of the penetrability of CEMILL mixes was conducted by injecting the mix into porous stone moulds prepared for the purpose with sands of preselected grain size cemented with epoxy resin (De Paoli, et al., 1992b). The groutability test results are summarized in Figure 5.

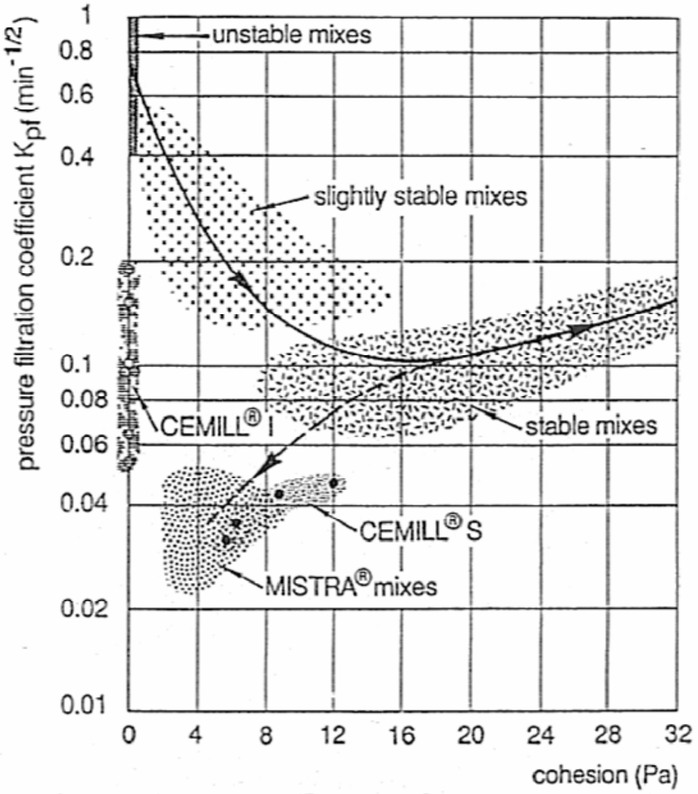

Figure 4. Relationship between stability under pressure and initial cohesion for CEMILL and other grouts prepared with cements of conventional fineness.

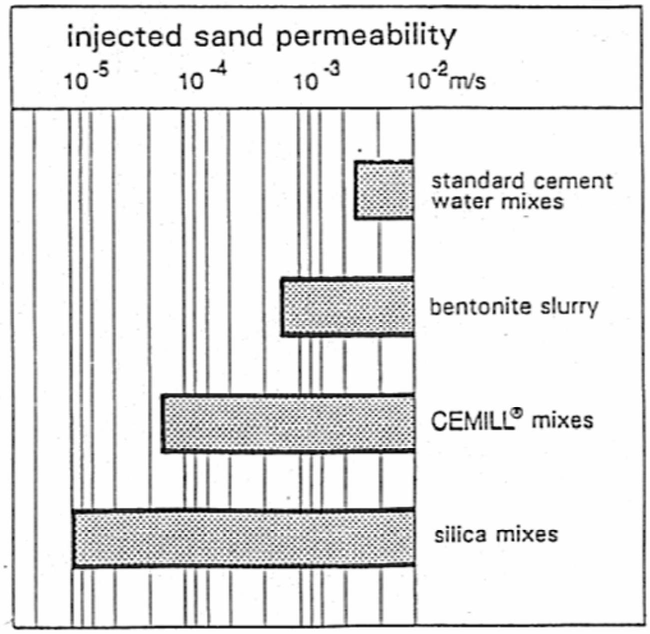

Figure 5. Limits of penetrability for different grouts.

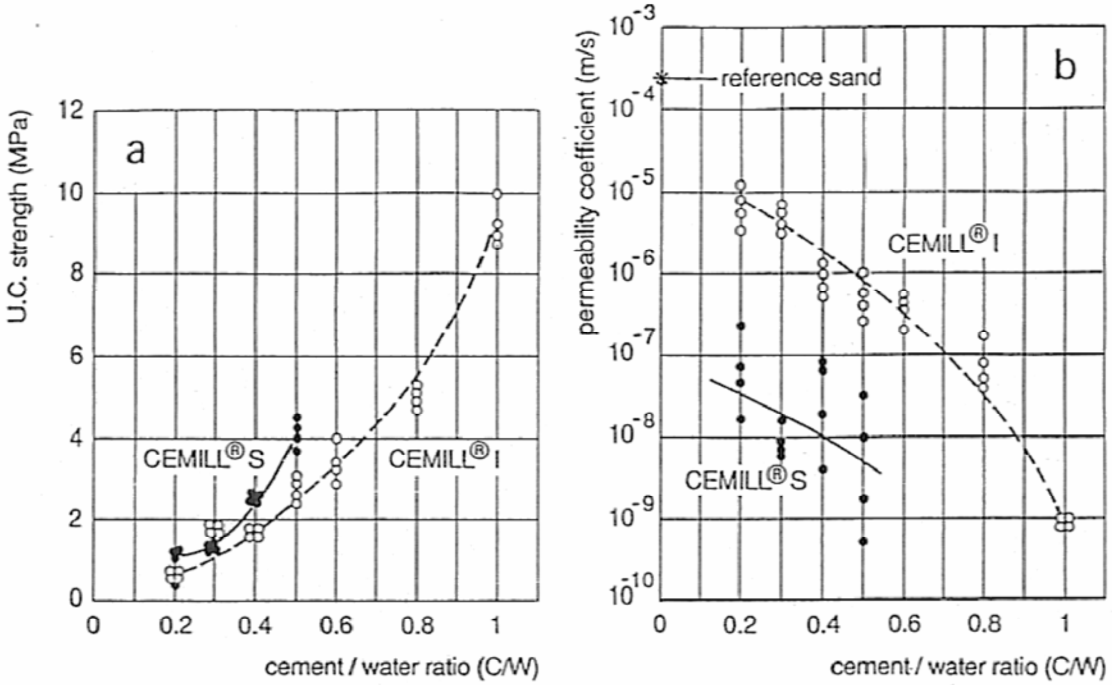

Figure 6. CEMILL grouts: (a) unconfined compressive strength and (b) permeability.

The injection of compacted sand moulds (grain size 0.1-1.0 mm) was conducted to evaluate the strength and permeability of treated sand. In Figure 6, compressive strength and permeability values are plotted as a function of C/W ratio of the grout. The compressive strength at 28 days varies in relation to the C/W ratio, from 1.0 to 4.0 MPa for sands treated with CEMILL-S and from 0.7 to 9.0 MPa for those treated with CEMILL-I. For the same samples the permeability coefficient, measured at 28 days, decreases from the original $2*10^{-4}$ m/s to $1*10^{-9}$ m/s. With equal cement content, the stable mixes (CEMILL-S) show higher strength and less permeability as compared to CEMILL-I.

Applications of CEMILL Mixes

Since 1989, CEMILL mixes have been successfully employed on several sites for consolidation or waterproofing purposes and for restoring concrete structures. A recent application of CEMILL grout is the soil waterproofing treatment carried out in 1991 at Famagosta Station, for the extension of line 2 of the Milano Metro. The station and approach tunnel were to be constructed inside an excavation supported by reinforced concrete diaphragm walls. The elevation of the bottom excavation was approximately 4 m below the water table.

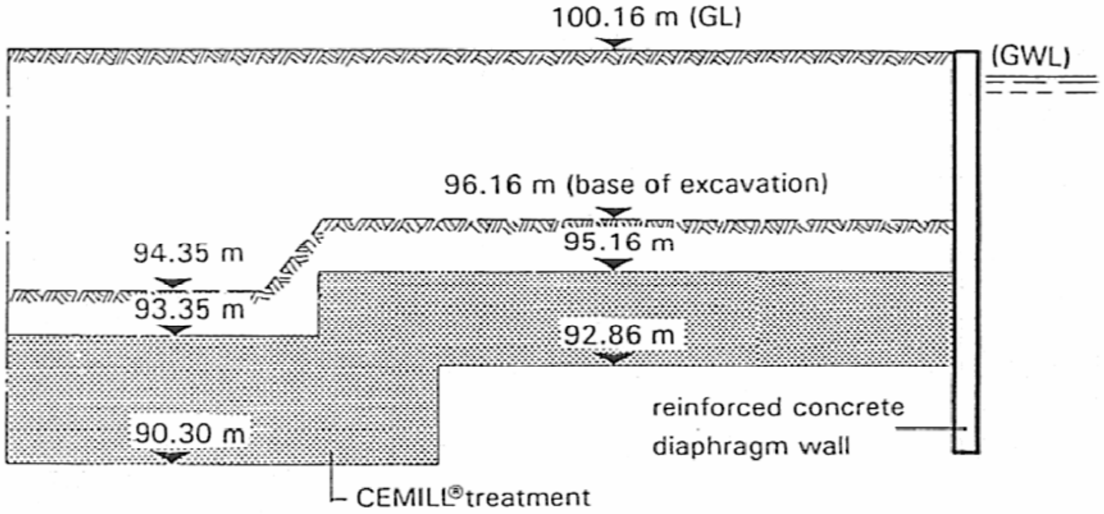

Figure 7. Milano Metro, Famagosta Station, typical section.

To avoid dewatering the excavation during construction, the sealing of the invert with cement based grouts was foreseen (Figure 7).

A preliminary detailed site investigation was performed in order to define the permeability and grain size distribution of the soils in question. The soils turned out to be the finest among those of the Milan area. They consisted of medium-fine silty sands with silty and peaty-silty interbeds (Figure 8), with a natural permeability of about $4*10^{-5}$ m/s.

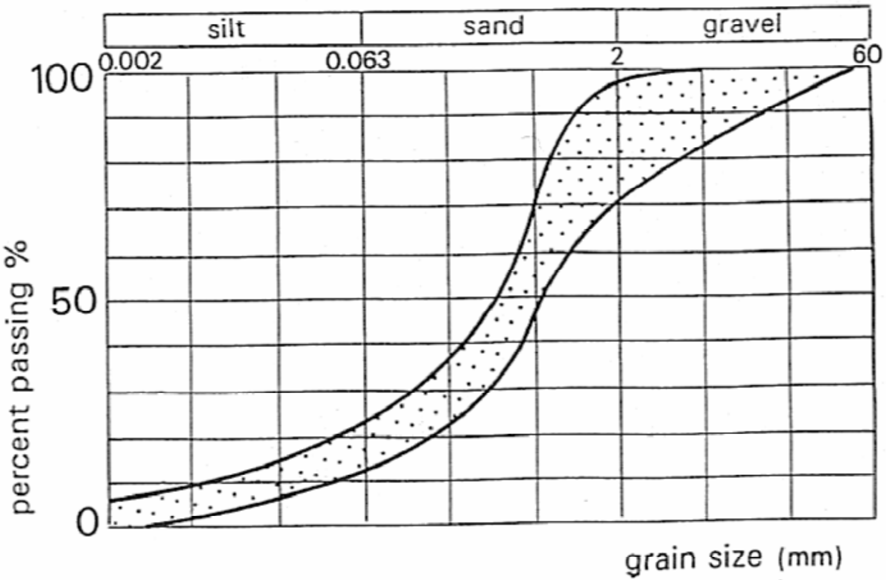

Figure 8. Milano Metro, Famagosta Station, grain size distribution of treated soil.

Under these conditions, it was necessary to resort to grouts featuring microfine solid content, low viscosity and cohesion but high waterproofing capability. These requirements led to the choice of a CEMILL-S grout with C/W ratio = 0.30 and bentonite-water ratio B/W = 4%.

Grouting was carried out from the surface through vertical tubes à manchette on a 1.50 triangular grid. The treatment was done in two phases by injecting a volume of mix approximately equal to 30% of the volume of the ground.

The results of the treatment were excellent: the grout permeated the finest voids in the soil without hydrofracturing. In situ measured permeability was close to $6*10^{-8}$ m/s. The average unconfined compressive strength of samples taken in the treated soil was 2.5 MPa. The excavation was then successfully undertaken without dewatering.

QUALITY ASSESSMENT OF THE JET GROUTING PROCESS

Jet grouting has been increasingly employed for soil improvement in advance of tunnelling (Tornaghi and Cippo, 1985; Mongilardi and Tornaghi, 1986; Bruce, 1987; Ceppi, et al., 1989; McWilliam, 1991). Experience has demonstrated that the achievable results depend on the geotechnical characteristics of the soil and the operational parameters, such as grout pressure and flow rate. For this reason, it is of prime importance for the contractor to rely on an efficient monitoring system during the grouting process. Such monitoring provides the opportunity to reduce production costs, as a result of improved final results and performances.

The recently developed electronic PAPERJET^{R} system is part of a new equipment generation including both patented software and hardware. The hardware (Figure 9) comprises the following:

- transducers and flowmeters;
- the acquisition unit which collects the analogical signals of these instruments and converts them into digital signals;
- a portable computer with a printer.

The PAPERJET system executes the following operations, in real time during grouting:

- real-time monitoring of the jet grouting main operational parameters (grout pressure; grout flow

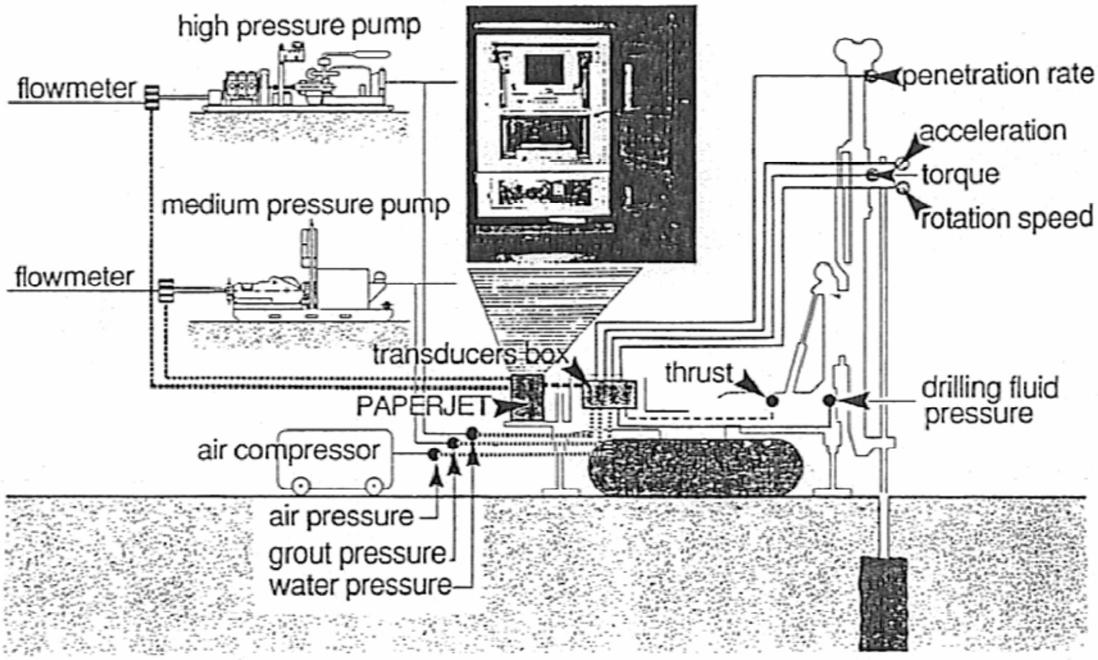

Figure 9. PAPERJET^R system of jet grouting electronic monitoring.

rate; withdrawal speed of the rods) and evaluation of the specific jet grouting energy;
- display and printing both in graphical form and numerical form of all the acquired numerical data and specific jet grouting energy;
- storage of the same data on magnetic support for later plotting and printing.

The specific jet grouting energy, for unit length of column, is calculated from the following equations (De Paoli, et al., 1991):

$$Es = P*Q / Vt \qquad [MJ/m]$$

where:

P = grout pressure [MPa]
Q = grout flow rate [m^3/h]
Vt = withdrawal speed [m/h]

With reference to the sequence of operations shown on Figure 10, the range for the main operational parameters and specific grouting energy typical of one, two, three fluid system are summarized in Table 1. When the three-fluid system is employed, Es includes the contribution of water and grout, while air is neglected.

BRUCE et al

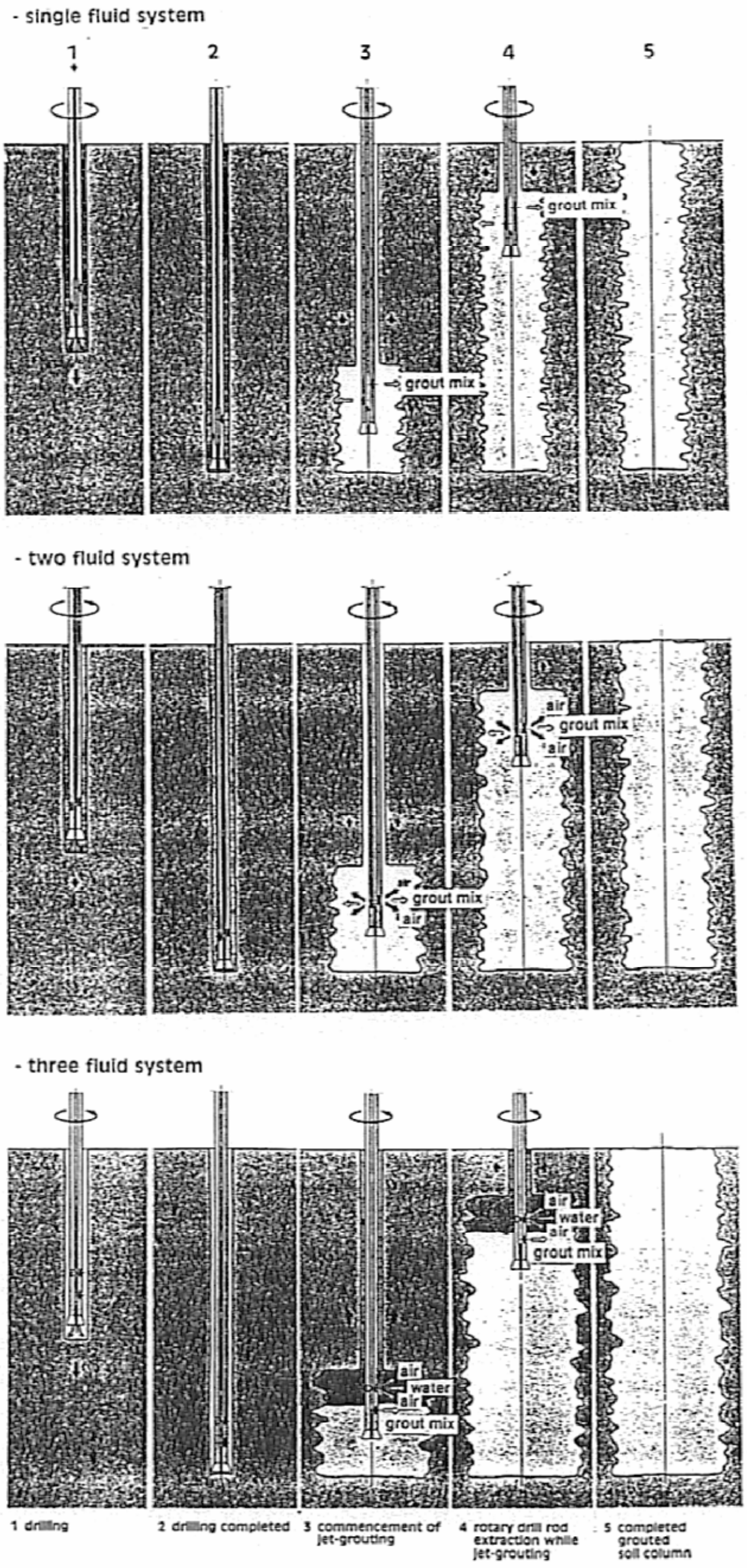

Figure 10. The three basic jet grouting systems: sequence of operations.

Brucé et al

system	fluid	V_t (m/h)		V (m^3/m)		Q (m^3/h)		P (MPa)		E (MJ/m)	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
single fluid	mix	15	35	0.2	0.3	3.6	7.2	30	50	3	24
two fluids	mix	4	18	0.5	1.5	5	9	30	50	8	110
	air			10	90	150	360	0.7	1.2		
three fluids	mix	2.5	18	0.5	2	5	9	1	10	1	20
	water			0.5	2	5	9	30	50	8	180
	air			10	150	150	360	0.7	1.2		

V_t = withdrawal speed
V = mix volume
Q = grout mix flowrate
P = grout mix pressure
E = grouting energy

Table 1. Typical range of jet grouting parameters.

The results of the PAPERJET system can be integrated with a soil investigation campaign carried out with PAPERO^R system (De Paoli, et al., 1987). This, by means of similar hardware, determines the specific drilling energy (Teale, 1965) required to drill a unit volume of soil. The comparison of the drilling energy in natural and treated soil with the grouting energy is a means of evaluating the efficiency of the treatment.

The PAPERJET system has several advantages. First, the rig operator can detect any mechanical malfunction (such as a drop of pressure or flow rate) and can then take timely corrective action. Second, the site engineer has real time control over the working process, which can be adjusted to meet unexpected soil conditions. Third, the client is provided with appropriate documentation certifying that jet grouting has been carried out correctly and within the design limits. Fourth, as a future development, a statistical comparison of grouting energy with drilling energy and sample strength, in different types of soil, will enable designers and contractors to make reliable predictions of jet grouting final results and performances.

A major application of the PAPERJET system has been at La Spezia, in Italy, where the expressway connecting the A12 highway and the city's harbor is at present under construction. One of the major structures is the 800 m long cut and cover tunnel underpassing the eastern part of the city. Along this tunnel the soil profile consists of peaty-silty clay and sandy-clayey silts with CPT point resistance ranging between 0.1 and 10 MPa. In order to allow safe excavation down to 10 m from ground level, the subgrade is being consolidated with three fluid jet grouting. Figure 11 shows a typical output diagram of the grouting energy along the treated depth, from 9 m to 14 m from ground level. The same figure shows the specific drilling energy measured with the PAPERO system, in both natural and grouted soil. The drilling energy increases from 0.05 GJm^3 in the natural soil to 0.45 GJ/m^3 in the treated soil, thus showing the success of the treatment.

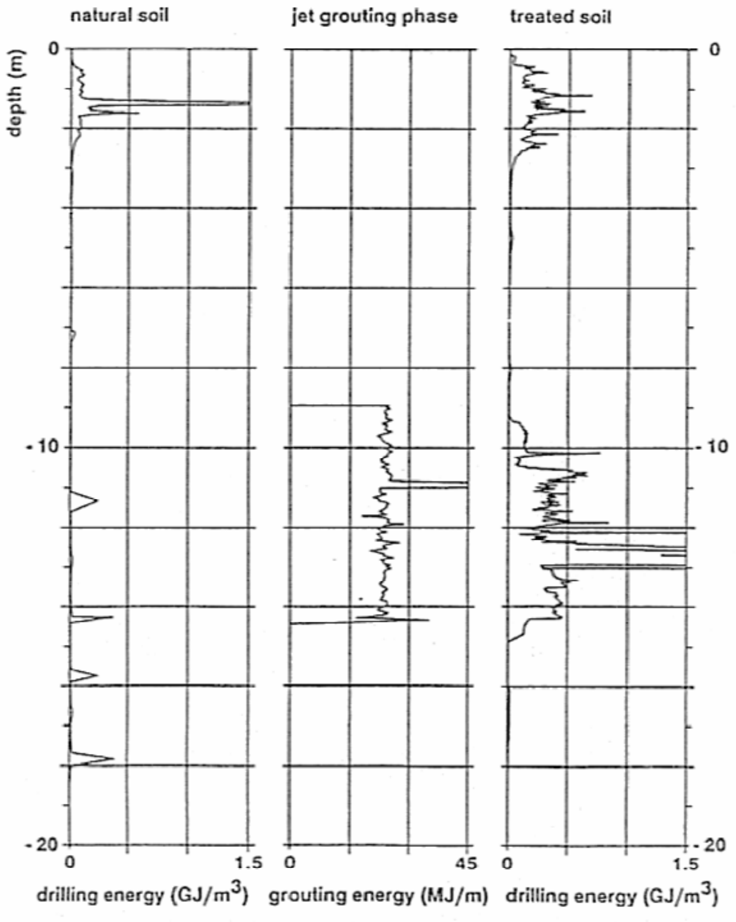

Figure 11. Three fluid jet grouting system: plots of the drilling energy in natural and treated soil, and grouting energy.

CONCLUSIONS

In the field of permeation grouting, the recently developed CEMILL grouts can be successfully employed in medium-grained soils, microfissured rock and concrete. They are non-polluting, microcement-based grouts capable of imparting to the treated medium the expected waterproofing and consolidation values.

The application of the PAPERO system to the jet-grouting process allows real-time quality control, with a potential for reduced production costs thanks to the superior final results and performance which can be attained.

REFERENCES

Baker, W.J., Cording, E.J., and MacPherson, H.H., 1983. "Compaction Grouting to Control Ground Movements During Tunnelling". Underground Space, 7, pp. 205-212.

Bruce, D.A., Boley, D.L., Gallavresi, F., 1987. "New Developments in Ground Reinforcement and Treatment for Tunnelling". Rapid Excavation and Tunnelling Conference, New Orleans, LA, June 14-17, Vol 2, pp. 811-835.

Ceppi, G., Maggioni, F., De Paoli, B., Stella C., Lotti, A., Pedemonte, S., 1989. "Horizontal Jet Grouting as a Temporary Support for the Monteolimpino 2 Tunnel". Int. Congress on Progress and Innovation in Tunnelling, Toronto, Canada, September 9-14.

Clarke, W., 1984. "Performance Characteristics of Microfine Cements". ASCE Geotechnical Conference, Atlanta, GA, May 14-18.

Deere, U.D., Lombardi, G., 1985. "Grout Slurries: Thick or Thin?". Proc. of the session sponsored by ASCE Geotechnical Engineering Division, Issues on Dam Grouting, ASCE Convention, Denver, CO, April 30, pp. 156-164

De Paoli, B., Viola, G. and Tomiolo, A., 1987. "The Use of Drilling Energy for Soil Classification". 2nd Int. Symp. on Field Measurement in Geomechanics. Kobe, Japan, April 6-9, 9 pp.

De Paoli, B., Bosco, B., Granata, R., Bruce, D.A., 1992a. "Fundamental Observations on Cement Based Grouts (1): Traditional Materials". Proc. ASCE Conference, "Grouting, Soil Improvement and Geosynthetics", New Orleans, LA, Feb. 25-28, 2 vols, pp. 474-485.

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

De Paoli, B., Stella, C., Perrelli Cippo, A., Locatelli, L., 1991. "A Monitoring System for the Quality Assessment of the Jet Grouting Process Through an Energy Approach". 4th Intl. DFI Conference, Stresa, Italy.

Krizek, R.J., Helal, M., 1989. "Some Properties of Microfine Cement Grouts". Second Annual Short Course on Grouting Practice, University of Wisconsin-Milwaukee, October 30-31.

Linney, L.F. and Essler, R.D., 1992. "Compensation Grouting Trial Works at Red Cross Way, London". Proc. ICE Conference, Grouting in the Ground, London, Nov. 25-26, 14 pp.

McWilliam, F., 1991. "Jet Grouting Under Bonn". Tunnels & Tunnelling, April.

Mongilardi, E. and Tornaghi, R., 1986. "Construction of Large Underground Openings and Use of Grouts". Proc. Intl. Conference on Deep Foundations, Beijing, China, September.

Teale, R., 1965. "The Concept of Specific Energy in Rock Drilling". Int. Jour. Rock Mechanics and Mining Science, Pergamon Press.

Tornaghi, R., Cippo, A.P., 1985. "Soil Improvement by Jet Grouting for the Solution of Tunnelling Problems". Proc. 4th Intl. Symposium Min. and Met. Tunnelling, Brighton, UK, March 10-15.

Tornaghi, R., Bosco, B., De Paoli, B., 1988. "Applications of Recently Developed Grouting Procedures for Tunnelling in the Milan Urban Area". 5th Intl. Symposium Tunnelling 88, London, UK, April 18-21.