Chapter 6

PERMEABILITY STUDIES ON THE GROUTED SOIL

6.1 Introduction

The effectiveness of grouting to improve the strength characteristics of loose sandy soils has already been established with the help of experimental results in Chapters 4 and 5. Grouting is normally undertaken to reduce the permeability of rock or soil formations and this process is used extensively in the construction of hydraulic structures such as dams, power houses, tunnels and in a wide variety of special cases. Various materials such as cement, sand, silt, clay, bentonite, chemicals etc. are used, depending upon the need and purpose of grouting and the nature of formations to be grouted. Even though the application of this grouting technique to reduce the permeability of rock formations has been reported in literature, no serious attempts are reported about the effective use of this technique to reduce the permeability of soil
formations. The results of experimental investigations carried out in this direction are presented in this chapter.

The results obtained from permeability tests conducted on different graded sand fractions such as fine, medium and coarse sand at a dry unit weight of 14.5 kN/m$^3$ is given in Table 6.1. As one would expect, the permeability increases with increase in grain size of soil particles.

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Soil type</th>
<th>Size range (mm)</th>
<th>Permeability (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fine sand</td>
<td>0.075 – 0.425</td>
<td>$0.54 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>Medium sand</td>
<td>0.425 – 2.0</td>
<td>$1.86 \times 10^{-4}$</td>
</tr>
<tr>
<td>3</td>
<td>Coarse sand</td>
<td>2.0 – 4.75</td>
<td>$2.69 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The technology of grouting now plays an important role in all the fields of foundation engineering such as seepage control in rock and soil under dams, advancing tunnels, cut off walls etc. in the evaluation of safety of any dam, problems connected with excessive leaching and seepage. Seepage not only causes loss of valuable water stored in the reservoir, but also poses problems by its existence through piping. Control of seepage through the dam foundation and minimizing exit gradient on the downstream, play key roles in the analysis and design of dams. When transit or utility tunnels are to be placed beneath the water table and the soils encountered have permeability greater than approximately $1 \times 10^{-5}$ m/s, water inflow can be expected. Along with this water inflow, soil can be eroded into the tunnel, resulting in piping collapses and adverse surface settlements. Remedial and rehabilitation measures for
arresting excess leaching and seepage mainly involve controlling the permeability of the soil strata by means of grouting.

Kenai et al. (2006) investigated the effect of compaction methods on mechanical properties and durability of cement stabilized soil. According to them the reduction in permeability could be attributed to the reduction of large pores by the cement particles and cement hydration products. Thus the treatment of soil with cement could lead to a better mechanical strength, lower permeability and hence better durability.

6.2 Cement as the grout material

For grout injected specimens, decreasing the water to cement ratio of the grout and increasing the curing time significantly lowered the permeability and increased the strength, whereas increasing the distance from the injection point had little effect on the permeability but produced meaningful reductions in strength. These trends are consistent with the sand acting as a filter for the grout suspension (Schwarz and Krizek, 1994).

In order to determine the effect of cement in reducing the permeability of the sand medium, permeability tests were conducted on specimens prepared in the permeability mould. For preparing the samples, medium sand (unit weight 14.5 kN/m$^3$) was mixed with different percentages of cement in the dry condition. Then 10 % (by weight of sand – cement mixture) water was added to the mixture, mixed well and filled in the mould for conducting the permeability test.
Figure 6.1 shows the effect of cement content on permeability of sandy soil treated with cement, at different curing periods. As one would expect, the permeability decreases with increase in the percentage of cement. The reduction in permeability is only marginal in case of specimens cured for 7 & 14 days, whereas the reduction is substantial as the curing period is increased to 28 days. Similarly increased use of cement (beyond 10%) can influence the permeability at higher curing periods only. The reduction in permeability with respect to the cement content and curing period is more clear in Fig. 6.2. It can be seen that the permeability got reduced by $1/7400$ in the case of 25% cement and cured for 28 days. When cement alone was added to the medium sand, the cement hydrates and occupied the voids of sand thereby decreasing the interconnectivity of soil voids by blocking the potential flow paths.
Permeability Studies on the Grouted Soil

The permeability and strength of grouted sand is strongly influenced by the method of grouting because different mechanisms govern the deposition and packing of cement particles within the pores structure. During the injection process, preferential flow paths allow the migration of cement particles into the soil and micro structural packing undoubtedly varies within the pore spaces of the grouted sand (Schwarz and Krizek, 1994).

Fig. 6.3 shows the effect of curing period on permeability of cement treated sand having different cement contents 4, 10 and 25 %. It can be also be seen that eventhough the permeability decreases with elapsed time, it becomes almost constant beyond 15 days of curing period for lower cement contents (i.e. 4 % and 10 %), but at higher contents (e.g. 25 %), the permeability goes on reducing drastically even after 15 days. Hence one can presume that reduction in permeability is directly related to the hydration of cement. The reduction in the permeability with reduction in the size of particles of the mixture (sand + cement) is quite clear from Fig. 6.4 which is a plot between the effective size $D_{10}$ of the
Fig. 6.3 Effect of curing time on permeability of cement treated sand

Fig. 6.4 Effect of effective size of particles on the permeability of cement treated sand
sand - cement mixture and the corresponding permeability. Similarly, the addition of cement (process taking place in cement grouting) will cause a reduction in the void ratio and consequently the permeability. The plot between the void ratios ‘e’ and the coefficient of permeability ‘k’ (Fig. 6.5) illustrates the reduction in permeability accompanied by the reduction in void ratio.

![Fig. 6.5 Plot between void ratio and permeability of sandy soil treated with cement](image)

### 6.3 Cement with admixtures

In most of the cases, the primary aim of grouting is to reduce or cut off seepage through sandy subsoil by making it impermeable by deposition of fine materials in pore spaces with grouting. The sand layers may be uniform mass of either very fine or coarse grains or it can also be a well graded media. The hydraulic conductivity of sand beds can be reduced by injecting fine materials (10 % cement + bentonite) into the interspaces of the formation (Lovely, 1998).
A soil bentonite mix is a three phase material of solids, water and air. Besides their different densities, the two components of the solid phase have different properties and must be considered separately. The bentonite particles have a very high specific surface ($5 - 12 \times 10^4$ m$^2$/kg) which allows them to retain a portion of water that displays inability to flow as freely as the remaining water in the pore space (Chapuis 1990). Fig. 6.6 presents the results of permeability tests conducted on medium sand treated with two different percentages – 4 % and 10 %. The different percentages of bentonite (0.2 to 1.5 % by wt. of the sand + cement mixture) was added and the permeability tests were conducted after a curing period of 15 days, as per the procedure discussed in section 3.4.3. It is clear that there is a phenomenal reduction in the permeability due to the addition of this admixture, i.e., bentonite. Another interesting observation is that, eventhough the permeability goes on decreasing with % of bentonite, at higher % of bentonite (e.g. 1.5 %), the permeability corresponding to 4 % cement and 10 % cement yield almost the same value.
This result can be advantageously used in field applications such as construction of subsurface check dams. i.e. by increasing the percentage of bentonite by a small amount, one can get a saving in the quality of cement to achieve the same permeability, thereby reducing the cost substantially.

6.4 Locally available clay

The permeability of granular soils may decrease substantially on account of the presence of even small amounts of fine silt and clay sized particles. The mineralogy and degree of aggregation or dispersion of the fines determine the magnitude of the decrease in permeability (Terzaghi et al., 1996).

The reduction in the coefficient of permeability, at constant void ratio, from kaolinite to illite to smectite is largely the result of a reduction in the size of individual flow channels and an increase in the tortuosity of the flow paths (Mesri and Olson, 1971).

Eventhough bentonite clay can be used for reducing the permeability of sandy soils, the availability of bentonite is confined to certain regions. Hence investigations were done to check whether the locally available clay could be used in place of bentonite to reduce the cost factor involved.

Cochin marine clay collected from a location in Elamkulam (properties given in table 3.3) in the Greater Cochin area was mixed with medium sand in different percentages and the permeability was measured.

The results are presented in Fig. 6.7. It can be seen that unlike cement (Fig. 6.1) where the permeability goes on reducing with cement content, the reduction in permeability with increase in the percentage of clay is marginal, upto a clay percentage of around 15 %. Thereafter, there is a drastic reduction in permeability with percentage of clay. Experiments were also conducted on
other sand fractions- i.e. fine and coarse. Different percentages of clay were mixed with these sand fractions and the permeability tests were conducted. The results of tests on these sand fractions are also given in Fig. 6.7.

![Fig.6.7 Effect of percentage of clay on Permeability](image_url)
Even though the permeability decreases with increase in clay percent in all the three cases, the variation in the permeability in case of fine sand and coarse sand are not in the same pattern. In the case of fine sand, there is a gradual reduction in the ‘k’ value and the lowest permeability that could be attained is only $3.4 \times 10^{-7}$ m/sec, even at a very high clay content of 25%. In contrast to this, there is no significant reduction in the permeability in case of coarse sand mixed with clay (up to around 17%), but the value suddenly drops beyond a clay content of 20% and a very low permeability of the order of $7.8 \times 10^{-9}$ m/sec can be achieved for a clay content of 25%. The permeability value for medium and coarse sand mixed with 25% clay is only 1/40th of that of the fine sand with the same amount of clay. Hence, if grouting can be performed with a high percentage of clay, more reduction in permeability can be attained in case of coarser fractions of sand.

In the above set of experiments, the same amount of clay (5, 10, 15, 20 & 25%) was mixed with all the three fractions of sand, the initial unit weight being 14.5 kN/m$^3$. Hence the void ratios of the specimens having the same clay content remain the same. The void ratio in each case and the corresponding permeability values for all the three fractions of sand are tabulated in Table 6.2. The wide variations in permeability for the three sand fractions having the same void ratio are quite clear from the table. In other words, we can get the same permeability for different sand fractions, even though their void ratios are different. For example, fine sand without any clay (void ratio = 0.83) and coarse sand having 20% clay (void ratio = 0.52) yield almost the same value of permeability.
Table 6.2 Effect of void ratio on permeability of sandy soil with clay

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>% of clay</th>
<th>Void ratio</th>
<th>Coefficient of permeability k (m/sec) for</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fine sand</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.83</td>
<td>5.0 x 10^{-5}</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0.74</td>
<td>3.0 x 10^{-5}</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.66</td>
<td>2.0 x 10^{-5}</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>0.59</td>
<td>1.0 x 10^{-5}</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>0.52</td>
<td>2.67 x 10^{-6}</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>0.46</td>
<td>3.36 x 10^{-7}</td>
</tr>
</tbody>
</table>

The above fact is also brought out by the figure 6.8, which is a plot between the effective size ($D_{10}$) of the particles in the specimen and the permeability. Eventhough the permeability is almost constant for all the soil fractions at higher values of $D_{10}$, it varies widely as the value of $D_{10}$ decreases.

![Fig.6.8 Effect of Permeability with grain size $D_{10}$](chart)
6.5 Bentonite

Bentonite clay, which is also used as an antibleeder along with cement grout was tried in order to reduce the permeability of the sand. Samples for permeability test were prepared by mixing medium sand (unit weight 14.5 kN/m³) and bentonite powder (in the dry condition) at different percentages and filling the mixture in the moulds. The results obtained from the permeability tests are given in Fig. 6.9. It can be seen from the figure that the permeability reduces drastically as the percentages of the bentonite increases. The figure also gives a comparison of the performance of bentonite in relation to the locally available clay and cement. The effectiveness of bentonite in relation to Cochin marine clay and cement in reducing the permeability of a sand medium is quite clear from this figure.

![Fig. 6.9 Effect of Permeability with additives](image)

6.6 Locally available clay along with cement/ lime

The improvement in strength characteristics of the locally available clay (Cochin marine clay) on treatment with lime or cement has been clearly brought
Fig. 6.10 Effect of additives on permeability of sandy soil treated with clay

out by Jose et al. (1987) and Abraham (1993). But the effect on permeability when this clay is treated with these additives has not been studied. Experiments were conducted in this direction by conducting permeability tests on the samples prepared by mixing medium sand and 25% Cochin marine clay treated with different percentages (by dry weight of clay) of cement or lime and cured for 15 days, in order to explore the possibility of getting further reduction in the permeability. The results are presented in Fig. 6.10. Eventhough smaller percentages of lime cause a reduction in permeability, it becomes more permeable as the lime content increases. But the treatment with cement causes a reduction in the permeability, the effect of which is more pronounced at higher percentages of cement. Hence the permeability of a sand medium can be reduced to any extent by the use of a proper combination of locally available clay and cement.
Chapter 7

SUMMARY AND CONCLUSIONS

7.1 Introduction

There has been a rapid development in the field of civil engineering requiring selection of site from considerations other than soil quality alone. This results in the need to make use of sites with very low bearing capacity/strength also, such as loose sandy soils. This investigation examines the scope of improving granular soils of low strength with cement grouting. Results on systematic studies carried out on strength of cement grouted sand medium from
the view point of bearing capacity are scanty. Based on the experimental investigations and test results, the following conclusions are made.

7.2 Strength improvement on densification

Investigations carried out to assess the improvement in the load carrying capacity of sand beds on densification through vibration techniques gave the following conclusions.

- The load carrying capacity of the sand medium depends not only on the density but also on the gradation and the load carrying capacity of finer fractions, is always higher compared to the coarser fractions irrespective of the density. This can be attributed to the increased contact area between the particles, in the case of finer fractions.

- Maximum densification improves the load carrying capacity of the sand at the loosest state by 16 times and even that would not be sufficient to serve as the bed for shallow foundations in the case of multistoreyed buildings.

7.3 Improvement of shear strength on grouting

The present investigations mainly focused at studies on the strength behaviour of these loose sandy soils when grouted with different materials such as cement with or without admixtures, lime etc. Grouted sand present the general characteristic of cemented soils and can be considered as an intermediate material between soil and concrete (Dano et al. 2004). The review of published experimental results related to grouted sand (Schwarz and Krizek 1994; Zebovitz et al. 1989) reveals a large discrepancy in the results due to a wide variety of parameters related to the soil (grain size distribution, density
specific area, etc), the grout (nature, type, particle size distribution etc) and the injection conditions (rate of discharge, grout pressure, injection procedure etc).

The conclusions drawn from the results of a series of direct shear tests, conducted on samples prepared (by hand mixing) with different grouting materials are given below.

7.3.1 **Grouted with cement alone**

- The shear strength of the loose sandy soil steadily increases with increase in cement content and also with curing period, for all sand fractions.
- The rate of increase in shear strength is very high at higher percentages of cement than at lower percentages in the case of all the sand fractions.
- Eventhough specimens of medium sand give higher shear strength than coarse sand specimens at lower cement contents; the coarse sand specimens register higher strength as the cement content increases.
- The influence of the increased initial water content of the grout is to decrease the shear strength of the grouted sand and the effect is more pronounced at higher cement contents.
- Shear strength of the grouted sand increases with increase in normal pressure. The stress–strain response exhibits a linear relationship prior to the peak, for all cement contents and the value of shear strength steadily increases with increase in cement content.

7.3.2 **Grouted with cement and admixtures**

Several admixtures are used along with the cement grout to improve the various properties of grout suspensions. The effects of these admixtures on the strength of grouted sand were not studied previously. The following
conclusions are made related to the shear strength of loose sand grouted with cement along with these admixtures.

- The effect of accelerators (Calcium chloride & sodium silicate) is to reduce the strength slightly, but while considering the other benefits such as improvement in properties like viscosity, stability and the early setting of the grout, this reduction in strength is within the tolerable limits. Among the two accelerators studied, the performance of calcium chloride is better, compared to sodium silicate with regard to shear strength.

- One has to be very careful in the use of tartaric acid (retarder) with cement grout. The results indicate a sharp decrease in shear strength value when the cement content is less than 0.15 %. The shear strength increases at lower percentage of triethanolamine and a marginal reduction is noticed as the percentage of this salt increases. Comparing the two retarders, triethanolamine gives much higher shear strength even at lower percentages and hence can be considered as a better retarder.

- The shear strength increases upto the optimum dosage (0.05 %) of detergent (fluidiser), thereafter the value is found to decrease.

- The use of optimum dosage (below 0.02 %) of aluminium powder (expander) increases the shear strength of the grouted sand.

- The shear strength is found to increase with increases in percentage of aluminium sulphate (antibleeder), eventhough there is a slight reduction at lower percentage of this salt. The addition of bentonite (which is also an antibleeder) to the cement grout causes a reduction (approx. 15 %) in shear strength.
7.3.3 Grouted with lime

- The shear strength of the loose sandy soil increases with increase in lime content and curing period, but this increase is negligible compared to the tremendous increase in shear strength when cement is used as the grout material.

7.4 Shear strength parameters

The effect of grouting on the shear strength parameters ‘c’ and ‘Ø’ are studied in detail and the following conclusions made.

7.4.1 Grouted with cement alone

The value of cohesion intercept c and angle of shearing resistance Ø steadily increase with increase in cement content and also with curing period. The rate of increase in Ø value is only marginal beyond a certain value of cement content (approx. 15%). The effect of curing period is more significant at higher percentages of cement than at lower percentages.

- The influence of the initial water content of the cement grout is very significant in the case of values of c and with Ø. While the value of c drastically reduces with increase in i.w.c., the effect on Ø- value is just opposite. i.e. the value of Ø goes on increasing with increase in the initial water content of the grout, except in the case of fine sand.

7.4.2 Grouted with cement and admixtures

- Among the two accelerators tried, the reduction in Ø- value is more with the addition of Calcium Chloride compared to Sodium Silicate but the greater increase in cohesion intercept results in increased shear strength.
The use of triethanolamine as a retarder causes only a marginal reduction in $\phi$-value which is compensated by the increase in cohesion intercept. The addition of even a very small percentage of tartaric acid (around 0.5%) brings down the $\phi$-value by 10%, but the same amount of reduction is experienced only at high percentages (8 to 10%) of triethanolamine. Hence these results also confirm that one has to be very careful in the use of tartaric acid as a retarder along with cement grouts.

The use of optimum dosage (0.05%) of the detergent (fluidiser) will not adversely affect the values of the shear strength parameters.

Unlike other admixtures, the addition of aluminium powder increases the $\phi$-value of the cement grouted sand. The use of optimum dosage (0.005%) will also not adversely affect the cohesion intercept.

Eventhough there is a marginal decrease in cohesion initially (at around 2%), increase in percentage of aluminium sulphate increases the cohesion intercept and the effect of curing period also significantly in the case of aluminium sulphate.

A comparison between the effects of the two antibleeders i.e., aluminium sulphate and bentonite on the cohesion intercept shows that the effect of aluminium sulphate is to increase the cohesion whereas bentonite causes a slight reduction in the value of cohesion intercept. But the $\phi$-value after an initial reduction, increases with increase in percentages of these two admixtures.
7.4.3 Grouted with lime

- When lime is used as a grouting material the cohesion intercept increases with increase in lime content and curing period, but decreases with increase in the initial water content.

- The $\phi$ value remains more or less constant at the initial stages, but the value increases at higher lime contents (beyond 15%). Another interesting observation is that in the case of lime also, the value of $\phi$ increases with increase in water content, which is not in line with the variation of $c$ value.

- The marginal improvement in the values of the shear strength parameters compared to the tremendous improvement when the loose sandy soil is grouted with lime and cement respectively, confirms the superiority of cement over lime in grouting granular beds.

7.5 Compressive strength

Determination of shear strength through direct shear test is a time consuming process and at higher cement contents it is very difficult to conduct this test till the failure at lower normal loads occurs. It is also difficult to collect three to four identical samples after grouting. Compressive strength tests were done on the grouted samples with the objective of arriving at some simple correlation between the compressive strength and the shear strength of grouted samples, since this test is very simple and can be done very accurately, irrespective of the cement content. The conclusions drawn from the test results are,

- Compressive strength goes on increasing with increase in percentage of cement content and curing period. Also, as in the case of shear strength,
Chapter 7

the compressive strength also decreases with increase in initial water content.

- The compressive strength increases with increase in cement content for all the three sand fractions – i.e. fine, medium and coarse sand. Even though the coarse fraction shows less strength than the fine & medium sand at lower cement contents, it overtakes the other two, as the cement content increases (beyond 15%)

- A comparison between the performance of calcium chloride and sodium silicate (accelerators) on the compressive strength shows that calcium chloride is preferred over sodium silicate as an admixture, along with cement grout.

- Among the retarders, the reduction in strength is much less in the case of triethanolamine compared to tartaric acid. Further the property of triethanolamine in reducing the viscosity of cement grouts can be taken advantage of in using this as an admixture along with cement grout.

- Use of aluminium powder (expander) in cement grouts does not affect the compressive strength.

- The effect of both the antibleeders - aluminium sulphate and bentonite - on the compressive strength of cement grouted sand is almost the same. Even though there is an initial reduction in strength at smaller percentages, it picks up strength as the percentage increases. Hence, both these admixtures can be used as antibleeders along with cement grouts without adversely affecting the compressive strength.
7.6 Relation between compressive strength and shear strength

Attempts to correlate the results from compressive strength and shear strength tests yield the following very useful relationships.

- Correlation between the cohesion intercept $c$ and compressive strength $p$ of the grouted soils gives an excellent straight line relationship with a high correlation coefficient of 0.95 as,

$$ c = 0.079p - 2.21 $$

- The relationship between the angle of shearing resistance $\Phi$ and the compressive strength $p$ is a non linear one and the equation is

$$ \Phi = 37.52 + 0.009p - 7.58E^{-7}p^2 $$

with a correlation coefficient of 0.83

- The relationship between shear strength $\tau$ and compressive strength $p$ is given by the following equation.

$$ \tau = 0.104p + 80.12 $$

with a high correlation coeff. of 0.96

7.7 Studies on cement grouted sand beds

In order to simulate the grouting process in the field, model tests were conducted on sand beds prepared in steel tanks in the laboratory. For this purpose, a grouting set up was designed and fabricated. The grouting nozzle was designed so as facilitate the flow of the grout smoothly both in the vertical and lateral directions. The following conclusions were drawn from the results of the model studies conducted using this set up developed in order to study the grouting efficiency.
7.7.1 Grouting efficiency from cross section dimensions

- A comparison of cross sectional area of grouted mass (medium sand) with 2, 4 and 6 % cement shows that the effective cross section area of the mass grouted with 4 % cement is maximum at all depths. A grouted volume as high as 78 % of the original volume was obtained in the case of 4 % cement grout, whereas it was only 45 % and 53 % in the case of 2 % and 6 % cement grouts respectively.

- In the case of coarse sand also, grouting with 4% cement gave the maximum areas of cross section, which is less than that of medium sand.

- Use of admixtures in cement grout does not enhance the cross section area of medium sand.

- The admixtures used play an important role in increasing the cross section areas of the grouted mass, in the case of coarse sand. 15 % bentonite and 0.05 % detergent (by weight of cement) prove to be very effective along with 6 % cement grout in coarse sand.

7.7.2 Grouting efficiency from actual cement contents

The efficiency of grouting mainly depends upon the penetration of cement grout through the pores of sand. The following conclusions are drawn from the results of cement contents determined by chemical analysis on samples from the grouted mass, in order to assess the quantity of lateral flow of grout into the soil mass.

- 4 % cement grout is more effective in medium sand and coarse sand compared to 2 % and 6 %, while considering the travel distance of the grout and the cement contents at various points in the grouted mass.
Use of admixtures enhances the lateral flow in the case of both medium & coarse sand. Aluminium sulphate performs better as an antibleeder compared to bentonite, when used along with cement grout, in the case of medium sand.

A combination of 15 % bentonite and 0.05 % detergent along with 6 % cement grout was found to be very effective in the case of coarse sand.

### 7.7.3 Grouting efficiency from load tests

The results of a series of load tests conducted on the grouted sand beds gave the following conclusions.

- A comparison in the strength behaviour between medium sand and coarse sand when grouted with 4% cement shows that the strength of the grouted coarse sand is much higher and it exhibits a brittle type failure.
- For coarse sand, a minimum cement content is required for the grouting to be effective. This may be due to the increased pore space available in the case of coarse sand compared to medium sand.
- Even though there is a slight reduction (around 20%) in strength in medium sand, the admixtures make the grouted sand bed to be more ductile, thus eliminating the chances of a sudden failure of foundations.
- In the case of coarse sand, the admixtures help to increase the load carrying capacity (twice the strength compared to the sand bed grouted without admixtures). This can be attributed to the increased lateral flow of the grout when admixtures are used along with cement in grouting coarse sand bed.
A comparison in strength of the medium sand beds grouted with cement (grout pumped through grout pump) with that of the uniformly mixed sand beds (ideal condition) stresses the need for developing more appropriate grouting tools and methods for making the grouting process more efficient so that the foundation design can be made more economical.

7.8 Permeability studies on the grouted soil

The following conclusions are drawn from the results of permeability tests conducted on sand samples prepared with different grouting materials.

- The permeability goes on reducing with increase in cement content.
- The effect of the curing period is to decrease the permeability of cement grouted sand. But at lower cement contents, the permeability remains more or less constant beyond a curing period of 15 days.
- The permeability got reduced by \( 1/7400 \)th in the case of medium sand grouted with 25% cement and cured for 28 days.
- Addition of small percentages of bentonite along with cement grout drastically reduces the permeability. A substantial reduction in cost can be achieved by reducing the cement content and slightly increasing the corresponding bentonite content to obtain a particular value of permeability.
- Locally available clay (Cochin marine clay) is found to be very effective in reducing the permeability of sand beds. With higher percentages of clay, greater permeability reduction is achieved in coarse sand fractions.
Among the various grouting materials tried, bentonite is found to be the most effective in reducing the permeability of granular beds.

The effect of cement is more pronounced, compared to lime, when used along with clay in reducing the permeability of sandy beds. The permeability of a sand medium can be reduced to any extent by the use of a proper combination of locally available clay and cement.

Thus the present study undoubtedly proves the effectiveness of using grouting as an efficient technique in improving the foundation beds of loose sandy soils.