Grouting of completely weathered granite with special reference to the construction of the Hong Kong Mass Transit Railway

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SYNOPSIS

The construction of the tunnels and stations of the three routes of the Hong Kong Mass Transit Railway has been under way since 1975. Difficult ground conditions and the practical limitations that are associated with civil engineering works in congested locales have dictated the use of specialist geotechnical processes as vital adjuncts to progress and safety in the overall construction. In particular, ground treatment, by cement and chemical injections, has been used widely, and data from a variety of sites have proved its effectiveness, especially in the ubiquitous completely decomposed granites.

Judged by the standard criteria of grading curve analyses and permeability, however, such materials should be but marginally, if at all, treatable by such methods, whereas post-grouting mass permeabilities of 1×10^{-7} m/s have been achieved in ground with more than 40% fines. In examining the working method and the observed mechanisms of the successive elements of the ground treatment the apparent paradox is resolved in the light of the peculiar microstructure that is to be expected in weathered rock of this type.

INTRODUCTION

Cut and cover methods were widely adopted during the construction of the first two lines of the Hong Kong Mass Transit Railway (MTR) – the Modified Initial System (MIS) and the Tsuen Wan Extension (TWE) (Fig 1). These lines, opened in 1980 and 1982 respectively, currently carry 1,200,000 passengers per day. Construction of the Island Line – the third major artery, which will double the traffic when fully operational by 1986 – was commenced in 1981. Its route coincides with the densely populated fringe of the north foreshore of Hong Kong Island itself and so underlies the commercial and trading heart of the Territory. To minimize the disruption of the already congested road traffic system the 10.5km of new subsurface track is being created in 8m diameter bored tunnels, and the ten new underground concourses are being constructed in off-street locations up to 50m away from the line of the tunnels.

Whereas approximately 6km of these tunnels is in hard granite bedrock, the balance is in soft or mixed ground – fill, marine deposits, alluvium, colluvium and various grades of decomposed granite. The tunnels are 25-35m below ground surface and their safe passage through saturated deposits (the water-table is generally within 2m of the surface) and under structures with old and questionable foundations has demanded meticulous planning and execution. Similar concerns about minimizing construction-related damage to adjacent property have seen the concourses being constructed by top down methods, within tight boxes formed by load-bearing diaphragm walls extending to rock head, to depths of 50m. Columns to support the intermediate floor and roof are constructed inside hand dug caissons in advance of excavation.

Given very variable ground conditions, and understandably demanding settlement criteria and construction programmes, contractors have exploited a wide range of geotechnical processes to secure and advance their works. Thus, anchoring, shotcreting and grouting have been common adjuncts to the diaphragm walling, piling and tunnelling activities that constitute the larger-scale processes. The grouting methodologies have been particularly interesting, featuring the exploitation of replacement (jet grouting) and flash setting (DDS, LAG) systems, as well as the more conventional, European approach of permeation grouting by the tube à manchette system.

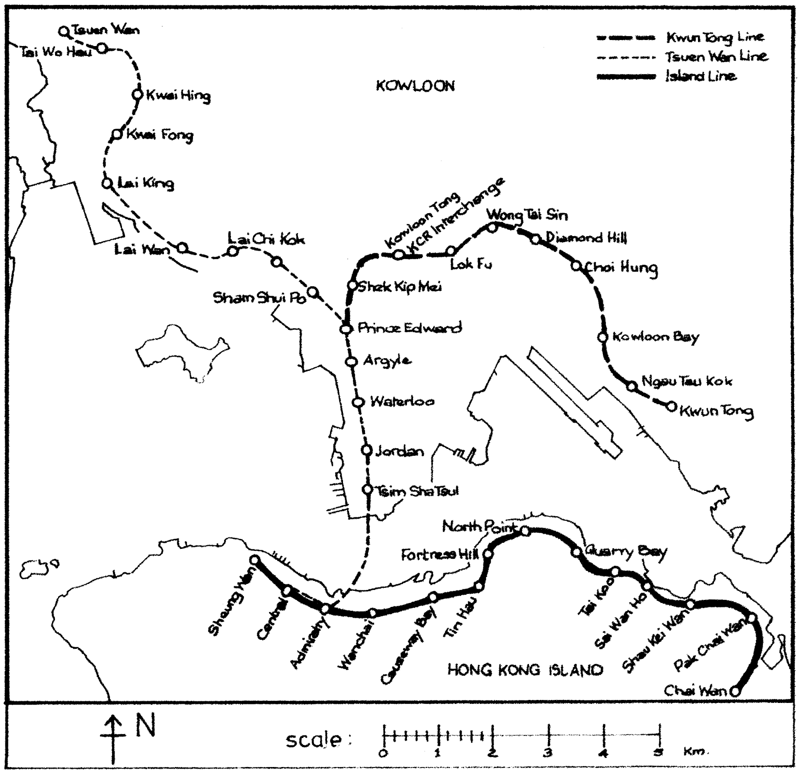


Fig 1. MTRC routes, Hong Kong

The beneficial effects of tube à manchette injection, in completely decomposed granites (cwg) in particular, were established during the construction of the MIS in 1976[1,2,3] and have since become an integral feature of construction. The work is executed to a common specification, which has, *inter alia*, facilitated the synthesis and assessment of performance data from the numerous working locations. These analyses have highlighted that the grouting of the cwg has been repeatedly effective – to the point of challenging the conventional limits of groutability consistent with current theory. This paper records the advances made and offers conclusions as to the surprisingly low permeabilities that have been achieved.

APPLICATIONS OF GROUTING IN MTR CONSTRUCTION

Specific applications of ground treatment are illustrated in Fig 2. In summary, the prime purpose of the grouting has been to maintain the stability of the ground and groundwater, thereby safeguarding against surface settlements and promoting safety and ease of construction underground.

CHARACTERISTICS OF CWG AS RELATED TO GROUTABILITY

The north foreshore of Hong Kong Island and the southern Kowloon peninsula are founded on a Cretaceous granite batholith intruded into volcanic rocks of Middle Jurassic age (Fig 3).[4] The rigours of a wet, sub-tropical climate have promoted extensive chemical weathering of the rock: feldspars and ferromagnesian micas have reduced, principally, to kaolinite and sericite, respectively. The quartz, which accounts volumetrically for 23-42% of the fresh rock[5], of course remains unaltered.

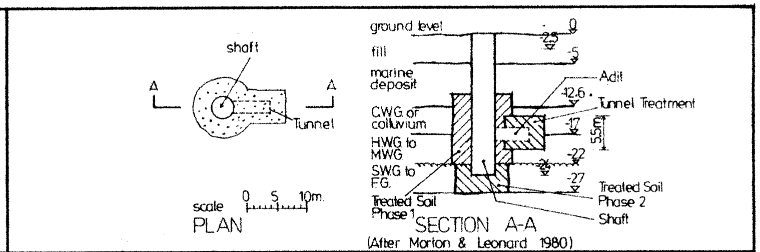
The results of chemical weathering on granite masses have long been recognized and are well documented[6,7]. A continuously grading profile from fresh jointed granite, through fresh 'corestones' in a weathered matrix, to completely decomposed residual soil can be identified (Fig 4). In Hong Kong major weathering effects have been recorded more than 50m below present sea-level, probably enhanced by the different global ocean levels of recent geological history. Zones of particularly deep weathering, such as are found at North Point, appear to be associated with ancient stream channels, and often parallel northeast-southwest-trending dyke swarms that post-date the batholith injection.

Completely weathered masses display permeabilities of 2×10^{-4} to 1×10^{-7} m/s. The specific example that was given by Morton and Leonard[3] shows a strikingly bimodal material with permeabilities of from 1×10^{-5} to 1×10^{-6} m/s. It would seem that this characteristic is

SHAFTS

1. To reduce permeability thereby limiting settlements related to lowering of water table.

2. To improve stability and safety of excavation.

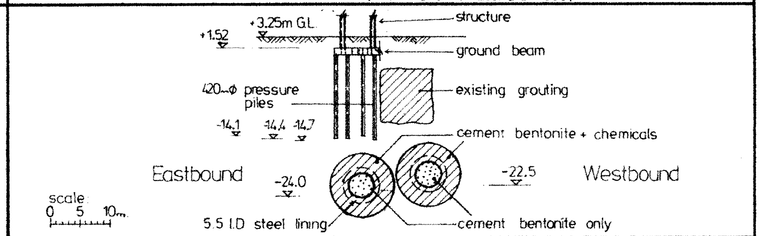


TUNNELS

1.)
2.) As for SHAFTS

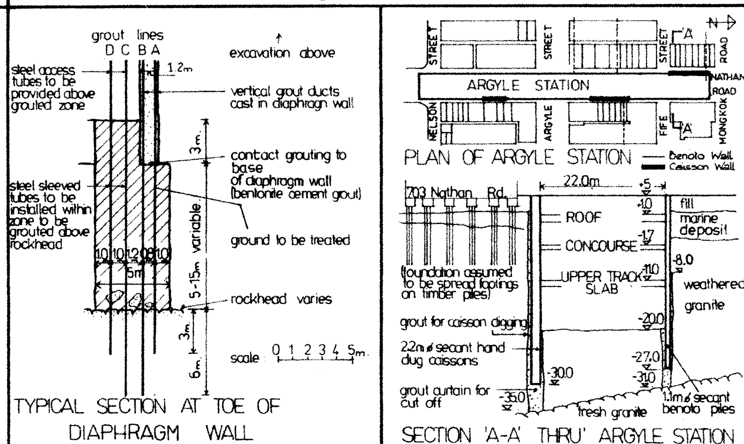
3. To reduce compressed air loss or eliminate need entirely.

4. To seal rock/soil interface.



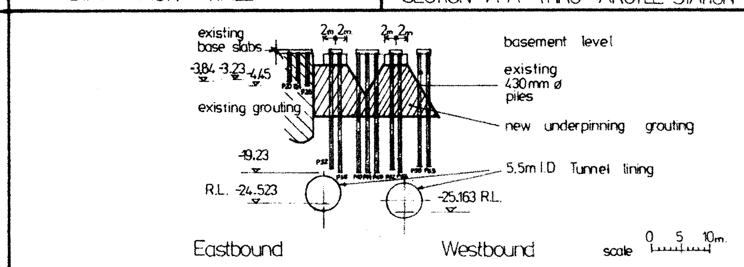
DIAPHRAGM, PILED AND CAISSON WALLS

1.)
2.) As for SHAFTS



EXISTING FOUNDATIONS

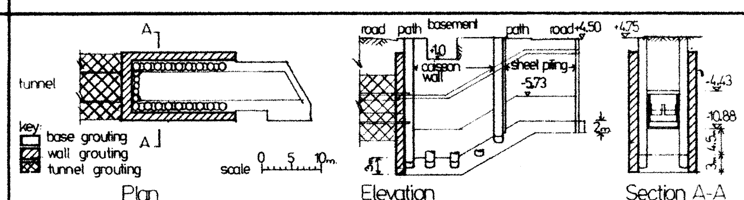
1. To improve the strength of the ground to prevent excessive and/or differential settlements, by underpinning.



EXCAVATIONS

1.)
2.) As for SHAFTS

3. As horizontal membrane to resist uplift forces.



REMEDIAL WORKS

For all the above purposes in cases where the foreseen method proves locally problemmatical.

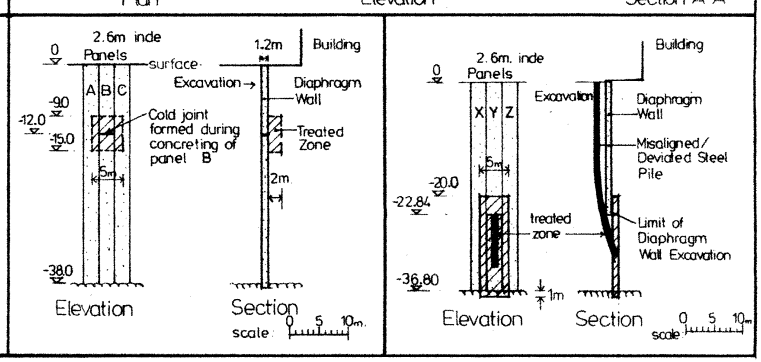


Fig 2. Summary of major grouting applications

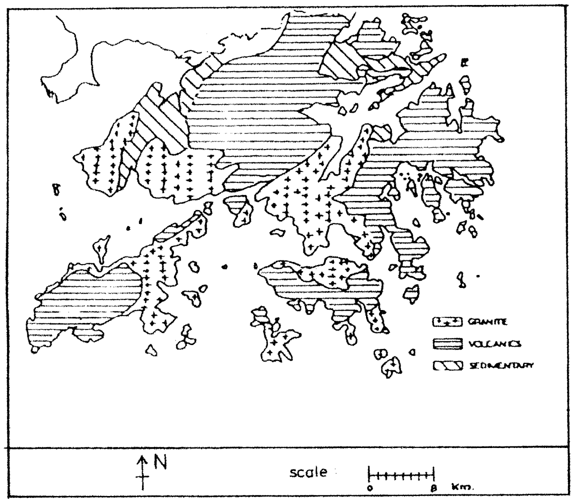


Fig 3. Geological sketch map of Hong Kong. After Lumb[4]

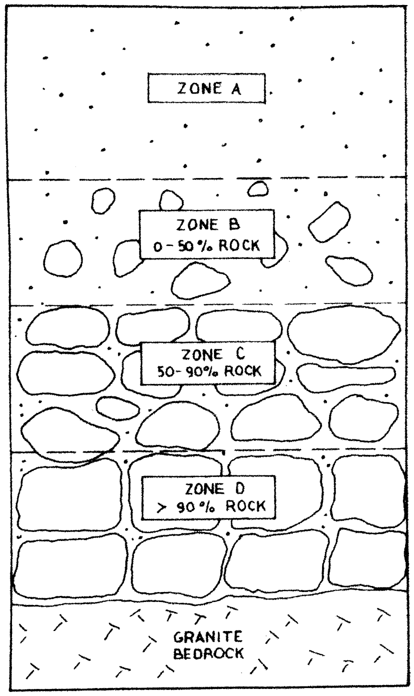


Fig 4. Idealized weathering profile of Hong Kong granite. After Linney[7]

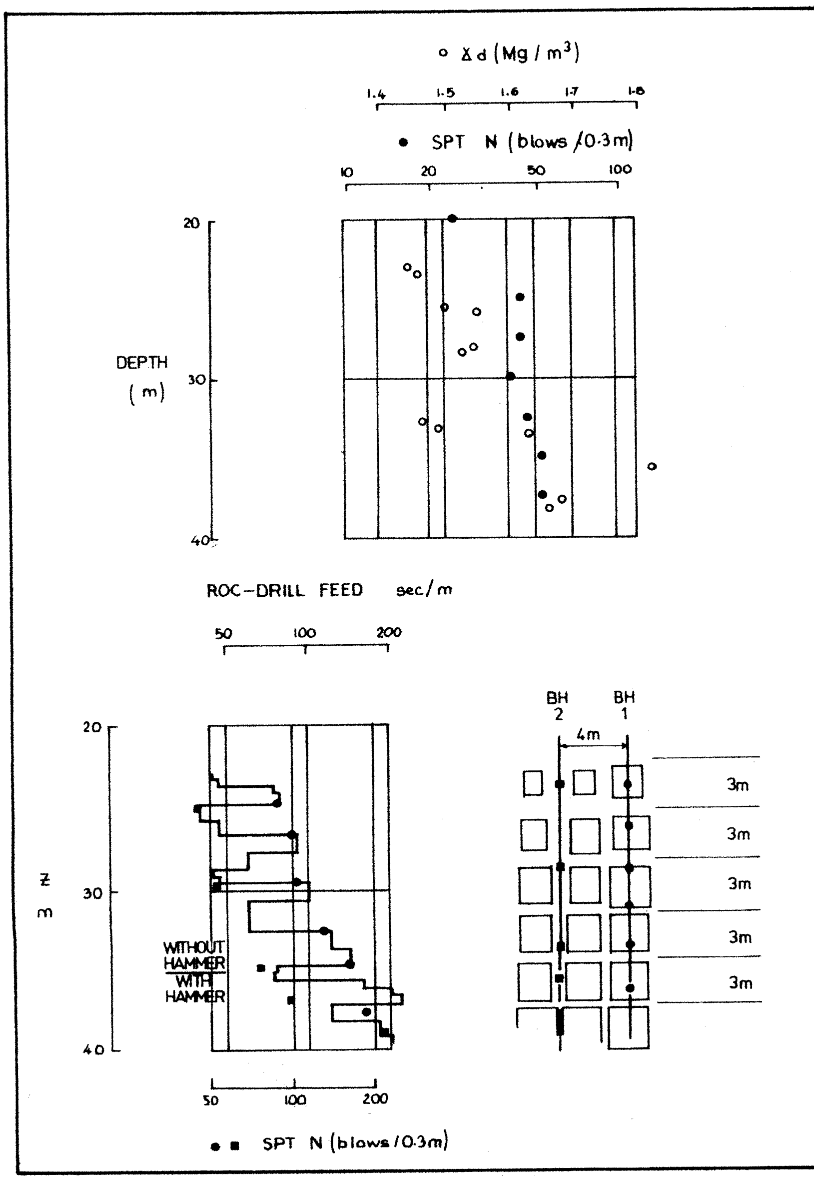


Fig 5. Dry density, SPT and drillability profile, MTR site, west Hong Kong. After Howat[8]

consistent with the varying degrees of weathering, and is reflected in the bimodal strength data recorded by Howat[8]. Typical dry density, SPT and drillability profiles recorded in west Hong Kong by the same author are shown in Fig 5.

Envelope grading curves are shown in Fig 6. Lumb[9] noted that the curves are all skew, with a wider range of fine material than coarse; with increasing decomposition the grading becomes bimodal as the quartz remains unchanged but the feldspar becomes progressively finer.

EXECUTION OF GROUTING

The MTR specification requires the basic method of treating materials other than rock to employ perforated pipes with rubber sleeve valves, and so the tube à manchette system, as described by Ischy and Glossop[10] is commonly used.

Rotary, and rotary percussive, duplex drilling with pneumatic and hydraulic drilling rigs (Fig 7) has proved to be necessary to penetrate the onerous ground conditions to permit the installation of the tubes. The inter-hole spacings, in the zones to be grouted, are from 1 to 1.5m (average 1.2m), but often holes have to be fanned from the surface to accommodate access and service restraints (Fig 8). The tubes are typically plastic, and approximately 50mm in diameter, although in certain cases, especially for deep holes under diaphragm walls, steel tubes have been used. Both types have injection sleeves at 0.33-m intervals.

A phase of cement-bentonite grouting is conducted prior to chemical treatment to 'repair' any damage to the ground caused during the (water-flushed) drilling activities, permeate any coarse, highly permeable zones and fill any major relic fissures in the mass (Flintoff and Cowland[11] referred to sets at 1.5- to 10.0-m spacings).

Injections are typically made at 1-m ascending stages over the entire volume to be treated. The specification calls for a minimum solids content of 350kg OPC and 35-70kg bentonite per cubic metre of grout.

At injection rates of up to 8 l/pump/min flow pressures of 5-15 bar are typical of the cwg, although pressures of up to 25 bar (more than twice overburden) have been exercised. Such pressures during tunnel pre-grouting have occasionally resulted in local surface heaves of up to 30mm, but they have at no time been judged deleterious. Target volumes are preset, based on notional groutable voids figures, and any groups of sleeves that accept this target volume at below overburden pressure are re-injected. Pressure-volume-time records are maintained for each injection. Back-analyses show typical cement-bentonite takes to be equivalent to 6-10% of the theoretical treated ground volume.

Chemical grouting is afterwards conducted through the same holes and, except in the case of certain shafts and tunnels, at the same horizons: in these cases the chemical treatment is restricted to an annuloid of thickness 2-3.5m. Flow rates and injection pressures are generally as for the cementitious phase, and reinjection is conducted wherever necessary. Injections are usually made at 0.33-m vertical intervals. Surface heave due to chemical injection is very rarely encountered, and has never exceeded 10mm.

The specification calls for the chemical grout to satisfy the following criteria: gelling time, 15-90min; non-toxic; confer to a standard fine sand a UCS of 0.2-0.3N/mm² under stipulated test conditions (a stronger gel is required for underpinning : 0.8-1.0N/mm²); viscosity <5 cP (<8 cP for stronger gel) for as much of the gelling period as possible; to remain effective for at least 30 months.

Excellent and long field experience, coupled with economic considerations, has led to the widespread adoption of silicate-based grouts (sodium silicate and an appropriate reagent). A popular choice of materials is noted in Table 1.

The effect on the chemical grout of varying the percentages of each component is illustrated, for the case of the 600 Series hardener, in Fig 9. Typical grouts comprised 33-40% silicate and 3.5-4.5% hardener (both by volume). Back-analyses of chemical grout takes indicates a notional consumption of 25-30% in cwg (approximately 20% in silty marine deposits, 35% in sandy marines, and >40% in alluvium and similar).

Sodium silicate	
Type 35-37° Bé SiO_2/Na_2O, 3.1 (wt radio) Sp.gr., 1.31	For normal purposes
or	
Type 40-42° Bé SiO_2/Na_2O, 3.0 (wt ratio) Sp.gr., 1.37 approx.	For underpinning purposes
Reagent Rhone Poulenc 600 Series hardener Long-chain compound diacid ester Sp.gr., 1.09 approx.	

Table 1. Typical materials for silicate group formulations.

ASPECTS OF GROUTING THEORY

Most grouting applications feature injections into *pre-existing* voids, fissures or pores and, by way of illustration, these may range from bulk infill[12], through rock grouting[13] to alluvial treatment[14]. The selection of the grouting material and methods reflects the purpose of achieving efficient safe and economic permeation at acceptable injection rates.

Typically, definitive texts on alluvial grouting show the limits of permeation to be expected (e.g. Fig 10) for standard grouting materials as a function of ground permeability, itself dictated by the natural ground microstructure. Empirical rules do exist[15], with their bases in

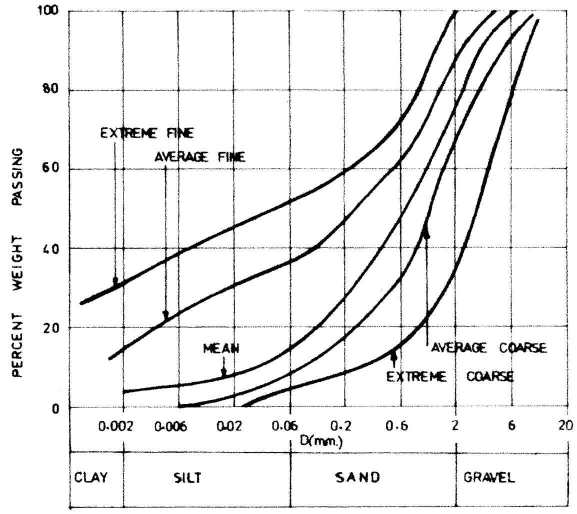


Fig 6. Limiting and average grading curves of decomposed granite (72 samples). After Lumb[9]

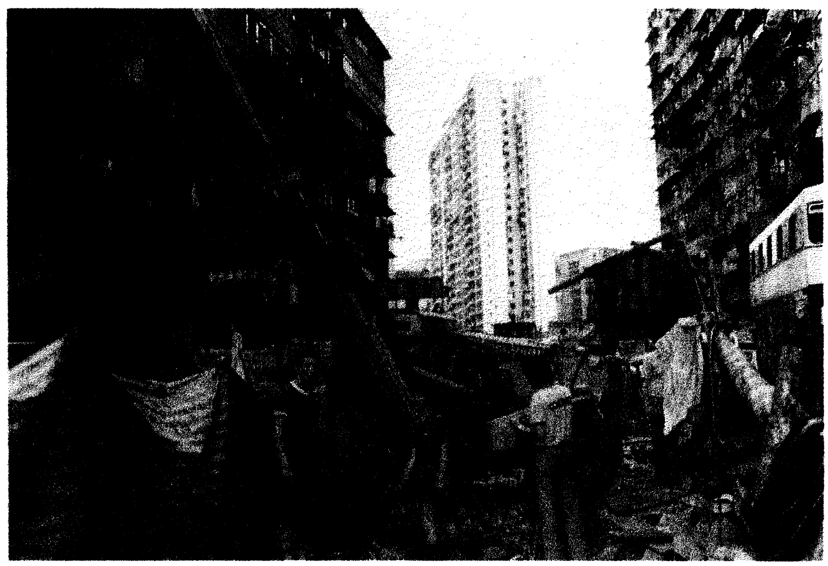
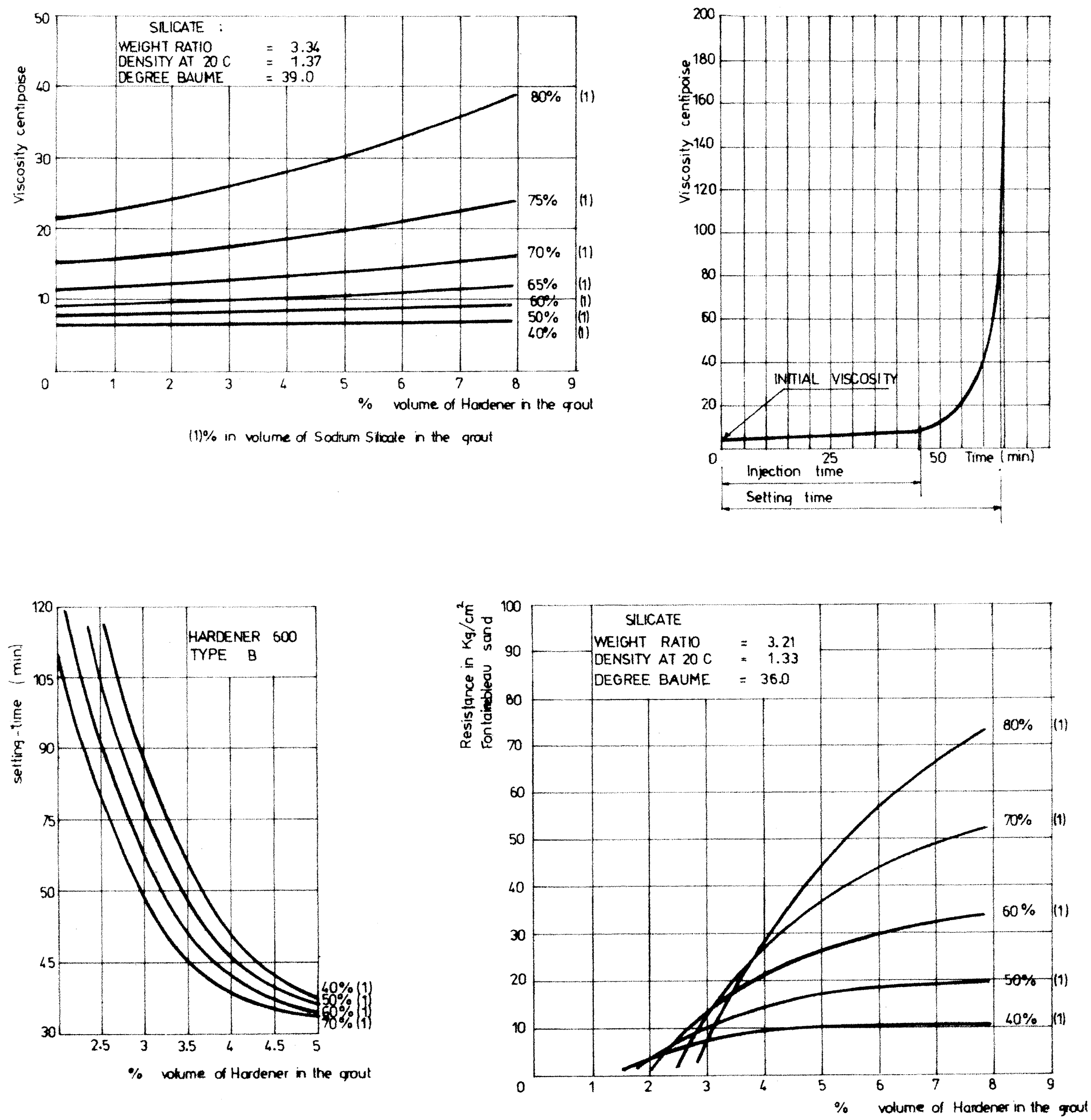


Fig 7. Diesel hydraulic drilling rig for installation of tubes

Fig 8. Placing of ducts to avoid damage to near- surface services



	Type B	Type C	Type D	Type E
Smell	very weak	very weak	very weak	very weak
Colour	dark brown	dark brown	dark brown	dark brown
Melting point	<-30°C	<-30°C	<-30°C	<-30°C
Boiling point	220°C	229°C	232°C	236°C
Flash point	> 93°C	> 93°C	> 93°C	> 93°C
Fire point (Cleveland)	118°C	>118°C	>118°C	>118°C
Density at 20°C	1.09	1.06	1.04	1.03
Viscosity at 20°C	5 cp	5 cp	5 cp	5 cp

Fig 9. Data on Rhone Poulenc 600 Series – silicate chemical grouts. From technical brochure

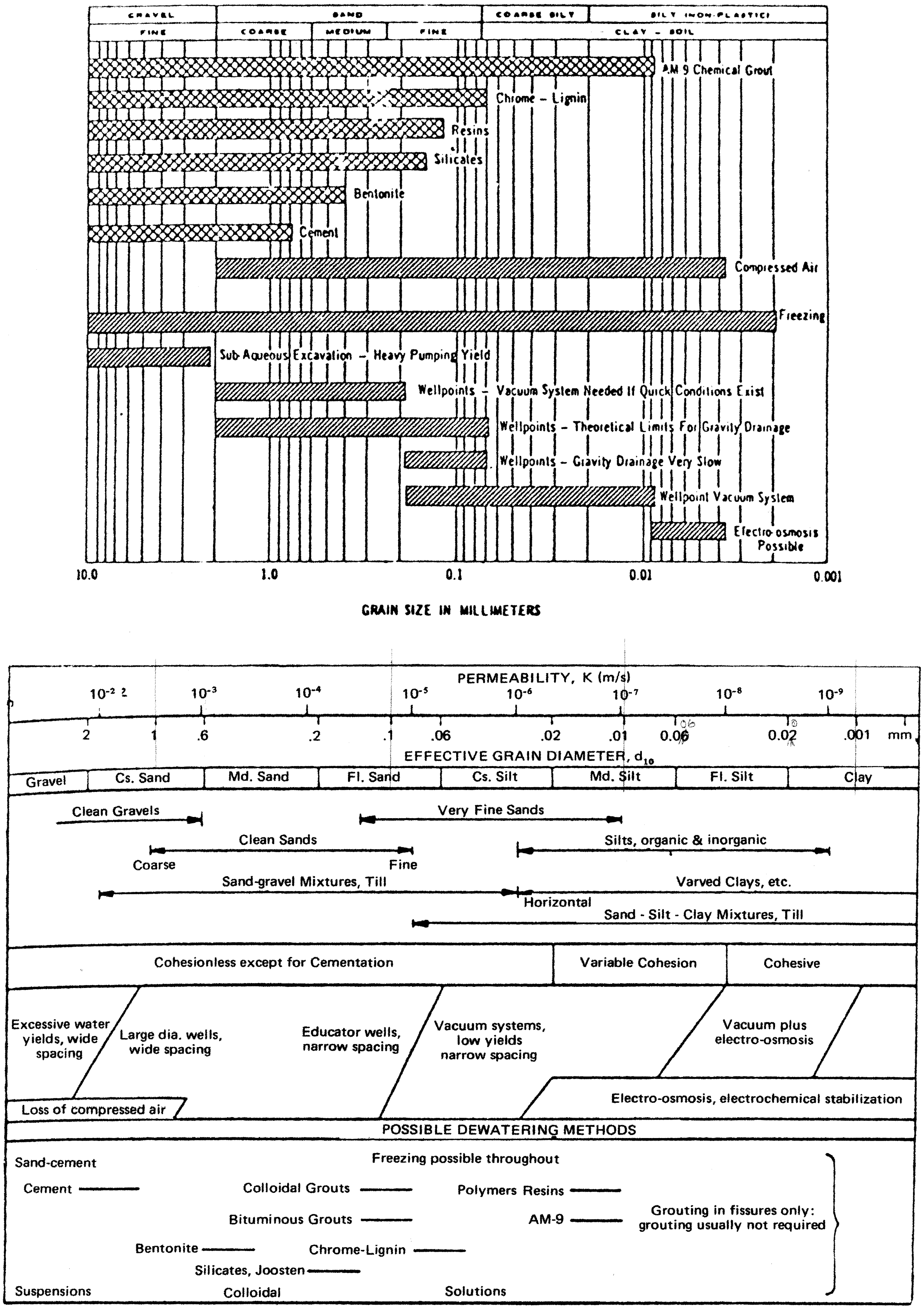


Fig 10. General theoretical limits of grout permeation. After FHA[15]

filter criteria, that attempt to quantify the limits of groutability. For example, D_{15}(soil) should be greater than $25D_{85}$(grout) for successful permeation. Similarly, for the specific case of silts Littlejohn and co-workers[16] recorded that the predominant pore size is approximately equal to the effective size (D_{10}) of the soil; statistical theory[15] indicates that blockage is highly probable when the pore size is less than three times the D_{90} of the material that is being injected. For silicate-based grouts Baker[17] proposed the limits of Fig 11, which indicates that permeation is possible in alluvial soils with up to 20% finer than 50μm, reflecting that even chemical grouts may contain particles up to 20μm.

The numerous mathematical analyses[18,19,20] that can be cited, however, are based on the assumption that chemical grouts behave as true fluids. These relate the injection hydraulic head, H, required for any given radius of treatment, R, directly to the flow rate, Q, and grout viscosity, μ, and inversely to ground permeability, K:

$$H = \frac{Q}{4\pi K}\left[\mu\left(\frac{1}{r}+\frac{1}{R}\right)+\frac{1}{R}\right] \qquad (1)$$

where r is radius of spherical injection source of length L, and diameter D, and $r = \frac{1}{2}\sqrt{L.D}$ approximately.

If the pressure that results from the choice of certain parameters in equation (1) is greater than the 'fracture resistance' of the ground, the phenomenon of hydrofracture or *claquage*[21] will result. Morgenstern and Vaughan[22] reported that this pressure could be calculated thus:

$$Pf = \frac{(\gamma h - \gamma w h w)(1+k)}{2} - \frac{(\gamma h - \gamma w h w)(1-k)}{2\sin\phi'} + c'\text{Cot}\,\phi' + \gamma w h w + L \qquad (2)$$

where Pf is injection pressure at fracture, γ is bulk density of material above the level under consideration, γw is density of water, h is height of material above the level, hw is height of groundwater above the level, k is principal stress ratio, L denotes losses during injection, ϕ' is angle of shearing resistance and c' is cohesion intercept.

Since losses, L, especially through tube à manchette systems, are difficult to identify, and ground strength is awkward to assess acurately, equation (2) is not widely used for specific calculations, and prior experience dictates safe grouting pressures to avoid hydrofracture, the results of which may be potentially dangerous, and always difficult to control. Equation (2) does emphasize, however, that fracture pressure, Pf, is also related to the 'ground strength' and not merely the overburden pressure.

PERFORMANCE OF GROUTING

Of the numerous applications outlined above, that which is subsequently demonstrated most clearly is grouting for tunnel or shaft stabilization. The results of excavating in untreated cwg were described by Haswell and Umney[1]: seepage occasioned degeneration, loss of cohesion and eventually ground collapse, as was noted by Peck[23].

To date, several hundred metres of tunnels up to 8m in diameter and often under 30m or more hydraulic head have been driven in treated cwg in free air. Minor seepage, compatible with permeabilities of $1 \times 10^{-6} - 1 \times 10^{-7}$ m/s, is commonly found, but does not lead to significant deterioration of the grouted mass. There is a marked and observable increase in strength: treated ground requires excavation with points, whereas clay spades suffice to remove untreated materials in compressed-air tunnels. Quantitification of this strength increase is practically impossible owing to the difficulty of measuring the properties of the virgin mass and the problems of obtaining undisturbed samples from the treated ground.

Exposure of tubes during tunnelling shows good regular geometries, with deviations of up to 1 in 50 at most over drilled depths of 40m. Cement-bentonite lenses of thickness 5-40mm, and extending for more than 10m, have been noted. Laboratory testing of recovered grout samples gives average densities just above 2Mg/m^3 ($\equiv$ w/c of less than 0.4) compared with mixed grout densities of typically 1.26Mg/m^3 (w/c almost 2.5). Clearly, an expression of water, into the ground, has occurred during the injection and stiffening phases, thereby leaving a grout of a strength that is considerably higher than the original.

With respect to the performance of the grouting as used to form curtains, Morton and Leonard[3] reported on reductions in permeability of between 300 and 1200 times in three-row curtains to >40m depth in cwg in Kowloon. In addition, they made extremely valid observations regarding the assessment of the degree of improvement in relation to tests conducted at a nearby shaft grouting location: initial borehole permeability tests gave virgin permeabilities around 5×10^{-5}m/s, apparently reduced after grouting to about 1.6×10^{-6}m/s (i.e. a reduction of 31 times). The actual seepage into the excavation was, however, consistent with an overall ground performance of 3×10^{-7}m/s (i.e. a reduction of 160 times), which was held to be far more meaningful. They strongly urged caution in executing and analysing borehole permeability tests in reasonably impermeable ground, bearing in mind that these results are very sensitive to leakage in the testing apparatus.* Observations that were made during tunnelling have been supplemented by Mazier core samples retrieved from test boreholes. Visual assessment of chemical permeation is facilitated by the technique of spraying fresh

*In constant head testing a post grouting permeability of 10^{-7} m/s is equivalent to injecting 20cm^3 water per minute. Hence, accurate results demand losses of less than 0.1cm^3/s. This is unrealistic regardless of the time and skill taken to form the 'test cell'. Such methods can therefore only be valid to 10^{-6}m/s.

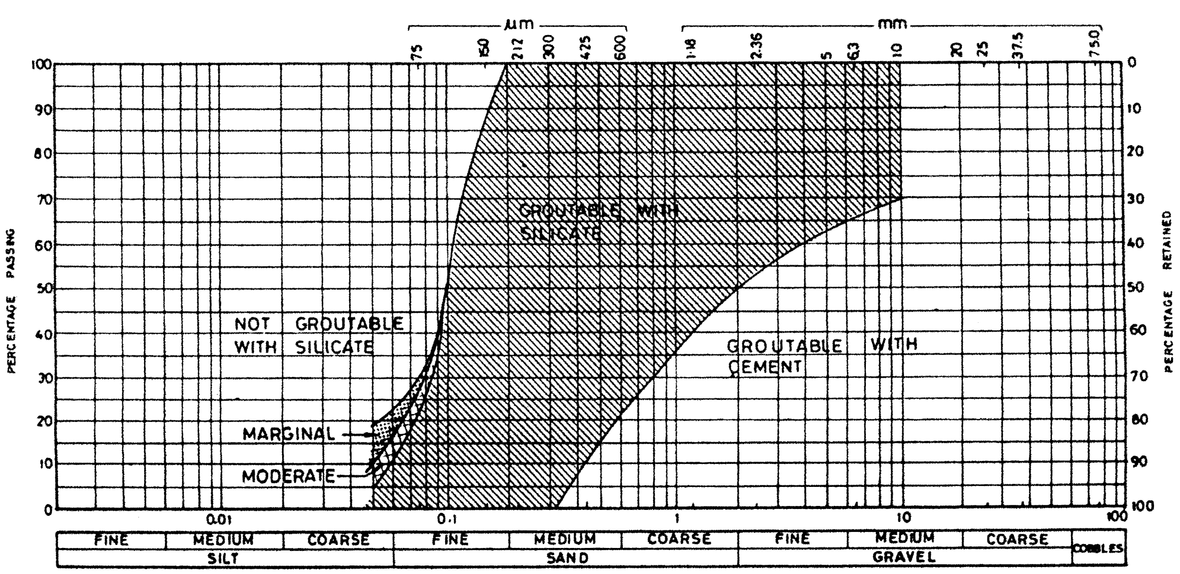


Fig 11. Limits of silicate permeation in alluvial soils. After Baker[17]

samples with phenol phthalene solution. This gives a red reaction from a *PkI* 9.7. Results from one particular site are shown in Fig 12. More generally, reaction results from 56 samples obtained from a variety of sites are shown in Table 2.

It is significant that 32 of the 43 grouted samples had at least 20% fines, whereas none that did not react had less than 20% fines. The averaged fines content of all samples was 31% (cf. the 15% mean of Lumb[9]): 78% of the samples showed positive reaction.

Fines in sample, %	0-10	10-20	20-30	30-40	40-50	50-60
Reaction to test for presence of chemical grout:						
Positive *(total, 43)	2	9	14	15	3	0
Negative *(total, 13)	0	0	5*	2	4	2

*Includes two samples in region not regrouted following initial low-pressure attempt.

Table 2. Summary of results obtained on 56 samples of treated cwg

DISCUSSION OF OBSERVATIONS AND TEST RESULTS

Demonstrably good results have been obtained by silicate-based treatment of the decomposed granites in Hong Kong. This success seems to contradict standard theory as related to permeability (virgin permeabilities have often been significantly lower than the conventional 1×10^{-5} m/s limit for successful permeation, and post-grouting permeabilities as low as 1×10^{-7} m/s are frequently recorded) and grading* (most samples treated successfully had fines contents far in excess of the 20% limit usually advocated). In formulating a reconciliation it is instructive to assess the contribution of each successive stage of the ground treatment process.

Installation of tubes. It has been established that the decomposed granites retain a relict structure, in a general way increasingly clearly defined with depth. Thus, the insertion of closely spaced plastic tubes, strong in tension, and surrounded by a cementitious annulus of appreciable strength (up to 4N/mm²) could be held to contribute to the overall mechanical improvement of the ground in a way similar to the *pali radice* principle described by Lizzi[22]. In support of this proposal are the numerous observations of exposed faces where large blocks of ground appear supported by adjacent tubes, especially so in inclined hole locations. In any event, the annulus grouting clearly contributes to the consolidation of the upper permeable fill horizons and so aids the formation of a shallow 'crust' in these regions.

Cement-bentonite grouting. The common observation of lenses of grout of appreciable thicknesses travelling many metres from source has been remarked on, and there would seem little doubt that the three principal aims of this phase, outlined above, are fulfilled. A common suggestion is that the travel of the grout in veins and lenses compresses the enclosed volumes of cwg, therefore reducing their voids ratio, increasing the frictional properties and reducing the permeability. Given the volume reduction commensurate with the increased density of the set grout now measured, however, it would seem that the actual strain exerted on the ground is small (probably less than 1%). Thus, the resultant degree of improvement in the strength and permeability of the cwg at the injection level would appear to be minimal.

Anomalously, in the fresher granites an improvement in mass permeability can be expected, as the grout will penetrate and seal rock fissures intersected by the tubes, dependent always, of course, on their geometry and cleanliness.

A secondary contribution of this phase, however, is often apparent. Excessive ground heave has not been recorded, even when injecting at flow pressures several times overburden. In addition, the presence of injected grout in the very permeable upper horizons has often been revealed during post-grouting coring programmes. (These horizons have also yielded permeability readings consistent with permeation by cement-bentonite grouts.) It is therefore reasonable to assume that upward migration of grout does occur, and that on reaching suitable ground it flows laterally, so forming a horizontal membrane over the ground designated for treatment. This blanket apparently dissuades the subsequent upward migration of the chemical grout, which is therefore constrained to flow laterally into the horizons bearing the

*It is noted that the fines contents of materials encountered on MTR works have generally been higher than the 'general cwg' figures quoted by Lumb[9]. It is suggested that since all of the MTR samples were taken from depths well below existing groundwater level little leaching out of (fine) decomposition products has occurred. In contrast, many of the 'general' samples were taken from hillside locations where leaching could well have taken place.

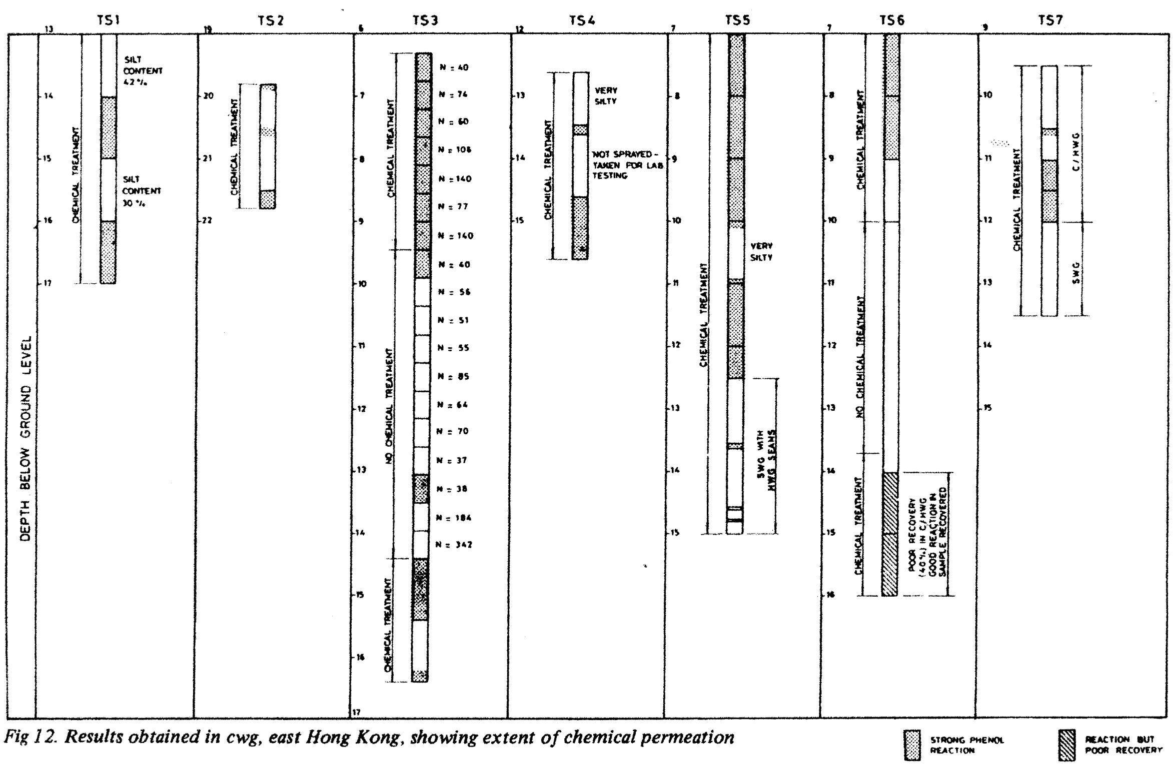


Fig 12. Results obtained in cwg, east Hong Kong, showing extent of chemical permeation

injection sleeves. In addition, it is reasoned that such horizontal grout curtains, lying above the face to be tunnelled or the toe to be sealed, act towards locally reducing the hydraulic forces that act on such openings and so contribute to the reduction of seepage. Soft, untreatable pockets occur inevitably: within the time frame of the construction cycle, however, they show little tendency to dislodge owing to seepage forces, although they can easily be disturbed by hand.

Chemical grouting. Observations have shown uniform permeation of chemical grout radiating away from injection points and, occasionally, following the lines of cement-bentonite travel. Coupled with the belief that the other steps in the ground treatment process do little to improve the properties of the cwg micro-fabric, it is held that its local reduction in permeability and increase in strength are largely due to the chemical grouting. Thus, silicate permeation is occurring in material of virgin permeability often as low as 1×10^{-6} m/s, and of high fines contents.

By way of explanation, one factor that merits consideration is the method of treatment. Modern reagents give acceptably high strength and stable gels at low concentrations and viscosities, and yield excellent viscosity-time characteristics. In addition, the natural 'strength' of the ground and the inferred presence of horizontal cement-grouted membranes permit relatively high grouting pressures to be exercised and so allow more work to be done on the ground while economic injection rates are maintained. More fundamental, however, would appear to be the rather special nature of the cwg itself, as suggested by the apparent contradiction of permeabilities and particle-size distribution: the average virgin permeability of the cwg (and its degree of groutability) are significantly higher than would seem consistent with the grading analysis. (The possibility of micro-fracturing in the cwg is not considered valid, as it is only in less weathered masses that such structural discontinuities are apparent.)

Baynes and Dearman[6] observed that weathering of feldspars produces a variety of micro-fabrics, including an extremely open feldspar micro-fabric consisting of thin struts of feldspar. extremely porous cardhouse clay micro-fabric and densely tightly packed clay aggregations.

It was also recorded that 'very variable micro-fabrics were often found in the same specimen indicating a marked variability of weathering environments'. Mitchell and Sitar[25] found that 'cementation of particles into clusters and aggregates by the sesquioxides and the hydrated state of some of the minerals is responsible for high voids ratios (low densities), high strength, low compressibility and sometimes high permeability, in relation to the plasticity and small particle size that would be anticipated on the basis of the content of clay size particles'.

Hence, the picture emerges of cwg being a material that features, in random distribution, dense agglomerations of clay minerals and very open permeable microstructures in other pores. Grading curve analyses will not differentiate the source of the large fines contents so held and, indeed, Gammon[26] recorded almost identical curves for an apparently clayey residual soil, and an apparently coarse-grained cwg. Such curves, therefore will indicate nothing of the pore size distribution and characteristics, and so the permeability and groutability[21]. Conversely, in the case of the deposits that are usually measured in providing standard curves (e.g. Fig 10) the fines may be expected to be more evenly distributed throughout the material, and so the link between their size and frequency, and therefore pore size, is more predictable.

CONCLUSIONS

Consistently excellent performances have been recorded by silicate-based permeation of cwg in association with the construction of the MTR in Hong Kong. These results are confirmed, despite the facts that virgin permeabilities of 1×10^{-6}m/s, and fines contents of more than 40%, have been measured for the cwg – both parameters consistent with 'ungroutable' ground on the basis of conventional theory. Certain aspects of the execution can be cited as contributory factors, such as the use of modern low-viscosity, stable, high-strength gels, and the facility to apply relatively high pressures without inducing hydrofracture or surface heave. It would seem, however, that it is the microstructure of the cwg itself, and, in particular, the concretionary nature of the fines distribution (and therefore the presence of atypically large pores), which has permitted effective permeation. Thus, although it is now valid to extend the theoretical and practical limits of silicate grouting in residual soils, there is no suggestion that reassessment of grouting theory in deposited materials is warranted, even given recent advances in grouting methodology.

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