PROPERTIES OF CEMENT BASED PERMEATION GROUT USED IN GROUND ENGINEERING

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2005
PROPERTIES OF
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GROUND ENGINEERING

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A THESIS SUBMITTED
FOR THE DEGREE OF MASTER OF ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING
NATIONAL UNIVERSITY OF SINGAPORE
2005
The author wishes to express his deep gratitude to his supervisors, Professor Y. K. Chow and Professor K. Y. Yong for their guidance and advice throughout the course of this study. Special thanks go to Emeritus Prof. S. L. Lee for the helpful discussion and advice on the research.

Many thanks go to the technical staff of the Geotechnical Engineering Laboratory and the Concrete and Structural Engineering Laboratory, Department of Civil Engineering, National University of Singapore for their assistance in the fabrication of test apparatus for grout permeability tests and the testing of cement grout viscosity using Rotary Viscometer, respectively.

The author is deeply grateful to his employer, Moh and Associates (S) Pte Ltd, who was responsible for the financial support of this research and his colleagues, Mr. Sutristno bin Mangon, Mr. Kang C. Y. and Mr. T. M. Than for their assistance in carrying out the grout permeability tests.

Last but not least, special recognition must go to Dr. Z. C. Moh for his encouragement throughout the author’s working and study periods and his wife, Tan Choo Leh, who has given him tremendous support and inspiration over the years of this study.
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This thesis presents the results of a study on the properties of cement based permeation grout, focusing on some important grout parameters, such as the rheological properties (i.e. yield stress and viscosity) and the injectability of cement grout, (i.e. coefficient of permeability to grout, \( k_G \)) which govern the performance of cement based permeation grouting in porous media. Due to the limited knowledge of these important grout parameters and other influencing factors, e.g. the stability, pressure filtration (i.e. loss of water under the applied pressure), setting time of cement grout, the pressure, rate and time of injection and the grout volume adopted in the field work, the application of cement based permeation grouting is still largely a trial and error process in the current practice, especially in the local construction industry.

According to Landry et. al. (2000), there are no truly reliable small scale (i.e. <100 mm in diameter) or laboratory methods which will accurately determine the injectability limits of soils characterized by grain size, water permeability coefficient and silt content. Research works on permeation grouting using ordinary Portland cement (Type I) are found to be limited and insufficient for practical reference. In the present research, an experimental study on the rheological properties of various cement grout mixes with water/cement ratio (W/C, by weight) of 0.6, 0.8, 1.0, 1.2 & 1.5 and its grout flow characteristics in porous media with particle size ranging from 2 mm to 6 mm which belongs to coarse sand with gravels (< 5%) in accordance with ASTM classification was carried out for enhancing the knowledge of the local practitioners in the application of cement based permeation grouting in coarse sand.

The flowability study was carried out using 3 different test apparatus consisting of i) triaxial test chamber in view of its common availability; ii) perspex pot in view of
its advantages of allowing a visual inspection on the flow characteristics of grout and
the better flowability of this test system as compared with that in the triaxial test
chamber iii) steel test chamber designed by the author based on his practical
experience with significant improvement in preventing problem associated with
sedimentation of cement particles and blockage as experienced in the other two (2)
test setup.

The present research provides the practitioners with the following useful
information for enhancing the design and application of cement based permeation
grouting using existing flow models (Raffle and Greenwood, 1961) in the local
practice.

1. The rheological properties of various grout mixes using ordinary Portland cement
   (Type I / trade name : Asia Cement) commonly adopted in the local construction
   industry were determined from a series of Viscometer Tests;

2. The influence of test set up (e.g. small tubing and pedestal in Triaxial System) to
   flow measurement, especially the under-estimation of water flow in coarse sand
   measured in Constant Head Triaxial Permeability Test was investigated and
   verified by tests ;

3. The impracticality of the empirical relationship between k and D_{10}, i.e. k (cm/sec)
   = C x (D_{10})^2 (Kutzner, 1996) for fine to medium sand (with grain size similar to
   the sandy soil commonly found in the local geological formation, i.e. Old
   Alluvium, OA and Bukit Timah Granite, BT) including the influenced percentage
   of fines (i.e. 10%) to water permeability was verified in the present research;
4. The non-effectiveness of cement based permeation grouting in fine to medium sand due to its low water permeability coefficient was demonstrated by a series of grout permeability tests with the feasible water/cement ratio (i.e. W/C = 6.0) for injection determined from the tests;

5. An indicative trend showing decreasing coefficient of permeability ($k_G$) with increasing injection pressure ($P_p$) was found for the injection of cement grout in tested coarse sand (i.e. 2 mm to 6 mm diameter) due to the non-linear relationship between hydraulic gradient ($i$) and flow velocity ($v$) of grout identified in the grout permeability tests.

6. The extent of treatment for a fixed value of soil permeability which could be improved by increasing the injection pressure was found to be less significant and could be limited for cement grout with low water/cement ratio of 0.6 due to its high viscosity and internal friction.

7. The relationships between $k_G$, $i$, $v$, W/C and viscosity for cement grout mixes with W/C=0.6, 0.8, 1.0, 1.2 & 1.5 were studied via a comprehensive experimental programme in the present research for more representative determination of the grout permeability coefficient ($k_G$) in permeation grout application, taking into consideration of the influence of injection pressure through the non-linear relationship between hydraulic gradient and velocity of cement grout flow established from the present works.

KEYWORDS : cement based permeation grout, rheological properties, Bingham’s fluid, injection pressure, Darcy’s law, coefficient of permeability, hydraulic gradient, flow velocity, coarse sand
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<thead>
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<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>A</td>
<td>cross-sectional area perpendicular to the direction of flow (m²)</td>
</tr>
<tr>
<td>C_c</td>
<td>Uniformity Coefficient = $D_{60} / D_{10}$</td>
</tr>
<tr>
<td>C_u</td>
<td>Coefficient of Curvature = $(D_{30})^2 / (D_{60} \cdot D_{10})$</td>
</tr>
<tr>
<td>D_10</td>
<td>10% finer size from grain size distribution curve of soil</td>
</tr>
<tr>
<td>D_15</td>
<td>15% finer size from grain size distribution curve of soil</td>
</tr>
<tr>
<td>D_30</td>
<td>30% finer size from grain size distribution curve of soil</td>
</tr>
<tr>
<td>D_60</td>
<td>60% finer size from grain size distribution curve of soil</td>
</tr>
<tr>
<td>d_85</td>
<td>85% finer size from grain size distribution curve of cement</td>
</tr>
<tr>
<td>d_95</td>
<td>95% finer size from grain size distribution curve of cement</td>
</tr>
<tr>
<td>e</td>
<td>void ratio</td>
</tr>
<tr>
<td>G_s</td>
<td>specific gravity of soil particles</td>
</tr>
<tr>
<td>h</td>
<td>hydraulic head (m)</td>
</tr>
<tr>
<td>i</td>
<td>hydraulic gradient (m/m)</td>
</tr>
<tr>
<td>k</td>
<td>coefficient of permeability to water (m/sec)</td>
</tr>
<tr>
<td>k_G</td>
<td>coefficient of permeability to grout (m/sec)</td>
</tr>
<tr>
<td>K</td>
<td>intrinsic (absolute) permeability coefficient of porous media (m²)</td>
</tr>
<tr>
<td>n</td>
<td>effective porosity of aggregate media</td>
</tr>
<tr>
<td>N_c</td>
<td>$D_{10} / d_{95}$</td>
</tr>
<tr>
<td>N</td>
<td>$D_{15} / d_{85}$</td>
</tr>
<tr>
<td>Pas</td>
<td>pascal-second =$1 \text{ N s/m}^2$</td>
</tr>
<tr>
<td>P_p</td>
<td>effective injection pressure (kN/m²)</td>
</tr>
<tr>
<td>Q</td>
<td>volumetric flow rate (m³/sec)</td>
</tr>
<tr>
<td>t</td>
<td>flow time (sec)</td>
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<table>
<thead>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>W/C</td>
<td>water / cement ratio (by weight)</td>
</tr>
<tr>
<td>η</td>
<td>apparent viscosity (Pas)</td>
</tr>
<tr>
<td>η_p</td>
<td>plastic viscosity (Pas)</td>
</tr>
<tr>
<td>τ</td>
<td>shear stress (Pa)</td>
</tr>
<tr>
<td>τ_o</td>
<td>yield stress (Pa)</td>
</tr>
<tr>
<td>˙γ</td>
<td>shear rate (s⁻¹)</td>
</tr>
<tr>
<td>ρ</td>
<td>density of fluid (kg/m³)</td>
</tr>
<tr>
<td>γ,t</td>
<td>total unit weight (kN/m³)</td>
</tr>
<tr>
<td>γ,d</td>
<td>dry unit weight (kN/m³)</td>
</tr>
<tr>
<td>γ,w</td>
<td>unit weight of water (kN/m³)</td>
</tr>
<tr>
<td>w</td>
<td>moisture content (%)</td>
</tr>
<tr>
<td>w_L</td>
<td>Liquid limit (%)</td>
</tr>
<tr>
<td>w_p</td>
<td>Plastic limit (%)</td>
</tr>
<tr>
<td>I_p</td>
<td>Plasticity index (%)</td>
</tr>
<tr>
<td>S_r</td>
<td>degree of saturation (%)</td>
</tr>
<tr>
<td>σ,</td>
<td>total, effective normal stress (kN/m²)</td>
</tr>
<tr>
<td>σ_1,</td>
<td>total, effective major principal stress (kN/m²)</td>
</tr>
<tr>
<td>σ_3,</td>
<td>total, effective minor principal stress (kN/m²)</td>
</tr>
<tr>
<td>σ_1-σ_3</td>
<td>deviator stress (kN/m²)</td>
</tr>
<tr>
<td>σ_c</td>
<td>consolidation pressure (kN/m²)</td>
</tr>
<tr>
<td>σ_v,</td>
<td>total, effective vertical stress (kN/m²)</td>
</tr>
<tr>
<td>σ_h,</td>
<td>total, effective horizontal stress (kN/m²)</td>
</tr>
<tr>
<td>σ_c</td>
<td>cell pressure in triaxial cell (kN/m²)</td>
</tr>
<tr>
<td>u</td>
<td>pore water pressure (kN/m²)</td>
</tr>
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xv
**NOTATIONS**

\( u_b \) \quad \text{back pressure in triaxial test (kN/m}^2) \)

\( p \) \quad \frac{\sigma_1 + \sigma_3}{2} \quad \text{(kN/m}^2) \)

\( \bar{p} \) \quad \frac{\bar{\sigma}_1 + \bar{\sigma}_3}{2} \quad \text{(kN/m}^2) \)

\( q, \ q \) \quad \frac{\sigma_1 - \sigma_3}{2} \quad \text{(kN/m}^2) \)

\( a \) \quad \text{intercept of } q_f \text{ versus } p_f \quad \text{(kN/m}^2) \)

\( \bar{a} \) \quad \text{intercept of } q_f \text{ versus } \bar{p}_f \quad \text{(kN/m}^2) \)

\( \alpha \) \quad \text{slope angle of } q_f \text{ versus } p_f \)

\( \bar{\alpha} \) \quad \text{slope angle of } q_f \text{ versus } \bar{p}_f \)

\( c \) \quad \text{apparent cohesion intercept (kN/m}^2) \)

\( \bar{c} \) \quad \text{effective cohesion intercept (kN/m}^2) \)

\( \bar{\phi} \) \quad \text{effective angle of shearing resistance (degree)} \)

\( \varepsilon \) \quad \text{linear strain (％)}
1.1 General

Grouting for ground engineering is a process for filling the voids, fissures or cavities existing in the soil and rock to improve water-tightness or mechanical characteristics of the grouted materials. Three (3) classes of grouting materials are generally recognized: i) suspension-type grouts, ii) emulsion-type grouts and iii) solution-type grouts. The suspension-type grouts include clay, cement and lime, while the emulsion-type grouts include bitumen and the solution-type grouts include a wide variety of chemicals. With the various pressures and operations applied in the grouting process, the improvement can be achieved in various forms, e.g. permeation or penetration, compaction or controlled displacement and hydrofracturing or uncontrolled displacement (Figure 1.1).

Due to the need for underground developments (e.g. basement, subway and MRT system, etc.) in the past two decades, application of grouting technique in solving problems associated with groundwater seepage, incompetent foundation soil and sensitive existing structures have been widely used in the substructure construction works in Singapore. Permeation grouting by injecting cement grout into soil via a pressure system, e.g. pump, was found commonly used in the construction industry for reducing seepage
effect induced by excavation in porous media, e.g. sand of high permeability and improving the stability and bearing resistance of ground in excavation and foundation works, respectively.

Due to the complexity of the rheological properties (e.g. yield stress and viscosity) of cement grout and its unclear flow behavior (i.e. groutability or injectability) in porous media underground, especially in the local sandy soil commonly found with high content of fines usually treated by using superfine cement grout or chemical grout overseas, the effectiveness of permeation grouting using ordinary Portland cement with high water cement ratio exceeding 3.0 by some local practitioners is not clear. Therefore, it appears that it is still largely a trial and error process in the current practice, especially in the local construction industry. If it is not satisfactorily done, it could lead to wastage or unsatisfactory performance (e.g. poor water tightness) of the soil improvement work.

Fig. 1.1 Various Forms of Improvement in Soil and Rock Grouting : (a) Permeation Grouting (Penetration), (b) Compaction Grouting (Controlled Displacement), (c) Hydrofacturing (Uncontrolled Displacement) [Koerner, 1985]
According to Landry et al. (2000), at present, there are no reliable small scale (i.e. <100mm in diameter) or laboratory methods which will accurately determine the injectability limits of soils characterized by grain size, permeability coefficient and silt content. It is the opinion of Landry et al. (2000) that the injectability tests currently being conducted in North America on a laboratory scale are usually fundamentally flawed due to the reasons that these tests do not accurately determine injectability limits or injectability into site specific soil conditions as it does not allow for grout mixing or injection to be performed in the same manner as it does in the field. Therefore the laboratory tests may only be useful for comparing various grout mix designs against the same criteria. The opinion of the author on this point will be described in Chapter 6.

In the current state of the art of grouting, the motion of a viscous fluid injected from borehole into soil was analyzed by considering the laminar flow (i.e. Newtonian fluid) from inside a spherical or cylindrical cavity into the mass of granular soil perfectly homogeneous. According to Tomiolo (1982), these two available flow models (Raffle and Greenwood, 1961) consider the flow of viscous fluids through the soil follows the same laws ruling the flow of water, all values (e.g. coefficient of permeability to grout, $k_G$) being amplified proportionally to the ratio of grout viscosity to water viscosity as shown in Eq. (1-1). It is the opinion of the author that such consideration may not be appropriate for cement grout with water/cement ratio (W/C, by weight) below 1.5 in view of the significant Bingham’s fluid characteristics possessed by these cement grout mixes and also the very high injection pressure applied in the cement based permeation grouting works, which may influence the validity of Darcy’s law.
\[
\frac{k}{k_0} = \frac{\eta}{\eta_w} \quad \text{(after Muller-Kirchenbauer, 1968)}
\]  

where  
\( k_0 = \text{permeability of soil to grout, m/s} \)  
\( k = \text{permeability of soil to water, m/s} \)  
\( \eta = \text{viscosity of Newtonian grout, Pas} \quad \text{(N \cdot s/m}^2) \)  
\( \eta_w = \text{viscosity of water, Pas} \)

For enhancing the application of cement based permeation grouting using the existing flow models in the local construction industry, proper understanding of the properties of cement grout, including the influences of the handling process to the measurement of viscosity of cement grout and grout flow characteristics taking into consideration of the influence of high injection pressure on the coefficient of permeability for cement grout \((k_0)\) in porous media, i.e. the validity of constant \(k_0\) value assumed based on Darcy’s law in the existing flow models, is needed.

A survey of the literature and local practice reveals the limited rheology study for cement grout in the published research work and the uncertainties about the application of cement based permeation grouting such as :

- Flow of Bingham’s fluid through porous media;
- Rheological properties (e.g. yield stress and viscosity) of cement grout with water cement ratio (W/C) ranging from 0.6 to 1.5 not available in the past research works, especially for the ordinary Portland cement commonly used in the local construction.
industry, taking into consideration of the time dependency and shear history dependency from different mixing and measuring programme;

- Water permeability characteristics of sand with grain size similar to those found in the local geology (e.g. Old Alluvium and Bukit Timah Granite) and the coarse sand (2 mm to 6 mm) including the validity of Darcy’s law and empirical formula for coefficient of permeability based on particle size;

- Influence of injection pressure on the flow characteristics of cement grout in porous media.

1.2 Use of Grouting for Ground Engineering

The use of grouting has become more popular in the recent years due to rapid development of sub-surface urban infrastructures (e.g. MRT), underground facilities (e.g. common services duct and deep tunnel sewer system) and underground space for commercial (e.g. carpark) and civil defense (e.g. shelter and storage) uses and the need in ground control during construction. Grouting can be used to improve the condition of site against possible construction problems, such as:

- To reduce permeability of soil for minimizing seepage effect
- To strengthen soils for improving its load carrying capacity, excavation stability and resistance in against liquefaction effect.
- To improve stability of existing structures and to adjust profile of distorted structures.
- To stabilize ground for facilitating tunnelling or shaft excavation.
- To form a barrier or cutoff to water or contaminant flow in the ground.
1.3 Scope and Objectives of Research

In view of the limitations and uncertainties as described in the last paragraph of Section 1.1, a research program involving laboratory experiments was carried out to enhance the practitioner’s knowledge in the rheological properties and flow characteristics of cement grout for improving the application of cement based permeation grouting in the local construction industry and include the following tasks.

(1) Overview of grouting and theoretical study including grout flow models and important grout parameters for the application of permeation grouting;

(2) Study of the rheological properties of various grout mixes formed by using Type I Portland cement with water/cement ratio (W/C) of 0.6, 0.8, 1.0, 1.2 and 1.5 in laboratory for representative determination of the important grout parameters; e.g. yield stress and viscosity taking into consideration of the influence of mixing time, time dependency and shear history dependency of the grout material for i) providing better simulation of the permeation process which was not properly considered in the practicing works and ii) enhancing the application of such cement grout mixes in permeation grouting using the existing flow models which is a function of the grout properties (e.g. unit weight and viscosity) and the test parameters (e.g. injection pressure and grouting rate);

(3) Study of the water permeability characteristics of fine to coarse sand under various injection pressure (up to 7 bars) as the fundamental study for flow characteristics of permeation grout including verification on the validity of Darcy’s law and the
empirical formula proposed for the determination of the water permeability \( k \) based on particle size \( d_{10} \) in geotechnical engineering practice;

(4) Study of the influence of test set up on the accuracy of flow measurement;

(5) Study of the flow characteristics of various cement grout mixes \( (W/C = 0.6 \text{ to } 1.5) \) in coarse sand including the influence of injection pressure to the coefficient of permeability to grout \( k_G \) which was found to be significant in the present research work and the validity of Darcy’s law for representative determination of \( k_G \) through the established “gradient–velocity” relationship of grout and hence the improvement to the application of existing grout flow models (Raffle and Greenwood, 1961) which assumes constant value of \( k_G \) (i.e. Newtonian flow according to Darcy’s law) without considering the influence of injection pressure (i.e. grouting flow);

(6) Determination of representative grout parameters, such as the viscosity \( \eta \) and the coefficient of permeability \( k_G \) of various cement grout mixes taking into consideration of the influence of injection pressure for enhancing the application of existing grout flow formula for the estimation of effective injection pressure and injection hole spacing required for the permeation grouting work;

(7) Providing the practitioners with useful cement grout parameters and a better understanding of the flow characteristics of various mixes of ordinary Portland cement grout \( (W/C = 0.6 \text{ to } 1.5) \) which are not available in the currently state of the art for enhancing the application of existing grout flow formula for the estimation of effective injection pressure and suitable injection hole spacing required in the permeation grouting work.
CHAPTER 2

LITERATURE REVIEW

2.1 Historical Development

The history of cement-based grouts commonly used in permeation grouting including grouting of fractures in rock masses as well as pores in soil deposits has been described in detail by Houlsby (1990), Weaver (1991) and Litteljohn (2003), from whose research much of the following data are drawn.

The concept of injecting a self-hardening cementitious slurry was first exploited in 1802 in Dieppe, France, to improve bearing capacity under a sluice. Over the next 40 years or so, various French engineers followed suit, concentrating on locks, docks, canals and bridges. In the United States, Worthen grouted the foundations of a flume in 1845, and nine years later had graduated to sealing a masonry pier on the New Haven Road at Westford.

From 1856 to 1858 in England, Kinipple who regarded himself as the inventor of cement grouting carried out experiments in creating in-situ concrete. Application did continue internationally and in 1876 the first dam grouting project was completed by T. Hawksley in Rochdale, England, and successful application in French and German mines, London tunnels, and Maltese and Scottish docks.
By 1915 the first technical paper devoted to the grouting of a rock foundation under a dam (Estacada, Ore.) was published (Rands, 1915), and much interest resulted. The grouting at Hoover Dam between 1932 and 1935 is said to mark the beginning of systematic design of rock treatment in the United States (Glossop, 1961).

Since then, development in rock fissure grouting have continued apace, with research into drilling and grouting technologies, water testing, and materials developments being well documented by Simonds (1947, 1958) and Leonard & Grant (1958) and in the proceedings/publications issued by USCE (1956), ASCE (1982, 1985, 1992), ICE (1963, 1992) and ACI (1984).

By 1933, Ischy had invented the tube-a-manchette system, a grout injection method ideally suited to the controlled treatment of soils with great operational flexibility. Thereafter, the approach to soil permeation was progressively enhanced and rationalized due to theoretical research (e.g. Maag, 1938), and materials developments. These latter focused on lowering viscosity, increasing gel time control, increasing strength, and improving durability. In 1963, the ICE Conference in London reviewed the contemporary state-of-the-art.

Since then, developments have continued principally into new materials, including those that are water reactive, elastic after gelling, highly durable, and environmentally compatible. Indeed, by 1983, Karol was able to list eight major research and review documents prepared directly by, or commissioned for, government agencies. These
documents were in addition to fundamental, classic works by Cambefort (1977) and Caron (1982), as prime examples. In the early nineties, renewed attention has been devoted to the microfine cement-based grouts (e.g. DePaoli et al., 1992a, b) and the whole concept of grout rheology as related to efficiency of injection (Deere and Lombardi, 1985).

Regarding processes, the Japanese in particular have been active, bringing to commercial use a series of drill and grout systems (Bruce, 1989a), which have enjoyed considerable success in soft ground tunneling projects in the Far East, although they have received little attention elsewhere.

The interest shown in the some literature (e.g. Karol, 1983, 1990, etc.) and at conferences (e.g. ASCE, 1992; ICE, 1992, IS-Tokyo, 1996 and ASCE, 2003) confirms that permeation grouting remains a very dynamic, challenging, and evolving topic. Typically, developments originate with specialty contractors or materials suppliers, and are then explored further by universities and governmental agencies before entering general usage.

2.2 Theory of Permeation of Grout through Porous Media

Grout permeation through soil is usually related to the grout’s permeability, measured in term of the coefficient of permeability \( k_G \) according to Darcy’s law provided that the flow remains laminar. For a particular fluid, \( k \) is primarily a function of the void ratio, but particle size distribution, soil structure, saturation, and other factors also influence its value. Permeation in uniform soils follows a very regular form which may be
correctly represented by simple mathematical models. These are usually based on either spherical or cylindrical flow model (Raffle and Greenwood, 1961) of Newtonian fluid as discussed in Chapter 3. Equations derived from these two available models as presented in Chapter 3 allow the estimation of pressure required for maintaining flow to a given distance and injection hole spacing for permeation grouting as the function of the grout material parameters (e.g. viscosity and coefficient of permeability for grout, \( k_G \), etc.) and grout method parameters (e.g. injection pressure and flow rate, etc.). The validity of these two grout flow models was not verified by any past research works covered in the literature review.

In view of the non-Newtonian fluid characteristics found for the cement grout mixes with water/cement ratio not exceeding 1.5 which, in the opinion of the author, the practical range of cement grout mixes for permeation grouting in ground improvement works and the influence of high injection pressure adopted in the permeation process to the flow characteristics (e.g. the coefficient of permeability for grout and the validity of Darcy’s law), important parameters such as the rheological properties (e.g. yield stress, viscosity and stability) of various cement grout mixes and its flow characteristics under different injection pressures, but not well studied and reported are essential in the study of cement based permeation grouting in the present research.

2.3 Studies on Rheological Characteristics of Cement Grout

The rheological properties (e.g. yield stress and viscosity) of grout including other influence factors such as mixing time, stability (bleeding), degree of saturation and
additives have been studied by various researchers since 1954. However, the information from all these studies are found more concentrated in the properties of solution grout, microfine cement grout or Portland cement grout with additives (e.g. bentonite, etc.) because of poor permeation of pure cement grout due to its high viscosity and short setting time, and the grout mixes considered in these studies are found not to cover the practical range of cement grout mixes, i.e. $W/C = 0.6$ to $1.5$, for effective application of permeation grouting in sand using ordinary Portland cement (i.e. Portland Type I) as adopted in the experimental program of the present research. Some comments/findings extracted from the past research works are summarized as follows.

Cambefort (1954) explained that cement grout has a well-defined shear stress that develops immediately after mixing and is characterized by its viscosity function.

Klein and Poloivka (1958) interpreted schematically the stages of cement grout after mixing as dormant, setting and hardening with strength of grout increasing with curing time approximately in exponential or power function.

Caron (1959) classified cement grout as Bingham’s grouts, as possessing rigidity and viscosity simultaneously, both increase with time and displacement can only begin beyond a certain pressure or so called yield stress.

Raffle and Greenwood (1961) developed a graphical relation (Figure 2.1) between the rheological characteristics of grout and its capacity to permeate soil and indicated that injection of neat cement grout is controlled by viscosity and shear strength in the early and
later stages, respectively. Obvious increases in the viscosity and shear strength were reported for the cement grout with water/cement ratio (W/C) not exceeding 0.6 as shown in Figure 2.1.

LittleJohn (1975) emphasized that a water/cement ratio between 0.4 and 0.45 gives a grout with sufficient fluidity to be pumped and placed easily in a small diameter borehole and yet retain sufficient continuity and strength after injection to act as a strengthening medium. He reported a rapid increase in viscosity and shear strength for cement grout with water/cement ratio less than 0.9 which is different from the ratio of 0.6 reported by both Burgin (1979) and the author.

![Fig. 2.1 Shear Strength and Viscosities for Cement Pastes with Varying Water/Cement Ratio (after Raffle and Greenwood, 1961)](image-url)
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Deere et al. (1982) classified cement grout as stable grout based on bleeding not exceeding 5% after 2 hours from completion of mixing and commented that small amount of bentonite appears to be preferable, sufficient to reduce sedimentation and bleeding but not so great as to improve the pumpability and penetrability.

Branfill (1983) showed that a mixing time of about 5 minutes is sufficient in order to get constant properties for both the yield value and the plastic viscosity. However, the volume of the mixed grout is not known.

Lombardi (1985) analyzed the flow conditions of a mix through a smooth rock fissure and concluded that the yield stress determines the maximum distance the grout can reach and the viscosity determines the flow rate and therefore the time necessary to complete the injection.

Paoli et al. (1992) discussed the fundamental observation on cement based grout and commented that permeation is controlled by the size of the particles more than by viscosity and yield stress of the grout material. The grout penetrability could be improved by reducing the size of the cement grains and improving the grout’s rheological properties, increasing the stability under pressure infiltration and reducing the yield stress values.

Hakansson et al. (1992) studied the rheological properties of microfine cement grouts with additives and concluded that yield stress and plastic viscosity increase with increasing specific surface and bentonite, and reduce with increasing plasticizing admixtures.
Krizek et al. (1992) studied the anisotropic behavior of cement-grouted sand and concluded that the permeability of grouted sand depends on the direction of flow relative to the direction of sedimentation. For sands injected with grout at a water/cement ratio less than 3.0, the horizontal permeability is about two orders of magnitude higher than the vertical.

Vipulanandan et al. (1992) studied the properties of cement grouts and grouted sands with additives and indicated that the maximum particle size must not exceed 1/3 to 1/10 the size of void in order to penetrate a formation at reasonable pressure and rate.

Helal & Krizek (1992) studied the orientation of pore structure in cement-grouted sand indicated that pore structure injected with a cement grout is a function of water/cement ratio and sedimentation behavior of the suspended particles.

Shroff et al. (1996) studied the rheological properties of microfine cement dust (MCD) grouts and reported that MCD grout is able to penetrate medium sand having permeability, $k = 7.89 \times 10^{-3}$ cm/sec. He also commented that MCD grout possesses not only penetration ability in medium to fine sand comparable to many chemical grouts but also imparts higher adherent strength to the grouted mass.

Perret et al. (2000) studied the effect of degree of saturation of sand on groutability and concluded that the propagation of grout through porous media is influenced not only by the particle size distribution of the soil and cement, the water permeability of the soil
and rheological characteristics of the grout but also the degree of saturation of sand. Water dilution of the grout is greater in unsaturated soil than in saturated soil, where the grout can displace the water, resulting in a layer of grout intermixed and diluted with water. The suction resulting from capillary pressure in the case of unsaturated sand and the non-continuous aqueous medium formed by the pore water in the soil are thought to have led to greater water dilution in the case of unsaturated sand.

2.4 Studies on Permeability Characteristics of Cement Grout

As mentioned in Chapter 1, presently there are no truly reliable small scale (i.e. <100mm in diameter) or laboratory methods which will accurately determine the injectability limits of soils characterized by grain size, permeability coefficient and silt content (Landry et. al., 2000). Only five (5) cases of laboratory injectability tests [Hetal & Krizek (1992), Shimoda et al. (1996), Lowther & Gabr (1997) and Perret et al. (1997, 2000)] as described below were found in the literature, but none of these studies measured the permeability ($k_c$) of cement grout (Portland Type I) in coarse sand which is essential in the study of cement based permeation grouting as in the present research.

Hetal & Krizek (1992) investigated the pore structure of 20/30 Ottawa Sand injected with different microfine cement grouts at water/cement ratios (W/C) of 1.0, 2.0 and 3.0. The grouted sand specimens were placed in PVC tubes two inches diameter and six inches long and saturated prior to injecting the grout at an injection pressure of approximately 10 psi. The pore structure of a soil injected with cement grout is a function of the water/cement ratio of grout and the sedimentation behavior of the suspended
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particles. The results of tests conducted using grout with W/C > 1.0 show that sedimentation and aggregation of the cement particles takes place in the soil voids prior to setting, and the resulting hydration products preferentially occupy the lower portions of the pore spaces and crevices between sand grains, whereas the accumulated bleed water occupies the upper portions of the pore spaces. In general, the percent sedimentation in a given pore appears to be independent of the pore size.

Fujii et al. (1996) studied the properties of microfine cement (average grain size = 4µm) grout and its injectability by carrying out grouting tests (i.e. one-dimensional grouting in 5φ x 50 to 200 cm cylindrical mold and two-dimensional grouting in 4.00 x 3.55 x 4.20 m tank) using saturated Silica Sand 7 (diameter ranges from 0.1 to 0.4 mm). The results of the one-dimensional grouting tests show that the permeation length reaches the maximum when water/cement ratio (W/C) is raised to 10. The results of the two-dimensional grouting tests using light grout with W/C=10 and 10% (by weight) of dispersing agent show the possibility of suspension type permeation grouting into fine sandy soil when the grain size of the grout is very small and the grains are fully dispersed.

Lowther & Gabr (1997) performed an experimental program to characterize the hydraulic conductivity and strength of urethane-grouted sand to be used as a barrier. The sand used for the testing program and grout injections was an air dried, uniformly graded 20/30 Ottawa Sand with particle size ranging mainly between 0.8 mm and 1.0 mm. For each injection, 5.5 liters of grout mixed for approximately 30 seconds was injected at a rate of 2 liter/min into the sample placed in 300 mm diameter acrylic columns. Six orders
of magnitude reduction in hydraulic conductivity was obtained as the test sand was grouted. A significant effect of saturation on the swell and strength characteristics (i.e. decrease due to saturation) of the grouted sand was observed. However, the hydraulic conductivity values were not affected by the excessive swelling upon saturation.

Perret et al. (1997) studied the injectability of fine sand (0.16 / 0.63 mm) using Type I & Type III Portland cement and a microfine cement in the laboratory according to the sand column test (22 mm diameter x 370 mm height) adopted from the European standard NF P18-901. The grouts were prepared with water/cement ratio varying between 0.5 and 2.0 and contained different concentrations of silica fume, superplasticizer and colloidal agent. The results of this study showed that it is possible to inject cement-based grouts in fine to medium sand using highly flowable cement grouts with admixtures. However, the penetration height of grout was low (i.e. <150 mm) for grouts with water/cement ratio not exceeding 0.6.

Perret et al. (2000) also studied the effect of saturation of sand (0.63 / 1.35 mm and 0.08 / 0.63 mm) on groutability of Type I cement grout and found that the propagation of grout through the partially saturated sand was faster compared with that in the saturated sand. The grout with cement/water ratio of 0.6, although highly flowable, was not capable of penetrating the bulk saturated sand. In both unsaturated and saturated sands, water dilution was noted.
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CHAPTER 3

OVERVIEW AND THEORETICAL BACKGROUND OF GROUTING

3.1 Principles of Grouting

3.1.1 Definition and Purpose of Grouting

Grouting is defined as the injection of fluidized materials into voids of the ground or space between the ground and adjacent structures. The main objectives of grouting are to produce a stronger, denser, and/or less permeable soil or rock; it may also simply serve to fill voids, which are otherwise inaccessible and may prevent adequate stress transfer within the ground or from a structure to the ground.

3.1.2 Categories of Grouting

The basic categories of grouting (Figure 3.1) distinguished by the mode of entry into the soil or rock are:

- Permeation grouting (intrusion, penetration)
- Displacement grouting
- Compaction grouting (including slab-jacking)
- Jet grouting
Fig. 3.1 Basic Modes of Grouting
3.1.3 Classification of Grout Materials

Three (3) basic types of grout are differentiated according to composition as follows:

- **Suspension**: Small particles of solids are distributed in a liquid dispersion medium, e.g. cement and clay in water, having a Bingham’s fluid characteristics.

- **Emulsions**: A two-phase system containing minute (colloidal) droplets of liquid in a disperse phase, e.g. bitumen and water that are evolutive Newtonian fluids in which the viscosity increases with time.

- **Solutions**: Liquid homogeneous molecular mixtures of two or more substances, e.g. sodium silicate, organic resins, and a wide variety of other so-called chemical grouts, nonevolutive Newtonian solutions in which the viscosity is constant until setting, within an adjustable period.

The type of grout material (i.e. cement) involved in the present study belongs to the suspension type of grout. The solution grouts are evolutive Newtonian liquids during their period of practical injectability, when permeation occurs in accordance with Darcy’s
law. However, the applicability of Darcy’s law to the complicated Bingham’s fluid characteristics of suspensions (e.g. cement grout) was not well investigated and verified.

3.2 Properties Study on Cement Grout in Porous Media

Since the properties of grout material and the handling / operation procedures of grout injection (i.e. grouting method) are essential in ensuring the successfully application of permeation grouting using cement grout, proper understanding of the parameters of the grout material and grouting method as described in the following sections are incorporated in the present study.

3.2.1 Grout Material Parameters

The permeability of particulate grouts in porous media depends on the following factors.

- Stability (i.e. bleed capacity)
- Pressure filtration (i.e. loss of water under the applied pressure)
- Rheology (principally yield stress and viscosity)
- Grain size concentration (i.e. grout dislodges fine particles from soil matrix, which in turn become part of the suspension grout and reduce penetration)

As mentioned above, the solution grouts are evolutive Newtonian liquids during their period of practical injectability, when permeation occurs in accordance with Darcy’s law. The principal controls over penetration distance and grout characteristics are therefore,
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- Ground permeability and porosity
- Initial grout viscosity and its evolution. Deere and Lombardi (1985) noted that cohesion (i.e. yield stress) determines distance of travel and viscosity determines the flow rate.
- Pressure (related to flow rate)
- Practical duration of injection

3.2.2 Grouting Method Parameters

The structure of the French Tunnelling Association (AFTES 1991) provides a logical approach, identifying four (4) main parameters:

- Grout volume, V
- Injection pressure, P
- Rate of injection, Q
- Time of injection, t = V/Q

3.2.3 Viscosity

Viscosity ($\eta$) is the proportionality factor relating the shear resistance ($\tau$) in fluid to the velocity gradient or rate of shear strain ($dv/dz$ or $\dot{\gamma}$ in $s^{-1}$) which represents the rate at which one layer of fluid moves relative to an adjacent layer (Newton’s law of viscosity). It is also called the apparent viscosity or absolute viscosity.
• for Laminar flow / Newtonian fluid (Figure 3.2)

\[
\tau = \eta \frac{dv}{dz} = \eta \dot{\gamma}
\]  
(3-1)

**Fig. 3.2** The Newtonian Liquid
for turbulent flow

\[ \tau = (\mu + \eta) \frac{dv}{dz} \]  

(3-2)

where \( \eta \): coefficient of viscosity in Pas (pascal-second)

\( \mu \): Dynamic Eddy Viscosity

\[ \nu = \frac{\mu}{\rho} = \frac{\mu \rho g}{\gamma} \]  

(Kinematic Viscosity)  

(3-3)

where \( g = 9.81 \text{ m/s}^2 \) (acceleration due to gravity),

\( \rho \): mass density

unit for \( \nu \): centistoke = \( 10^{-6} \text{ m}^2/\text{s} = 1 \text{ cSt.} \)

- Suspensions generally do not behave as Newtonian fluid but as Bingham’s liquids,

\[ \tau = \tau_o + \eta_p \frac{dv}{dz} = \tau_o + \eta_p \dot{\gamma} \]  

(3-4)

where \( \eta_p \) is the plastic viscosity in Pas

Bingham’s fluids are marked by the flow limit or yield stress or threshold resistance (i.e. \( \tau_o \) in Pa as shown in Figure 3.3). The yield point strongly depends on external parameters, e.g. environmental conditions specific for the application. An initial shear resistance must be surmounted to start flowing. After this the shear stress and the
shear gradient are proportional to each other as far as the viscosity can be assumed to be constant which was found valid for Bingham’s fluids.

Fig. 3.3 The Bingham Model
3.2.4 Apparent Viscosity

Darcy’s law can be extended to non-Newtonian fluid by introducing an apparent viscosity ($\eta$) for the viscosity term in the permeability coefficient (Vossoughi, 1999). The apparent viscosity can be obtained by writing the Bingham equation in term of viscosity as follows.

$$\eta = \eta_p + \frac{\tau_o}{\dot{\gamma}} \quad (3-5)$$

where $\eta$ in Pas is the equivalent Newtonian viscosity of a non-Newtonian material at a specific shearing rate, called the apparent viscosity.

![Fig. 3.4 Apparent Viscosity ($\eta$)]
3.2.5 Modified Darcy’s Law

According to Zhang (2002), the modified Darcy’s law for Bingham’s fluid is as follows:

\[ v = -\frac{K_{pg}}{\eta} i \]  

(3-6)

where \( K = \frac{k\eta}{\rho g} \), intrinsic (absolute) permeability coefficient of porous media (m\(^2\))

The coefficient of permeability (\( k_G \)) for grout in the same form of Darcy’s law is as follows:

\[ k_G = \frac{K_{pg}}{\eta} \]  

(3-7)

“\( k_G \)” for various cement grout mixes in coarse sand were determined from the grout permeability tests in the present study to take into account the influence of high injection pressure observed in the experiments. Such pressure effect can not be reflected in the determination of \( k_G \) for cement grout using the above equation, therefore, it is recommended that the relationship between velocity and hydraulic gradient established for various cement grout mixes in this study be used for the determination of \( k_G \) for permeation grouting according to the selected injection pressure. The details of the grout permeability tests and the established relationship between velocity and hydraulic gradient for various grout mixes are presented in Chapter 6.
3.2.6 Thixotropy

A more complete representation of the rheological behavior of cement grout can be obtained when additional properties, such as thixotropy is considered. Thixotropy is the property of Non-Newtonian substances where the viscosity decreases under shear due to structural breakdown (Figure 3.5). The substance will eventually regain their viscosity after the shearing has stopped. In the case of a thixotropy loop test when an upward and down shear ramps are applied cyclically on the same sample, the down curve registers lower shear stresses than the up curve and a hysteresis loop is formed as an area enclosed in between (Tanner, 1985). The cyclic shearing conducted in the viscometer tests as presented in Section 4.3 shows that cement grout of low water/cement ratio (e.g. 0.6 & 0.8) has a smaller hysteresis loop area, indicating that the thick cement grout has a more stable internal structure, thus less sensitive to further shearing as compared with the light cement grout with water/cement ratio above 1.0.

![Rheologic Properties of Thixotropic Suspensions](Nonveiller, 1989)

- a-b : laminar flow, b-c : turbulent flow
- $\tau_o$ increases to $\tau_t$ when the suspension is at rest for some time and reduces to $\tau_o$ when stirred at "d"
- where $\tau_t$ : thixotropic strength

Fig. 3.5 Rheologic Properties of Thixotropic Suspensions (Nonveiller, 1989)
3.3 Permeation Grouting of Soils

Permeation grouting is a technique in which the pore fluid is replaced (i.e. squeezed out) with grout injected at a steady injection without causing any change in the soil structure (Figure 3.1). As grout penetration depends on the permeability of the ground, the technique is generally restricted to clean sands and gravel or open fills that can be penetrated with low-viscosity grouts. As a general guide, it is difficult to permeate soils with a permeability coefficient (water) of less than $5 \times 10^{-4}$ m/sec (LittleJohn, 1982) using ordinary cement grout (Portland Type I). European Standard (1996) suggests a higher coefficient of permeability for water, i.e. above $5 \times 10^{-3}$ m/sec as guide for cement based permeability grouting. For the direct injection of grout into soil as in the process of permeation grouting, it is important to understand how the voids in the foundation soils are filled by the grout and which are the factors influencing the grout permeation. In general, the injected grout will penetrate the ground in the following ways.

- Permeation through granular soils
- Permeation through fissures
- Filling fissure and voids with cement grout

3.3.1 Grouting Test and Grouting Technique

In the present study, grouting tests developed from the concept of constant head laboratory permeability test (vertical flow measurement) using different test chambers including one special test chamber designed by the author are conducted to study the flow characteristics of cement grout through porous media (i.e. sand). They are actually grout
permeability tests for measuring the ability of cement grout, characterized by viscosity and yield stress, to flow in a mould packed with sandy materials of particular grain size distribution, under different injection pressures. The design of the special test chamber is presented in Chapter 6.

Permeation grouting is influenced primarily by the permeability of the ground. The substantial variation in permeability found in natural soils and rocks required a range of grout and grouting technique (Table 3.1) for effective treatment. As the $k$ values given in Table 3.1 do not take into consideration of the influence of viscosity (i.e. W/C ratio) on the injectability of grout and the method of measurement for $k$ value is not reported, therefore, it should be used as a general guide only.

<table>
<thead>
<tr>
<th>Type of ground</th>
<th>Permeation</th>
<th>Compaction/hydro-fracture/jet grouting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel, coarse sand and sandy gravel $k &gt; 5 \times 10^{-3}$ m/sec</td>
<td>Pure cement suspensions, cement-based suspensions</td>
<td>Mortars, cemented based suspensions</td>
</tr>
<tr>
<td>Sand, medium sand $5 \times 10^{-3} &lt; k &lt; 1 \times 10^{-5}$ m/sec</td>
<td>Micro-fine suspensions, solution</td>
<td>Cemented based suspensions</td>
</tr>
<tr>
<td>Fine sand, silt, silty clay $5 \times 10^{-4} &lt; k &lt; 1 \times 10^{-6}$ m/sec</td>
<td>Specific chemicals</td>
<td>Cement-based mortars Cemented based suspensions</td>
</tr>
</tbody>
</table>

$k$: coefficient of permeability to water (method of measurement not reported)

Permeability assessment therefore forms an important part of the investigation of groutability of soils. In soils, empirical groutability ratios, i.e. $N=D_{15}/d_{85}$ and $N_c=D_{10}/d_{95}$
can be used to assess the penetrability of particular grout (Mitchell, 1981) as shown below.

- $N > 24$  Successful Grouting
- $Nc > 11$  Cement grouting is consistently possible
- $Nc < 6$  Cement grouting is not possible

Where $D_{10}$ - 10% finer size from grain size distribution curve of soil
$D_{15}$ - 15% finer size from grain size distribution curve of soil
$d_{85}$ - 85% finer size from grain size distribution curve of cement
$d_{95}$ - 95% finer size from grain size distribution curve of cement

Landry (2000) has reported that some practitioners have found that this is a debatable rule of thumb as the pressure infiltration and the solid content of the grout were not taken into account nor the fact that silt are picked up by the suspension grout as it runs through the pores and reduces penetrability and therefore should also be used as a general guide.

### 3.3.2 Theory of Grout Flow through Porous Media

Grout permeation through soil is related to the grout’s permeability, measured in term of the coefficient of permeability $k$ according to Darcy’s law. For a particular fluid, $k$ is primarily a function of the void ratio, but particle size distribution, soil structure, saturation, and other factors also influence its value. Permeation in uniform soils follows a very regular form which may be represented by simple mathematical models. Spherical and cylindrical flow models (Raffle and Greenwood, 1961) for a porous media as shown in the following two sections have been proposed for permeation grouting of soil from boreholes.
3.3.2.1 Spherical Flow Model for Porous Media (Newtonian Fluid)

Net pressure \( P_e \) in excess of local hydrostatic pressure necessary to maintain the flow from a spherical cavity of radius of \( R_o \) is a function of the grouting rate, the soil permeability and the viscosity of grout as expressed in the following relationship:

\[
P_e = \frac{Q \gamma}{C k_o} = \frac{Q \gamma \eta}{C k \eta_w} \tag{3-8}
\]

where  
\( Q = \) grouting rate, \( m^3/s \) 
\( \gamma = \) unit weight of grout, \( kN/m^3 \) 
\( C = \) shape coefficient = \( 4\pi R_o \) for a sphere having radius \( R_o \) 
\( k_o = \) permeability of soil to grout, \( m/s \) 
\( k = \) permeability of soil to water, \( m/s \) 
\( \eta = \) viscosity of Newtonian grout, \( Pas \) 
\( \eta_w = \) viscosity of water, \( Pas \)

Note: 1 Pas (pascal-second) = 1 N·s/m² 
\( \eta_w = 10.09 \) mPas at 20 °C

During spherical grout permeation in time \( dt \), the grout taken in time \( t \) can be found by integration from :

\[
Q \ dt = 4\pi r^2 n \ dr, \tag{3-9}
\]

where  
\( n = \) porosity of soil (volume of voids/total volume) 
\( dr = \) grout travel distance
The time required to travel a distance R from a spherical cavity with radius $R_o$ can be computed by:

$$t = \frac{4\pi n}{3Q} (R^3 - R_o^3)$$  \hspace{1cm} (3-10)

Fig. 3.6  Flow from Spherical Pocket

3.3.2.2  
Radial Flow from a Cylindrical Cavity (Newtonian Fluid)

Equations equivalent to Eqs. (3-8) & (3-10) for the case of radial flow from a cylindrical hole into a layer having a thickness of m can be expressed as follows:

$$P_e = \frac{Q\gamma\eta}{2\pi nk\eta_w} \ln \frac{R}{R_o}$$  \hspace{1cm} (3-11)

where \( R = \) distance from grouting point

\( R_o = \) radius of injection hole
From these models it is possible to estimate from the properties of the grout and the ground the time \( t \) for penetration to a given radius \( R \) from which estimates of injection hole spacing can be derived.

\[
t = \frac{\pi mn}{Q} (R^2 - R_0^2)
\]  
(3-12)

For a confined aquifer being charged, the pressure \( p(R) \) of the grout diminishes with distance \( R \) from the borehole according to,

\[
p(R) = p_e - \frac{Q \gamma \eta}{2 \pi m k \eta_e} \ln \frac{R}{R_0}
\]  
(3-13)

The above equations demonstrate that the time required \( (t, \text{ which shall not be greater than the setting time of the grout}) \) to treat soil over a given distance from the injection hole depends on the grouting rate \( (Q) \), which can be increased by using a higher pressure (not causing fracturing of the ground) of grouting or a lower viscosity grout. Higher pressure is required at a given distance for injection through larger hole.
3.4 Natural Physical Constraints on Grout Permeation

The effectiveness of permeation grouting depends upon accurate assessment of the typical pore size of the soil to be treated through measurements of particle size distribution and permeability. Three (3) main restraints offering resistance to grout penetration are:

(i) *Filtration of particles* contained in the grout which are too big to pass through the void spaces in the ground;

(ii) *Internal shear resistance* due to the interaction of grout particles as the grout flow through the tortuous soil pore spaces;

(iii) *Viscosity of the grout* which restricts the rate at which the liquid flows into the soil pore spaces

Only the influence of the measurable parameter, i.e. viscosity of grout to the flow characteristics of cement grout in coarse sand is included the present research work.

3.5 Concluding Remarks

The two available flow models [i.e. Eqs. (3-8) & (3-11), Raffle and Greenwood, 1961] consider the flow of viscous fluids (i.e. Newtonian fluid) through the soil follows the same laws ruling the flow of water, all values [e.g. $k_G$ as shown in Eq. (1-1)] being amplified proportionally to the ratio of grout viscosity to water viscosity (Tomiolo, 1982). It is the opinion of the author that such consideration may not be appropriate for cement grout with water/cement ratio (W/C) not exceeding 1.5 in view of the significant Bingham’s fluid characteristics possessed by these cement grout mixes and also the very
high injection pressure adopted in the cement based permeation grouting works which may influence the validity of Darcy’s law. In view of this reason, proper investigation on the Bingham’s fluid characteristics of cement grout and its permeability characteristics in coarse sand under high injection pressure through an experimental framework is considered necessary and incorporated in the program of the present research works.
CHAPTER 4

PROPERTIES OF CEMENT GROUT

4.1 General

When using cement grout to permeate into joints or pores, it is not only the rheological properties (i.e. yield stress and viscosity) of cement grout that are important and influenced the success of the grouting operation but also the size of the cement particles which may be too big to pass through the void spaces in the ground and induce resistance to grout penetration due to filtration of particles. The properties of the type of Portland cement (i.e. trade name: Asia Cement) commonly used in local construction industry were investigated in the laboratory to verify its effectiveness in permeation and the typical grout parameters (e.g. yield stress, viscosity, stability etc.) of various grout mixes to ensure the validity and effectiveness of the application of cement based permeation grouting. The cement powder possesses an average Specific Gravity (Gs) value of $3.235 \pm 0.037$ which was determined from the present tests (ASTM D854:1998).

4.2 Particle Size of Cement

As the stability and permeation of grout are influenced by the particles in the grout, the particle size distribution of the type of Portland cement used in the present study was analyzed by using hydrometer method (ASTM 422:83 / Re-approved 1998) as
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presented in Figure 4.1. The result of analysis shows that 97% of the cement particles
have a diameter smaller than 0.1 mm and the grain size distribution appears to be similar
to that of the ordinary Type I Portland cement studied by Schwarz et al. (1992). The
values of \(d_{85}\) and \(d_{95}\) of cement grout are 0.06 mm and 0.09 mm, respectively. According
to the criteria for limits of particle size for effective grouting as recommended by various
authors as shown below (Shroff & Shah, 1999 and Mitchell, 1981), this type of cement
commonly used in the local construction industry appears to be applicable to the injection
in sand possessed with the following \(D_{15}\) values only. The \(D_{15}\) value (i.e. 2.2 mm, Chapter
5) of coarse sand used in the present research was found to meet the 2\(^{\text{nd}}\), 3\(^{\text{rd}}\) and 4\(^{\text{th}}\)
criteria.

- \(D_{15} = 5 \cdot d_{85}\) to \(24 \cdot d_{85} = 0.3 – 1.44\) mm (Kravetz, 1958)
- \(D_{15} \geq 16 \cdot d_{85} = 0.96\) mm (King & Bush, 1961)
- \(D_{15} \geq 25 \cdot d_{85} = 1.5\) mm (Johnson, 1958), (Karol, 1960)
- \(D_{15} \geq 24 \cdot d_{85} = 1.44\) mm (Mitchell, 1981)

Fig. 4.1  Grain Size Distribution of Portland Cement (Type I)
4.3 Stability of Cement Grout

According to Tomiolo (1982), “stability” indicates the ability of a grout to maintain its characteristics during the grouting process without sedimentation or increase in density. Suspended particles settle in a fluid at rest under the action of gravity with a velocity which is proportional to the square of the particle diameter. The coarse grains settle first, followed by fine grains. Very fine particles are subjected not only to force of gravity, but also to mutually acting electrochemical forces and to Brownian motion which appears in suspensions of colloidal particles less than 1 µm in diameter, so that the velocity of sedimentation becomes lower than the one corresponding to the Stoke’s law. Such effect appears to be not critical for the cement powder with particle size greater than 20 µm (Figure 4.1) adopted in the present research. A cement grout is “stable” if the sedimentation due to gravity is zero or kept at a minimum. Unstable grout mixes will easily pressure filtrate or form flocs, causing anisotropic characteristics in grouted soils, i.e. high residual permeability in horizontal direction and low residual permeability in vertical direction (Hetal & Krizek, 1992).

4.3.1 Measuring Device for Stability of Cement Grout

The stability of cement-based grouting suspensions is determined by simple laboratory tests (sedimentation test) using 1000 c.c. cement grout contained in a standard glass cylinder with an uniform diameter of 60 mm. The sedimentation ratio (dV/V) defined as the volume of clear water (dV) segregated on top the suspension divided by the original grout volume (i.e. V = 1000 c.c.) is recorded at
selected intervals (Figure 4.2) to evaluate the stability of a suspension. Deere et al (1985) classified the suspension as “stable suspension” based on sedimentation ratio not higher than 5% after two hours and Kutzner (1996) based on a ratio less than 10%. High sedimentation ratio is typical of pure cement grouts and have great practical consequences because if sedimentation of solids occurs during grouting, the voids being treated and the grouting pipelines may be plugged and the grout can not flow any further. According to the study on pore structure of cement-grouted sand carried out by Hetal & Krizek (1992) using microfine cement grout (i.e MC-100, MC-300 & MC-500), the percentage of original ungrouted pore space occupied by the hydration products and bleed water was found to be a function of water/cement ratio of grout. For the more unstable grout with water/cement ratio (W/C) exceeding 1.0 which show sedimentation ratio greater than 5% during initial stage (i.e. < 30 min) of test, sedimentation and aggregation of cement particles takes place in soil voids prior to setting with accumulated bleed water occupies the upper portions of the pore space, causing anisotropic characteristics in grouted soils.

4.3.2 Results of Stability Measurement for Cement Grout

The results for the five (5) cement grout mixes in the represent study are presented graphically, as presented in Figure 4.3. As shown in Figure 4.3, all the grout mixes except for grout with W/C = 0.6 were found with sedimentation ratio greater than 10%. None of the grout mixes can satisfy for stable sedimentation criteria (i.e. sedimentation rate <5% after 2 hours) specified by Deere et al (1985) and Kutzner
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Fig. 4.2  Sedimentation Test for Cement Grout (water/cement ratio, W/C = 0.6, 0.8, 1.0)

Fig. 4.3  Sedimentation of Cement Suspensions
This implies that precautionary measures for minimizing segregation effect, such as continuous stirring by using an agitator prior to injection should be provided in the application of light grout mixes (i.e. water/cement ratio ranging from 0.8 to 1.5) in permeation grouting work.

4.4 Rheological Properties of Cement Grout

Rheology is the study of flow of materials. For cement grout, the rheological properties are primarily the yield stress and the viscosity which need to be properly measured in view of the possible influence from the handling and testing process (e.g. sample preparation and method of test, etc.) on the accuracy of measurement.

4.4.1 Experimental Programme for Rheological Measurement

For ensuring the accuracy of rheological measurement for cement grout, necessary verification of the possible influence of mixing time, stability and set time to the accuracy of viscosity measurement are included in the experimental program to ensure that the determined grout parameters are representative for practical use.

4.4.1.1 Measuring Device for Viscosity of Cement Grout

4.4.1.1.1 Marsh Cone

Marsh Cone or Marsh Funnel is the simplest device commonly used for the measurement of viscosity of cement grout in term of time (i.e. second) which is usually co-related with the viscosity values of various grout mixes for quality
control at the site because of its simplicity and easy operation. Figure 4.4 shows the details of Marsh Cone according to API standard and the measurement of Marsh Funnel Viscosity for the five (5) different grout mixes prepared in the present study. In this case, the viscosity is expressed as the time in seconds needed for the discharge of 947 c.c. of suspension from a test specimen of 1,500 c.c. in volume placed in the cone. As pointed out by Lombardi (1985), the Marsh Cone measures a combination of rheological properties, rather than viscosity alone, and its results should be termed “apparent viscosity”.

As indicated in Figure 4.4, the Marsh Funnel Viscosity value was found increasing slightly with reducing water/cement ratio (W/C) between W/C = 0.8 and W/C = 1.5. The measured value for grout with W/C = 0.6 was found very much larger than those recorded for the other grout mixes (W/C = 0.8 to 1.5). As shown in Figure 4.4, this observed trend was found consistent with that reported by Burgin (1979) based on 1000 c.c. flow.

![Fig. 4.4 Marsh Cone Viscosity of Various Cement Grout Mixes](image)
4.4.1.2 Viscometer

There are several types of viscometers (Tatterall & Branfill, 1983) which provide more accurate measurement on the viscosity of cement grout as compared with the performance of Marsh Cone. Figure 4.5 shows one of the well known and commonly used devices, i.e. Rotary Viscometer with immersion cylinder (ISO 2555). The device consists of a coaxial-cylinder which is submerged in the test fluid and rotated at different rotational velocities during the test. The resistance of the fluid against movement as measured in the test gives the values of viscosity and yield stress of the tested fluid. For the type of cement grout with water/cement ratio below 2.0 investigated in the present study, the cement suspensions show Bingham’s fluid behavior (Kutzner, 1996) with the flow curve intercepting the stress axis at a value called yield stress or flow limit or threshold resistance. A series of viscometer tests was conducted on various cement grout mixes to investigate its rheological properties as presented in the following sections.

4.4.1.2 Sample Preparation

4.4.1.2.1 Cement Grout Mix

For the study of permeation grouting in the present study, cement based grout mixes with water/cement ratio, W/C (by weight) of 0.6, 0.8, 1.0, 1.2 and 1.5 were prepared by using a high speed power stirrer (Figure 4.6) at a constant stirring
Fig. 4.5  Rotary Viscometer (Rheometer) with Coaxial-cylinder

Fig. 4.6  Mixing of Cement Grout using High Speed Power Stirrer
speed of 1300 -1500 rpm. The range of W/C ratio adopted in the present study was selected based on the flowability of cement grout in sand for practical and effective improvement. The unit weight of various grout mixes with W/C of 0.6, 0.8, 1.0, 1.2 & 1.5 determined from the laboratory tests are 1.72, 1.60, 1.49, 1.41 & 1.37 kg/cm³, respectively.

4.4.1.2.2 Influence of Mixing Procedure

Not much information on the influence of mixing time is available from the literature review. Mixing time of 5, 6-12 and 1-10 minutes were adopted by Banfill (1983), Paoli et al. (1992) and Schwarz (1992), respectively but the volume of mix was not known. For the purpose of quantifying the effect of mixing procedure on the viscosity of cement grout, three (3) specimens stirred at 1500 rpm for a duration of 5, 10 and 15 minutes were prepared for each grout mix for the viscosity measurement using a rotary viscometer (Rheometer) with immersion cylinder (ISO 2555) in the laboratory. Minor differences in temperature (i.e. 0.7 to 2.6°C) was found between same mix of grout stirred for 5 and 15 min in the present study. The temperature of grout at the end of stirring was generally found to decrease slightly with increasing stirring time except for grout of 0.6 water/cement ratio which showed increase with increasing stirring time. This observation could be attributed to the completed hydration process in the light cement grout mixes (W/C = 0.8 to 1.5). Figures 4.7 to 4.11 show the plots of viscosity value of grout measured during the Viscometer Tests.
The temperature of grout as measured in the viscometer during testing was generally found between 24.9 and 25.1°C except for grout of W/C = 0.6 stirred at 5 min and 10 min which showed a temperature fluctuation of 24.7 to 24.8°C and 25.2 to 25.5°C, respectively.

As shown in Figures 4.7 to 4.11, fluctuation of viscosity value measured during the test was found to be not sensitive to the effect of stirring time for grout with W/C ratio ranging from 0.6 to 1.0 under the high stirring speed of 1500 rpm. Some fluctuations in the measured viscosity were observed during test for the grout mix with water/cement ratio above 1.0. The fluctuation was found to be more obvious for grout with high water/cement ratio, it is especially during the first 25 seconds of measuring time. However, it tends to stabilize after a measuring time of 175 seconds. The development of shear stress measured during the up-ramp
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Fig. 4.8  Plot of Apparent Viscosity of Cement Grout (W/C = 0.8)

Viscosity of Cement Grout
(W/C=0.8)

- Stirring Time = 5 min
- Stirring Time = 10 min
- Stirring Time = 15 min

Viscosity of Cement Grout
(W/C=1.0)

- Stirring Time = 5 min
- Stirring Time = 10 min
- Stirring Time = 15 min

Fig. 4.9  Plot of Apparent Viscosity of Cement Grout (W/C = 1.0)
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Viscosity of Cement Grout
(W/C=1.2)

Fig. 4.10  Plot of Apparent Viscosity of Cement Grout (W/C = 1.2)

Viscosity of Cement Grout
(W/C=1.5)

Fig. 4.11  Plot of Apparent Viscosity of Cement Grout (W/C = 1.5)
shearing process of 1st Shearing Cycle (Figure 4.12) where the shearing rate is increasing with time, show typical Bingham’s fluid characteristics for the cement grout with water/cement ratio below 0.8 and a trend of increasing yield stress with decreasing W/C ratio. The measured yield stress was found slightly reduced with increasing stirring time possibly due to the more complete destroy of structural bonding in the longer stirring process.

Figures 4.13 shows the variation of viscosity value measured for the cement grout prepared under 1500 rpm stirring speed for 5, 10 and 15 minutes, respectively. The results of measurement show significantly high value of viscosity for grout mix of 0.6 water/cement ratio possibly due to its high consistency resulted from the non-excessive water content in the hydration process as compared with the values of the other four (4) grout mixes. Figure 4.14 shows the plot of viscosity (measured at the end of test, i.e. about 200 seconds) of various grout mixes prepared under 5, 10 and 15 minutes stirring time. The test grout mixes were found to be not sensitive to stirring time except for the grout of 0.6 water/cement ratio which showed higher viscosity value (i.e. by 17 mPas) under the shortest stirring time (i.e. 5 minutes). Mixing time of 15 minutes was found suitable for the high speed mixing of cement grout sample (not exceeding 200 c.c.) for viscosity test in the laboratory. Mixing time for grout volume exceeding 200 c.c. commonly involved in the field application should be adjusted according to the volume of grout mix and verified by tests (e.g. Marsh Cone and mud balance) to ensure that complete mixing for uniform grout mix is achieved.
Fig. 4.12 Plot of Shear Stress with Time for Various Mixes of Cement Grout
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Fig. 4.13  Plot of Apparent Viscosity with Time for Various Mixes of Cement Grout
4.4.2 Results of Rheological Measurement and Discussion

In the present study, the grout samples were subjected to 3 shearing cycles consisting of 6 shearing stages (i.e. up-ramp shearing in 1\textsuperscript{st}, 3\textsuperscript{rd} & 5\textsuperscript{th} shearing stages and down-ramp shearing in 2\textsuperscript{nd}, 4\textsuperscript{th} & 6\textsuperscript{th} shearing stages) to investigate its rheological properties. Obvious fluctuations in viscosity value were observed in the tests of cement grout with water/cement ratio above 1.0 (Figures 4.15 to 4.20). Such fluctuation could be attributed to the unstable suspension existing in these light cement slurries (i.e. W/C > 1.0) where sedimentation of cement particles as anticipated to be significant was observed during the test. Such possibility appears to be likely as indicated by the segregation between cement and water and the behavior of grout (i.e. high viscosity value observed in 5\textsuperscript{th} shearing stage) observed in the time effect study.
Fig. 4.15  Rheological Properties of Cement Grout (W/C = 0.6)
Fig. 4.16  Rheological Properties of Cement Grout (W/C = 0.6 with Stirring)
Fig. 4.17  Rheological Properties of Cement Grout (W/C = 0.8)
Fig. 4.18  Rheological Properties of Cement Grout (W/C = 1.0)
Fig. 4.19  Rheological Properties of Cement Grout (W/C = 1.2)
Fig. 4.20 Rheological Properties of Cement Grout (W/C = 1.5)
4.4.2.1 Time Dependency

Before injection, the time dependency of viscosity could be under mixing disturbance from subsequent agitation (if applied). In the process of permeation grouting, the time dependency of viscosity after injection is free from further mixing disturbance. Study on “time effect”, i.e. time after mixing, as presented in Figures 4.21 to 4.26 show that the cement grout with water/cement ratio (W/C) ranging from 0.8 to 1.5 are found to be not sensitive to elapsed time due to the long setting time of these light cement slurries. Slightly sensitive response was observed in the tests conducted on grout with water/cement ratio of 0.6. Abnormal increase in viscosity values were found in the 5th shearing stage (i.e. up-ramp shearing of 3rd Shearing Cycle) of light cement slurry (water/cement ratio >0.8) as shown in Figure 4.27. The high viscosity values are believed to be attributed to the effect of sedimentation accumulated in the 5th shearing stage.

![Graph showing apparent viscosity of cement grout versus elapsed time (W/C = 0.6)](image_url)

Fig. 4.21  Apparent Viscosity of Cement Grout versus Elapsed Time (W/C = 0.6)
Fig. 4.22 Apparent Viscosity of Cement Grout versus Elapsed Time (W/C = 0.8)

Fig. 4.23 Apparent Viscosity of Cement Grout versus Elapsed Time (W/C = 1.0)
Fig. 4.24  Apparent Viscosity of Cement Grout versus Elapsed Time (W/C = 1.2)

Fig. 4.25  Apparent Viscosity of Cement Grout versus Elapsed Time (W/C = 1.5)
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Fig. 4.26  Apparent Viscosity of Cement Grout versus Elapsed Time (Down- ramp shearing of 1st Shearing Cycle)

Fig. 4.27  Apparent Viscosity of Cement Grout Recorded between 1st and 3rd Shearing Cycles
On the basis of the process of permeation grouting, i.e. start with high shear rate at beginning of injection to low shear rate at end of injection and avoid effect due to setting and sedimentation of grout, viscosity measurement during 2nd shearing stage in Viscometer, i.e. down-ramp shearing of 1st Shearing Cycle with shear stress decreasing with time, which best simulate the grout flow condition in the permeation grouting progress is considered to be the most representative measurements for the viscosity of cement grout (W/C = 0.6 to 1.5) used in the present study. Figures 4.28 and 4.29 show the Bingham models (Eq. 3-4) of cement grout with water/cement ratio of 0.6, 0.8, 1.0, 1.2 & 1.5 adopted in the present research. Figure 4.30 shows the plastic viscosity (Eq. 3-4) and apparent viscosity (Eq. 3-5) for the various mixes of cement grout determined from the experimental works.

4.4.2.2 Shear History Dependency

4.4.2.2.1 Mixing Programme

Shear history experienced by the cement grout during mixing has significant influence on its rheological property. For the high speed mixing adopted in the preparation of cement grout in permeation grouting, the high shear generated by the high speed stirring breaks down the internal structure of cement grout more efficiently, producing grout with low viscosity and more stable internal structure. The well mixed cement grout formed by high speed shearing is less sensitive to further shearing and shows lower stress values for the upward curve due to a more severe exposure to shearing during the mixing.
Fig. 4.28  Bingham Model of Cement Grout (W/C = 0.6, 0.8 & 1.0)
W/C=1.2 / 2nd Stage-downramp / 0 min after mixing

\[ \tau = 0.7111 + 0.0099 \dot{\gamma} \]
\[ R^2 = 0.8287 \]

W/C=1.5 / 2nd Stage-downramp / 0 min after mixing

\[ \tau = 0.1824 + 0.0093 \dot{\gamma} \]
\[ R^2 = 0.8952 \]

Fig. 4.29  Bingham Model of Cement Grout (W/C = 1.2 & 1.5)
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**4.4.2.2.2 Measuring Programme**

Cement grout experiences different shear history under various flow conditions, e.g. different injection pressures (i.e. reflected in shear rate in present tests), resulting in different viscosity of the grout. Different measuring programmes, e.g. different range of shear rate, will result in different values of viscosity.

**4.5 Concluding Remarks**

In view of the time and shear history dependencies of cement grout as identified in the present tests, the rheological properties of ordinary Portland cement grout which
possess Bingham’s fluid characteristics sensitive to the handling and testing process should be properly measured according to the procedures adopted in the present study to ensure the accuracy of the property measurement. Plot of viscosity for various grout mixes as presented in Figure 4.30, show insignificant Bingham’s fluid characteristics for the cement grout with high W/C ratio of 1.5 as indicated by the very small difference between the plastic viscosity and apparent viscosity determined in the viscometer tests. Therefore, it is considered not necessary to extend the rheology study for the light cement grout mixes with water/cement ratio exceeding 1.5.
CHAPTER 5

PERMEABILITY CHARACTERISTICS OF SOIL

5.1 Introduction

In order to have a proper understanding of the permeability of soil to cement grout which is essential in the study of permeation grouting, investigation of the permeability characteristics of soil including factors influencing the permeability of soil (Lambe, 1969) is considered necessary and is therefore incorporated in the present study. A series of remoulded sand samples with particle size distribution (Figure 5.1) similar to that possessed by the fine to medium sand from two local geological formations (Poh et al., 1985, 1987), Old Alluvium (OA) - Changi to Simei and Bukit Timah Granite (BT) were tested in the laboratory to determine its coefficient of permeability to water and grout.

![Fig. 5.1 Grain Size Distribution of Remoulded Sand Samples (Fine to Medium Sand) and Envelop of “BT” & “OA”](image-url)
5.2 The Determination of Permeability of Soil in Laboratory

The determination of the coefficient of permeability to water in soil in the laboratory is commonly carried out using Constant Head Method in triaxial test chamber (Figure 5.2) in accordance with BS1377 : Part 6 : 1990 Method 6. A cylindrical sample of 5cm in diameter and 10cm in height was used for the vertical permeability determination. The test sample is encased within two (2) rubber membranes and connected to two (2) volume change indicators at the two ends through porous stones. The specimen is first saturated and consolidated under a back pressure of about 200 kN/m² commonly used in the industry practice. After each stage of consolidation, a hydraulic gradient is applied by increasing the pore water pressure at one end of the specimen. The flow volume of water measured by the volume change indicator was recorded at regular time intervals until an equilibrium stage of seepage (i.e. inflow volume of water equal to the outflow) was observed. The coefficient of permeability (k) can then be computed from Eq. (5-1) derived by using Darcy’s law.

Fig. 5.2 Constant Head Triaxial Permeability Test
Chapter 5  PERMEABILITY CHARACTERISTICS OF SOIL

\[ k = \frac{Qh}{HAt} \]  \hspace{1cm} (5-1)

where  
\( Q \) = volume of flow of water, cm\(^3\)
\( h \) = length of sample, cm
\( H \) = difference in water head, cm
\( A \) = cross-sectional area of the specimen, cm\(^2\)
\( t \) = time required for \( Q \), sec

The permeability at temperature \( T \), \( k_T \) can be correlated to that at 20°C, \( k_{20^\circ C} \), by using Eq. (5-2) commonly reported for the laboratory permeability tests (Lambe, 1975).

\[ k_{20^\circ C} = \frac{\mu_T}{\mu_{20^\circ C}} \ast k_T \] \hspace{1cm} (5-2)

where  
\( \mu_T \) = viscosity of water at temperature \( T \)
\( \mu_{20^\circ C} \) = viscosity of water at temperature 20°C

All \( k \) values with water presented in this thesis are referred to the coefficient at temperature 20°C.
5.3 **Factors Influencing Permeability of Soil**

According to Lambe (1969), the following five (5) factors influence the permeability of soil to water.

(i) Particle size

(ii) Void ratio (with linear relationship found between the k value and the void ratio function, i.e. \( \frac{e^3}{1+e} \), \( \frac{e^2}{1+e} \) and \( e^2 \))

(iii) Composition (e.g. content of fines and coarse sand)

(iv) Fabric

(v) Degree of saturation

All these influence factors are also found applicable to the permeability of soil to cement grout (Mitchell, 1981 & Perret et al., 2000). For the saturated sandy soil adopted in the present study, the first three (3) factors which have significant influence on the permeability characteristics of sand have been studied as presented in the following sections.

5.4 **Permeability Characteristics of Fine to Medium Sand to Water**

The permeability of a series of remoulded samples consisting of fine to medium sand with \( C_u = 4.4 \) to 14.0 and \( C_c = 0.8 \) to 1.5 (Table 5.1 & Appendix A) and an effective angle of shearing resistance (\( \phi' \)) of 32° [determined from Consolidated-drained Triaxial Compression (\( CID \)) Test according to BS1377:Part 8:1990 Method 8] was measured in the laboratory using de-aired water under Constant Head Triaxial Permeability Test.
Chapter 5    PERMEABILITY CHARACTERISTICS OF SOIL

Method (BS1377:Part 6:1990 Method 6). The results of tests as presented in Figures 5.5 & 5.6 and Table 5.2 indicate that the permeability of sand is sensitive to the percentage of fines, the void ratio and the uniformity of the sand samples. Low values of the coefficient of permeability (k) were measured for specimens with fines >15% (Figure 5.5). Obvious change in the relationship between k and void ratio function (Figure 5.6) was also found for specimens containing high percentage of fines ranging from 12 to 43%. The empirical relationship between k and D_{10}, proposed by Kutzner (1996) for clean sand and sandy gravel (see Eq. 5-3) was found not representative for the type of sand used in the present tests which show low k/D_{10}^2 ratio ranging from 0.3 to 6.5 as compared empirical values of 57 to 126 (Table 5.2). This could be attributed to the percentage of fines content which was found to be significant in the present study of sand and can’t be quantified by the only material parameter (i.e. D_{10}) in the formula. More investigation through permeability tests are needed to verify the validity of this empirical relationship in local engineering practice.

Empirical relationship between k and D_{10}, proposed by Kutzner (1996) for clean sand and sandy gravel:

\[ k \text{ (cm/sec)} = C \times (D_{10})^2 \]  \hspace{1cm} (5-3)

where \( D_{10} \) : soil particle size of which 10\% by weight are smaller (in cm)

\[ *C = 141.6 \left( C_u \right)^{-0.285} \]

* co-related by author based on values proposed by Hazen (1892) for \( C_u \leq 5 \) and by Beyer (1964) for \( C_u > 5 \)
Table 5.1 Particle Size Index and Groutability Ratio of Remoulded Sand Samples

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>USCS</th>
<th>D$_{10}$ (mm)</th>
<th>D$_{15}$ (mm)</th>
<th>D$_{30}$ (mm)</th>
<th>D$_{60}$ (mm)</th>
<th>C$<em>{u}$ ($D</em>{60}/D_{10}$) (&gt;4)</th>
<th>C$<em>{c}$ ($D</em>{30}/D_{10}$) (1 to 3)</th>
<th>N$<em>c$ ($D</em>{10}/d_{95}$) (&gt;6)**</th>
<th>N = $D_{15}/d_{85}$ (&gt;).24)**</th>
</tr>
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<tbody>
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<td>Sample 1</td>
<td>SW-SM</td>
<td>0.100</td>
<td>0.158</td>
<td>0.400</td>
<td>1.140</td>
<td>11.4</td>
<td>1.4</td>
<td>1.1</td>
<td>2.6</td>
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<tr>
<td>Sample 2</td>
<td>SW-SM</td>
<td>0.070</td>
<td>0.103</td>
<td>0.210</td>
<td>0.570</td>
<td>8.1</td>
<td>1.1</td>
<td>0.8</td>
<td>1.7</td>
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<td>Sample 3</td>
<td>SM</td>
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<td>-</td>
<td>0.082</td>
<td>0.210</td>
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<td>-</td>
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<td>Sample 4</td>
<td>SC</td>
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<td>0.067</td>
<td>0.110</td>
<td>0.240</td>
<td>4.4</td>
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<td>0.6</td>
<td>1.1</td>
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<td>SP</td>
<td>0.153</td>
<td>0.180</td>
<td>0.300</td>
<td>0.770</td>
<td>5.0</td>
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<td>1.7</td>
<td>3.0</td>
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<td>4.4</td>
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<td>0.8</td>
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<td>0.090</td>
<td>0.210</td>
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<td>14.0</td>
<td>1.3</td>
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<td>1.0</td>
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<td>5.3</td>
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<td>2.188</td>
<td>2.510</td>
<td>3.160</td>
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<td>2.202</td>
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<td>23.9</td>
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<td>1.0</td>
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<td>2.202</td>
<td>2.490</td>
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<td>2.202</td>
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<td>0.9</td>
<td>23.7</td>
<td>36.7</td>
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</tbody>
</table>

Notes: * Similar grain size distribution

USCS: Unified Soil Classification System

d$_{95}$ = 95% finer size of cement from Fig. 4.1 = 0.09mm

d$_{85}$ = 85% finer size of cement from Fig. 4.1 = 0.06mm

** Groutability Ratio (Mitchell, 1981)

N > 24 Successful Grouting

Nc > 11 Cement grouting is consistently possible

Nc < 6 Cement grouting is not possible
Chapter 5  PERMEABILITY CHARACTERISTICS OF SOIL

Constant Head Triaxial Permeability Tests for Remoulded Sand Specimens

Fig. 5.3  Plot of Coefficient of Permeability ($k_{20}$) versus Consolidation Pressure

Constant Head Triaxial Permeability Tests for Remoulded Sand Specimens

Fig. 5.4  Plot of Coefficient of Permeability ($k_{20}$) versus Void Ratio
## Table 5.2 Permeability of Remoulded Sand Specimens

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Soil Type</th>
<th>% of Fines</th>
<th>C_u (cm)</th>
<th>D_{10} (cm)</th>
<th>k_1 (cm/sec)</th>
<th>k_2 (cm/sec)</th>
<th>k_3 (cm/sec)</th>
<th>k_4 (cm/sec)</th>
<th>Ave. k (cm/sec)</th>
<th>k/(D_{10})^2 (measured)</th>
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</thead>
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<tr>
<td>1</td>
<td>SW-SM</td>
<td>5.1</td>
<td>0.01</td>
<td>3.21E-04</td>
<td>2.98E-04</td>
<td>2.99E-04</td>
<td>3.03E-04</td>
<td>3.05E-04</td>
<td>3.1</td>
<td>e = 0.813</td>
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<td>C = 126.1</td>
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</table>

Method of Test: Constant Head Triaxial Permeability Test

\[ k_(cm/sec) = C \times (D_{10})^2 \] for clean sands and sandy gravel,

where \( D_{10} \) in cm

\[ C = 141.6 \times (C_u)^{0.285} \] after Allan Hazen (1892) for \( C_u \leq 5 \), after Beyer (1964) for \( C_u > 5 \)

\* C. Kutzner(1996)
Triaxial Permeability Test on Sand Samples

**Fig. 5.5** Plot of Coefficient of Permeability ($k_{20}$) versus Per Cent of Fines

**Fig. 5.6** Plot of Coefficient of Permeability ($k_{20}$) versus Void Ratio Function
Chapter 5  PERMEABILITY CHARACTERISTICS OF SOIL

5.5    Flow Characteristics of Coarse Sand

The flow characteristics of water in coarse sand (i.e. 2mm to 6mm in particle size within the feasible range of cement injection and $k = 2 \times 10^{-2}$ cm/sec) which was adopted in the study of permeation grouting in the present research was also investigated to verify the validity of Darcy’s law for this coarse grained materials. A series of water permeability tests covering a pressure range between 0.1 to 5 bars were conducted on coarse sand to evaluate the validity of Darcy's law under various speed of flow. The results of tests as presented in Figure 5.8 show that the water flow under low-pressure (i.e. not exceeding 100 kPa) remains laminar with linear relationship between hydraulic gradient ($i$) and velocity ($v$). The velocity of flow was computed by dividing the volume

![Triaxial Permeability Test on Sand Samples](image)

Figure 5.7  Plot of Coefficient of Permeability ($k_{20}$) versus $D_{10}$
of flow (Q) measured within a time period of “t” with the cross-sections area (A) of the specimen and the measuring time (t). Although the R-squared value for this Linear Regression is 0.85, which is higher than those determined from “Power” or “Exponential” Regression and is considered to be the best fitting for “i” and “v” of water flow under low injection pressure (i.e. <100 kPa).

However, this linear relationship between “i” and “v” can’t be found for tests under high injection pressure exceeding 1 bar, where turbulent flow due to high velocity of flow is anticipated (Figure 5.8).

Fig. 5.8 Plot of Hydraulic Gradient versus Velocity for Water in Coarse Sand Measured in Triaxial Test Chamber
5.6 Influence of Porous Stone to Flow Measurement

Additional Triaxial Permeability Tests have also been carried out to evaluate the influence of porous stones to the water permeability of coarse sand. The results of the present tests as presented in Figure 5.9 show that slight increase in flow velocity \(v\) was observed in the present tests (without porous stones) due to the slightly low permeability of the porous stone as compared with the highly permeable characteristics of coarse sand used in the present study. This observed flow characteristics show that the measurement of permeability of coarse sand in the laboratory should be carefully conducted to minimize possible influence from the conventional test setup for highly permeable materials.

![Fig. 5.9 Influence of Porous Stone to Velocity of Water in Coarse Sand Measured in Triaxial Test Chamber](image-url)
5.7 Concluding Remarks

As shown in Figure 5.10, the relationship between ‘i’ and ‘v’ for water in coarse appears to be non-linear due to the turbulent flow characteristics under high injection pressure (i.e. high flow velocity) and can be well delineated by the “Power” fitting. Linear relationship may be used for injection pressure below 100 kN/m² (Figure 5.8) where a stable flow condition following Dracy’s law is anticipated. However, the velocity of flow measured in the triaxial test chamber was found very much lower than those recorded in the tests conducted using the metal test chamber (as detailed in Section 6.7) fabricated for grout permeability tests (Figure 5.11) in the present study. It appears to be likely as indicated by the verification tests (Figure 5.12) that the set up of triaxial test system consisting of small tubing (2 mm I.D.) between top cap and pedestal may have influence to the velocity of flow and resulted in lower flow rate as compared with those recorded in the tests conducted using metal test chamber with 5 mm (I.D.) tubing directly connected to the inlet valve. This implies that the measurement of flow in highly permeable materials, such as coarse sand as adopted in the present study, is sensitive to the set up of the test system and the injection pressure. Permeability measurement (i.e. water) for coarse sand and gravels using field permeability test instead of Triaxial Permeability Test is recommended.
Chapter 5  PERMEABILITY CHARACTERISTICS OF SOIL

Fig. 5.10  Water Flow Characteristics of Coarse Sand Measured in Triaxial Test Chamber

Fig. 5.11  “v”–“i” Measured in Triaxial Test Chamber and Metal Test Chamber
Fig. 5.12  Influence of Size of Tubing to Measured Flow Rate of Water
CHAPTER 6

GROUTING TESTS FOR SAND

6.1 General

Although the current available laboratory test methods (i.e. in small scale with diameter <100mm) for the determination of the grout injectability in soil were commented by Landry et al. (2000) to be fundamentally flawed due to the poor simulation of field condition in the laboratory test as described in Chapter 1, it is the opinion of the author that the laboratory experiments are essential in further exploration of the field characteristics of cement-based permeation grout for enhancing the performance of the field application. Similar to other laboratory experiments for soil and rock, the findings from the laboratory tests do provide the researchers / practitioners with the valuable parameters, e.g. the influence of viscosity, permeability and injection pressure to groutability, etc., from fundamental approach with good control of testing conditions (e.g. uniformity of test specimens and direction of flow, etc.) as compared with those provided in the field tests. In view of the above reasons, the present research which may not able to simulated perfectly the field condition due to the limitations of the current laboratory facilities.

As described in Chapter 2, only five (5) cases of laboratory injectability tests [Hetal & Krizek (1992), Shimoda et al. (1996), Lowther & Gabr (1997) and Perret et al. (1997, 2000) were found in the literature review, but none of these studies measured the
Chapter 6  GROUTING TESTS FOR SAND

permeability \(k_c\) and the influence factors of Type I Portland cement grout in coarse sand as required for the study of cement based permeation grout in the present research.

In view of the above reasons, determination of the necessary grout flow parameters for cement based permeation grouting as described in Chapter 3 and study of the injectability of cement grout in sand from local geological formation including influence of measuring system were carried out in the present research work via a series of grout permeability test conducted on the fine to medium sand adopted in the water permeability tests (Chapter 5) to evaluate the injectability and flow characteristics of cement grout in this sand material. Although fine to medium sand is known to be not suitable for the application of cement based permeation grouting in view of its small pore size and low permeability to water, a series of water and grout permeability tests were also included in the present research for a better understanding of the flow characteristics (both water and cement grout) of this local sandy soil and its feasibility (i.e. feasible water/cement ratio) for cement grout injection, which will be beneficial to the local practitioners in the application of cement based permeation grouting in this local geological formation.

6.2  Models of Grouting Test

In the present research, grouting tests were conducted under vertical flow model where grout was injected vertically downward through sandy media in a cylindrical test chamber with uniform cross-sectional area under constant injection pressure for measurement of flow volume. The vertical flow measurement adopted in the present study is found to be quite similar to that adopted in the injectability tests carried out by few
researchers (Hetal & Krizek, 1992; Shimoda et al., 1996; Lowther & Gabr, 1997; Perret et al., 1997, 2000) in the investigation of grout penetration under low injection pressure (i.e. not exceeding 1.5 bars) and pore structure of grouted sand except that the grout was injected vertically upward for the measurement of grout penetration (i.e. grout level) under low injection pressure in the test specimens in small test chamber (e.g. 22 mm in diameter).

6.3 Equipment and Experimental Set Up

6.3.1 Test Apparatus

For the investigation of the flowability of cement grout in sand as in the present research, 3 different test apparatus consisting of i) conventional triaxial test chamber in view of its common availability and practicality and for purpose of verifying its accuracy of in the flow measurement; ii) perspex pot (6.2 cm I.D. x 8.5 cm height) in view of its advantages of allowing a visual inspection on the characteristics of grout flow including the influence from the sedimentation of cement particles during the injection process and better flowability as compared with triaxial test chamber iii) steel test chamber designed by the author with significant improvement to the flowability of grout via larger inlet/outlet valves and smoother flow path using stone base for preventing choking of cement grout commonly encountered in the other two test systems and enhancing the accuracy of flow measurement.
6.3.2 Pressure System

The injection of cement grout was achieved by using the air-water pressure system of the triaxial test system (Figure 6.1) which allows the application of various injection pressures up to 8 bars in the present grout permeability tests.

![Fig. 6.1 Air-water Pressure System for Injection of Grout](image)

6.3.3 Measuring System

The quantity of grout flow through the test specimen under each applied injection pressure was measured by using a graduated cylinder (Figure 6.2). The time for each discharge of grout flow was recorded by a stopwatch for the computation of flow rate and the determination of coefficient of permeability for grout.
6.4 Groutability of Fine to Medium Sand in Triaxial Test Chamber

Experiments for the investigation of the permeability of fine to medium sand specimen (i.e. OA and BT, Figure 5.1) to cement grout were conducted in the laboratory using triaxial test chamber and constant head method. Due to the low groutability ratios, \( N = D_{15}/D_{85} = 1.1 \) to 7.6 < 25 and \( Nc = D_{10}/D_{95} = 0.6 \) to 3.0 < 6 (Mitchell, 1981) and the unsatisfactory test setup consisting of small tubing for cement injection, difficulties were encountered in the grout permeability tests of fine to medium sand in triaxial test chamber, especially for the cement grouts with low water/cement ratio of 0.6 and 0.8.
Grout flow readings can only be obtained for this fine to medium sand until a high water/cement ratio of 6.0 was adopted in the grout permeability test conducted on a sand specimen (i.e. Sample No. 12) which possess a triaxial permeability coefficient (with water) value of $3.23 \times 10^{-5} \text{ cm/sec} \ (3.23 \times 10^{-7} \text{ m/sec})$. The permeability coefficient of this sample measured by using grout of 6.0 water/cement ratio is $4.31 \times 10^{-8} \text{ cm/sec} \ (4.31 \times 10^{-10} \text{ m/sec})$. The poor groutability is likely to be attributed to the low permeability (i.e. less than $5 \times 10^{-4} \text{ m/sec}$ or 0.05 cm/sec, LittleJohn 1982) and the unsuitable particle size for cement injection of fine to medium sand (Figure 5.1) as compared with the practical range of particle size recommended for cement injection (Figure 6.3). This implies that light cement grout even with water/cement ratio exceeding 3.0 as commonly used by some local contractors for improvement to the fine to medium sand in OA or BT (Figure 5.1) may not be effective.

Fig. 6.3  Limits of Grout Acceptance by Particle Size
The results of grout tests as described above show that the type of fine to medium sand commonly found in the local geological formation (e.g. OA and BT) is not feasible for effective improvement using cement grout. The triaxial test chamber was also found not suitable for carrying out the grout permeability test due to possible blockage associated with small tubing and small drainage holes (i.e. top cap and pedestal) in the triaxial test system. A more permeable media, such as coarse sand with improved test setup designed by the author taking into consideration of the influence of apparatus dimensions (e.g. valve and tubing) and the imperfect flow path of existing test setup (e.g. sedimentation at flow outlet) was then adopted in the study to improve the flowability of grout and the measurement of grout permeability coefficient in the laboratory (see Section 6.5).

6.5 Groutability of Coarse Sand in Perspex Pot without Stone Base Improvement

Further to the series of Triaxial Permeability Tests conducted on remoulded samples consisting of fine to medium sand with particle size similar to the sand commonly found in OA and BT (Section 5.4) which was identified to be not injectable for cement grout with water/cement ratio below 6.0 due to its low permeability coefficient (i.e. $10^{-4}$ to $10^{-6}$ cm/sec or $10^{-6}$ to $10^{-8}$ m/sec beyond the groutable range suggested by LittleJohn, 1982) and the problems associated with the limitations of the triaxial system (e.g. small tubing and small drainage holes) encountered in the grout permeability tests, remoulded samples consisting of coarse sand with particle size ranging from 2 mm to 6 mm (Figure 6.4) within the practical range of cement injection were subsequently used in the grout
permeability tests (without stone base improvement) to investigate the characteristic of cement grout flow in this highly permeable material ($k = 2 \times 10^{-2}$ cm/sec or $2 \times 10^{-4}$ m/sec to water). The experiment was first tried with falling head method and subsequently replaced with constant head method to improve the flow and injection pressure of the test.

The first six sets of coarse sand samples contained in a Perspex Pot (Figure 6.5) were prepared and tested for the permeability coefficient ($k_G$) using various grout mixes with water/cement ratio of 0.6, 0.8, 1.0, 1.2 and 1.5. Grout was supplied from pressurized tubing (up to 8 bars) through inlet valve (Figures 6.6a & 6.6b) at top of the Perspex Pot and flow out through the outlet valve at the base of the Perspex Pot. The speed of grout flow was found to reduce gradually with time; especially for grout of W/C $\leq$ 0.8 (i.e. after 100 sec of elapsed time from commencement of test) due to the accumulation of cement particles at base of the Perspex Pot (Figure 6.7). Figure 6.8 shows the plot of water/cement

Fig. 6.4 Grain Size Distribution of Remoulded Sand Specimens (Coarse sand - 2 to 6mm)
ratio versus coefficient of permeability ($k_G$) for the coarse sand samples tested. The $k_G$ values were determined from the results of several trials on each permeability test based on 1000 c.c. grout discharge, except for grout mixes of W/C = 0.6 and 0.8 which were calculated based on the elapsed time and grout discharge measured prior to the stoppage of flow take place. It is believed that the measured $k_G$ values with grout in the coarse sand determined in the above-mentioned test set-up could be under-estimated due to the easy accumulation of cement particles over the drain outlet valve in this test setup.
Chapter 6  GROUTING TESTS FOR SAND

Fig. 6.6b  Grout Permeability Test (Constant Head Method)

Fig. 6.7  Accumulation of Cement Particles at Base of Specimen
6.6 Groutability of Coarse Sand in Perspex Pot with Stone Base Improvement

To minimize the effect of sedimentation due to test setup and its influence on the grout flow, a layer of coarse stones (about 10 mm in thickness and 0.5 cm to 1.0 cm in particle size as shown in Figure 6.9a) was placed at the base of the pot for further investigation. The improvement to the grout flow process and hence the measurement of permeability coefficient of grout ($k_G$) can be clearly seen in the plot of water/cement ratio versus $k_G$ for subsequent tests (i.e. Sample Nos. 21 to 28 as shown in Figure 6.9b). The results of these tests show that the $k_G$ value of cement grout flow increased with increasing water/cement ratio (W/C) and the increase become not significant for grout with water/cement ratio above 1.0, probably due to the relatively close viscosity values of these
light grout mixes. The measured permeability coefficient of grout was found to reduce with time for grout with W/C not exceeding 1.0 (Figure 6.10) due to the more obvious accumulation of cement particles observed. However, the set up of test system needs to be further improved in view of the blockage of tubing (Figure 6.11) occasionally encountered for grout with W/C ratio below 0.8 in the present tests.

Fig. 6.9a  Stone Base Improvement

Fig. 6.9b  Plot of Coefficient of Permeability to Grout ($k_G$) versus Water/Cement Ratio for Coarse Sand in Perspex Pot with Stone Base Improvement
Cement Grout Permeability Tests conducted on Coarse Sand

Fig. 6.10  Plot of Coefficient of Permeability to Grout ($k_G$) versus Elapsed Time

Fig 6.11  Blockage of Grout Tubing
6.7 Groutability of Coarse Sand in Metal Test Chamber

For the purpose of solving the choking problem associated with cement sedimentation encountered in the tests as described in the previous sections and improving the flow measurement in the grout permeability tests, a special test chamber (Figures 6.12a & 6.12b) capable of resisting injection pressure up to 60 bars was designed by the author for further study of the flowability of cement grout in coarse sand in the present research.

As shown in Figures 6.12a & 6.12b, the design of the special test chamber which consists of three major components, namely i) top MS plate with inlet valve, ii) steel cylinder with PVC jacket and iii) base MS plate with steel cone and outlet valve was a new concept based on the author’s practical experience in the measurement of vertical flow (i.e. cylindrical flow) in laboratory taking into consideration of the necessary enhancement to the sample assembly, injection, flow measurement and handling of the grouted soil specimen in each test. Figure 6.13 shows the set up of grout permeability test using the metal test chamber. A series of permeability tests have been conducted on coarse sand (2 to 6mm) using various mixes of grout with water/cement ratio of 0.6, 0.8, 1.0, 1.2 and 1.5 (Figure 6.14). Significant improvement in the measurement of grout permeability were found in the tests conducted on coarse sand using the special test chamber as indicated by the smooth and more complete drainage of grout in the tests. Figure 6.14 shows the variation of coefficient of permeability to grout (kG) with W/C ratio measured in the grout permeability tests.
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Fig. 6.12a  Schematic Diagram of Metal Test Chamber
Fig. 6.12b  Schematic Diagram of Metal Test Chamber
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Fig. 6.13  Grout Permeability Test using Metal Test Chamber
6.8 Influence of Injection Pressure on Grout Flow in Coarse Sand

According to the results of the grout permeability tests, an indicative trend showing decreasing coefficient of permeability for grout ($k_G$) with increasing injection pressure ($P_p$) was found in the grout permeability tests conducted on coarse sand used in the present study (Figure 6.15). The speed of grout flow ($v$) was also found to be influenced significantly by the injection pressure ($P_p$) or the hydraulic gradient which can be expressed in the following co-relation (Eq. 6-2) determined from the present tests with $P_p$ ranging from 50 to 700 kN/m$^2$. 

![Cement Grout Permeability Test Conducted on Coarse Sand (2 to 6 mm)](image)

Fig. 6.14 Variation of $k_G$ with W/C Ratio
Chapter 6  GROUTING TESTS FOR SAND

\[ i = \frac{P_p}{H} \]  \hspace{1cm} \text{(Eq. 6-1)}

where \( H \) = height of specimen = 11 cm, then

\[ i = \frac{[P_p \text{ (kPa)} / 9.81]}{11 / 100} \]

\[ i = 0.9267 \times P_p \text{ (kPa)}, \text{ or} \]

\[ P_p \text{ (kPa)} = 1.0791 \times i \]  \hspace{1cm} \text{(Eq. 6-2)}

Due to the non-linear relationship between “i” and “v” observed for water flow in coarse sand under high injection pressure (i.e. above 1 bar) as described in Chapter 5, the flow characteristics of cement grout determined from the present tests were re-analyzed assuming non-linear relationship between “i” and “v” for best simulation of the flow.

![Cement Grout Permeability Test Conducted on Coarse Sand (2 to 6mm)](image)

**Fig. 6.15** Variation of \( k_G \) with Effective Injection Pressure
characteristics of cement grout permeating through coarse sand in view of the high injection pressure adopted in the permeation grouting works. Details of these analyses are presented in Section 6.9.

6.9 Established Relationship between Hydraulic Gradient (i) and Velocity (v) for Cement Grout Flow in Coarse Sand

As shown in Figure 6.16, the non-linear fitting are found to well describe the injection flow behavior of cement grout with high water/cement ratio of 1.0, 1.2 and 1.5 as indicated by the high “R-squared value” of 0.94 and above obtained from the present study.

For cement grout with low water/cement ratio of 0.6 and 0.8, relatively poor non-linear relationship between “i” and “v” which is believed to be influenced significantly by the high viscosity of these thick cement grout or possibly the complicated flow resistance (i.e. internal shear resistance not quantifiable at this stage) in coarse sand was found for these thick grout mixes as indicated by the lower R-squared value of 0.66 and 0.82, respectively as shown in Figure 6.17. However, such non-linear fitting is still found to be better than other fitting method, e.g. linear assumption for Newtonian fluid.
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Fig. 6.16  Non-linear Relationship between Hydraulic Gradient (i) and Velocity (v) of Cement Grout (W/C= 1.0, 1.2 & 1.5)
Fig. 6.17 Non-linear Relationship between Hydraulic Gradient ($i$) and Velocity ($v$) of Cement Grout ($W/C=0.6$ & $0.8$)
6.10 Concluding Remarks

Figure 6.18 shows the plot of “v” versus “i” for various cement grout mixes (W/C = 0.6 to 1.5) measured in the metal test chamber designed by the author. These test results provide practitioners useful information for comparing the injectability (i.e. the effectiveness of injection pressure to grout flow) of various cement grout mix designs (W/C = 0.6, 0.8, 1.0, 1.2 & 1.5) in coarse sand (2 to 6mm) which are not available in the current state of the art for permeation grouting.

It can be seen from Figure 6.18 that the rate of grout flow (i.e. in term of flow velocity as shown in Figure 6.18) or the extent of treatment for a fixed value of soil permeability could be improved by increasing the injection pressure or by reducing the viscosity of the grout (i.e. increasing W/C ratio) which is consistent with the statement made by Tomiolo (1982). However, the improvement which can be achieved by increasing the injection pressure is found to be less significant and could be limited for cement grout with low water/cement ratio of 0.6 due to its high viscosity and internal friction. This implies that proper selection of the grout mix design and injection pressures [e.g. proper selection of injection pressure (Pp = 1.0791 i) for effective enhancement of flow velocity according to the relationship between hydraulic gradient and flow velocity established for the various mixes of cement grout as shown in Figure 6.18] are essential in ensuring the effective application of permeation grouting in both the laboratory and the field using ordinary Portland cement (i.e. Type I) in coarse sand.
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\[ y = 167.79e^{0.4632x} \quad R^2 = 0.6639 \quad W/C=0.6 \]

\[ y = 102.02e^{0.2956x} \quad R^2 = 0.8175 \quad W/C=0.8 \]

\[ y = 29.836x^{1.5569} \quad R^2 = 0.9742 \quad W/C=1.0 \]

\[ y = 26.987x^{1.5742} \quad R^2 = 0.9495 \quad W/C=1.2 \]

\[ y = 23.34x^{1.5039} \quad R^2 = 0.9377 \quad W/C=1.5 \]

**Legend:**
- □ W/C=0.6,
- △ W/C=0.8,
- ☻ W/C=1.0,
- ★ W/C=1.2,
- ✗ W/C=1.5

**Effective Injection Pressure (Pp) adopted in Tests, (kN/m²)**

<table>
<thead>
<tr>
<th>W/C = 0.6 &amp; 0.8</th>
<th>W/C = 1.0 &amp; 1.2</th>
<th>W/C = 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 to 700</td>
<td>50 to 700</td>
<td>50 to 400</td>
</tr>
</tbody>
</table>

Fig. 6.18  Non-linear Relationship between Hydraulic Gradient (i) and Velocity (v) of Various Cement Grout Mixes
Permeation grouting work is largely a trial and error process in the current construction industry. An experimental study on the rheological properties of various cement grout mixes with water/cement ratio (W/C, by weight) of 0.6, 0.8, 1.0, 1.2 & 1.5 and the grout flow characteristics in coarse sand (2 to 6mm) was carried out in the present research for the determination of important grout parameters, such as yield stress, viscosity, density, and coefficient of permeability of cement grout for enhancing the application of cement based permeation grouting works. Based on the results of the present study, the following conclusions are drawn and recommendations are made.

7.1 Conclusions

(1) Darcy’s law was found not well delineating the flow characteristics of cement grout with water/cement ratio ranging between 0.6 and 1.5 which possess non-linear relationship between hydraulic gradient (i) and flow velocity (v) due to the influence of the viscosity of this Bingham’s grouts and the high injection pressure applied in the permeation grouting works.

(2) According to Tomiolo (1982), the two available flow models (Raffle and Greenwood, 1961) consider the flow of viscous fluids through the soil follows the same laws governing the flow of water, all values (e.g. coefficient of permeability
to grout, $k_c$) being amplified proportionally to the ratio of grout viscosity to water viscosity as shown in Eq. (1-1). It is the opinion of the author that such consideration may not be appropriate for cement grout with water/cement ratio (W/C, by weight) below 1.5 in view of the significant Bingham’s fluid characteristics possessed by these cement grout mixes and also the very high injection pressure which may influence the applicability of Darcy’s law, adopted in the cement based permeation grouting works.

(3) Equations derived from these two available flow models allow the estimation of pressure required for maintaining flow to a given distance and injection hole spacing for permeation grouting as a function of the grout material parameters (e.g. viscosity and permeability coefficient of grout, etc.) and grout method parameters (e.g. injection pressure and flow rate, etc.). These required grout parameters are studied and presented in this thesis for the reference of the practitioners.

(4) For the cement grout formed by ordinary Portland cement (Trade name : Asia Cement) commonly used in the local construction industry as adopted in the present study, ninety-seven per cent (97%) of the cement particles was found with diameter smaller than 0.1 mm ($D_{85} = 0.06$ mm and $D_{95} = 0.09$ mm) and the grain size distribution appears to be similar to that of the ordinary Type I Portland cement studied by Schwarz et al (1992). According to the criteria for limits of particle size for effective grouting as recommended by various authors, this type of cement commonly used in the local construction industries appears to be applicable to the injection in sand with the following $D_{15}$ values only. The $D_{15}$
Chapter 7 CONCLUSIONS AND RECOMMENDATIONS

value (i.e. 2.2 mm) of coarse sand used in the present research was found to meet the last three criteria.

- \( D_{15} = 5 \ d_{85} \text{ to } 24 \ d_{85} = 0.3 \text{ – } 1.44 \ mm \) (Kravetz, 1958)
- \( D_{15} \geq 16 \ d_{85} = 0.96 \ mm \) (King & Bush, 1961)
- \( D_{15} \geq 25d_{85} = 1.5 \ mm \) (Johnson, 1958), (Karol, 1960)
- \( D_{15} \geq 24d_{85} = 1.44 \ mm \) (Mitchell, 1981)

(5) Mixing time of 15 minutes was found suitable for the high speed mixing of cement grout sample for viscosity test in the laboratory. Mixing time for grout volume exceeding 200 c.c. as used in the field applications shall be adjusted and checked (e.g. Marsh Cone Test and density test, etc.) to ensure the complete mixing for uniform grout mix is achieved.

(6) The viscosity of cement grout with water/cement ratio (W/C) ranging from 0.8 to 1.5 are found not sensitive to elapsed time after mixing in the measurements carried out in Viscometer Tests, possibly due to the long setting time of these light cement slurries which could be recovered from the slightly stirring using a glass rod prior to setup in the viscometer for viscosity test. Slightly sensitive response as indicated by fluctuation in viscosity value was observed in the tests conducted on grout with water/cement ratio of 0.6. This implies that some permanent changes to the grout structure due to elapsed time (i.e. setting of cement) may have been induced to this thick grout slurry (i.e. W/C = 0.6) and could not be recovered by sample stirring.
(7) For the cement grout mixes adopted in the present study, the measured yield stress was found slightly reduced with increasing stirring time possibly due to the more complete destroy of structural bonding in the longer stirring process and the impact to the engineering characteristics of grout is not expected to be significant.

(8) All the grout mixes except for grout with W/C = 0.6 were found with sedimentation rate greater than 10%. None of the grout mixes in the present study can satisfy the stable sedimentation criteria (i.e. sedimentation rate <5% after 2 hours) specified by Deere et al (1985) and Kutzner (1996). This implies that precautionary measures for minimizing segregation effect, such as continuous stirring by using an agitator prior to injection should be provided in the application of light grout mixes (i.e. water/cement ratio ranging from 0.8 to 1.5) in the permeation grouting work. However, timely handling process should be provided in the application of cement grout with W/C = 0.6 in view of possible influence (e.g. flowability) caused by the setting of this thick cement grout.

(9) On the basis of the process of permeation grouting which starts with high shear rate at the beginning of injection to low shear rate at end of permeation and for avoiding minimizing the effect of setting and sedimentation of grout, viscosity measurement during 2nd shearing stage in Viscometer, i.e. down-ramp shearing of 1st Shearing Cycle is considered to be the most representative measurements for the viscosity of cement grout (W/C = 0.6 to 1.5) for study of permeation grouting.
The water permeability of remoulded samples consisting of fine to medium sand with grain size distribution similar to the sand from the local geology (i.e. OA and BT) were found sensitive to the percentage of fines, the void ratio and the uniformity of the sand samples. Low coefficient of permeability \( k \) values and obvious change in the relationship between \( k \) and void ratio function were found for sand specimens with fines >10%.

The empirical relationship between \( k \) and \( D_{10} \) (Eq. 5-3, Kutzner, 1996) for clean sand and sandy gravel was found not representative of the type of sand used in the present tests which show low \( k/D_{10}^2 \) ratio ranging from 0.3 to 6.5 as compared with the Kutzner’s empirical values of 57 to 126 (Table 5.2) possibly due to existence of fines content. More investigation through permeability tests are needed to verify the validity of this empirical relationship in the local ground engineering practice.

Measurement of flow in highly permeable materials, such as coarse sand as adopted in the present study, is sensitive to the set up of the test system and the injection pressure. Water permeability measurement for coarse sand using field permeability test instead of Triaxial Permeability Test is recommended.

In view of the unavailability of reliable small scale (i.e. <100 mm in diameter) or laboratory methods for the measurement of the coefficient of permeability for cement grout in the current state of the art for permeation grouting, a special test chamber was designed by the author for the measurement of the injectability of various cement grout mixes (W/C = 0.6, 0.8, 1.0, 1.2 & 1.5) in coarse sand adopted
in the present research. The design of the special test chamber which consists of three major (3) components, namely i) top MS plate with inlet valve, ii) steel cylinder with PVC jacket and iii) base MS plate with steel cone and outlet valve was developed from the author’s practical experience in the measurement of vertical flow (i.e. cylindrical flow) in laboratory taking into consideration of the necessary enhancement to the sample assembly, injection, flow measurement and handling of the grouted soil specimen in each test.

(14) Grout flow readings from Constant Head Triaxial Permeability Test can only be obtained for the fine to medium sand (k to water =3.23 x 10^{-5} cm/sec or 3.23 x 10^{-7} m/sec) commonly found in the local geology (e.g. OA & BT) until a high water/cement ratio of 6.0 was adopted. This implies that the application of cement based permeation grouting using light cement grout even with high water/cement ratio of 3.0 as commonly used by some local contractors for improvement to the fine to medium sand in OA or BT may not be effective.

(15) It was found from the present study for grout mixes of W/C = 0.6 to 1.5 that the rate of grout flow (i.e. in term of flow velocity) or the extent of treatment for a fixed value of soil permeability could be improved by increasing the injection pressure or by reducing the viscosity of the grout (i.e. increasing W/C ratio) which is consistent with the statement made by Tomiolo (1982).

(16) The improvement to grout flow by increasing the injection pressure is found to be less significant and could be limited for cement grout with low water/cement ratio
(W/C) of 0.6 as compared with other grout mixes with W/C ranging from 0.8 to 1.5. This implies that proper selection of the grout mix and injection pressures are essential in ensuring the effective application of permeation grouting in both the laboratory and the field using ordinary Portland cement (i.e. Type I) in coarse sand.

(17) Relationship between $k_G$, $i$, $v$, W/C and viscosity including the influence of injection pressure ($P_p$) to $k_G$ (in Figure 6.15 and also in Figure 6.18 expressed in terms of “$i$” and “$v$”, where $P_p = 1.0791 \times i$) which are not generally available in the published literature for cement based permeation grouting have been established for the various grout mixes with water/cement ratio ranging from 0.6 to 1.5 for enhancing the estimation of effective injection pressure and suitable injection hole spacing for permeation grouting in coarse sand (2 to 6 mm) using the existing grout flow models.

(18) The present research work provides the practitioners with the important grout parameters (e.g. viscosity of various grout mixes and its permeability under high injection pressure in coarse sand) which are not available in past research work for useful comparison between the characteristics of different grout mixes which are essential in the proper design and effective application of cemented based permeation grouting using ordinary Portland cement (Portland Type I) with water/cement ratio of 0.6, 0.8, 1.0, 1.2 & 1.5, especially in the local construction industry.
7.2 Recommendations

It is recommended that the study on the permeability characteristics of permeation grout be extended to the ordinary cement grout with W/C of 0.4 and 2.0 to 3.0 to explore its applicability in coarse sand and fine to medium sand from local geological formation (i.e. Old Alluvium, OA and Bukit Timah Granite, BT) for enhancing the application of permeation grouting in the local construction industry.

Other factors, such as the effect of additives on the stability (i.e. bleeding) of cement grout, the influence of the degree of saturation of soil and the dimensions of test chamber (i.e. diameter over 100 mm) on the accuracy of flow measurement and the performance of the grout permeation are also recommended to be included in future research work.


ASCE (2003), Proceedings of the Third International Conference on Grouting and Ground Treatment. Feb 10-12, New Orleans, Louisiana. Geotechnical Special Publication No. 120. ASCE.


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Institute of Civil Engineers (ICE) (1992), Grouting in the Ground. Nov. 25-26, London.


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REFERENCES


REFERENCES


REFERENCES


REFERENCES

APPENDIX A

LABORATORY TEST RESULTS
TRIAXIAL PERMEABILITY TEST

Borehole No.  -          Type of Test:  Multi Stage Constant Head Test
Sample No.:  Sample 1      Depth (m) :  -

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Liquid Limit (%)</th>
<th>Plasticity Limit (%)</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (Initial) Content</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(%) (Final)</td>
<td>17.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit Weight (kN/m³)</td>
<td>14.24</td>
<td></td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SW-SM</td>
<td></td>
<td>Initial Void Ratio</td>
<td>0.851</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20°C</th>
<th>Vertical Permeability at 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kN/m²</td>
<td>cm/sec</td>
<td>cm/sec</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>180</td>
<td>42.0</td>
<td>0.813</td>
<td>-</td>
<td>3.21E-04</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>42.0</td>
<td>0.776</td>
<td>-</td>
<td>2.98E-04</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>44.0</td>
<td>0.772</td>
<td>-</td>
<td>2.99E-04</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>42.0</td>
<td>0.770</td>
<td>-</td>
<td>3.03E-04</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20°C, cm/sec
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 2 Depth (m): -

<table>
<thead>
<tr>
<th></th>
<th>Water Content(%) (Initial)</th>
<th>Liquid Limit (%)</th>
<th>Plasticity Limit (%)</th>
<th>Initial Void Ratio</th>
<th>Void Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.2</td>
<td>NP</td>
<td>NP</td>
<td>0.783</td>
<td></td>
</tr>
<tr>
<td>Unit Weight (kN/m³)</td>
<td>15.11</td>
<td>Specific Gravity</td>
<td>2.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SW-SM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure kN/m²</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20°C cm/sec</th>
<th>Vertical Permeability at 20°C cm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>34.0</td>
<td>0.758</td>
<td>-</td>
<td>2.34E-04</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>34.0</td>
<td>0.755</td>
<td>-</td>
<td>2.09E-04</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>34.0</td>
<td>0.751</td>
<td>-</td>
<td>2.08E-04</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>40.0</td>
<td>0.745</td>
<td>-</td>
<td>1.99E-04</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20°C, cm/sec
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 3 Depth (m): -

<table>
<thead>
<tr>
<th>Water (Initial)</th>
<th>Liquid Limit (%)</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conten(%) (Final)</td>
<td>Plasticity Limit (%)</td>
<td>NP</td>
</tr>
<tr>
<td>Unit Weight (kN/m3)</td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>Initial Void Ratio</td>
<td>0.802</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure (kN/m²)</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20°C (cm/sec)</th>
<th>Vertical Permeability at 20°C (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>22.0</td>
<td>0.772</td>
<td>-</td>
<td>3.40E-04</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>22.0</td>
<td>0.767</td>
<td>-</td>
<td>3.13E-04</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>20.0</td>
<td>0.763</td>
<td>-</td>
<td>3.01E-04</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>24.0</td>
<td>0.762</td>
<td>-</td>
<td>3.15E-04</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20°C, cm/sec

A-4
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 4 Depth (m) :

<table>
<thead>
<tr>
<th>Water Content(%) (Initial)</th>
<th>3.7</th>
<th>Liquid Limit (%)</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasticity Limit (%)</td>
<td>23.6</td>
<td></td>
<td>NP</td>
</tr>
<tr>
<td>Unit Weight (kN/m³)</td>
<td>14.84</td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SC</td>
<td>Initial Void Ratio</td>
<td>1.173</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure (kN/m²)</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20° C (cm/sec)</th>
<th>Vertical Permeability at 20° C (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>32.0</td>
<td>0.789</td>
<td>-</td>
<td>2.17E-04</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>30.0</td>
<td>0.781</td>
<td>-</td>
<td>1.88E-04</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>38.0</td>
<td>0.776</td>
<td>-</td>
<td>1.89E-04</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>36.0</td>
<td>0.768</td>
<td>-</td>
<td>1.93E-04</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20° C, cm/sec

A-5
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test

Sample No.: Sample 5 Depth (m): -

<table>
<thead>
<tr>
<th>Property</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (Initial) Content (%) (Final)</td>
<td>2.9</td>
<td>20.9</td>
<td>NP</td>
</tr>
<tr>
<td>Plasticity Limit (%)</td>
<td></td>
<td></td>
<td>NP</td>
</tr>
<tr>
<td>Unit Weight (kN/m3)</td>
<td>15.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Gravity</td>
<td></td>
<td></td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SP</td>
<td></td>
<td>0.699</td>
</tr>
<tr>
<td>Initial Void Ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage Nc.</th>
<th>Consolidation Pressure (kN/m²)</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20°C (cm/sec)</th>
<th>Vertical Permeability at 20°C (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>34.0</td>
<td>0.669</td>
<td>-</td>
<td>1.90E-04</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>32.0</td>
<td>0.666</td>
<td>-</td>
<td>1.76E-04</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>40.0</td>
<td>0.662</td>
<td>-</td>
<td>1.70E-04</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>30.0</td>
<td>0.659</td>
<td>-</td>
<td>1.62E-04</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20°C, cm/sec
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 6 Depth (m): -

<table>
<thead>
<tr>
<th>Property</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (Initial)</td>
<td>1.9</td>
<td>Liquid Limit (%)</td>
<td>59.6</td>
</tr>
<tr>
<td>Content(%) (Final)</td>
<td>18.9</td>
<td>Plasticity Limit (%)</td>
<td>33.9</td>
</tr>
<tr>
<td>Unit Weight (kN/m3)</td>
<td>14.92</td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SC</td>
<td>Initial Void Ratio</td>
<td>0.781</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20° C</th>
<th>Vertical Permeability at 20° C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kN/m²</td>
<td>cm/sec</td>
<td>cm/sec</td>
<td>cm/sec</td>
<td>cm/sec</td>
</tr>
<tr>
<td>1</td>
<td>180</td>
<td>44.0</td>
<td>0.702</td>
<td>-</td>
<td>1.97E-05</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>40.0</td>
<td>0.676</td>
<td>-</td>
<td>1.97E-05</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>40.0</td>
<td>0.666</td>
<td>-</td>
<td>1.62E-05</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>46.0</td>
<td>0.659</td>
<td>-</td>
<td>1.61E-05</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20° C, cm/sec
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 7 Depth (m): -

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content (Initial)</td>
<td>2.0</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>-</td>
</tr>
<tr>
<td>Content (Initial) (Final)</td>
<td>15.0</td>
</tr>
<tr>
<td>Plasticity Limit (%)</td>
<td>-</td>
</tr>
<tr>
<td>Unit Weight (kN/m3)</td>
<td>14.76</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SC</td>
</tr>
<tr>
<td>Initial Void Ratio</td>
<td>0.803</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure (kN/m²)</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20° C (cm/sec)</th>
<th>Vertical Permeability at 20° C (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>50.0</td>
<td>0.711</td>
<td>-</td>
<td>1.29E-05</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>50.0</td>
<td>0.887</td>
<td>-</td>
<td>1.29E-05</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>51.0</td>
<td>0.686</td>
<td>-</td>
<td>1.27E-05</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>36.0</td>
<td>0.573</td>
<td>-</td>
<td>9.32E-06</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20° C, cm/sec

A-8
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 8 Depth (m): -

<table>
<thead>
<tr>
<th>Water (Initial)</th>
<th>1.0</th>
<th>Liquid Limit (%)</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content(%) (Final)</td>
<td>16.6</td>
<td>Plasticity Limit (%)</td>
<td>-</td>
</tr>
<tr>
<td>Unit Weight (kN/m3)</td>
<td>14.76</td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SC</td>
<td>Initial Void Ratio</td>
<td>0.786</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure kN/m²</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20°C cm/sec</th>
<th>Vertical Permeability at 20°C cm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>40.0</td>
<td>0.642</td>
<td>-</td>
<td>3.87E-06</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>32.0</td>
<td>0.633</td>
<td>-</td>
<td>2.80E-06</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>34.0</td>
<td>0.624</td>
<td>-</td>
<td>2.07E-06</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>32.0</td>
<td>0.612</td>
<td>-</td>
<td>1.96E-06</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20°C, cm/sec

A-9
TRIAXIAL PERMEABILITY TEST

Borehole No.: -  Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 9  Depth (m): -

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content (Initial)</td>
<td>7.7%</td>
<td>Liquid Limit (%)</td>
<td>-</td>
</tr>
<tr>
<td>Water Content (Final)</td>
<td>18.34%</td>
<td>Plasticity Limit (%)</td>
<td>-</td>
</tr>
<tr>
<td>Unit Weight (kN/m³)</td>
<td>17.00</td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SW</td>
<td>Initial Void Ratio</td>
<td>0.653</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure (kN/m²)</th>
<th>Hydraulic Gradient (cm/sec)</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20° C (cm/sec)</th>
<th>Vertical Permeability at 20° C (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>40.0</td>
<td>0.624</td>
<td>-</td>
<td>2.25E-04</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>38.0</td>
<td>0.618</td>
<td>-</td>
<td>1.97E-04</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>40.0</td>
<td>0.614</td>
<td>-</td>
<td>1.72E-04</td>
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<tr>
<td>4</td>
<td>330</td>
<td>40.0</td>
<td>0.611</td>
<td>-</td>
<td>1.55E-04</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20° C, cm/sec

Consolidation Pressure, kN/m²

0 50 100 150 200 250 300 350

1.00E-05 1.00E-04 1.00E-03

A-10
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 10 Depth (m): -

<table>
<thead>
<tr>
<th>Property</th>
<th>Initial Values</th>
<th>Final Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content (%)</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>Plasticity Limit (%)</td>
<td>16.4</td>
<td>-</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>14.79</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SC</td>
<td>0.782</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20°C</th>
<th>Vertical Permeability at 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kN/m²</td>
<td>cm/sec</td>
<td>cm/sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>180</td>
<td>36.0</td>
<td>0.700</td>
<td>-</td>
<td>5.69E-06</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>32.0</td>
<td>0.668</td>
<td>-</td>
<td>5.44E-06</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>34.0</td>
<td>0.643</td>
<td>-</td>
<td>4.91E-06</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>34.0</td>
<td>0.624</td>
<td>-</td>
<td>4.40E-06</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20°C, cm/sec
TRIAXIAL PERMEABILITY TEST

Borehole No. -
Sample No.: Sample 11

Type of Test: Multi Stage Constant Head Test
Depth (m): -

<table>
<thead>
<tr>
<th>Water (Initial)</th>
<th>2.6</th>
<th>Liquid Limit (%)</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content(%) (Final)</td>
<td>25.0</td>
<td>Plasticity Limit (%)</td>
<td>-</td>
</tr>
<tr>
<td>Unit Weight (kN/m3)</td>
<td>14.79</td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SP-SC</td>
<td>Initial Void Ratio</td>
<td>0.810</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure kN/m²</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20°C cm/sec</th>
<th>Vertical Permeability at 20°C cm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>32.0</td>
<td>0.780</td>
<td>-</td>
<td>3.32E-04</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>34.0</td>
<td>0.775</td>
<td>-</td>
<td>3.19E-04</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>24.0</td>
<td>0.772</td>
<td>-</td>
<td>3.00E-04</td>
</tr>
<tr>
<td>4</td>
<td>330</td>
<td>30.0</td>
<td>0.767</td>
<td>-</td>
<td>2.81E-04</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20°C, cm/sec
TRIAXIAL PERMEABILITY TEST

Borehole No.   -   Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 12   Depth (m) : -

<table>
<thead>
<tr>
<th>Water (Initial)</th>
<th>2.4</th>
<th>Liquid Limit (%)</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content(%) (Final)</td>
<td>21.0</td>
<td>Plasticity Limit (%)</td>
<td>-</td>
</tr>
<tr>
<td>Unit Weight (kN/m3)</td>
<td>15.09</td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SM</td>
<td>Initial Void Ratio</td>
<td>0.771</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure (kN/m²)</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20° C (cm/sec)</th>
<th>Vertical Permeability at 20° C (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>52.0</td>
<td>0.743</td>
<td>-</td>
<td>3.23E-05</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20° C, cm/sec

A-13
TRIAXIAL PERMEABILITY TEST

Borehole No. - Type of Test: Multi Stage Constant Head Test
Sample No.: Sample 13 Depth (m): -

<table>
<thead>
<tr>
<th>Water (Initial) Content(%) (Final)</th>
<th>1.0</th>
<th>Liquid Limit (%)</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight (kN/m3)</td>
<td>15.39</td>
<td>Plasticity Limit (%)</td>
<td>-</td>
</tr>
<tr>
<td>Type of Soil</td>
<td>SW</td>
<td>Specific Gravity</td>
<td>2.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Initial Void Ratio</td>
<td>0.713</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Consolidation Pressure (kN/m²)</th>
<th>Hydraulic Gradient</th>
<th>Void Ratio</th>
<th>Horizontal Permeability at 20° C (cm/sec)</th>
<th>Vertical Permeability at 20° C (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>11.6</td>
<td>0.702</td>
<td>-</td>
<td>2.41E-04</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Coefficient of Permeability at 20° C, cm/sec
Test No. CID-1

Borehole No. : -
Sample No. : Sample-10
Depth (m) : -
Soil Description : Remoulded SAND

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Initial</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Content (%)</td>
<td>Total Unit Weight (kN/m²)</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
<td>14.79</td>
</tr>
</tbody>
</table>

\[ \sigma' = 0.0 \text{ kN/m}^2 \]
\[ \phi' = 32.3 \text{ deg} \]

\[ \alpha' = 28.1 \text{ deg} \]
\[ c' = 0.0 \text{ kN/m}^2 \]

---

A-15
### Test No. CID-2

<table>
<thead>
<tr>
<th>Borehole No.</th>
<th>Sample No.</th>
<th>Depth (m)</th>
<th>Soil Description</th>
<th>Type of Test</th>
<th>Date Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample-11</td>
<td>-</td>
<td>Remoulded SAND</td>
<td>Isotropically Consolidated Drained</td>
<td>23-Nov-98</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Consol. Pressure</th>
<th>Back Pressure</th>
<th>Water Content</th>
<th>Total Unit Weight</th>
<th>Water Content</th>
<th>Total Unit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kN/m²)</td>
<td>(kN/m²)</td>
<td>(%)</td>
<td>(kN/m²)</td>
<td>(%)</td>
<td>(kN/m²)</td>
</tr>
<tr>
<td>0</td>
<td>330</td>
<td>350</td>
<td>2.6</td>
<td>14.79</td>
<td>25.3</td>
<td>18.50</td>
</tr>
</tbody>
</table>

\[ \alpha' = 0.0 \text{ kN/m}^2 \]
\[ \phi' = 31.7 \text{ deg} \]

\[ c' = 0.0 \text{ kN/m}^2 \]

---

### Graphs

**Shear Stress, \( \sigma \) (kN/m²)** vs **Mean Effective Stress, \( p \) (kN/m²)**

**Principal Stress Ratio** vs **Axial Strain, (%)**

**Volume Change Ratio** vs **Axial Strain, (%)**
FLOW CHART FOR CLASSIFYING INORGANIC & ORGANIC FINE GRAINED SOIL
FLOW CHART FOR CLASSIFYING COARSE-GRAINED SOIL
### SOIL CLASSIFICATION CHART

#### Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests

<table>
<thead>
<tr>
<th>Soil Classification</th>
<th>Group Symbol</th>
<th>Group Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravels Cu ≥ 4 and 1 ≤ Cc ≤ 3</td>
<td>GW</td>
<td>Well-graded gravel</td>
</tr>
<tr>
<td>Gravels Cu &lt; 4 or 1 &gt; Cc &gt; 3</td>
<td>GP</td>
<td>Poorly graded gravel</td>
</tr>
<tr>
<td>Gravels with Fines Fines classify as ML or MH</td>
<td>GM</td>
<td>Silty gravel</td>
</tr>
<tr>
<td>Gravels with Fines Fines classify as CL or CH</td>
<td>GC</td>
<td>Clayey gravel</td>
</tr>
<tr>
<td>Sands Cu ≥ 6 and 1 ≤ Cc ≤ 3</td>
<td>SW</td>
<td>Well-graded sand</td>
</tr>
<tr>
<td>Sands Cu &lt; 6 or 1 &gt; Cc &gt; 3</td>
<td>SP</td>
<td>Poorly graded sand</td>
</tr>
<tr>
<td>Sands with Fines Fines classify as ML or MH</td>
<td>SM</td>
<td>Silty sand</td>
</tr>
<tr>
<td>Sands with Fines Fines classify as CL or CH</td>
<td>SC</td>
<td>Clayey sand</td>
</tr>
</tbody>
</table>

### PLASTICITY CHART (ASTM D 2487-90)

The plasticity chart is used to classify fine-grained soils and fine-grained fraction of coarse-grained soils based on their liquid limit (LL) and plasticity index (PI) values. The chart is divided into several zones indicating different soil types: CL (clay), ML (mud), OL (organics), MH (medium), OH (organic), and CH (clayey). The chart helps in determining the type of soil based on the graphical representation of the soil properties.