Chapter 4

COMPACTION BEHAVIOUR OF SWELLING AND NON-SWELLING SOILS

4.1 INTRODUCTION

Soils which support the constructional activities will be subjected to compaction process to obtain some specific dry density at some specific placement water content, before subjected to external loading. The compaction behaviour of fine-grained soils is expected to be a function of soil clay mineralogical composition in addition to other parameters. This chapter discusses the compaction behaviour of seven soils with different mineralogical composition grouped into three categories.

4.2 RESULTS AND DISCUSSIONS

4.2.1 Compaction curves

4.2.1.1 Effect of soil type

It has been generally accepted that, as the liquid limit increases, OMC increases and $\rho_{d_{\text{max}}}$ decreases. The studies of Pandian et al (1997) indicated that the compaction characteristics had a direct bearing on the liquid limit of soils. Fig. 4.1(a) and 4.1(b) present the light compaction curves for soils of same low liquid limit group and same high liquid limit group respectively. Fig. 4.1(c) presents the light compaction curves for soils with wide variation in their liquid limits. Fig. 4.2(a) and 4.2(b) present the heavy compaction curves for soils of low liquid limit group and high liquid limit group respectively. Fig. 4.2(c) presents the heavy compaction curves for soils with wide variation in their liquid limits.

Table 4.1 presents the values of OMC and $\rho_{d_{\text{max}}}$ obtained from light and heavy compaction tests for the soils under study.
Fig. 4.1(a): Light compaction curves for soils of same low liquid limit group

<table>
<thead>
<tr>
<th>Soil</th>
<th>G</th>
<th>( w_l ),%</th>
<th>Ip,%</th>
<th>OMC,%</th>
<th>( \rho_{\text{dmax}} ), g/cm(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-Soil</td>
<td>2.74</td>
<td>55</td>
<td>29</td>
<td>23.2</td>
<td>1.61</td>
</tr>
<tr>
<td>M-Soil</td>
<td>2.85</td>
<td>54</td>
<td>28</td>
<td>20.1</td>
<td>1.64</td>
</tr>
</tbody>
</table>

Fig. 4.1(b): Light compaction curves for soils of same high liquid limit group

<table>
<thead>
<tr>
<th>Soil</th>
<th>G</th>
<th>( w_l ),%</th>
<th>Ip,%</th>
<th>OMC,%</th>
<th>( \rho_{\text{dmax}} ), g/cm(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-M Soil</td>
<td>2.69</td>
<td>67</td>
<td>37</td>
<td>28.0</td>
<td>1.432</td>
</tr>
<tr>
<td>M-Soil</td>
<td>2.72</td>
<td>68</td>
<td>35</td>
<td>30.2</td>
<td>1.361</td>
</tr>
<tr>
<td>K-Soil</td>
<td>2.67</td>
<td>68</td>
<td>38</td>
<td>34.5</td>
<td>1.340</td>
</tr>
</tbody>
</table>
Fig. 4.1(c): Light compaction curves for soils of extreme liquid limit group

<table>
<thead>
<tr>
<th>Soil</th>
<th>G</th>
<th>wL:%</th>
<th>Ip:%</th>
<th>OMC:%</th>
<th>( \rho_{\text{dmax}} ): g/cm(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-Soil</td>
<td>2.61</td>
<td>48</td>
<td>15</td>
<td>32.25</td>
<td>1.320</td>
</tr>
<tr>
<td>M-Soil</td>
<td>2.70</td>
<td>165</td>
<td>138</td>
<td>18.00</td>
<td>1.593</td>
</tr>
</tbody>
</table>

Fig. 4.2(a): Heavy compaction curves for soils of low liquid limit group

<table>
<thead>
<tr>
<th>Soil</th>
<th>G</th>
<th>wL:%</th>
<th>Ip:%</th>
<th>OMC:%</th>
<th>( \rho_{\text{dmax}} ): g/cm(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-Soil</td>
<td>2.74</td>
<td>55</td>
<td>29.00</td>
<td>17.4</td>
<td>1.762</td>
</tr>
<tr>
<td>M-Soil</td>
<td>2.85</td>
<td>54</td>
<td>28.00</td>
<td>14.4</td>
<td>1.846</td>
</tr>
</tbody>
</table>
Fig. 4.2(b): Heavy compaction curves for soils of high liquid limit group

Fig. 4.2(c): Heavy compaction curves for soils of extreme liquid limit group
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Soil</th>
<th>Light Compaction Test</th>
<th>Plasticity index</th>
<th>Liquid limit</th>
<th>OMC: %</th>
<th>$\rho_{\text{max}}$: g/cm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Soils of same low liquid limit group</td>
<td>K-soil</td>
<td>26</td>
<td>55</td>
<td>17.40</td>
<td>1.640</td>
</tr>
<tr>
<td>S2</td>
<td>Soils of same high liquid limit group</td>
<td>M-soil</td>
<td>28</td>
<td>54</td>
<td>14.40</td>
<td>1.846</td>
</tr>
<tr>
<td>S3</td>
<td>Soils of same high liquid limit group</td>
<td>K-M-soil</td>
<td>37</td>
<td>67</td>
<td>20.00</td>
<td>1.762</td>
</tr>
<tr>
<td>S4</td>
<td>Soils of extreme liquid limit group</td>
<td>K-soil</td>
<td>38</td>
<td>68</td>
<td>30.20</td>
<td>1.432</td>
</tr>
<tr>
<td>S5</td>
<td>Soils of extreme liquid limit group</td>
<td>M-soil</td>
<td>34.50</td>
<td>68</td>
<td>1.340</td>
<td>1.665</td>
</tr>
<tr>
<td>S6</td>
<td>Soils of extreme liquid limit group</td>
<td>K-soil</td>
<td>1.5</td>
<td>48</td>
<td>32.25</td>
<td>1.664</td>
</tr>
<tr>
<td>S7</td>
<td>Soils of extreme liquid limit group</td>
<td>M-soil</td>
<td>27</td>
<td>165</td>
<td>1.593</td>
<td>1.591</td>
</tr>
</tbody>
</table>
Figs. 4.3(a) and 4.3(b) present the variation of OMC obtained from light compaction tests with the liquid limit and plasticity index of the soils. Figs. 4.4(a) and 4.4(b) present the variation of $p_{\text{dmax}}$ obtained from light compaction tests with the liquid limit and plasticity index of the soils. These figures indicate the absence of any definite relationship between the liquid limit / plasticity index and compaction characteristics of the soils under study.

Nagaraj (2000) showed a good relationship between OMC from standard Proctor test $[(OMC)_{SP}]$ and the plastic limit ($w_p$) of the soils in the form

$$\text{(OMC)}_{SP} = 0.92 \, w_p$$  \hspace{1cm} (4.1)

![Graph](image)

Fig. 4.3(a): Variation of OMC of soils obtained from light compaction tests with liquid limit of soils
Fig. 4.3(b): Variation of OMC of soils obtained from light compaction tests with plasticity index of soils

Fig. 4.4(a): Variation of $\rho_{\text{dmax}}$ of soils obtained from light compaction tests with liquid limit of soils
Fig. 4.4(b): Variation of $\rho_{\text{dmax}}$ of soils obtained from light compaction tests with plasticity index of soils

Fig. 4.5: Relationship between OMC obtained from light compaction tests with plastic limit of soils
This observation was supported by Gurtug and Sridharan (2004). Fig. 4.5 presents the relationship between the values of OMC obtained from light compaction tests \((\text{OMC})_{LC}\) with the plastic limit of the soils under present study. The regression equation for this data with a correlation coefficient of 0.989 is of the form

\[
(\text{OMC})_{LC} = 0.916 w_p
\] (4.2)

This observation, in addition to supporting the findings of Nagaraj (2000) and Gurtug and Sridharan (2004), can be considered as an useful information in the preliminary design works concerned with soil compaction.

Gurtug and Sridharan (2004) also tried to correlate the maximum dry unit weight obtained from standard Proctor compaction test \([(\gamma_{d,\text{max}})_{SP}]\) with the dry unit weight at the plastic limit water content of the soils \((\gamma_{dPL})\), assuming the soils to be fully saturated at plastic limit water content. The dry unit weight at plastic limit water content can be calculated using the equation,

\[
\gamma_{dPL} = \frac{G \gamma_w}{(1 + w_p G)}
\] (4.3)

They observed a very good relation between \((\gamma_{d,\text{max}})_{SP}\) and \(\gamma_{dPL}\)

\[
i.e \, (\gamma_{d,\text{max}})_{SP} = 0.98 \gamma_{dPL}
\] (4.4)

Fig. 4.6 presents the relationship between maximum dry density obtained from light compaction tests of the present work \([(\rho_{d,\text{max}})_{LC}]\) with the dry density corresponding to plastic limit \(\rho_{dPL}\). The regression equation for this data with a correlation coefficient of 0.999 is of the form.

\[
(\rho_{d,\text{max}})_{LC} = 0.972 \rho_{dPL}
\] (4.5)

This observation that the maximum dry density or dry unit weight corresponding to light compaction tests and the dry density or dry unit weight at plastic limit of the soils are almost equal, which supports the observations of Gurtug...
and Sridharan (2004), can be seem to be of great practical significance in the preliminary design works connected with soil compaction.

Table 4.1 also presents the values of OMC and $\rho_{\text{dmax}}$ obtained from heavy compaction curves for the soils under study. Figs. 4.7(a) and 4.7(b) present the variation of OMC obtained from heavy compaction test $[(\text{OMC})_{\text{HC}}]$ with the liquid limit and plasticity index of the soils. Figs. 4.8(a) and 4.8(b) present the variation of $\rho_{\text{dmax}}$ obtained from heavy compaction tests $[(\rho_{\text{dmax}})_{\text{HC}}]$ with the liquid limit and plasticity index of the soils. These figures also indicate the absence of any definite relationship between the liquid limit or plasticity index and compaction characteristics of the soils under study.

![Graph](image)

**Fig. 4.6:** Relationship between $\rho_{\text{dmax}}$ obtained from light compaction tests with the dry density corresponding to plastic limit of soils
Fig. 4.7(a): Variation of OMC of soils obtained from heavy compaction tests with liquid limit of soils

Fig. 4.7(b): Variation of OMC of soils obtained from heavy compaction tests with plasticity index of soils
Fig. 4.8(a): Variation of $\rho_{\text{dmax}}$ of soils obtained from heavy compaction tests with liquid limit of soils

Fig. 4.8(b): Variation of $\rho_{\text{dmax}}$ of soils obtained from heavy compaction tests with plasticity index of soils
Gurtug and Sridharan (2004) established a relationship between the values of OMC obtained from modified Proctor compaction test \([\text{OMC}_{\text{MP}}]\) and plastic limit of the soils as given by the equation

\[
\text{(OMC)}_{\text{MP}} = 0.70 \, w_p \tag{4.6}
\]

They also established a relationship between the maximum dry unit weight obtained from modified Proctor compaction tests \([\gamma_{d_{\text{max}}}^{\text{MP}}]\) and the dry unit weight at the plastic limit of the soils in the form

\[
(\gamma_{d_{\text{max}}}^{\text{MP}}) = 1.07 \, \gamma_{d_{\text{PL}}} \tag{4.7}
\]

Fig. 4.9(a) presents the relationship between OMC obtained from heavy compaction tests of the present study with the plastic limit of soils. The regression equation for this data with a correlation coefficient of 0.992 is given by

\[
(\text{OMC})_{\text{HC}} = 0.637 \, w_p \tag{4.8}
\]

Fig. 4.9(b) presents the relationship between \(\rho_{d_{\text{max}}}\) obtained from the heavy compaction tests with the dry unit weight at plastic limits of the soils. The regression equation for this data with a correlation coefficient of 0.999 is given by

\[
(\rho_{d_{\text{max}}})_{\text{HC}} = 1.136 \, \rho_{d_{\text{PL}}} \tag{4.9}
\]
Fig. 4.9(a): Relationship between OMC obtained from heavy compaction tests with plastic limit of soils

\[(OMC)_{HC} = 0.637 w_p\]
\[r = 0.992\]

Fig. 4.9(b): Relationship between \(\rho_{d_{max}}\) obtained from heavy compaction tests with the dry density corresponding to plastic limit of soils

\[(\rho_{d_{max}})_{HC} = 1.136 \rho_{d_{PL}}\]
\[r = 0.999\]
In the present study, it has been noticed that the two soils of same low liquid limit group namely K-soil and M-soil have OMCs of 23.2% and 20.1% respectively in the light compaction tests, and they exhibit OMCs of 17.4% and 14.4% respectively in the heavy compaction tests. These soils have maximum dry densities from light compaction tests as 1.61 g/cm$^3$ and 1.64 g/cm$^3$ respectively and maximum dry densities from heavy compaction tests as 1.762 g/cm$^3$ and 1.846 g/cm$^3$ respectively. Similarly, the soils of same high liquid limit group namely K-M-soil, M-soil, and K-soil have OMCs from light compaction tests as 28%, 30.2% and 34.5% respectively and OMCs from heavy compaction tests as 20%, 22.6% and 21.2% respectively. These soils have maximum dry densities from light compaction tests as 1.432 g/cm$^3$, 1.361 g/cm$^3$ and 1.34 g/cm$^3$ respectively and maximum dry densities from heavy compaction tests as 1.665 g/cm$^3$, 1.664 g/cm$^3$ and 1.591 g/cm$^3$ respectively.

These results indicate that the soils with same liquid limit (of low liquid limit group or of high liquid limit group) exhibit different values of OMC and maximum dry density at lower as well as higher compacting energy levels. In other words, they support the findings of Sridharan and Nagaraj (2005) that single parameter namely liquid limit cannot explain the compaction characteristics of fine-grained soils.

4.2.1.2 Effect of compactive effort

Figs 4.10(a) through 4.10(g) present the light and heavy compaction curves for the seven soils under study subjected to both light and heavy compaction efforts. From these figures, it can be noted that as the compactive effort increases, dry density increases with a decrease in OMC for the same soil.

Fig. 4.11(a) presents the comparison between the values of OMC obtained from light compaction tests with those obtained from the heavy compaction tests of the present study. The relation between them has a correlation coefficient of 0.997 and is given by

$$\text{(OMC)}_{HC} = 0.692 \times \text{(OMC)}_{LC} \tag{4.10}$$

Fig. 4.11(b) presents the comparison between the values of $\rho_{d\text{max}}$ obtained from light compaction tests with those obtained from the heavy compaction tests of
the present study. The relationship between them with a correlation coefficient of 0.999, is given by

\[(\rho_{\text{dmax}})_{\text{HC}} = 1.167 (\rho_{\text{dmax}})_{\text{LC}}\]  \hspace{1cm} (4.11)

Even though there is a general trend of variation between the quantities involved, these figures show some points deviating away from the general trend. These deviating points correspond to the commercial kaolinite clay minerals and bentonite-sand mixture. If the points corresponding to field soils only are considered, their relationship between the quantities considered can be observed to be excellent. For the field soils under study, the relationship between the values of OMC obtained from light and heavy compaction tests (Fig. 4.11c) is given by eq. 4.12 with a correlation coefficient of 0.999

\[(\text{OMC})_{\text{HC}} = 0.734 (\text{OMC})_{\text{LC}}\]  \hspace{1cm} (4.12)

Fig. 4.10(a): Light and heavy compaction curves for K-soil of same low liquid limit group

<table>
<thead>
<tr>
<th>Compactive effort</th>
<th>OMC: %</th>
<th>(\rho_{\text{dmax}}): g/cm(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light compaction</td>
<td>23.2</td>
<td>1.610</td>
</tr>
<tr>
<td>Heavy compaction</td>
<td>17.4</td>
<td>1.762</td>
</tr>
</tbody>
</table>

K-Soil \((w_L = 55\%; I_p = 29\%\)
Fig. 4.10(b): Light and heavy compaction curves for M-soil of same low liquid limit group

Fig. 4.10(c): Light and heavy compaction curves for K-M-soil of same high liquid limit group
**M-Soil (w_L = 68%; I_p=35%)**

<table>
<thead>
<tr>
<th>Compactive effort</th>
<th>OMC:%</th>
<th>( \rho_{\text{dmax}}: \text{g/cm}^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light compaction</td>
<td>30.2</td>
<td>1.361</td>
</tr>
<tr>
<td>Heavy compaction</td>
<td>22.6</td>
<td>1.664</td>
</tr>
</tbody>
</table>

**K-Soil (w_L = 68%; I_p=38%)**

<table>
<thead>
<tr>
<th>Compactive effort</th>
<th>OMC:%</th>
<th>( \rho_{\text{dmax}}: \text{g/cm}^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light compaction</td>
<td>34.5</td>
<td>1.340</td>
</tr>
<tr>
<td>Heavy compaction</td>
<td>21.2</td>
<td>1.591</td>
</tr>
</tbody>
</table>

**Fig. 4.10(d):** Light and heavy compaction curves for M-soil of same high liquid limit group

**Fig. 4.10(e):** Light and heavy compaction curves for K-soil of same high liquid limit group
Fig. 4.10(f): Light and heavy compaction curves for K-soil of extreme liquid limit group

Fig. 4.10(g): Light and heavy compaction curves for M-soil of extreme liquid limit group

63
Fig. 4.11(a): Relationship between OMCs obtained from heavy compaction tests with those obtained from light compaction tests

\[ (OMC)_{HC} = 0.692 (OMC)_{LC} \]

\[ r = 0.997 \]

Fig. 4.11(b): Relationship between the values of \( \rho_{d_{\text{max}}} \) obtained from heavy compaction tests with those obtained from light compaction tests

\[ (\rho_{d_{\text{max}}})_{HC} = 1.167 (\rho_{d_{\text{max}}})_{LC} \]

\[ r = 0.999 \]
Fig. 4.11(c): Relationship between OMCs obtained from heavy compaction tests with those obtained from light compaction tests for field soils

\[(\text{OMC})_{HC} = 0.734 (\text{OMC})_{LC}\]

\[r = 0.999\]

Fig. 4.11(d): Relationship between the values of $\rho_{\text{dmax}}$ obtained from heavy compaction tests with those obtained from light compaction tests for field soils

\[(\rho_{\text{dmax}})_{HC} = 1.145 (\rho_{\text{dmax}})_{LC}\]

\[r = 0.999\]
Similarly, the relationship between the values of maximum dry density obtained from light and heavy compaction tests for the field soils under study (Fig. 4.11d) is given by eq. 4.13 with a correlation coefficient of 0.999.

\[(\rho_{\text{d,max}})_{HC} = 1.145 (\rho_{\text{d,max}})_{LC}\]  

\[(4.13)\]

4.2.1.3 Effect of clay mineralogy

- Soils of same low liquid limit group:

Even though the two soils of this group have the same liquid limit and plasticity indices, K-soil is kaolinitic and M-soil soil is montmorillonitic. It is observed that the K-soil has higher values of OMC and lower values of maximum dry density in both light and heavy compaction tests, when compared with the values obtained for M-soil.

Montmorillonitic soils are expected to have higher OMC and lower maximum dry density than the kaolinitic soils of the same liquid limit due to higher resistance offered by them to a given compactive effort. However, the results of the present study show the opposite trend for the first look. The contradiction can be attributed to the presence of inert sand fraction in both the soils. To prove this point, the values of OMC and maximum dry densities are corrected by assuming that the sand fraction has only dilution effect.

Table 4.2 presents the actual values of OMC and maximum dry density for K-soil and M-soil along with the values corrected for the presence of sand content.

From this table, it can be noted that M-soil, which is montmorillonitic has higher or almost same OMC and lower maximum dry density when compared with the values obtained for kaolinitic K-soil. This justifies the argument that, a montmorillonitic soil will have higher OMC and lower maximum dry density than the kaolinitic soil of same low liquid limit group in the absence of any mechanical interfering components such as sands.

- Soils of same high liquid limit group.

Among the three soils in this group, M-soil is montmorillonitic while K-M-soil is composed of both kaolinitic and montmorillonitic clay minerals to the same extent of domination. K-soil is a pure kaolinite clay mineral. All these three soils
Table 4.2: Values of OMC and $\rho_{d\text{max}}$, actual and corrected for the presence of sand content, for the soils of same low liquid limit group

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Soil</th>
<th>OMC (actual): %</th>
<th>$\rho_{d\text{max}}$ (actual): g/cm$^3$</th>
<th>OMC (Corrected) = [(OMC)actual] / [percent fines]: %</th>
<th>$\rho_{d\text{max}}$ (Corrected) = $\rho_{d\text{max}}$(actual) \times (OMC)actual / [percent fines]: g/cm$^3$</th>
<th>OMC (Corrected): %</th>
<th>$\rho_{d\text{max}}$ (Corrected): g/cm$^3$</th>
<th>$\rho_{d\text{max}}$(Corrected) = $\rho_{d\text{max}}$(actual) \times (OMC)actual / [percent fines]: g/cm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Soils of same low liquid limit group</td>
<td>K-soil</td>
<td>23.2</td>
<td>1.61</td>
<td>32.50</td>
<td>1.15</td>
<td>17.40</td>
<td>1.762</td>
</tr>
<tr>
<td>S2</td>
<td>M-soil</td>
<td>20.10</td>
<td>1.64</td>
<td>33.50</td>
<td>0.984</td>
<td>14.40</td>
<td>1.846</td>
<td>24.00</td>
</tr>
</tbody>
</table>
do not have any sand content. The values of OMC and maximum dry density for these soils are listed in Table 4.1, which indicates that the montmorillonitic M-soil soil has higher values of OMC and lower values of \( \rho_{d_{\text{max}}} \) compared with mixed clay mineral soil namely K-M-soil. This observation justifies the argument discussed and verified for soils of same low liquid limit group. However, K-soil exhibits higher OMC and lower maximum dry density in light compaction test when compared with montmorillonitic M-soil. This can be attributed to the fact that the behaviour of pure kaolinitic clays, such as China clay (i.e., K-soil) is dominantly controlled by their flocculent fabric which can resist the compactive effort more than the soils of dispersed fabric even at higher water content. Similar observation can be made with the results of heavy compaction test on China clay (i.e., K-soil). The relatively lower value of OMC of China clay (K-soil) under heavy compaction can only be attributed possibly to partial break down of flocculent fabric under higher compactive effort.

### 4.2.2 Correlation between maximum dry unit weight and OMC

A few attempts have been made in the past to correlate \( \gamma_{d_{\text{max}}} \) and OMC obtained from standard and modified Proctor compactive energy levels (Sridharan et al., 2001; Gurtug and Sridharan 2004).

Studies of Gurtug and Sridharan (2004) have shown that the values of \( \gamma_{d_{\text{max}}} \) and OMC, considering all energy levels (i.e. standard Proctor, reduced standard Proctor, modified Proctor and reduced modified Proctor), can be related either through a linear relationship (eq. 4.14) with a correlation coefficient of 0.97 or through a curvilinear relationship (eq. 4.15) with a correlation coefficient of 0.98.

\[
\gamma_{d_{\text{max}}} = 22.26 - 0.28 \text{OMC} \quad \text{(4.14)}
\]

\[
\gamma_{d_{\text{max}}} = 22.68 e^{-0.013 \text{OMC}} \quad \text{(4.15)}
\]

An attempt has been made in the present work to correlate maximum dry unit weight with OMC for the soils under study and to check whether the soils of the present study fit into the correlations already reported in the literature.
Fig. 4.12(a) presents $\gamma_{d_{\text{max}}}$ v/s OMC relationship for the soils of the present study subjected to light compactive effort. The linear regression equation with a correlation co-efficient of 0.944 is given by

$$\gamma_{d_{\text{max}}} (\text{kN/m}^3) = 19.892 - 0.2053 \text{ OMC} \quad (4.16)$$

Fig. 4.12(b) presents a similar relationship for the soils of present study subjected to heavy compactive effort. The linear regression equation for the data presented with a correlation coefficient of 0.96 is given by

$$\gamma_{d_{\text{max}}} (\text{kN/m}^3) = 22.591 - 0.3086 \text{ OMC} \quad (4.17)$$

Fig. 4.12(c) presents $\gamma_{d_{\text{max}}}$ v/s OMC relationship for the soils of present study considering both light and heavy compactive efforts. The linear regression equation for the data presented in Fig. 4.12(c) with a correlation coefficient of 0.959 is given by,

$$\gamma_{d_{\text{max}}} (\text{kN/m}^3) = 21.582 - 0.263 \text{ OMC} \quad (4.18)$$

The best fit for the data presented in Fig. 4.12(c) as shown in Fig. 4.12(d) is an exponential relationship given by eq. 4.19, which has a correlation coefficient of 0.965.

![Graph showing linear relationship between maximum dry unit weight and OMC for light compactive energy level](image)
Fig. 4.12(b): Linear relationship between maximum dry unit weight and OMC for heavy compactive energy level

Fig. 4.12(c): Linear relationship between maximum dry unit weight and OMC considering both light and heavy compactive energy levels
Eqns. 4.18 and 4.19 obtained for the soils under study match very well with the eqns. 4.14 and 4.15 reported in the literature.

Fig.4.13(a) presents the relationship between \( \gamma_{d,\text{max}} \) and OMC obtained from standard Proctor compactive effort / light compactive effort considering the data from the present study and from the literature as well (Al-Khafaji, 1987; Blotz \textit{et al}, 1998; Gurtug and Sridharan, 2004; Sridharan and Nagaraj, 2005). The linear regression equation for the data shown in Fig. 4.13(a) with a correlation coefficient of 0.97 is given by

\[
\gamma_{d,\text{max}} \text{ (kN/m}^3\text{)} = 22.234 - 0.282 \text{ OMC} \quad (4.20)
\]

The best fit for the data shown in Fig. 4.13(a) is an exponential relationship (eq. 4.21), which has a correlation coefficient of 0.981 (Fig.4.13(b)).
\[ \gamma_{d\text{max}} (\text{kN/m}^3) = 23.541 - e^{-0.0177 \text{OMC}} \]  \hspace{1cm} (4.21)

Fig. 4.14(a) presents the relationship between \( \gamma_{d\text{max}} \) and OMC obtained from modified Proctor compactive effort/ heavy compactive effort considering the data from the present study and from the literature as well (Benson and Trast, 1995; Blotz et al, 1998; Gurtug and Sridharan, 2004). The linear regression equation with a correlation coefficient of 0.965 for the data shown in Fig. 4.14(a) is given by

\[ \gamma_{d\text{max}} (\text{kN/m}^3) = 23.867 - 0.37 \text{OMC} \]  \hspace{1cm} (4.22)

The best fit exponential relationship for the data shown in Fig. 4.14(a) is shown in Fig.4.14(b). This relationship has a correlation coefficient of 0.97 and is given by

\[ \gamma_{d\text{max}} = 22.234 - 0.282 \text{OMC} \]

\[ r = 0.97 \]

Fig. 4.13(a): Linear regression relationship between maximum dry unit weight and OMC for soils of present study and soils from literature at standard Proctor / light compactive energy level
Fig. 4.13(b): Exponential best fit relationship between maximum dry unit weight and OMC for soils of present study and soils from literature at standard Proctor / light compactive energy level

\[ \gamma_{\text{dmax}} = 23.541e^{(0.0177 \cdot \text{OMC})} \]
\[ r = 0.981 \]

Fig. 4.14(a): Linear regression relationship between maximum dry unit weight and OMC for soils of present study and soils from literature at modified Proctor / heavy compactive energy level

\[ \gamma_{\text{dmax}} = 23.867 - 0.37 \cdot \text{OMC} \]
\[ r = 0.965 \]
Fig. 4.14(b): Exponential best fit relationship between maximum dry unit weight and OMC for soils of present study and soils from literature at modified Proctor/heavy compactive energy level

\[ \gamma_{\text{dmax}} (\text{kN/m}^3) = 24.787 e^{(-0.02 \text{ OMC})} \]  

(4.23)

Fig. 4.15(a) presents the correlation between \( \gamma_{\text{dmax}} \) and OMC for all soils (soils under present study and also from the literature), for both standard Proctor/light and modified Proctor/heavy compactive efforts. The linear regression equation for the data with a correlation coefficient of 0.968 is given by

\[ \gamma_{\text{dmax}} (\text{kN/m}^3) = 22.778 - 0.306 \text{ OMC} \]  

(4.24)

The best fit exponential relationship for the data shown in Fig. 4.15(a) is shown in Fig. 4.15(b) with a correlation coefficient of 0.98. The regression equation is,

\[ \gamma_{\text{dmax}} (\text{kN/m}^3) = 23.93 e^{(-0.0185 \text{ OMC})} \]  

(4.25)

The general equations obtained as above (i.e. eqs. 4.24 and 4.25) match well with the relationships suggested in the literature (i.e. eqs. 4.14 and 4.15).
Fig. 4.15(a): Linear regression relationship between maximum dry unit weight and OMC for soils of present study and soils from literature at all energy levels.

\[ \gamma_{\text{dmax}} = 22.778 - 0.306 \text{OMC} \]
\[ r = 0.968 \]

Fig. 4.15(b): Exponential best fit relationship between maximum dry unit weight and OMC for soils of present study and soils from literature at all energy levels.

\[ \gamma_{\text{dmax}} = 23.93e^{(-0.0185 \text{OMC})} \]
\[ r = 0.98 \]
4.2.3 Variation of degree of saturation along the compaction curve

4.2.3.1 Light Compaction Curves

Figs. 4.16(a), 4.16(b) and 4.16(c) present the variation of degree of saturation with the moulding water content adopted during light compaction tests on soils of same low liquid limit group, same high liquid limit group and soils having extreme liquid limits, respectively.

Following are the observations made from these figures.

- For all soils, the variation of degree of saturation with moulding water content adopted for light compaction tests is linear up to OMC. Beyond OMC the variation becomes non-linear.

- At any given moulding water content on the dry side of optimum, the degree of saturation of kaolinitic soils will be less than that of montmorillonitic soils. On the wet side of optimum, the degree of saturation of kaolinitic soils at any moulding water content can be more than that of montmorillonitic soils.

![Diagram](image-url)

Fig. 4.16(a): Variation of degree of saturation in light compaction tests for soils of same low liquid limit group
**Fig. 4.16(b):** Variation of degree of saturation in light compaction tests for soils of same high liquid limit group

**Fig. 4.16(c):** Variation of degree of saturation in light compaction tests for soils of extreme liquid limit group
This can be very well seen in Fig. 4.16(a) (between K-soil and M-soil) and in Fig. 4.16(b) (between K-soil and M-soil). This observation can be justified as indicated below.

Kaolinitic soils will have relatively more flocculant fabric than the montmorillonitic soils on the dry side of optimum. This can be seen from the compaction curves (Figs. 4.1(a) and 4.1(b)) where the compaction curves of kaolinitic soils are found to lie below those of M-soils on the dry side of optimum. However, on the wet side of optimum, the situation may get reversed. Due to increase in diffuse double layer repulsion, M-soils will have lower compacted density and hence, lower degree of saturation than those of K-soils. In other words, on the dry side of optimum, the extent of flocculation controls the degree of saturation achieved and on the wet side of optimum, the double layer repulsion may control the degree of saturation achieved when two soils having same liquid limit are compared.

It can also be seen from Fig. 4.16(b) that K-M-soil has higher degree of saturation than M-soil even on the dry side of side of optimum, in spite of having the same liquid limit as that of M-soil. This is possibly because of the fact that K-M-soil has both kaolinitic and montmorillonitic clay minerals.

Fig. 4.16(c) indicates the variation of degree of saturation along the compaction curve for soils having extreme liquid limits, which also shows a similar trend except the fact that the reversal of the tendency of variation of degree of saturation with moulding water content takes place at much higher water content above OMC of M-soil (Bentonite-sand mixture). This can be due to following reasons.

- Bentonite (i.e., M-soil) and kaolin (i.e., K-soil) are pure clays of extreme clay mineralogy.
- Bentonite-sand mixture (i.e., M-soil) is relatively well graded than kaolin (i.e., K-soil), which can be visualised through their compaction curves (Fig. 4.1(c)).

Fig. 4.17 shows the normalised curves depicting the variation of degree of saturation with w/OMC where w is the moulding water content during compaction for all soils under study. It can be seen that the variation of degree of saturation on the dry side of optimum for all soils is restricted over a narrow band.
4.2.3.2 Heavy Compaction Curves

Figs. 4.18(a), 4.18(b) and 4.18(c) present the variation of degree of saturation with the moulding water content adopted during heavy compaction tests on soils of same low liquid limit group, same high liquid limit group and soils having extreme liquid limits respectively.

Observations similar to those made from light compaction tests can also be made from these figures from heavy compaction tests.

Fig. 4.19 shows the normalised curves depicting the variation of degree of saturation with (w/OMC), where w is moulding water content during compaction for all soils under study. It can be seen that the variation of degree of saturation on the dry side of optimum for all soils is restricted over a narrow band.

![Diagram](image)

**Fig. 4.17: Variation of degree of saturation with (w/OMC) for all soils subjected to light compaction**
Fig. 4.18(a): Variation of degree of saturation with moulding water content for soils of same low liquid limit group subjected to heavy compaction

Fig. 4.18(b): Variation of degree of saturation with moulding water content for soils of same high liquid limit group subjected to heavy compaction
Fig. 4.18(c): Variation of degree of saturation with moulding water content for soils of extreme liquid limit group subjected to heavy compaction.

Fig. 4.19: Variation of degree of saturation with \((w/OMC)\) for all soils subjected to heavy compaction.
4.2.4 Degree of Saturation at optimum compacted conditions

The degree of saturation at optimum compacted condition is always less than 100%, and it is believed to be around 95% for standard Proctor compaction (HMSO, 1957). The studies reported in the literature dealing with the degree of saturation at optimum compacted conditions are very scanty. Gurtug and Sridharan (2004) observed no definite trend of variation of degree of saturation with OMC for the data obtained from reduced Proctor, standard Proctor and modified Proctor compactive efforts. They opined that the correct determination of specific gravity was essential to obtain better results. In the present work, an attempt has been made to study the variation of degree of saturation with OMC for soils subjected to both light and heavy compactive efforts.

Figs. 4.20(a) and 4.20(b) show the variation of degree of saturation at OMC with OMC obtained from light compaction and heavy compaction tests respectively for all soils under study. It can be seen from these figures that, the degree of saturation has an increasing tendency with an increase in OMC. Fig.4.21(a) and 4.21(b) show the variation of degree of saturation with OMC for the data obtained from the present experimental
Fig. 4.20(b): Variation of degree of saturation with OMC in heavy compaction tests (present study)

work and from the literature (Al-Khafaji, 1987; Benson and Trast, 1995; Blotz et al, 1998; Gurtug and Sridharan, 2004; Sridharan and Nagaraj, 2005), for both standard Proctor / light and modified Proctor / heavy compactive energy levels put together.

While Figs. 4.21(a) shows an exponential fit (eq. 4.26) to the data with a correlation coefficient of 0.454, Fig. 4.21(b) presents a polynomial fit (eq. 4.27) to the same data with a correlation coefficient of 0.476

\[ S_r(\%) = 77.852 \times e^{(0.00414 \times OMC)} \]  \hspace{1cm} (4.26)

\[ S_r(\%) = 70.678 + 0.941 \times OMC - 0.0111 \times (OMC)^2 \]  \hspace{1cm} (4.27)

Figs. 4.21(a) and 4.21(b) show a definite trend of variation of degree of saturation with OMC, however with some scatter.
Fig. 4.21(a): Variation of degree of saturation with OMC at all compactive energy levels – exponential best fit

\[ S_r = 77.852 e^{0.00414 \text{ OMC}} \]
\[ r = 0.454 \]

Fig. 4.21(b): Variation of degree of saturation with OMC at all compactive energy levels – polynomial best fit

\[ S_r = 70.678 + 0.941 \text{ OMC} - 0.0111 (\text{OMC})^2 \]
\[ r = 0.476 \]
4.2.5 $S_r$ v/s $G$ relationship

Gurtug and Sridharan (2004) attributed the scatter in the relationship between degree of saturation and OMC to the deviation of the specific gravity of soil solids used in the computation from its correct value. An effort is made in this present experimental work to throw more light on their observation.

$S_r$ and OMC are related through eq. 4.28.

$$S_r = \frac{w_{opt}G}{G \rho_w - 1}$$  \hspace{1cm} (4.28)

where $w_{opt}$ is OMC and $\rho_{d_{max}}$ is the corresponding maximum dry density. The values of OMC and $\rho_{d_{max}}$ are directly obtained values from the actual tests conducted. However, the values of $S_r$ are indirectly calculated from eq. 4.28, which depends upon the value of $G$ of the soil. For a given set of (OMC, $\rho_{d_{max}}$) value, the value of $S_r$ can vary depending upon the value of $G$ used in eq. 4.28. Any error committed in obtaining the value of $G$ from the laboratory tests may lead to an error in the value of degree of saturation calculated and hence, contribute to the scatter in the $S_r$ v/s OMC relationship.

A parametric study is carried out to confirm the effect of $G$ on the degree of saturation at optimum conditions corresponding to both light and heavy compactive energy levels for the soils under study.

Figs. 4.22(a) through 4.22(g) present the variation of degree of saturation at optimum compacted conditions at both light and heavy compactive energy levels with the specific gravity of the soils under study. The arrow mark in these figures indicate the values of specific gravity of soil solids obtained from the laboratory tests and used in the present study. It can be noted from these figures that, the degree of saturation varies quite a bit with the variation in $G$. Table 4.3 shows the extent of variation of $S_r$ with the variation in the value of $G$ for the soils under study.
Fig. 4.22(a): Variation of degree of saturation at optimum compacted conditions with specific gravity of soil solids for K-soil ($w_L = 55\%$)

Fig. 4.22(b): Variation of degree of saturation at optimum compacted conditions with specific gravity of soil solids for M-soil ($w_L = 54\%$)
Fig. 4.22(c): Variation of degree of saturation at optimum compacted conditions with specific gravity of soil solids for K-M-soil ($w_L = 67\%$)

Fig. 4.22(d): Variation of degree of saturation at optimum compacted conditions with specific gravity of soil solids for M-soil ($w_L = 68\%$)
Fig. 4.22(e): Variation of degree of saturation at optimum compacted conditions with specific gravity of soil solids for K-soil ($w_L = 68\%$)

Fig. 4.22(f): Variation of degree of saturation at optimum compacted conditions with specific gravity of soil solids for K-soil ($w_L = 48\%$)
Fig. 4.22(g): Variation of degree of saturation at optimum compacted conditions with specific gravity of soil solids for M-soil (WL = 165%)

The range of degree of saturation obtained for different values of $G$ for the same soil as seen in Table 4.3 confirms the observation of Gurtug and Sridharan (2004) that the value of $G$ used in eq. 4.28 to calculate degree of saturation is responsible for the scatter in $S_s$ v/s. OMC relationship. The scatter will reduce to obtain an unique and definite relationship between $S_s$ and OMC, if the value of $G$ used in eq. 4.28 tends towards its correct value.

4.3 SUMMARY

The compaction behaviour of compacted swelling and non-swelling soils at both light and heavy compactive energy levels has been studied. Following are the important conclusions drawn from the present study.

- There is a definite relationship between OMC & Plastic limit of the soils and between maximum dry density & the dry density at plastic limit water content of the soil.
Table 4.3: Extent of variation of $S_r$ with the variation in the value of $G$ for the soils under study

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Soil</th>
<th>G of the soil</th>
<th>Range of G</th>
<th>Range of $S_r$ obtained: %</th>
<th>$S_r$ at OMC and $\rho_{\text{max}}$: %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Light compaction</td>
<td>Heavy Compaction</td>
</tr>
<tr>
<td>S1</td>
<td>Soils of same low liquid limit group</td>
<td>K-soil</td>
<td>2.74</td>
<td>2.64–2.86</td>
<td>95.72–85.2</td>
</tr>
<tr>
<td>S2</td>
<td>M-soil</td>
<td>2.85</td>
<td>2.64–2.86</td>
<td>87.0–77.3</td>
<td>88.4–75.0</td>
</tr>
<tr>
<td>S3</td>
<td>K-M-soil</td>
<td>2.69</td>
<td>2.64–2.86</td>
<td>87.6–80.3</td>
<td>90.2–79.7</td>
</tr>
<tr>
<td>S4</td>
<td>Soils of same high liquid limit group</td>
<td>M-soil</td>
<td>2.72</td>
<td>2.64–2.86</td>
<td>84.8–78.4</td>
</tr>
<tr>
<td>S5</td>
<td>K-soil</td>
<td>2.67</td>
<td>2.64–2.86</td>
<td>93.9–87.0</td>
<td>84.9–76.0</td>
</tr>
<tr>
<td>S6</td>
<td>K-soil</td>
<td>2.61</td>
<td>2.61–2.86</td>
<td>86.1–79.1</td>
<td>88.1–77.7</td>
</tr>
<tr>
<td>S7</td>
<td>M-soil</td>
<td>2.70</td>
<td>2.64–2.86</td>
<td>72.3–64.7</td>
<td>87.0–71.8</td>
</tr>
</tbody>
</table>

* More than 100% for $G < 2.667
• There is a definite relationship between the values of OMC obtained from heavy compaction tests with those obtained from light compaction tests. Similarly, there is a good correlation between the values of maximum dry density obtained from light compaction tests with those obtained from heavy compaction tests.

• Clay mineralogical composition of a natural soil has a definite bearing on the compaction characteristics. Montmorillonitic soil exhibit higher OMC and lower maximum dry density than the kaolinitic soil, the liquid limit of both the soil being the same, in the absence of interference of sand content of the soils.

• There is a very good correlation between the dry unit weight and OMC of soils at all compactive energy levels, which is exponential in nature.

• Degree of saturation of soils varies linearly with the moulding water content adopted during the compaction process up to OMC, and beyond OMC, the variation becomes non-linear.

• On the dry side of optimum, the degree of saturation of kaolinitic soil is less than that of montmorillonitic soil at any given moulding water content, the liquid limits of both the soils being the same. The degree of saturation at optimum compacted conditions has an increasing trend with OMC.

• The degree of saturation calculated at the optimum compacted conditions is strongly dependent on the specific gravity of the soil solids used in the computation.

• The degree of saturation at OMC for M-soils is less than that of K-soils in both light and heavy compaction tests.