Permeability Characteristics of Lime Treated Soils

A Thesis
by
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The effects of lime content on the permeability of lime-treated soils were investigated. Three soils, namely, a fine sand, a relatively coarse sand and a clay were collected from different areas of Bangladesh for these purposes. After collecting the soil-mass from the field, they were dried and cleaned. The clay was made powdered by using a grinding machine. Lime, in the predetermined proportion, was mixed thoroughly with the soil. Water was mixed with it for reaction to occur and then a sufficient time was allowed to complete hydration. Afterwards, the sample was subjected to permeability test. Permeability of sandy soils was determined by performing falling head permeability tests on the respective samples, while for clay soil consolidation tests were performed.

Falling head permeability test was performed using a 62.5mm dia and 100.0mm high cylindrical sample enclosed in a perpex permeameter. On the other hand, consolidation test on lime treated clay was performed on 62.5 mm dia and 25.4 mm thick cylindrical sample. In the research scheme, lime content was varied up to 5% and the reaction time was varied up to 14 days, i.e., after mixing a particular soil with a definite percent of lime and sufficient water, the mixture was allowed to complete hydration at room temperature for 4, 5, 8 and 14 days before testing.

Test results show that regarding to permeability, cohesive soil was more sensitive than cohesion-less soils. Permeability increased in case of fine-grained soils (i.e., both the fine sand and clay) with the increase of lime content, but it decreased for relatively coarse-grained soil. Void ratio of lime treated soil was influenced by the addition of lime. For soils with having substantial amount of fines (say, a fine sand and the clay), it was observed that void ratio increased, while for the sand having less fines exhibited a decrease in void ratio with lime content. The permeability characteristic also changed accordingly. Aging had no affect on the permeability and void ratio of untreated soils, but after a certain period of time, the lime treated sand exhibited more- or less stable permeability characteristics during a span of about 30 hrs.
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Notation

\( k \) = Coefficient of permeability.
\( n \) = Porosity
\( S \) = Specific surface area of the soil solids.
\( S_s \) = Surface area per unit volume.
\( \eta \) = Viscosity
\( C_s \) = Shape factor
\( c_c \) = Compression index
\( c_v \) = Co-efficient of consolidation
\( a_v \) = Co-efficient of compressibility
\( e \) = Void ratio
\( D \) = Effective dia. of the particle.
\( G_s \) = Specific gravity of the soil solid.
\( \gamma_w \) = Unit weight of water
\( V \) = Volume of soil mass.
\( W_s \) = Dry weight of soil grain.
\( C_u \) = Uniformity coefficient of soil.
\( C_c \) = Coefficient of concavity of soil.
\( \gamma_d \) = Dry density of soil
\( w_p \) = Plastic limit
\( w_l \) = Liquid limit

MIT = Massachusetts Institute of Technology
ASTM = American Society of Testing Materials
AASHTO = American Association of State High ways and Transportation Officials.
1.1 General

The soil improvement technique, stabilization, is applied when there is a particular and obvious deficiency in the potential a material property. The usual deficiencies are associated with strength and stiffness, excessive sensitivity to change in moisture content, high permeability, poor workability, tendency to erode, etc. By stabilization or treatment of soil, one or more of such deficiencies are improved up to the desired level by altering the associated properties. In the past, soil stabilization with lime was used in the field of highway, railroads and airport construction to improve rail beds and bearing layers. Meanwhile this method is employed also to the construction of embankments, soil exchange in sliding slopes, the backfill of bridge abutments and retaining walls, soil improvement under foundation slabs and for lime piles (for foundation, excavation pits and slope stabilization.)

A lot of works on cement and lime stabilization were reported in literature, such as for general behavior of lime-treated soils (Brandl, 1981), for construction of roads (Ingles and Metcalf, 1972; Naasra, 1986; Haunsmann, 1990), for agricultural road network (Kezdi, 1979; Ahmed, 1984; Rajbonshi, 1997), for sub-base and base construction of roads on non-plastic alluvial soils of flood plains (Bangladesh Transport Survey, 1974), etc. In these works, the major engineering benefits are expected to increase strength, stiffness, durability and volumetric stability.

At present Bangladesh is moving forward with large development projects including construction of high rise buildings, bridges, oil storage tank, harbor and port structures, pond constructions, haor and beel development structures such as fish-pass, regulator, etc. Slope and settlement failures are not unusual in Bangladesh. So, during this stage of infrastructure development in Bangladesh, a detailed knowledge and sound understanding of flow rate of water through soil and its effects on the deformation behavior of soil are of utmost importance.

Bangladesh is a land of rivers and canals. Its ground formation mainly consists of alluvial deposits. There are many large natural depressions known as beel, haor, baor
and many natural or man-made ponds. The hydraulic properties of naturally deposited soils in many areas do not fulfil the requirement of construction especially related to aquaculture. Due to lower water table in dry seasons, water flows from storage reservoir, ponds, etc. through the soil by percolation or seepage. This problem is severe in case of projects constructed on sandy and silty types of soils. Improvement of strength and other properties of the soil by the addition of lime as admixture is simply referred to as lime stabilization. Soil improvement in some locality is, therefore, essential particularly for water retention purpose (especially, in Tangail, Manikgong, Thakurgaon, Serajgong, Rangpur, Dinajpur, Cox’s Bazar area). Nowaday, different mechanical, chemical or electrical stabilization technique of soil has been developed. Depending upon the availability of equipment and technology, generally mechanical technique (compaction) is used to reduce the permeability. However, this procedure is limited to clay and silty soils. On the other hand, cement, lime, cow-dung, bitumen, fly ash, etc. can be used as stabilizing material for sandy soil. Of them, cow-dung, fly ash, rice-husks, lime, etc are used for solving the water retention problem at locations where sandy soils dominate the permeability characteristics. Besides, cow-dung and lime serve special purposes in aquaculture, such as the better growth of phytoplankton and zooplankton, reducing pH and turbidity etc. Lime facilitates sunlight so as to promote photosynthesis and thereby increases dissolved oxygen in water. Lime also provides a thin layer and thus separates water from coming in contact with permeable layer, and subsequently changes permeability of base soil.

Although a number of researches were carried out to investigate the strength and deformation characteristics of stabilized soils, little attempt has been made to assess the hydraulic characteristics of such treated soils in Bangladesh. The characterization of hydraulic properties of such soil is important for permeability and seepage analysis of highways, barrage, dyke, foundation, ponds, etc. if the underlying or the protecting soil is stabilized with a method mentioned earlier. This has special importance in fishery sector, where the ponds or dykes for aquaculture consist of sandy or silty soil (e.g. the northern part of Bangladesh). In such places, water retention is ensured usually by providing clay lining on the high permeable deep-seated soil-mass. On the other hand, lime is periodically added to pond water for better production of fish as stated above. Therefore, lime is always mixing up with soil, which after some time may behave just like lime treated soil.
In Pisci-culture, lime is frequently used in water for various purposes (not related to permeability characteristics). Liming may best be viewed as a remedial procedure necessary in acidic ponds to accomplish one or more of the following tasks:

a) To improve or permit survival of aquaculture species,
b) To permit normal reproduction and growth, and
c) To insure response of fish population to fertilization and other management procedure.

The most spectacular benefits of liming result when lime applications permit fishes to survive, reproduce and grow in bodies of water, which were previously too acidic for fish (Boyed, 1990). Hicking (1962) stated that liming is a technique for increasing the response to fertilization; it is not a substitute for fertilization. Liming increases pH of water and improves survival, reproduction, and growth of aquatic life. Liming increases the pH of bottom mud and thereby increases the availability of phosphorus added in fertilizer (Boyed and Scarsbrook, 1974). Bowling (1962) demonstrated that liming increased benthic production in fertilized ponds apparently through increased nutrient availability rather than increased pH. Pammatmat (1960) suggested that liming increased microbial activities and diminishes the accumulations of organic matter in pond bottoms and fibrous recycling of nutrients. Liming increases the alkalinity of water, thereby increasing the availability of carbon dioxide for photosynthesis (Arce and Boyed, 1975). Greater alkalinity after liming also buffers water against drastic daily changes in pH common in eutrophic ponds with soft water. The net effect of changes in water quality following liming is to increase phytoplankton productivity, which in turn, leads to increased fish production.

To support the proposition, Brandl (1981) showed that the permeability of lime treated soil may be changed over one or two decimal exponent. Therefore, a possibility exists that lime treated sand and silt can be used as a lining instead of clay lining in the aquaculture projects facing water retention problem.

In early day, ponds/water reservoir is generally constructed in a region, where the water retention capacity is more and other hydraulic properties are favorable to the aquaculture. There was an ample opportunity for the engineers to avoid unsuitable site or unsuitable construction material source whenever the required condition did not
fulfilled. But nowadays, this scope has been limited. In the developing countries, considering the conventional construction materials that are being adopted today, there appears to be an ample scope for exercising further economy by the way of incorporating locally available materials and adopting the soil stabilization technique to the maximum extent possible (Khan, 1989).

1.2 Objective with specific aims and possible outcome

The study is aimed at determining the permeability characteristics of lime-treated soils. The objectives of the study are:

i) To characterize the alteration in permeability nature of soils after being treated with lime.

ii) To evaluate, for a given soil, the effects of lime content on the permeability characteristics.

iii) To investigate, the long-term (i.e. time effects) permeability characteristics of lime treated soils.

iv) To evaluate the effect of curing age (reaction time) of lime during mixing on permeability.
2.1 General

Considering the existing atmospheric condition and economy, lime stabilization is performed to increase strength, to improve permeability and erodibility of the side slope of embankment, to increase overall durability of the pond and earthen dyke so that the overall aquatic production would be increased. It has been proved that the use of lime is favorable for fish production. The aqua scientists use it extensively to improve the water quality. Liming increases the pH of bottom mud and thereby increases the availability of phosphorus added in fertilizer (Boyd and Scarsbrook, 1974).

In Civil Engineering purposes, field as well as laboratory experiments were started by the Texas Highway Dept. in 1948. Development of theory, for the mechanism of lime stabilization was started from 1950 and the extensive study on mechanism of lime stabilization was done from 1960. In this regard, Eades and Grimes (1960), Kezdi (1979), Broms (1984) did the major work.

Lime stabilized soil are used to improve the engineering properties of soil in the field of highway, railroad, airport construction. Brandl (1981) showed that lime could also be used for the construction of embankment slopes, in the back fill of bridge abutments and retaining wall. He also showed that specific gravity of lime treated soil takes longer duration to get stabilized thus indicating long-term transformations of the chemical bound water and the gel. By adding lime, permeability of treated soil can be changed one or two decimal exponents.

Kezdi (1979) pointed out that lime stabilization is the addition of calcium in the form of CaO or Ca(OH)₂ which will reduce soil plasticity, increases strength and durability, decreases water absorption and swelling.
2.2 Mechanism of lime stabilization

Many researchers, even now a day is working with the theory of lime stabilization. Indian Road congress (IRC, 1973b) and Haunsmann (1990) have described the basic mechanism of soil-lime interactions. The basic mechanism of lime stabilization can be classified as follows.

a. Cat-ion exchange
b. Flocculation/Agglomeration
c. Carbonation
d. Pozzolanic reaction

a. Cat ion Exchange

Cat-ion exchange capacity of soil depends upon the pH value of the soil. Clay soils composed of different mineral and have different cation. Replace-ability of cation primarily depends on diffused double layers. The general order of replace-ability of common cat-ion is Na⁺<K⁺<Ma⁺⁺<Ca⁺⁺. Mono-valent cations are usually replaced by divalent or multivalent cations.

The reaction of lime with three layers material, which are montmorillonite, Kaolinite and illite, begin by the replacement of existing cat-ions between the silicate sheets with Ca⁺⁺. Following the saturation of inter layer positions with Ca⁺⁺, the whole clay minerals deteriorate without the formation of substantial new crystalline phases. Eades and Grimes (1960) indicated to the formation of new crystalline phases in the soil lime electrolyte system due to the addition of lime to the soil in presence of water, which are tentatively identified as calcium silicate hydrate. Cat-ion exchange capacity increases as the pH of the soil increases.

b. Flocculation/Agglomeration

Flocculation of the soil particle occurs due to the mixing of soil with lime in presence of water. After cation exchange of soils and lime take place, agglomeration of the flocculated particle occurs. Kezdi (1979) pointed out that immediately after mixing,
the soil structure starts to undergo a transformation. Flocculation and coagulation begin, and then the clay particles form much larger grains in the silt fraction. This, in turn, will modify the Atterberg limits and the compaction properties and so in practice the soil becomes much easier to handle in the course of earthwork. Diamond and Kinter (1965) suggested that the rapid formation of hydrated calcium aluminate (which is a cementing material) is responsible in the development of flocculation/agglomeration tendencies in the soil lime mixture.

c. Carbonation

When soil lime mixture is exposed to air, lime react with atmospheric carbon dioxide to form relatively weak cementing agents such as calcium carbonate or magnesium carbonate (Haunsmann, 1990). This reaction is the slowest of all the reactions involved in a soil-lime system and as in pozzolanic reaction, requires that the mixture must be thoroughly compacted. Eades et al. (1962) demonstrated that although carbonation takes place, the strength gain by virtue of cementation of soil grains with calcium carbonate is negligible.

d. Pozzolanic reaction

Long-term chemical reaction of lime with certain clay minerals (silicate and aluminates) of soil, in presence of water is referred to pozzolanic reaction. The minerals that react with lime to produce a cementing material are known as pozzolans. Possible source of silica and alumina in a typical soil include clay minerals are quartz, feldspars, mica and similar silicate or alumino-silicate minerals either in crystalline or amphorous in nature. When lime is added to the soil in presence of water causes an instantaneous rise in $p^H$ of the molding water due to the dissociation of the $\text{Ca(OH)}_2$ in water.

Eades and Grims (1960) observed that high $p^H$ causes silica and alumina to be dissolved out of the structure of the clay minerals and it combines with the calcium to form calcium silicate and calcium aluminates. The calcium ions combine with reactive hydrous silica and alumina and form gradually hardening cementitious material. This reaction will continue as long as $\text{Ca (OH)}_2$ exists in the soil and there is available silica. This mechanism may be referred as “Through Solution”. Soil lime pozzolanic reaction
usually does not appear until after long curing period and then only in cases where a high percentage of lime was added. Pozzolans possess little or no cementitious value in finely divided form, but in the presence of moisture, it chemically reacts with calcium hydroxide at ordinary temperature to form components possessing cementitious properties.

2.3 Factor affecting permeability of lime stabilized Soils

Permeability of lime-stabilized soil depends upon various factors. In the following section some of the factors are discussed.

2.3.1 Soil

a. Soil types i.e. shape and size of the soil particle

Permeability varies approximately as the square of the grain size since soils consist of many different sized grains. Based on the experimental report on sand filter, (0.1mm and 0.3mm) Hazen (1892) suggested the following formula for permeability determination.

\[ k = CD_{10}^2 \]  \hspace{1cm} (2.1)

Where C is constant approximately equal to 100 when effective diameter \( D_{10} \) is in cm. and the formula is also useful for permeability determination of clean sand and Gravel.

Cassagrande (1937) stated the empirical relation for permeability determination of fine or clean sand with bulky grains as

\[ k = 1.40 \times k_{0.85} \epsilon^2 \]  \hspace{1cm} (2.2)

where, \( k_{0.85} \) is the permeability at void ratio = 0.85

Different attempt has been taken to correlate permeability with the specific surface area of the particle. Kozeny (1907) gives one such relationship

\[ k = \frac{1}{K_s \eta S_v} \times \frac{n^2}{1 - n^2} \]  \hspace{1cm} (2.3)

where, \( k \) = Coefficient of permeability in cm/sec per unit hydraulic gradient.
\( n = \) Porosity,  
\( S_s = \) Specific surface of particle \((\text{cm}^2/\text{cm}^3)\),  
\( \eta = \) Viscosity \((\text{y-sec/cm}^2)\),  
\( K_k = \) Constant, equal to 5 for spherical particle.

On the basis of experiment, Loudon (1952-53) developed an empirical formula

\[
\log_{10}(kS_s^3) = a + bn 
\]

Where \( a \) and \( b \) are constant and equal to 1.365 and 5.15 at 10\(^0\)C. Loudon demonstrated that the permeability of course grained soils inversely proportional to the specific surface, at a given porosity.

Kozeney-Carman (Kozeney, 1927; Carman, 1956) developed the formula as

\[
k = \frac{1}{C_sT^2} \frac{e^3}{S_s} \times \frac{1}{1-e} \]

Where, \( k = \) Absolute permeability  
\( T = \) Tortuosity  
\( S_s = \) Surface area per unit volume of soil solid’s.  
\( C_s = \) Shape factor.

This formula is worked well for coarse-grained soils such as some sand and silts and has serious discrepancies for clay soil. The discrepancies between the theoretical and experimental value are shown in Fig. 2.1 and Fig 2.2 based on consolidation-permeability tests.
Fig. 2.1 Coefficient of permeability for sodium illite after Olsen (1961).

Fig. 2.2 Ratio of the measured flow rate to that predicted by the Kozeny-Carman equation for several clays. Curve 1: Sodium illite, $10^{-1}\text{N NaCl}$. Curve 2: Sodium illite, $10^{-4}\text{N NaCl}$. Curve 3: Natural Kaolinite, Distilled water $H_2O$. Curve 4: Sodium Boston blue clay, $10^{-4}\text{N NaCl}$. Curve 5: Sodium Kaolinite, $1\%$ (by Wt.) sodium tetraphosphate. Curve 6: Calcium Boston blue clay, $10^{-4}\text{N NaCl}$, after Olsen (1961).
b. Void ratio of the soil

Permeability increases with increases of void ratio. For coarse grained soil

\[ \frac{k_1}{k_2} = \frac{C_1 e_1^3}{1 + e_1} \times \frac{1 + e_2}{C_2 e_2^2} \]

For coarse-grained soil, \( C \) changes a little and can be written as

\[ \frac{k_1}{k_2} = \frac{e_1^3}{1 + e_1} \times \frac{1 + e_2}{e_2^2} \]

where, \( k_1 \) and \( k_2 \) are the coefficient of permeability of a given soil at void ratio \( e_1 \) and \( e_2 \) respectively. Based on the mean hydraulic radius concept for the soil, the following relationship is obtained

\[ \frac{k_1}{k_2} = \frac{e_1^2}{e_2^2} \]

It has been found that a semi-logarithmic plot of void ratio versus permeability is approximately straight line for fine grained as well as coarse-grained soil. A typical plot worked on uniform Madison sand is presented in Fig. 2.3 based on constant head test.

![Fig. 2.3 Plot of k against permeability function after Das (1983).](image-url)
c. Degree of saturation

When air is entrapped in the voids, it reduces the degree of saturation and permeability decreases. Water contains dissolved air and it may get liberated while changing the permeability. So, permeability increases with the increases of degree of saturation. The variation of the value of permeability ($k$) with degree of saturation for Madison sand as shown in Fig. 2.4 and Fig. 2.5.

![Graph showing the relationship between degree of saturation and permeability for Madison sand.](image_url)

Fig. 2.4 Influence of degree of saturation on permeability of Madison sands after Mitchell et al. (1965).
Fig. 2.5 Influence of degree of saturation on permeability of compacted silty clay. (Note: Samples aged 21 days at constant water content and unit weight after compaction prior to test) Redrawn after Mitchell et al. (1965).

d. Compaction of soil particles

For sands and silts this is not important; however for soils with clay minerals, this is one of the most important factors. Permeability in this case depends on the thickness of water held to the soil particles, which is a function of cation exchange capacity, valence of the cations, etc. Other factors remaining the same, the coefficient of permeability decreases with increasing thickness of the diffuse double layer.

e. Soil structure

Fine-grained soils with a flocculated structure have a higher permeability than those with a dispersed structure. This fact is demonstrated in Fig. 2.6 for the case of silty clay. The test specimen was prepared to constant dry unit weight by kneading...
compaction. When Moisture content increases the soil becomes more dispersed. With increasing degree of dispersion, the permeability decreases.

Fig. 2.6 Dependence of permeability on the structure of silty clay. Redrawn after Mitchell et al. (1965).

f. Property of the Permeant

Permeability is directly proportional to the unit weight of water and inversely proportional to its viscosity. Through the unit weight of water does not change much with the change in temperature there is a great variation in viscosity with temperature. When other factor remaining same, permeability at a given temperature \( k_T \) is given by

\[
k_{20} = k_T \frac{\eta_T}{\eta_{20}} \tag{2.6}
\]

where, \( \eta \) is the viscosity of water.
Muskat (1937) pointed out that a more general co-efficient of permeability called the physical permeability \( K_p \) is related to the Darcy's co-efficient of permeability \( K \) as follows:

\[
K_p = K \frac{n}{\lambda_w}
\] ........................(2.7)

In any soil, \( K_p \) has the same value at temperatures as long as the void ratio and the structure of the soil skeleton are not changed for all fluids.

g. **Organic matters present in the soil**

Presence of organic matter influences the permeability. Organic matter has the tendency to move towards critical flow channels and choke them up and thus decreasing the permeability. Rodriguez et al. (1988) noted that lime has little effect on highly organic soil or soils without clays.

h. **Adsorbed water with soil particle**

Adsorbed water surrounding the fine soil particles are not free to move thus reduces the effective pore space available for the passage of water. Casagrande's crude approximation is to take 0.1 as the void ratio occupied by the adsorbed water hence it is the square of the net void ratio (i.e., void ratio= \( e - 0.1 \)).

i. **Effect of stratified soil layer**

In general, natural soil layer is stratified. Their bedding planes may be horizontal inclined or vertical. Assuming each layer homogeneous and isotropic, it has own value of co-efficient of permeability. The average permeability to the whole deposit will depends upon the direction of flow with relation to the direction of the bedding planes. Typical values of coefficient of permeability for various soils are given in Table 2.1
Table 2.1 Typical value of coefficient of permeability

<table>
<thead>
<tr>
<th>Materials</th>
<th>Coefficient of permeability (mm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>$10$ to $10^3$</td>
</tr>
<tr>
<td>Fine Gravel, Coarse and medium sand</td>
<td>$10^{-2}$ to $10$</td>
</tr>
<tr>
<td>Fine sand, Loose silt</td>
<td>$10^{-4}$ to $10^{-2}$</td>
</tr>
<tr>
<td>Dense silt, Clay silt</td>
<td>$10^{-5}$ to $10^{-4}$</td>
</tr>
<tr>
<td>Silty Clay, Clay</td>
<td>$10^{-8}$ to $10^{-5}$</td>
</tr>
</tbody>
</table>

2.3.2 Lime

a. Lime Content

Since lime reacts with soil to form some new compounds, which improve the engineering properties of soil, lime content is an important factor. The usual content of hydrated lime for different types of soil are given in Table 2.2 and 2.3.

Table 2.2 Usual content of hydrated lime in different soil (% by weight of dry soil to lime) after Naasra (1987).

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Stabilization (lime %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed rock</td>
<td>not recommended</td>
</tr>
<tr>
<td>Well-graded clayey gravel's</td>
<td>2</td>
</tr>
<tr>
<td>Pure sand</td>
<td>not recommended</td>
</tr>
<tr>
<td>Silty sand</td>
<td>not recommended</td>
</tr>
<tr>
<td>Clayey sand</td>
<td>2-4</td>
</tr>
<tr>
<td>Clayey silt</td>
<td>2-4</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>2-6</td>
</tr>
<tr>
<td>Plastic clay</td>
<td>3-9</td>
</tr>
<tr>
<td>Highly plastic day</td>
<td>3-9</td>
</tr>
<tr>
<td>Organic soil</td>
<td>not recommended</td>
</tr>
</tbody>
</table>
Table 2.3 Usual content of hydrated lime in different soil (% by weight of dry soil)

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Stabilization (Lime %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed rock</td>
<td>not recommended</td>
</tr>
<tr>
<td>Well-graded clayey gravel's</td>
<td>3</td>
</tr>
<tr>
<td>Sands</td>
<td>not recommended</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>5</td>
</tr>
<tr>
<td>Silty clay</td>
<td>2-4</td>
</tr>
<tr>
<td>Plastic clay</td>
<td>3-8</td>
</tr>
<tr>
<td>Highly plastic clay</td>
<td>3-8</td>
</tr>
<tr>
<td>Organic soil</td>
<td>not recommended</td>
</tr>
</tbody>
</table>

From the above table, it can be seen that the usual content for lime for silty sand is 2-4% and for sandy clay it is 5%. It can be also observed that lime percent increases as the soil become coarser to fine grained from stabilization viewpoint. Brandl (1981) pointed out that the more cohesive and more reactive the untreated soil is, the more increases the permeability of the mixture according to the immediate flocculation. The maxima are gained at lime amounts between 1% for inactive silt to 10% for active clays. Kezdi (1979) classify the soil from lime stabilization viewpoint into three categories that is represented in figure 2.7. From the figure, it is observes that in range-A, no stabilization is possible since the available equipment simply cannot work these.
course materials. In range B, the soil behavior is governed mainly by the grain distribution itself. In range C, mechanical stabilization is not fruitful by hydraulic binders, cement, etc. It would only be economical in the case of clay soil.

**Optimum lime content:** May be defined as the lime content at which the percentage of such additional lime increment will not produce appreciable increase in the plastic limit. According to Diamond and Kinter (1965), lime content above the lime fixation point for a soil will generally contribute to the improvement of soil workability, but may not result in sufficient increases of strength.

From the literature review, it can be concluded that lime percent varies from soil to soil. To achieve the minimum and the maximum permeability, strength and specific gravity (i.e., overall durability of the structure) optimum lime contents is the lime content by which the maximum strength and the maximum or the minimum permeability of soil can be achieved.

b. **Lime types**
Lime may be divided into three categories as follows:

i. **Fat Lime:** This lime known as fat lime because it increases 2 to 2.5 times in volume, when slacked. It contains about 95% calcium oxide and about 5% other materials in form of impurities. This lime is also sometime known as pure lime, rich lime, white lime or high calcium lime. It is obtained by burning lime stone which containing mostly calcium carbonate in atmosphere, carbon dioxide is driven out, leaving back calcium oxide (CaO), known as quick lime. Fat lime is obtained by slacking quick lime. Setting of this lime is entirely dependent upon the atmospheric oxygen. For setting, this lime absorbs carbon dioxide (CO₂) from atmosphere and after chemical reaction gets converted into calcium carbonate (CaCO₃), which is quite hard substance, insoluble in water. Setting and hardening actions of this lime are very slow.

ii. **Hydraulic lime:** This lime has the property of setting under water. It is obtained by burning limestone, containing lot of clay and other substances that develop hydraulicity. Hydraulicity of this lime depends upon the amount of clay and type of clay present in it. Silica, alumina and or iron oxide are present in chemical combination
with calcium oxide. Depending upon the amount of clay (silica and alumina) present, hydraulic limes may be further divided into following three categories.

**Feebly hydraulic lime:** It contains clay (silica, alumina or iron oxide) less than 15%. The usual percentage of these constituents varies between 5% to 10%. On slacking, it increases in volume by very small amount. It slacks slowly.

**Moderately hydraulic lime:** This lime contains 15 to 25% silica and alumina. On slacking, it increases in volume by very small amount. It slacks very slowly.

**Eminently hydraulic lime:** This lime contains 25 to 30% silica and alumina. It resembles very much to Portland cement in chemical composition. Slacking of this lime is hardly noticeable. Its initial setting starts after two hours and the final setting within 48 hours.

c. **Poor lime:** This lime contains more than 30% of clay. It slacks very slowly. It does not dissolve in water. It forms a thin plastic paste with water. This lime is also known as lean lime or impure lime and hardens and sets very weak slowly.

Boyed (1990) pointed out that liming material most frequently used is agricultural limestone, which is prepared by finely crushing limestone. Agricultural lime (Calcium carbonate) is not suitable for stabilization. Dolomitic lime is usually not as effective as calcium lime. In order to give a common quantitative base, lime content is expressed as equivalent 100% pure hydrated lime. On a mass basis pure quick lime is equivalent to 1.32 unit of hydrated lime. Limestone is calcite (CaCO₃), dolomite [CaMg(CO₃)₂] or some blend of these two substances. There is some confusion to the actual composition of locally available liming material. Basic slag, a by-product of steel making, contains calcium carbonate and phosphorous, so it is both a liming material and fertilizer. Blast furnace slag, also a by-product of steel making, is comprised largely of calcium silicate, but these calcium silicate slags are not suitable for fish culture in pond.

Lime rapidly reacts with any available water producing hydrated lime, releasing considerable amount of heat. The water content of common slurry lime can range from 80-200%. Table 2.4 presents the property of hydrated, quick and slurry lime.
Table 2.4 Properties of lime after Naasra (1986)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Hydrated lime</th>
<th>Quick Lime</th>
<th>Slurry Lime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>Ca(OH)₂</td>
<td>CaO</td>
<td>Ca(OH)₂</td>
</tr>
<tr>
<td>Form</td>
<td>Fine Powder</td>
<td>Granular</td>
<td>Slurry</td>
</tr>
<tr>
<td>Equivalent Ca(OH)₂ / Unit Mass</td>
<td>1.00</td>
<td>1.32</td>
<td>0.56 to 0.33</td>
</tr>
<tr>
<td>Bulk Density (Kg/m³)</td>
<td>450 to 560</td>
<td>1050</td>
<td>1250</td>
</tr>
</tbody>
</table>

According to Mateos (1964), lime can be divided chemically into two categories.

**Hydrated lime:** It is divided into three groups
Calcite [Ca(OH)₂], commonly known as hydrated lime, slaked lime or builder’s lime. Dolomitic monohydrate, Ca(OH)₂+MgO and Dolomitic dehydrate Ca(OH)₂+Mg(OH)₂.

**Quick lime:** It is divided into two groups
Calcitic (CaO) and Dolomitic [CaO+MgO]

On chemical analysis of calcitic hydrated lime has found 75.677% quick lime and 24.33% water. Dolomitic monohydrate lime has 15.79% water and 84.21% dolomitic quicklime. Dolomitic hydrated lime has 27.27% water and 72.73% dolomitic quicklime. Table 2.5 shows the different constituents of quicklime and hydrated lime after Ingles and Metcalf (1972) and Table 2.6 shows different properties for soil stabilization after Ghos R. M (1987).

Table 2.5 Requirements that must be meet by limestone’s on natural calcium carbonates in order to provide stabilizing lime after Ingless and Metcalf (1972)

<table>
<thead>
<tr>
<th>Property</th>
<th>Quicklime (CaO)</th>
<th>Hydrated lime Ca(OH)₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium magnesium oxides</td>
<td>not less than 92%</td>
<td>Not less than 95%</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In the oven</td>
<td>not more than 3%</td>
<td>Not more than 5%</td>
</tr>
<tr>
<td>Out of the oven</td>
<td>not more than 5%</td>
<td>Not more than 7%</td>
</tr>
<tr>
<td>Fineness</td>
<td></td>
<td>Not more than 12% retained on No. 180 sieve.</td>
</tr>
</tbody>
</table>
Table 2.6 Properties of the Theoretically Pure Lime after Ghos R. M (1987)

<table>
<thead>
<tr>
<th>Chemical name</th>
<th>Quicklime</th>
<th>Hydrated Lime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calcium or</td>
<td>Calcium or</td>
</tr>
<tr>
<td></td>
<td>Calcium</td>
<td>Magnesium</td>
</tr>
<tr>
<td></td>
<td>oxide</td>
<td>magnesium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>oxide</td>
</tr>
<tr>
<td>Chemical formula</td>
<td>CaO</td>
<td>MgO</td>
</tr>
<tr>
<td>Crystalline formula</td>
<td>cubic</td>
<td>cubic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Melting point</td>
<td>2570°C</td>
<td>2800°C</td>
</tr>
<tr>
<td>Decomposition point</td>
<td>-</td>
<td>580°C</td>
</tr>
<tr>
<td>Boiling point</td>
<td>2850°C</td>
<td>3600°C</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>36.09</td>
<td>40.32</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>3.40</td>
<td>3.65</td>
</tr>
</tbody>
</table>

It shows from the above discussion that for soil stabilisation Hydraulic or Poor lime will be best variety to work. If they are used in the hydrated form, duration of effective curing time will be small.

2.3.3 Water

Distilled water is preferred for any research work. When requirement of the water is high, potable water is used for lime stabilization. Water containing organic matter should be avoided. Seawater may be used, where bituminous seal do not exist.

2.3.4 Compaction condition

Compaction is the process by which soil particles are re-arrange and packed together in a close state of contact by mechanical or any other means in order to decreases porosity of the soil and then increases the dry density, which reduce the permeability. Compendium (1987) pointed out that the maximum dry density normally continues to decrease as the lime content increases. Further more the optimum moisture content increases with the increase of lime content. Haunsmann (1990) stated that the
Flocculation and cementation will make the soil more difficult to compact and the maximum dry density achieved with a particular compactive effort, is reduced.

2.3.4.1 Compactive effort

Compaction on the lime-stabilized soil as well as untreated soil can be done by different methods in the field and in the laboratory. Three recognized methods of compaction are namely:

a. Standard proctor test method
b. Modified Standard proctor test method
c. Harvard miniature compaction

Singh and Punnia (1965) pointed out that, on increasing compaction effort results in an increase in maximum dry density and decrease in optimum moisture content (Fig 2.8).

![Fig 2.8 Effect of compactive effort on compaction of natural soil after Sing and Punnia (1965).](image-url)
2.3.4.2 Moisture content for Compaction

Moisture content plays an important role for soil compaction. Generally for soil compaction, as the moisture content increases, it increases soil strength up to the optimum moisture content and then decreases. Optimum moisture content depends on soil type and compactive effort. At different compactive efforts different optimum moisture content of the soil can be obtained. For lime treatment, about 47% water is required for hydration of lime. So the optimum moisture content of the lime stabilised soil differs from the optimum moisture content of the untreated soil for the same compactive effort. Serajuddin (1992) pointed out that at the equal level of compactive effort, CBR value varies appreciably on the variation of the moisture content during compaction. He also stated that optimum water content occur at 2% to 3% higher water content than the optimum moisture content of the soil depending on the soil types.

2.3.4.3 Compaction delay time

Compaction delay time is the time interval between mixing of lime with soil and compaction. As the reaction of lime with soils occurs slowly, it is not essential to compacts the specimen immediately after mixing the soil with lime. Townsend and Klyn (1970) observed that the compaction delay time of 24 hours can reduces the strength of the specimen up to 30% as compared to the specimen prepared by compacting immediately after mixing of lime. Sastry and Rao (1987) pointed out that the delay of time for two hours between mixing and compaction; there is practically no reduction in strength. But for further delay, the strength of soil-lime mixture continues to fall (Fig. 2.9) Compendium (1987) pointed out that granular soil lime mix should be compacted as soon as possible and the delay time upto two days are not detrimental, especially if the soil is not allowed to dry out. Fine-grained lime treated soil can be delayed upto four days after mixing.
Therefore, there are many controversial statements on the effect of strength due to the compaction delay time. Among them, most of the authors stated that 24 hours has no marked effect on the strength. On the other hand, some authors stated that compaction delay time of 24 hours has marked effect on the strength of lime stabilized soil. Fine-grained soil has less effect on the compaction delay time than those of coarse-grained soil do.

2.3.4.4 Mixing of lime with soil before compaction

Mixing of lime with soil can be done in different ways. Compendium (1987) pointed out that one or two stage mixing, lime can be used for compaction. In two stage mixing, half of the lime is mixed and the rest is added after 18 hours. He observed that
due to two stages mixing unconfined compressive strength of the stabilized soil increased. The reason for the improvement was due to the fact that on the first stage of mixing the soil become more friable and as a result, soil becomes more effective in lime stabilization.

2.3.5 Age effect on lime stabilized soil

It has been stated earlier that effect on lime stabilized soil occur slowly. Lime reacts with soil and the gain of strength is higher at initial stage of curing and the rate of gain of strength reduces as the time goes on. Arman and Muhfakh (1972) stated that lime has an initial reaction with soil taking place during first 48-72 hours after mixing and the secondary reaction starts after that period and continues.

The rate of gain of strength is time dependent and depends on soil types. For some types of soil, the rate of gain of strength with curing time is high but for others the rate is slow: Brandl (1981) observed that the time dependent increase in shear strength is approximately linear with the logarithm of time. From his study, it is seen that the permeability decreases with curing time. With increasing curing time, the mineral particles are cemented within the soil-lime-mixture; the fine skeleton is embedded partly within a gelatinous intermediate mass, hardening products of the binder grow into the voids of soil aggregate changing the void structure.

2.4 Effect of lime treatment on the physical and engineering properties of soil

Lime reacts with soil silica or alumina in the presence of water causing the change of the physical properties of soil. The chemical-physical reactions in the soil are rather complex and can be generalized only in some cases. Some changes of the soil parameters being interesting for practical application. Some of the important properties of soil, which are changed due to the stabilization of soil with lime, are Atterberg limit, permeability, strength, compressibility, stress strain character, volume change, shear strength etc. In the following sections the various physical and engineering properties of lime stabilized soils are reviewed.
2.4.1 Atterberg limit

Plasticity is the property of the soil, which allows to be deformed rapidly without ruptures, without elastic rebound and without volume change. Due to the addition of lime, structural transformation and flocculation begin immediately. This causes a rapid change on the Atterberg limits. Brandl (1981) stated that higher the amount of colloidal clay and the chemo-physical activity of the soil, the more likely is the decrease of liquid limit (Figs. 2.10.a, b and c). Silts reach in natural calcium show an increase. The plasticity limit rises without exception, only with silts and sand reach in calcium and dolomite the value in almost constant. Too much lime causes the transgression of the point of reversal (liquid limit, $w_L$ and plastic limit, $w_p$). Generally both liquid and plastic limits increase with time, because the attractive forces between the soil particle increase and the absorbed water film is influenced. Thus the plasticity of reactive soils is reduced considerably easing the workability on construction site. Only inactive soil becomes even more plastic.

(Symbol used were soil I, open circle (-o-) clay A-7-6 (sand 21%, silt 54%, clay 25%); soil II, solid circle (-.-) silt A4 (sand 15%, silt 73%, clay 12%); soil V, cross (-x-) silt sa. A-2-4 (A-4) (sand 59%, silt 36%, clay 5%)}

![Fig 2.10 Alteration of atterberg limit by adding lime; Reaction time (curing age) in days as parameter (drawn in rectangle): period from stabilization till test performance after Brandl (1981).](image-url)
Generally soils with high clay content or soils exhibiting a high initial plasticity index require greater quantity of lime for achieving the non-plastic condition. If it can be achieved at all, the amount of reductions in plasticity index varies with the quantity and types of lime and also of soil (IRC, 1976).

Ahmed (1984) pointed out that plastic limit of a silty clay increases with the increase of lime content, while liquid limit and plasticity index decreases with increasing lime content (Fig 2.11 and Fig 2.12). Shrinkage limit and linear shrinkage of a clayey soil are also affected by addition of lime. The shrinkage limit increases while linear shrinkage reduces as the lime content increases (IRC, 1976). Hilt and Davidson (1960), Pietsch and Davidson (1962) pointed out that the plastic limit of soil generally increases with the addition of small amount of lime until certain critical lime content. Called “lime fixation point”. Rodriguez et al. (1988) stated that lime generally reduce the plasticity index of high plastic soil but has little influence on the plasticity index of the low plastic soils.

![Effect of lime content on Atterberg limits of a silty clay soil reported from Ahmed (1984).](image-url)
2.4.2 Specific gravity

The specific gravity of any substance is defined as the unit weight of the material divided by the unit weight of distilled water at 4°C. Due to addition of lime, specific gravity changes. Brandl (1981) stated that changes of specific gravity are time dependent, which indicates long-term transformations of the chemical bound water and the gel; the formation of new minerals is responsible too.

The change of specific gravity are presented for in Fig 2.13, Which shows that for inactive soil i.e. silts A-4 [symbol used was solid circle (•••), sand 15%, silt 73%, clay 12%] specific gravity initially increases with the increases of lime content, but after 2.5% lime content it starts decreasing with the increasing lime. But for active soil i.e. clay A-7-6 [symbol used were, open circle (○○○), sand 21%, silt 54%, clay 25%] specific gravity always almost decreases with the increases lime content. In case of active soil, the specific gravity is further affected by the curing time, That is, with the increases of curing time, specific gravity significantly decreased.
2.4.3 Permeability

Permeability is the property of soil, which permits the passage of water through its interconnected void space. Townsend and Klyn (1970) pointed out that the permeability of soil increases due to addition of lime. While conducting the experiment with heavy clay, they observed a marked increase in permeability, while for silty clay, erratic or no change of permeability was observed. Brors and Boman (1977) show that the addition of lime usually increases the permeability of soft clay. The increase in permeability is associated with flocculation, where larger pore between the flocks enables the fluid to flow more readily in between the clay and corresponding change in grain size distribution.

Variation of permeability with lime stabilized soil with lime percent for different curing period as presented by Brandl (1981) is shown in Fig 2.14. From the figure, it can be seen that the permeability for silt A-4 (symbol used were, solid circle (●●), (sand 15%, silt 73%, clay 12%) increases with lime up to 1% lime content and then decreases.
Fig 2.14 Alteration of Permeability coefficients by adding lime; reaction time (curing age) in days as parameter (drawn in rectangle); period from stabilization till test performance after Brandl (1981).

Where, k= water permeability, cm/sec.

Brandl (1981) pointed out (Fig. 2.14) that the more cohesive and more reactive the untreated soil is, the more increases the permeability of the mixtures according to the immediate flocculation. The maxima are gained at lime content between 1% for inactive silts to 10% for active clays. He also pointed that the change of permeability over one or two decimal exponent is easily possible. He also pointed out that with increasing curing time the mineral particles are cemented within the soil lime mixtures. The fine skeleton is embedded partly within a gelatinous intermediate mass; hardening products of the binder grows into the voids of the soil aggregates changing the void structure. Additionally, the stabilized soil grains surround themselves with a wider film of bound water in a way that finally, the remaining void space becomes smaller and thus the permeability decreases with curing time marching on.
2.4.4 Compressibility

Compressibility is the property of the soil of resisting deformation due to the applied load upon it. In principle, the optimum water content increases, thus the compactibility is eased. Only when the soil lime mixtures remain uncompacted and if it is able to carbonate, the contrary effect happens because the coagulating particles behave like ‘sandy’ grains. The proctor density decreases after adding lime Brandl (1981). The results are shown in Fig. 2.15.

[The symbol used were, open circle (-o-), clay A-7-6 (sand 21%, silt 54%, clay 25%); solid circle (-•-), silt A4 (sand 15%, silt 73%, clay 12%); solid triangle (-\(\nabla\)-), silt A-4 (clay A-6), sand 30%, silt 48%, clay 22%]

![Fig. 2.15 Alteration of optimum water content at proctor density after Brandl (1981).](image)

where, \(w_{\text{opt}}\) = Optimum water content at proctor density;
\(\lambda_d\) = Proctor density

Broms and Boman (1977) stated that the lime-stabilized soil is normally firm to hard and the texture is grainy. It has a low compressibility compared with untreated soil. Broms (1984) also observed that the deformation and strength properties of the lime-stabilized soil are same as those of heavily consolidated stiff fissured clay in the desiccated dry zone.
3.1 General

As mentioned earlier, the permeability of soil depends upon various factors, such as size and shape of the particle, particle orientation, temperature of liquid, soil compaction, etc. In addition to this, permeability of lime treated soil depends on lime types, lime content, procedure of mixing, curing time (reaction time) and procedure of curing, etc. The main objective of this research is to investigate the influence on permeability of lime treated soil of lime content, reaction time, etc.

Three types of soils were used for this research work. The soils were collected from Bolurana, Anwara, Chittagong (soil type-1), Toraghat, Manikgonj (soil type-2) and Farmgate, Dhaka (soil type-3). The site locations are shown in Fig 3.1. Soil sampling was carried out as per procedure (ASTM D420-87). For each location, approximately 1.5m x 1.5m area was excavated to a depth 1.5m by shovels. Proper care was taken to remove any loose materials, debris and vegetation from the bottom of the excavated pit. All disturbed sample were packed in a large polythene bags and were covered by gunny bags and were eventually transported to the Geotechnical Engineering Laboratory of BUET, Dhaka.

All the soils were fine-grained, that is, about 90 to 95% materials of each soil were smaller than 0.5 mm size. Of them, soils 1 and 2 were sandy soils and soil-3 was a clayey soil. In this research, lime content was varied up to 5%, while the reaction time was varied up to 14 days. Note that reaction time was defined as the time span passed after mixing lime and water with sand or clay for the purpose of hydration to complete.

3.2 Test Programme

All the soils were treated with lime in percentage (by weight) of 1%, 3% and 5%. Permeability tests on various lime treated samples were done at various reaction times. Tests on each type soil consisted of the following works in sequence, such as the collection of lime from market and soil from the field, prepare both lime and soil for
mixing, mixing lime and soil at the definite proportion, watering, thorough mixing, leaving the mixture at room temperature for a period (defined earlier as the reaction time) to complete hydration, making test specimens of the required size and finally, subjected the specimen to permeability determination testing. The entire work is shown sequentially in a flow diagram in Fig. 3.2. The whole laboratory test program consisted of carrying out the following tests on the three soils (Table 3.1):

a) Routine tests, such as grain size distribution and specific gravity tests on three types of soil were performed in the laboratory to classify the soil. Atterberg limit tests were done for the clayey soil.

b) Falling head permeability tests were performed for soil type–1 and 2. Permeability was determined at 4 day (for soil type –1), 5 day (for soil type –2), 8 day (for soil type 1 and 2) day and 14 day (for soil type 1 and 2) reaction time following procedure ASTM D2434-68. To confirm the repeatability of sample preparation (on which permeability depends significantly), two samples were prepared with similar testing conditions (i.e. with the same lime content, moisture content during mixing and the same reaction time).

c) Consolidation tests were performed for soil type-3 to determine its permeability.

Table 3.1 Detail of laboratory test performed on the three types of soils

<table>
<thead>
<tr>
<th>Types of Test</th>
<th>Sample</th>
<th>No. of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil type-1</td>
<td>Soil type-2</td>
</tr>
<tr>
<td>Sieve Analysis and Hydrometer Test</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>untreated</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>treated</td>
<td>9</td>
</tr>
<tr>
<td>Permeability test (Short time)</td>
<td>untreated</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>treated</td>
<td>18</td>
</tr>
<tr>
<td>Permeability test (Long time)</td>
<td>untreated</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>untreated</td>
<td>3</td>
</tr>
<tr>
<td>Consolidation test</td>
<td>untreated</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>untreated</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. 3.1. Map of Bangladesh showing study locations.
Fig. 3.2 Flow Chart of the experimental work

Total Work

Collection of lime

Lime prepared for soil treatment

Soil lime dry mixture at the definite percentages of lime

Adding water

Mixed sample left for hydration

Test specimen preparation

Falling head permeability test (for soil type 1 and 2)

Consolidation test (For soil type-3)

Presentation of the Work
3.3 Material used

The test materials used are described below.

3.3.1 Soils

As mentioned earlier, three types of soil were selected for investigation. The grain size distribution of three soils is given in Fig. 3.3. The different fractions of sand, silt and clay of soil-1 were 96%, 4% and 0%, respectively and those for soil-2 were 99%, 1%, and 0%, respectively. These fractions were obtained according to MIT Textural Classification (1931). According to unified (ASTM D2487) and AASHTO (M 145-66) soil classification, the soil were fallen into the groups SP-SM and A-3, SP and A-3, respectively. Table 3.2 shows different properties of the soil.

Soil type-1: As mentioned earlier, this soil was collected from Anwara, Chittagong at a depth 1.5m below the existing ground level. It was fine sand with \( FM=0.26 \) \( D_{10}=0.075 \) mm, \( D_{50}=0.11 \) mm, \( G_s=2.69 \), Fine content, defined as material passing through #200 sieve, was 8%.

Soil type-2: This soil was collected from Toraghat, Manikgonj at a depth 1.5 below the existing ground level. It was a local sand, generally used in building construction. Physical properties of the sand were: \( FM=1.29 \), \( D_{10}=0.15 \) mm, \( D_{50}=0.26 \) mm, \( G_s=2.72 \), Fine content passing through #200 sieve was 1%.

Soil type-3: This soil was collected from Farmgate, Dhaka from a depth 1.5 below the existing ground level. It was typical Dhaka clay (reddish). Basic properties of this soil were \( G_s=2.74 \), \( LL=50.1\% \), \( PL=11\% \), and \( c_v=0.11 \) (using reconstituted sample). The optimum moisture content using standard proctor energy was 15.3% and the corresponding dry density was 15.49 kN / cu.m. According to MIT classification, the clay was consisted of 10.5% sand, 39.4% silt and 50.1% clay (Fig. 3.3).

Specific gravity \( (G_s) \) of untreated soils can be available in Fig. 3.4, when lime content was 0%. In the same figure, \( G_s \) was also plotted for various lime-treated soils. It can be seen that due to lime treatment, the value of \( G_s \) changed slightly.
### Table 3.2 Physical properties of the soil used for lime treatment

<table>
<thead>
<tr>
<th>Properties of the soil</th>
<th>Soil Type-1</th>
<th>Soil Type-2</th>
<th>Soil Type-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textural composition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand % (2mm to 0.06)</td>
<td>96.0</td>
<td>99.0</td>
<td>10.5</td>
</tr>
<tr>
<td>Silt % (0.06 mm to 0.002)</td>
<td>4.0</td>
<td>1.0</td>
<td>39.4</td>
</tr>
<tr>
<td>Clay % &lt;0.002</td>
<td>-</td>
<td>-</td>
<td>50.1</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.69</td>
<td>2.72</td>
<td>2.74</td>
</tr>
<tr>
<td>Classification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unified (ASTM-1976)</td>
<td>SP-SM</td>
<td>SP</td>
<td>CH</td>
</tr>
<tr>
<td>AASHTO (1993)</td>
<td>A-3</td>
<td>A-3</td>
<td>A-7-6 (13)</td>
</tr>
</tbody>
</table>

### 3.3.2 Lime

Lime used for soil treatments were collected from open market. It was kept sealed to prevent carbonation until immediately before use. Chemical analysis reported by Mollah (1997) was one of the commercially available lime in Bangladesh, which is presented in Table 3.3. Note that in this research, chemical analysis of the lime used was not done. Market survey showed that apparently similar types of lime are commercially available in the market. It was assumed that it would have similar constituents as Mollah (1997).

### Table 3.3 Constituents of lime from chemical analysis after Mollah (1997)

<table>
<thead>
<tr>
<th>Name of the ingredient</th>
<th>Quantity of ingredient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>48.72</td>
</tr>
<tr>
<td>MgO</td>
<td>17.60</td>
</tr>
<tr>
<td>Fe, Al, Na, K etc.</td>
<td>8.18</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1.80</td>
</tr>
<tr>
<td>*Loss due to ignition</td>
<td>23.7</td>
</tr>
</tbody>
</table>

*The loss on inanition is due to the removal of water from Ca(OH)₂ and Mg(OH)₂.
Fig. 3.3: Grain size distribution of untreated soils.
Fig. 3.4: Specific gravity of soils at different lime content
3.3.3. Water
Tap water was used for mixing and testing purpose.

3.4 State variables
The permeability of lime treated soil, change with the state variable. Those of the different variable used in this research are presented below.

3.4.1 Soil: Three soils as mentioned earlier, were used throughout the test to investigate the effects of soil type on the permeability of lime-treated soil.

3.4.2 Lime content: Commercial limes as available at the local open market were used in the test program. Permeability of the lime treated soils was determined at 1%, 3% and 5% lime content.

3.4.3 Reaction time: Reaction time is the time interval between wet mixing and preparation of sample for test. This time was allowed before testing to occur reaction and hydration of lime. After thorough mixing, soil lime mixture were again mixed with 20-25% (by weight) of tap water. The water quantity was such that it is sufficient to wet the soil particle but not excess which might cause the lime to wash out from the soil grain. The samples (soil type 1 and 2) were then left over a watertight table to complete reaction in room temperature. The samples for soil type 1 and 2 were then tested after 4 day (for soil type-1), 5 day (for soil type-2), 8 day (for soil type 1 and 2) and 14 days (for soil type 1 and 2). In the case of soil type 3, soil sample mixed in the same procedure and kept in airtight polythene bag in a sealed condition and subjected to consolidation test after 3 days of mixing.

3.4.4 Compaction energy: The apparatus for falling head permeability test was such that the application of larger load could not be possible. To confirm the repeatability of sample preparation and to obtain test specimens of same density (and hence same void ratio), one-kilogram weight load was applied on the soil specimen for the purpose of compaction during reconstitution. However, this additional load was applied only on sandy soils during reconstitution in the permeameter.
3.5 Preparation of the lime-treated soil specimen

Untreated soils type-1, type-2 and type-3 were first air-dried and the lumps were broken by wooden hammer. The soil was then passed through sieve # 4. All the materials retained on this sieve were then discarded. Then the representative soil sample of required quantity was taken for oven dry. After oven drying for 24 hours, the soil sample was cooled naturally and lime of predetermined percentages was then added. The percentage of lime, calculated on the basis of oven dry weight of the soil sample, was varied 1%, 3% and 5% in each soil. The soil and lime were thoroughly mixed until the color became uniform. Then water was added and the mixture was thoroughly blended with 20-25% (on weight basis) water. Attention was paid not to mix excess water that might cause the lime to wash out from the soil grain. The percentage of water content was so selected as to complete maximum hydration as possible during reaction time. The soil-mass was then kept on a watertight platform for reaction to occurs in the case of soil type I and 2, while for soil-3, the sample was keep in an airtight polythene bag.

Preparation of the soil sample for permeability tests

The lime treated soils (for soil type 1 and 2) after the reaction time of designated period become globular and formed weak bonded lumps. They were collected and thoroughly broken by using wooden hammer. Test specimen for lime-treated sandy soils and also for untreated sandy soils was 63.5 mm diameter and 100mm height. Each specimen was prepared in the permeameter immediately before testing. One complete specimen was prepared in 5 steps, each consisted of 20mm height. In each step, the hydrated lime-treated or untreated soil was poured into the permeameter in the required quantity using a spoon. A metal disc of size similar to the upper porous stone backed by a spring of sufficient strength was inserted into the permeameter and was placed on to the soil-mass. Then an additional load of weighing 1 kg was applied on the spring so that the load was applied on the soil-mass poured into the permeameter. The load so imposed was kept for 5 minutes, after which the required compaction was assumed to complete. After that the load and the spring attached metal disc was removed. Soil-mass was poured as before for the 2nd steps, which was
followed by loading and compaction, and so on. After completing 5 steps in this manner, the test specimen was said to be ready for testing.

For the case of soil type-3, lime-treated clay soil was collected from polythene bags after three-day reaction time. Lumps were broken and were compacted following procedure ASTM D 698-70 in a 100mm diameter compaction mould by 25 nos. of blow in three layer with 5 lbs hammer dropping from a height of 0.75m. The 63.5mm diameter and 25.4mm thick soil sample was extracted from the middle part of the mould following procedure ASTM D 2435-70. Note that the clay soil was reconstituted at a moisture content above standard Proctor density (i.e., which was varied in the range between 20% and 25%). Both treated and untreated soil was initially mixed with this moisture content and left the mixture for 3 days. During this period, hydration occurred in case of lime treated clay, but for untreated clay, the time was sacrificed so as to attain a similar state / stage with respect to moisture before the actual consolidation test was commencing.

Different relation used for calculation purposes.

For the calculation of void ratio of soil type 1 and 2 the following relation is used.

\[
e = \frac{G_d V_r - 1}{W_s} \quad \text{(3.1)}
\]

Where \(W_s\) is the dry weight of the soil grain and is calculated by the difference between air-dry sample weight and moisture content at the stage of testing and \(V_r\) is the total volume of soil.

Permeability of soil sample 1 and 2 are determined from relation 3.2.

\[
k = \frac{a L}{A} \ln \frac{h_1}{h_2} \quad \text{(3.2)}
\]

Where
- \(a\) = Cross sectional area of the stand pipe
- \(A\) = Cross sectional area of the soil sample.
- \(h_1\) = Hydraulic head across sample at beginning of the test.
- \(h_2\) = Hydraulic head across sample at end of the test.
- \(L\) = Length of the soil sample.
Viscosity of water was corrected from the following equation

\[ k_{20} = k_0 \frac{\nu}{\eta_0} \]  \hspace{2cm} (3.3)

Where \( \eta = \) Viscosity of fluid (water)

For soil type-3

Compression Index,

\[ C_c = \frac{d \varepsilon}{d (\log_{10} P)} \]  \hspace{2cm} (3.4)

Coefficient of compressibility,

\[ \alpha_v = \frac{0.435 c_c}{p_{av}} \]  \hspace{2cm} (3.5)

Where \( p_{av} = \) Average pressure for the increment.

Coefficient of Permeability,

\[ k = \frac{c_v \alpha_v \eta_w}{1+e} \]  \hspace{2cm} (3.6)

and coefficient of consolidation,

\[ C_v = \frac{0.197H^2}{t_{50}} \]  \hspace{2cm} (3.7)

Where \( H = \) Average length of the longest drainage path during the given load.

\( t_{50} = \) Time for 50% consolidation in minute.
CHAPTER FOUR
Results and Discussions

4.1. General

Permeability of three different re-constructed soils (two sandy and a clay soil) was treated in the laboratory to investigate the effect of lime treatment. The soils were treated by using lime of different percentages (e.g. 1%, 3%, and 5%). Soils 1 and 2 were cohesion-less, so permeability of these soils was determined by using falling head method. For the case of soil sample-3 (clayey soil), consolidation test was performed to evaluate its permeability. The tests were performed on the treated samples at 4 day (for soil type-1), 5 day (for soil type-2), 8 day (for soil 1 and 2) and 14 day (for soil 1 and 2) after mixing and subsequently cured for reaction to occur in air-dry state (the curing period was defined earlier as the reaction time). The reaction time was 3 days after the reconstitution of clay soil.

4.2. Test results and discussions

Laboratory tests were performed to investigate the effects of lime content, and reaction time (after mixing) on the permeability of lime-treated two sandy and a clayey soils. The samples were reconstituted in the laboratory. Since permeability of a lime treated soil is very sensitive to void ratio, soil fabric and structure, aging after reconstitution, stress level, etc., attention was given to maintain these controlling factors unchanged among the tests except the lime content and aging (which was termed as the reaction time). To check the repeatability of test samples, two samples were prepared with the similar testing conditions (i.e. with the same lime content, moisture content during mixing and the same reaction time). After testing, it was observed that although testing conditions were similar, both void ratio and permeability were varied noticeably. Figure 4.1a shows such test results in which void ratio in observation 1 was plotted against that obtained in observation 2. Although a 1:1 relationship (which confirms repeatability) was not observed, the data were not deviated from 1:1 line significantly. Similar results can be observed from Fig. 4.1b when permeability was plotted in the identical fashion of Fig. 4.1a.
Average permeability and void ratio were calculated from the test results of samples subjected to similar test conditions and are summarized in Table 4.1. Other results related to this table will be discussed later. In the following discussion, the average values of the test results for soil type 1 and 2 were used. It was already mentioned that for a given soil, various percentages of lime were used for the investigation and besides, for a given percentage of lime content, the reaction time was also varied (up to 14 days).

For soil type-3, consolidation test results were plotted in the Appendix. The relationships between dial reading and time were shown in Fig. A4.1 for 0% lime (untreated soil), Fig. A4.2 for 1% lime content, Fig. A4.3 for 3% lime and Fig. A4.4 for 5% lime content. Each test was performed for load-steps 6.25 kPa, 12.5kPa, 25.0 kPa, 50.0 kPa, 100.0 kPa, 200.0 kPa, 400.0 kPa and 800.0 kPa. From each plot of dial reading vs. time (Fig. A4.1 to A4.4), the values of t_{50} for each curve were determined and the corresponding values of c_v were determined using Eq. 3.7. Log-pressure versus instantaneous void ratio was plotted in Fig. A4.5. From the above curve, the value of compression index (c_v) was determined as the slope of the recession part (linear) of the curve and the value of coefficient of compressibility (a_v) was determined by using Eq. 3.5. From the evaluated values of c_v and a_v, the permeability within the particular loading range was determined using Eq. 4.6 and are summarized in Table 4.2. The relationships between the coefficient of permeability and the lime content were shown in Fig. 4.2 for different load ranges. The same data were plotted to observe the relationships between permeability and load range in Fig. 4.3. In the latter plot, the similar relationships were plotted for lime content 0%, 1%, 3% and 5%. The following trends of behavior can be seen from these figures (Figs. 4.2 and 4.3): a) the coefficient of permeability was maximum at about 1% lime content (which was at least 5 times the permeability value for the untreated soil) while the permeability was smaller for lime contents both greater and smaller than 1%; b) the coefficient of permeability had a decreasing tendency with the increase of vertical pressure, which was quite obvious; c) at about 3–5% lime content, the coefficient of permeability was little sensitive to the applied pressures.
Figures 4.4 through 4.8 show the results obtained by performing permeability tests (falling-head test) on cohesion-less soils. As mentioned earlier, two different cohesion-less soils — soil type-1 (a fine sand with FM=0.26) and soil type-2 (relatively coarser sand with FM=1.29) — were used for this purpose. Test variables were lime content varying from 0 to 5% and reaction time varying from 4 to 14 days. Figure 4.4a and b show the relationships (e-Lc) between void ratio (e) and lime content (Lc) obtained from soil 1 and 2, respectively. In the same plots, such e-Lc relationships were plotted for different reaction time. In calculating the void ratio, the specific gravity (Gs) used was not constant for different test samples (although the base soil was the same), which could be due to the change of lime content (see Fig. 3.3). However, the change was very small. The following behavior can be observed from Fig. 4.4a and b: (i) for fine sand (Fig. 4.4a), void ratio increased with the increase of Lc up to about 3%, at which the value of e was the maximum; the rate of change of void ratio decreased slightly for Lc > 3%; (ii) For relatively coarse sand (Fig. 4.4b), the void ratio decreased with the increase of Lc while the rate of decrease was large up to 1 ~ 2% of Lc, beyond which the rate became small. The difference in behavior of these two cohesionless soils could be due to the difference in their grain size characteristics. It seems that fines or the smaller particles have significant influence in the lime treated cohesion-less soil. If such particles are present significantly, the addition of lime increased their effective sizes (probably, due to coagulation) and hence increased the void ratio. On the other hand, if these particles are absent (or present in small amount), the presence of lime cannot coagulate the dominating ‘larger’ particles; rather they reduce the voids between the larger particles effectively coagulating with fine particles (which are small in proportion). As a result the void ratio decreases.

However, this increase or decrease in void ratio was not proportionate with permeability (Fig. 4.5a and b). For example, in case of soil-1 void ratio was increased up to 1.5 times at Lc=3 % compared to that was when Lc=0% (Fig. 4.4a). For this, it was expected that the permeability would be increased at least 2 times at Lc= 3% compared to when it was for Lc= 0 %, because it is known that permeability of cohesion-less soil is proportional to the square of the mean particle diameter Dm (i.e., k = CDm 0.5 , Eq. 2.1, where C being a proportionality constant). But for soil-2 (Fig. 4.5b), on the other hand, the decrease in permeability with the increasing Lc was
consistent with the decrease in void ratio. The data of Figs. 4.4a were re-plotted in Figs. 4.6a and b, respectively, to show the relationships between void ratio and reaction time, and the permeability and reaction time. Similar data from Fig. 4.4b (of soil-2) were plotted in Fig. 4.7a and b, respectively. In all the figures (Figs. 4.6-4.7), the respective variation/relationships were plotted for different Lc. Note that the relationships corresponding to Lc= 0% were for the untreated soils. The following trends of behaviour can be observed from the above relationships: (a) both void ratio and permeability were insensitive to the age of the untreated sample (here the term reaction time is not valid for untreated soil); (b) void ratio decreased with reaction time slightly for both soil-1 and soil-2; (c) with the decreasing tendency of void ratio with increasing reaction time, soil-1 exhibited insensitiveness in the change of permeability while permeability of soil-2 was decreased accordingly. This difference in behavior of the two cohesion-less soils could be due to the role of fine content (as described earlier).

Long-term stability of permeability of lime treated sands (soil 1 and 2) were investigated. For this purpose, after certain days of reaction time, the permeability of the treated soil was determined (following the same procedure as stated before) intermittently during a span of 30 to 40 hours. The reaction time allowed before this investigation was 4 days to 14 days for both sandy soils. Lime content for Soil-1 and Soil-2 was 5%. The relationships between the permeability and the elapsed time showing the long-term stability of permeability are shown in Figs. 4.8a and b. Although some scatters can be observed in data, the permeability of lime treated sands was more-or-less stable throughout the investigating period.

All the permeability data for lime treated sands (Soil-1 and Soil-2) shown in Figs. 4.4 through 4.5 were plotted against the void ratio (e) in Figs. 4.9a and b, respectively, for Soil-1 and Soil-2. The data were plotted disregarding the lime content of the individual specimen. In the same figures, the permeability data were also plotted against the functional value of a void ratio function $f(e) = \frac{e^3}{1+e}$. Note that many authors shown that the permeability of a cohesionless is proportional to a void ratio function $f(e)$ passing through the origin (Fig. 2.3 after Das, 1983). Among many other void ratio functions, the commonly used one is $f(e) = \frac{e^3}{1+e}$. The following trends of behavior can be observed from Figs. 4.9a and b: (i) like untreated cohesionless soil, the
The permeability of lime treated sandy soil was proportional to its void ratio and a void ratio function. (ii) although the permeability was proportional to the functional value of the void ratio function f(e), the linear relationship did not pass through the origin; rather it exhibited an offset on the void ratio function axis denoting a range of void ratio (and hence a range of the corresponding functional value) up to which the lime treated sand would show 'no or very little' permeability; (iii) the 'no permeability' range of the void ratio functional value was larger (>0.50) in fine sand than that was (≈0.20) in the coarser sand (which was also a fine sand by definition of FM). The above discussion reveals that the same void ratio function, which is applicable for a cohesionless soil, may not be applicable for the same soil after the lime treatment.

Table 4.1: Some test results from soil 1 and 2 (Sandy soils)

<table>
<thead>
<tr>
<th>Lime content</th>
<th>Soil Type-1</th>
<th>Soil type-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reaction Time (day)</td>
<td>Void ratio</td>
</tr>
<tr>
<td>0%</td>
<td>-</td>
<td>0.9896</td>
</tr>
<tr>
<td>1%</td>
<td>4</td>
<td>1.1871</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.131</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>1.0573</td>
</tr>
<tr>
<td>3%</td>
<td>4</td>
<td>1.2832</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.2125</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>1.0412</td>
</tr>
<tr>
<td>5%</td>
<td>4</td>
<td>1.2361</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.2095</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>1.1339</td>
</tr>
</tbody>
</table>
Table 4.2: Some test results from soil type-3

<table>
<thead>
<tr>
<th>Lime Content</th>
<th>Load kPa</th>
<th>$c_v$ (sq.cm/min)</th>
<th>$a_v (x10^{-5})$ kPa</th>
<th>$\gamma_w$ gm/cc</th>
<th>Void ratio (e)</th>
<th>$c_{kT}$</th>
<th>$k_{20} (x10^{-5})$ cm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>0.0</td>
<td>-</td>
<td>6.25</td>
<td>-</td>
<td>0.9957</td>
<td>-</td>
<td>0.7967</td>
</tr>
<tr>
<td></td>
<td>200.0</td>
<td>0.0525</td>
<td>6.25</td>
<td>-</td>
<td>1.04584</td>
<td>1.04584</td>
<td>9.132</td>
</tr>
<tr>
<td></td>
<td>400.0</td>
<td>0.0781</td>
<td>6.25</td>
<td>-</td>
<td>1.03571</td>
<td>1.03571</td>
<td>6.882</td>
</tr>
<tr>
<td></td>
<td>800.0</td>
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*K_T* = Absolute or kinematics fluid viscosity correction factor (at average temperature 30°c)
Fig. 4.1a: Relationship of void ratios between two observations under otherwise similar test conditions for soil-1

Fig. 4.1b: Relationship of permeability between two observations under otherwise similar test conditions for soil-2
Fig. 4.2: Relationships between permeability and lime content for soil-3

Fig. 4.3: Relationships between permeability and vertical load for soil-3
Fig. 4.4a: Relationships between void ratio and lime content for soil-1

Fig. 4.4b: Relationships between void ratio and lime content for soil-2
Fig. 4.5a: Relationships between permeability and lime content for soil-1

Fig. 4.5b: Relationships between permeability and lime content for soil-2
Fig. 4.6a: Relationships between void ratio and reaction time for soil-1

Fig. 4.6b: Relationships between permeability and reaction time for soil-1
Fig. 4.7a: Relationships between void ratio and reaction time for soil-2

Fig. 4.7b: Relationships between permeability and reaction time for soil-2
Fig. 4.8a: Long-term permeability after different reaction time for soil-1

Fig. 4.8b: Long-term permeability after different reaction time of soil-2
Fig. 4.9a: Relationship between void ratio or \( f(e) \) and permeability of soil-1

\[
f(e) \approx \frac{e^3}{(1+e)}
\]

Fig. 4.9b: Relationship between void ratio or \( f(e) \) and permeability of soil-2

\[
f(e) \approx \frac{e^3}{(1+e)}
\]
CHAPTER FIVE

Conclusions and Recommendations for the future Research

5.1 General

In this research work, three soils were used after collecting from three different locations to investigate permeability and its characteristics after lime treatment. Soils were treated with lime at different percentages (1%, 3%, and 5%). The tests were performed on air-dry sample after allowing different reaction time (curing age). Soils 1 and 2 were cohesion-less and their permeability was determined by using falling head method. On the other hand, soil-3 was cohesive one and so consolidation test was performed to determine its permeability characteristics. After mixing soil with lime at a definite proportion, a time (denoted earlier as reaction time) was allowed for the reaction of lime to occur with water and soil particles. The reaction time was varied from 4 to 14 days. Long-term stability of permeability of the cohesionless soils was investigated after the elapse of certain days of reaction time. The duration of long-term stability of permeability was 30 to 40 hours. In this period, the permeability of a specimen (lime-treated) was determined intermittently. Overall permeability of lime treated soil and its void ratio (irrespective of lime content) and the functional values of a void ratio function $f(e)$ were also investigated to check whether they follow the same rule as those of the untreated soil condition.

5.2 Conclusions

The following conclusions can be drawn based on the results obtained after investigating various aspects related to permeability characteristics of lime treated soils:

a). Overall increase in permeability of lime-treated clay was observed. But the influence of lime content on permeability was not similar throughout the investigated range of lime content. That is, the permeability was maximum for
the specimen treated with 1% lime (at least 5 times of the untreated clay), but it was not change noticeably in the range 3 to 5% lime.

b. Regarding to permeability characteristics, the cohesive soil was more sensitive to lime content than cohesionless soil. In the investigated range of lime treatment, the permeability of cohesive soil increased at least 5.0 times of its untreated value, while the permeability of relatively fine-grained (FM=0.26, fines = 8% passing through # 200 sieve) sand increased up to 1.3 times and the 'coarser' sand (FM=1.29, fines = 1%) decreased to 0.72 times of their respective untreated values.

c. Void ratio of lime-treated cohesion-less soils was influenced by the presence of fines or small particles in sand. Sand (soil-1) with having substantial fines exhibited an increasing tendency of void ratio with the increase of lime content, while that with 'coarser' particles showed a decreasing tendency of void ratio with the increase of lime content. The difference in behavior could be due to the increase of the effective size of 'finer' particles after coagulation with lime particles resulting in larger voids in the interparticle spaces. As a result of this particle rearrangement, void ratio configuration of the soil mass was increased. However, in case of 'coarser' particle, such coagulation of lime particle and 'coarser' grains effectively reduced the interparticle spaces inside the soil mass and subsequently reduced the void ratio.

d. Consistently with the void ratio pattern, the permeability of lime-treated sands was also changed. That is, the decrease in void ratio was resulted in the increase in permeability. However, the degree of change was not consistent with that would occur in case of the untreated sand.

e. Aging had no affect on the permeability and void ratio of untreated sands. But the void ratio and hence permeability of lime treated sand was slightly changed with the reaction time.
f. The permeability of lime treated sands (after the completion of certain period of reaction time) was more-or-less stable throughout the investigation period of 40 hours.

5.3 Recommendation for future study

It is recommended to extent the research work in the following field to have a better understanding about lime-treated soils:

a) More similar soils should be investigated to obtain a general conclusion based on the present findings.

b) Permeability characteristics can be investigated using the additives such as cow-dung, fly ash separately or lime-cow-dung, lime-fly ash, fly ash-lime combinedly.

c) Various engineering properties including permeability of stabilized soils can be investigated after the application of different compaction efforts such as kneading, preloading, vibration, etc.
REFERENCES


Hickling, C. F. (1962), Fish culture, Faber and Faber, London. 295p.


Kulkarni G. J. (1977), Engineering materials, Start book service, Punna, India


APPENDIX
Fig. A4.1a Dial reading vs. time curve for soil type-3 (0% Lime; 6.25~50 kPa)
Fig. A4.1b  Dial reading vs. time curve for soil-3 (0% lime; 100.0 – 800.0 kPa)
Fig. 4.2a Dial reading vs. time curve for soil-3 (1% Lime; 6.25-50.0 kPa)
Fig. A4.2b Dial reading vs. time curve for soil-3 (1% lime; 100.0–800.0 kPa)
Fig. A4.3a Dial reading vs. time curve for soil-3 (3% Lime; 6.25–50.0 kPa)
Fig. A4.3b Dial reading vs. time curve for soil-3 (3% lime; 100.0-800.0 kPa)
Fig. A4.4a Dial reading vs. time curve for soil-3 (5% Lime; 6.25–50.0 kPa)
Fig. A4.4b Dial reading vs. time curve for soil-3 (5% Lime; 100.0 -800.0 kPa)
Fig. A4.5 Void ratio vs. Log-pressure curve for soil type-3