Chapter 6

PERMEABILITY BEHAVIOUR OF COMPACTED SWELLING AND NON-SWELLING SOILS

6.1 INTRODUCTION

Permeability behaviour of fine-grained soils is important by virtue of the dependency of the consolidation process of fine-grained soils on the permeability characteristics of fine-grained soils. Importance of permeability of compacted clayey soils gets enhanced as the compacted clayey soils are also used for compacted clay liners at landfills. Considerable work has been done in the past on the study of permeability behaviour of fine-grained soils (section 2.3.5). However, very less information is available on the permeability behaviour of compacted soils with particular reference to the influence of soil clay mineralogical composition, and almost no information is available on the studies related with validity of Darcy’s law for flow through compacted soils.

In this context, in the present experimental work, it is intended to study the permeability behaviour of compacted swelling and non-swelling soils and to check the validity of Darcy’s law for the flow through compacted swelling and non-swelling soils.

6.2 PERMEABILITY MEASUREMENTS

Variable head permeability tests were conducted on two compacted soils of same low liquid limit group and also on three compacted soils of same high liquid limit group. Permeability tests were conducted on soil samples obtained from two different processes.

- Soil samples compacted to 0.95 $\rho_{d_{\text{max}}}$ on dry side of optimum, compacted to optimum condition and 0.95 $\rho_{d_{\text{max}}}$ on wet side of optimum.
- Over consolidated soil samples obtained by subjecting the soils samples remoulded at water contents slightly more than their liquid limit water contents to a predefined effective consolidation stress and then unloading to a seating effective stress of 6.25 kPa.

Permeability tests were conducted on both compacted and remoulded-reloaded soil samples under an effective consolidation stress of 6.25 kPa during the forward
loading process and also before dismantling the specimen from consolidation apparatus. In all these tests, times corresponding to different hydraulic heads causing flow through the soil samples were recorded. From these readings the values of velocity of flow through the soil samples corresponding to different hydraulic gradient were calculated. The values of coefficient of permeability of the soils were calculated with the help of this data as explained in the following section.

6.3 VELOCITY OF FLOW v/s HYDRAULIC GRADIENT CURVES

The Darcy's law tacitly assumes the relationship between velocity of flow and the hydraulic gradient to be a straight line through the origin of the graph, the constant slope of which representing the coefficient of permeability of the soil. However, all the compacted soil samples have been observed to exhibit non-Darcian behaviour.

In most of the cases of the present study, the velocity of flow v/s. hydraulic gradient curves exhibit characteristic threshold gradient (i_c) beyond which the relationship between velocity of flow and hydraulic gradient can be approximated to be linear within the purview of the range of hydraulic gradient adopted during the measurement (i.e., i ≤ 5). It has also been noted that at higher hydraulic gradients, the velocity v/s hydraulic gradient relationship becomes non-linear. The velocity measurements at higher gradients were not made to avoid the sample disturbance due to upward flow at higher hydraulic gradients.

Figs. 6.1(a) through 6.1(e) show typical velocity of flow v/s hydraulic gradient relationships for the soils under study at an effective consolidation stress of 6.25 kPa during loading process. Similarly Figs. 6.2(a) and 6.2(b) show typical velocity of flow v/s hydraulic gradient curves at an effective stress of 6.25 kPa during unloading process. The coefficient of permeability is calculated as the slope of the linear portion of the velocity of flow v/s hydraulic gradient curve.
Fig. 6.1(a): Velocity of flow v/s hydraulic gradient relationship for K-soil of same low liquid limit group compacted on dry side of optimum at $\sigma' = 6.25$ kPa (forward loading)

Fig. 6.1(b): Velocity of flow v/s hydraulic gradient relationship for M-soil of same low liquid limit group compacted on dry side of optimum at $\sigma' = 6.25$ kPa (forward loading)
Fig. 6.1(c): Velocity of flow v/s hydraulic gradient relationship for K-M-soil of same high liquid limit group compacted at OMC at $\sigma' = 6.25$ kPa (forward loading)

Fig. 6.1(d): Velocity of flow v/s hydraulic gradient relationship for M-soil of same high liquid limit group compacted on dry side of optimum at $\sigma' = 6.25$ kPa (forward loading)
Fig. 6.1(e): Velocity of flow v/s hydraulic gradient relationship for K-soil of same high liquid limit group compacted on dry side of optimum at $\sigma' = 6.25$ kPa (forward loading)

Fig. 6.2(a): Velocity of flow v/s hydraulic gradient relationship for K-soil of same low liquid limit group compacted on dry side of optimum at $\sigma' = 6.25$ kPa (unloading)
6.4 COEFFICIENT OF PERMEABILITY OF COMPACTED SOILS

6.4.1 General

Tables 6.1 and 6.2 list the values of coefficient of permeability of the soils under study obtained at an effective consolidation stress of 6.25 kPa during loading process and during unloading process respectively along with the values of threshold gradient. The permeability measurements were dispensed within certain cases, where the disturbance to soil sample was feared.

6.4.2 Effect of placement condition

From Table 6.1 it can be noted that the coefficient of permeability, for all compacted soils, is maximum when compacted dry of optimum. It drastically reduces (by about one to three orders of magnitude) when the soils were compacted at OMC. The value of coefficient of permeability shows a decrease or a small increase in its value for soil samples compacted on wet side of optimum.
Table 6.1: Values of coefficient of permeability of soils under study during loading process

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Soil</th>
<th>Dry side of optimum</th>
<th>At optimum</th>
<th>Wet side of optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>e</td>
<td>i_c</td>
<td>k: m/s</td>
</tr>
<tr>
<td>S1</td>
<td>Soils of same low liquid limit group</td>
<td>K-soil</td>
<td>0.784</td>
<td>0.47</td>
</tr>
<tr>
<td>S2</td>
<td>M-soil</td>
<td>0.80</td>
<td>1.62</td>
<td>3.826×10⁻⁷</td>
</tr>
<tr>
<td>S3</td>
<td>K-M soil</td>
<td>0.969</td>
<td>3.0</td>
<td>1.818×10⁻⁶</td>
</tr>
<tr>
<td>S4</td>
<td>Soils of same high liquid limit group</td>
<td>M-soil</td>
<td>1.0</td>
<td>0.49</td>
</tr>
<tr>
<td>S5</td>
<td>K-soil</td>
<td>1.066</td>
<td>0.84</td>
<td>1.136×10⁻⁶</td>
</tr>
</tbody>
</table>
Table 6.2: Values of coefficient of permeability of soils under study during unloading process

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Soil</th>
<th>Dry side of optimum</th>
<th>At optimum</th>
<th>Wet side of optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>e</td>
<td>i&lt;sub&gt;c&lt;/sub&gt;</td>
<td>k: m/s</td>
</tr>
<tr>
<td>S1</td>
<td>Soils of same low liquid limit group</td>
<td>K-soil</td>
<td>0.398</td>
<td>0.47</td>
</tr>
<tr>
<td>S2</td>
<td></td>
<td>M-soil</td>
<td>0.398</td>
<td>1.35</td>
</tr>
<tr>
<td>S3</td>
<td>Soils of same high liquid limit group</td>
<td>K-M soil</td>
<td>0.682</td>
<td>0.25</td>
</tr>
<tr>
<td>S4</td>
<td></td>
<td>M-soil</td>
<td>0.620</td>
<td>--</td>
</tr>
<tr>
<td>S5</td>
<td>K-soil</td>
<td>0.645</td>
<td>0.42</td>
<td>7.08×10&lt;sup&gt;-7&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
On the dry side of optimum, the compacted soils will have relatively flocculant fabric and hence, yield higher values of coefficient of permeability. At OMC, the compacted soil fabric is fairly dispersed, which results in a drastic decrease in the value of coefficient of permeability. On the wet side of optimum compacted state, the compacted soil fabric is of highly dispersed type. With the result, the value of coefficient of permeability reduces from that at optimum compacted state. A slight increase in the value of coefficient of permeability at wet side compacted state than at optimum compacted state is observed for M-soil of high liquid limit group, which may be attributed to higher void ratio at wet side compacted state than at optimum compacted state. The increase in the void ratio may be due to double layer swelling.

Similar observation can be made in Table 6.2 also. In addition, the values of coefficient of permeability in Table 6.2 can be observed to be lower than the corresponding values in Table 6.1, which is obviously due to a reduction in void ratio resulted as a consequence of consolidation.

6.4.3 Effect of clay mineralogy
6.4.3.1 Soils of same low liquid limit group

The K-soil has a higher coefficient of permeability than M-soil (i.e., 3.925 x 10⁻⁶ m/sec for K-soil as against 3.826 x 10⁻⁷ m/sec for M-soil) on dry side of optimum, which essentially can be attributed to the fact that the fabric of K-soil is more flocculent than that of M-soil.

The fabric of the K-soil changes drastically from flocculent on dry side of optimum to dispersed type at optimum compacted state. This results in nearly 2.5 order of decrease in its coefficient of permeability (i.e., 3.925 x 10⁻⁶ m/sec to 1.554 x 10⁻⁹ m/sec). On the other hand, M-soil fabric changes from relatively less flocculent type at dry side of optimum compacted state to dispersed type at optimum compacted state. In addition, M-soil has higher sand content (i.e., 40 % as against 28.5 % in K-soil). This results in relatively less decrease in the value of coefficient of permeability (i.e., 3.826 x 10⁻⁷ m/sec to 9.659 x 10⁻⁹ m/sec).
6.4.3.2 *Soils of same high liquid limit group*

The three soils of same high liquid limit group can be seen to have almost of
the same order of coefficient of permeability on the dry side of optimum. While
moving over from dry side of optimum compacted state to optimum compacted state,
the M-soil shows a drastic decrease in its value of coefficient of permeability (i.e.,
$5.594 \times 10^{-6}$ m/sec to $1.289 \times 10^{-9}$ m/sec) when compared with the other two soils,
even though the void ratio of M-soil at OMC is more than those of other two soils at
OMC. This may be attributed to the presence of relatively higher montmorillonite
content in the clay size fraction of M-soil.

The above discussion indicates the effect of clay mineralogical composition on
the value of coefficient of permeability.

6.4.3.3 *General comments*

The study of Tables 6.1 and 6.2 gives some more additional and useful
information as indicated below

- The values of threshold gradient do not have any bearing on soil type.
- The soil sample (of same soil type) having almost same void ratio exhibits
drastically higher value of coefficient of permeability on the dry side of
optimum when compared with that on wet side of optimum (Fig. 6.3). This
clearly is an indication that void ratio is not the only factor controlling the
coefficient of permeability. On the other hand, it is the soil fabric / effective
pore size which controls the coefficient of permeability at the same void ratio
level. The relatively more flocculant fabric of the dry side compacted soil is
responsible for the higher values of coefficient of permeability.

Hence the following factors appear to control the coefficient of permeability:

- Placement condition
- Clay mineralogical composition
- Void ratio
- Soil fabric / effective pore size.

The holistic study of the coefficient of permeability data presented in this
work indicates that the effects of the above factors are interdependent.
Fig. 6.3: Variation of coefficient of permeability with void ratio for soils compacted at 0.95 $\rho_{d_{\text{max}}}$ on dry side of optimum, at optimum and at 0.95 $\rho_{d_{\text{max}}}$ on wet side of optimum at $\sigma' = 6.25$ kPa (forward loading)

Table 6.3: Comparison of values of coefficient of permeability of soils compacted at OMC with those in the remoulded-reloaded state

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Soil</th>
<th>Compacted at OMC</th>
<th>Remoulded-reloaded state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$e$</td>
<td>$i_c$</td>
</tr>
<tr>
<td>S1</td>
<td>K-soil</td>
<td>0.697</td>
<td>0.10</td>
</tr>
<tr>
<td>S2</td>
<td>M-soil</td>
<td>0.736</td>
<td>0.88</td>
</tr>
<tr>
<td>S3</td>
<td>K-M soil</td>
<td>0.881</td>
<td>0.40</td>
</tr>
<tr>
<td>S4</td>
<td>M-soil</td>
<td>1.024</td>
<td>0.72</td>
</tr>
<tr>
<td>S5</td>
<td>K-soil</td>
<td>0.983</td>
<td>--</td>
</tr>
</tbody>
</table>
6.5 COEFFICIENT OF PERMEABILITY OF REMOULDED-RELOADED SOIL SAMPLES

Table 6.3 compares the values of coefficient of permeability at an effective consolidation stress of 6.25 kPa obtained during loading process for soils compacted at OMC with the values obtained for the same soils in the remoulded (at or slightly higher than liquid limit water content) -reloaded state.

The study of this table leads to the following observations.

- The K-soil of same low liquid limit group has slightly greater value of coefficient of permeability in the remoulded-reloaded state than in the optimum compacted state, which can be attributed to higher void ratio of the soil at remoulded-reloaded state.

- The M-soil of same low liquid limit group has a lower value of coefficient of permeability, in spite of having higher void ratio, in the remoulded-reloaded state than that of the same soil in the optimum compacted state. This could be attributed to highly dispersed fabric of M-soil resulted during the remoulding process, which has assisted in an effective development of diffuse double layer, when compared with the relatively less flocculant fabric on the same soil in the optimum compacted state.

- The M-soil of same high liquid limit group shows coefficient of permeability of the same order in both optimum compacted state and remoulded-reloaded state. This observation is suggestive of the possibility of higher level of dispersed fabric induced in the soil during remoulding process.

- The K-M soil of same high liquid limit group shows a lower value of coefficient of permeability (about 2.5 order of magnitude) in the remoulded-reloaded state when compared with value at optimum compacted state. It can be noted that K-M soil is a mixture of both montmorillonitic and kaolinitic clay minerals. While the kaolinitic clay mineral fraction of the soil undergoes a drastic change from relatively flocculent fabric to more dispersed fabric during remoulding, the montmorillonitic clay fraction also exhibits highly dispersed fabric as a consequence of remoulding. As a consequence of this combined effect, the K-M soil, having relatively higher value of coefficient of permeability in the optimum compacted state as a consequence of flocculent
fabric of kaolinitic clay mineral fraction, exhibits a much lower value of coefficient permeability in the remoulded-reloaded state.

• The absence of threshold gradient for the soils in the remoulded-reloaded state indicates the validity of Darcy's law for the soils of different clay mineralogy, in the remoulded-reloaded state, within the range of hydraulic gradient adopted for the permeability measurements.

6.6 COEFFICIENT OF PERMEABILITY FROM $c_v$ VALUES

The values of coefficient of permeability can also be calculated using the values of coefficient of consolidation ($c_v$) of the soil under any given stress increment using eq. 6.1.

$$k = c_v m_v \gamma_w$$ (6.1)

where $m_v = \text{coefficient of volume compressibility of the soil for the stress increment considered.}$

$\gamma_w = \text{unit weight of water.}$

Sridharan and Prakash (2006) did a comparative study of the values of coefficient of permeability obtained from direct measurement and calculated from coefficient of consolidation using eq. 6.1. Following is the summary of their findings.

• The coefficient of permeability obtained from direct measurement at the end of consolidation under each stress increment is a steady flow parameter.

• The value of the coefficient of permeability calculated from coefficient of consolidation represents an unsteady flow parameter.

• The value of coefficient of permeability calculated from $c_v$ depends upon the curve fitting procedure adopted to evaluate the value of coefficient of consolidation and hence, can vary over a wide range. Depending upon the methodology adopted to evaluate $c_v$, the value of coefficient of permeability calculated can be more than or equal to or less than the coefficient of permeability obtained from direct measurement, even though such a comparison is strictly untenable.
Table 6.4: Comparison of coefficient of permeability values obtained from direct measurement with those calculated from $c_v$

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Soil</th>
<th>Dry side of optimum</th>
<th>Coefficient of permeability (k): m/s</th>
<th>Wet side of optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured value @ 6.25 kPa</td>
<td>Calculated from $c_v$</td>
<td>Measured value @ 6.25 kPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pre yield region</td>
<td>Post yield region</td>
<td>Pre yield region</td>
</tr>
<tr>
<td>S1</td>
<td>Soils of same low liquid limit group</td>
<td>K-soil 3.925 x 10^-6</td>
<td>1.654 x 10^{-12} to 3.472 x 10^{-9}</td>
<td>9.577 x 10^{-10} to 4.084 x 10^{-9}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M-soil 3.826 x 10^{-7}</td>
<td>9.773 x 10^{-14} to 5.573 x 10^{-11}</td>
<td>4.733 x 10^{-14} to 4.420 x 10^{-11}</td>
</tr>
<tr>
<td>S2</td>
<td>Soils of same high liquid limit group</td>
<td>K-M soil 1.818 x 10^{-6}</td>
<td>1.552 x 10^{-12} to 4.303 x 10^{-10}</td>
<td>2.812 x 10^{-14} to 3.377 x 10^{-12}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M-soil 5.594 x 10^{-6}</td>
<td>1.812 x 10^{-11} to 6.253 x 10^{-11}</td>
<td>1.329 x 10^{-12} to 7.457 x 10^{-11}</td>
</tr>
<tr>
<td>S5</td>
<td>K-soil 1.136 x 10^{-6}</td>
<td>2.623 x 10^{-11} to 3.346 x 10^{-9}</td>
<td>1.572 x 10^{-10} to 1.017 x 10^{-9}</td>
<td>1.204 x 10^{-12} to 2.646 x 10^{-10}</td>
</tr>
</tbody>
</table>
In the present experimental study, direct measurement of permeability was done only at the 6.25 kPa effective consolidation stress level, but not at the end of consolidation under each stress increment. This was done in view of prohibitively longer time taken for the consolidation under each stress increment itself and also for the permeability measurement. However, the range of values of coefficient of permeability calculated from the coefficient of consolidation determined by one point method are given in Table 6.4 for the sake of completeness.

The study of Table 6.4 clearly indicates that the measured values of coefficient of permeability @ 6.25 kPa are, in almost all cases, are much higher than the values of coefficient of permeability calculated from coefficient of consolidation (specifically in the pre-yield region). This observation is in good agreement with the documented geotechnical engineering literature according to which the measured values of coefficient of permeability of soil samples are always more than the values of coefficient of permeability calculated indirectly from cy.

### 6.7 SUMMARY

From the study of permeability behaviour of compacted swelling and non-swelling fine-grained soils, following conclusions can be drawn.

- The maximum values of coefficient of permeability are obtained for dry side compacted soils.
- The least values of coefficient of permeability are obtained at optimum compacted condition or wet side compacted condition.
- The clay mineralogical composition has a controlling influence on the values of coefficient of permeability.
- At the same void ratio, the fabric of the soil controls the values of coefficient of permeability.
- The Darcy’s law appears to be valid for compacted fine-grained soils beyond a threshold gradient.
- The values of coefficient of permeability obtained from direct measurement are always much greater than those calculated indirectly from cy values.