Prediction of Compaction and Compressibility Characteristics of Compacted Soils

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Abstract

Determination of the compaction characteristics of soils in the laboratory is essential for use by practicing engineers in earthwork constructions. The purpose of compacting earth fills such as earthen dams, embankments in highway, railway and canal constructions is to produce a soil mass that will result in increasing the strength and stability apart from reducing the permeability. For preliminary design and assessment, correlations with the liquid limit have been attempted by various investigators. Though many a researcher focused on developing empirical correlations between basic properties and compaction characteristics, it has not yet been possible to bring out the functional relationships in an unified and coherent manner. This paper presents the data of eight soil samples selected to represent the wide spectrum of soils usually encountered in this region. The samples are compacted using Standard Proctor’s Specifications and the respective compaction characteristics are obtained. The soils are further tested in oedometer consolidation, compacted at optimum moisture content, to evaluate consolidation characteristics. The test results are examined to propose a rational approach in understanding the compaction and compressibility behaviour in terms of basic properties such as grain size characteristics and Atterberg limits. The test results indicate that a rational method can be proposed to predict the compaction characteristics and compressibility properties for use by practicing engineers.

Keywords: Atterberg limits, grain size characteristics, compaction properties, compression index. Functional relations

Notation:

- \( w_{ml} \): Modified plastic limit %
- \( OMC \): Optimum moisture content %
- \( (\gamma d)_{max} \): Maximum dry density kN/m^3
- \( CF/FF \): Grain size index
- \( (w_{ml}) \): Modified liquid limit %
- \( I_{mp} \): Modified plasticity index %
- \( C_c \): Compression index
- \( C_s \): Swelling index
- \( C_c/C_s \): Ratio of compression index and Swelling index
- \( P_s \): Swell pressure kPa

1. INTRODUCTION

Compaction of soil is one of the important geotechnical engineering applications in the development of infrastructure projects. Compaction is a process of densifying the soil by application of stress which causes expulsion of air in the interstices of soil mass. Millions and millions of tonnes of soil masses are compacted daily around the world in geotechnical engineering practice involving construction of roads, flyovers retaining structures and many land reclamation works.

Out of the number of methods used to improve soil at a site, compaction is usually the least expensive and the most widely used. It is a procedure employed frequently to densify soils to enhance its strength and reduce its compressibility and hydraulic conductivity. It is virtually the universal method used for placement of engineered fills. Standard Proctor Test is also often termed as dynamic compaction test. This method was introduced in the year 1933 to compact soil subjected to precise amount of energy, as specified in IS: 2720 Part VII. The test consists of compacting soil into a mould of standard dimensions. After compaction, optimum moisture content and dry density of the soil are determined. This experiment is repeated at varying moisture contents to obtain compaction curve. Dry density of a soil obtained by a given compactive effort depends on the amount of water the soil contains during compaction. For a given soil and for a given compactive effort there is one water content called optimum moisture content that will result in a maximum density of the soil, and water contents both greater and smaller than this optimum value will result in densities less than the maximum.

The purpose of compacting earth fills such as earth dams and embankments (highway, railway and canal) is to produce a soil mass that will satisfy the two basic criteria: reduction in settlement, and increase in shear strength. Many other engineering structures constructed on soils, such as highways, railway sub-grade and airfield pavements, also require compaction. Compaction increases the strength characteristics of soils, which in turn increases the bearing capacity of foundations constructed over them. It also decreases the amount of undesirable settlement of structures and increases the stability of slopes of embankments. Compaction plays a crucial role in the grounding of a good compacted soil liner in waste impoundment sites to make them relatively impermeable to leachates and thereby reduce the threat of groundwater contamination. Thus compaction is used as a practical means of achieving the desired strength and...
compressibility and also hydraulic conductivity characteristics of the soils used (Sridharan and Nagaraj, 2003). The compaction characteristics of a soil as obtained from a laboratory compaction test are maximum dry unit weight ($Y_d$) max and optimum moisture content (OMC). In the construction of many earth structures, such as embankments, it is essential to assess the suitability of a soil with respect to the compaction characteristics. Also, such projects require large quantities of soil, and it may be difficult to obtain the desired type of soil from one borrow area alone. To obtain the compaction characteristics from laboratory compaction requires considerable time and effort. So, for a preliminary assessment of the suitability of soils required for the project, it is preferable to use the correlation of engineering properties with simple index tests. Attempts have been made in the past to correlate the compaction characteristics with the liquid limit. However, such correlations appear to be less than satisfactory.

2. SCOPE OF THE PRESENT STUDY

Empirical correlations are extensively used in geotechnical engineering practice to estimate the engineering properties of soils. Useful functional relationships exist between the index properties obtained from simple routine testing and the engineering properties of cohesive soils among others. For practical purposes the results of routine index tests and correlations can be used as a first approximation of the soil parameters for use in initial design of geotechnical structures, and later as a means to authenticate the results of laboratory tests. Results from several index tests obtained for a given site can be used to assess the variation in the properties of the soil. The correlations that exist in literature are concerned with basic properties and compaction characteristics. Very limited information is available to predict the compressibility and swell characteristics of compacted soils with the help of index properties. Accordingly, an attempt has been made to characterize the compaction and compressibility behaviour in relation to easily determinable basic properties such as grain size characteristics and Atterberg limits. A carefully planned experimental programme has been devised consisting of basic tests, compaction and consolidation tests. The test results are examined to propose a rational approach for prediction of engineering parameters needed in the design and construction of compacted soil structures.

3. BASIC CONSIDERATIONS:

Compaction properties of soils assume lot of importance from the application of geotechnical engineering perspective. Any effort to find out a functional relationship to estimate the desired properties should be based on sound observation and will have to be dependable for application in engineering practice. Many researchers in the past observed that plastic limit of soil fraction passing 425 micron sieve size, bears a good correlation with the compaction characteristics. However, most of the tropical soils would have particles of all sizes that includes fraction coarser than 425 micron sieve size. It therefore becomes necessary to consider the effect of coarse fraction in characterising the overall soil behaviour. Nagendra Prasad et al (2013, 2007) reinforced the dilution concept originally brought out by Srinivasamurthy et al (1987) in order to bring out the relative effect of the overall fractions represented by a given Clayey Soil rather than making the test results of properties passing 425 micron sieve size to represent the total response of the soil system. The present investigation considers the modifications of the conventional Atterberg limits as given by the following relations:

$$w_{mll} = w_{li} X \frac{F}{100}$$
$$w_{mpl} = w_{pl} X \frac{F}{100}$$
$$I_{mp} = I_p X \frac{F}{100}$$

Where, $w_{mll}$ = modified liquid limit
$w_{mpl}$ = modified plastic limit
$I_{mp}$ = modified plasticity index
$w_l$, $w_{pl}$, $I_p$ are liquid limit, plastic limit and plasticity index for the soil samples passing 425 micron sieve size.
$F$= percent finer than 425 micron sieve size

4. BACKGROUND INFORMATION

4.1 Compaction behaviour and correlations

Laboratory compaction test involves adequate time and effort. Preliminary evaluation of the suitability of soils required for any such project, it is desirable to propose correlation of engineering properties with simple physical properties, namely Atterberg limits, which are obtained through simple tests known as index tests. Correlations making use of the Atterberg limits are fairly common in soil mechanics literature, and can be quite useful (Wesley, 2003).

One of the first attempts to relate compaction characteristics with index properties was by Jumikis (1946). He developed a correlation equation to estimate optimum moisture content with liquid limit and plasticity index. Later continuous attempts have been made by various researchers to predict compaction characteristics with simple physical and index properties. Rohan and Graham (1948) tried to relate optimum moisture content with for a geotechnical engineer, it is essential to predict the compaction characteristics of natural soils, which do have soil fractions greater than 425 lm, and has to be accounted for while using the index properties to develop a relation with the compaction characteristics. Johnson and Sallberg (1962) developed a chart to predict only the optimum moisture content, but did not suggest any correlative chart or method to predict maximum dry unit weight. Without knowing the maximum dry unit weight the prediction of compaction characteristics is not complete. The method suggested by Pandian et al. (1997) predicts the compaction characteristics in terms of liquid limit alone. Using liquid limit alone in predicting engineering properties...
has limitations, in that soils having the same liquid limit but different plasticity characteristics will behave differently.

### 4.2 Compressibility of soils and correlations:

It is necessary to determine the compressibility parameters of soils such as the compression index (C<sub>c</sub>) and the recompression index (C<sub>r</sub>) for safe and economic design of civil engineering structures. In order to calculate the consolidation settlement of normally consolidated and over-consolidated saturated fine-grained soils, the compressibility parameters are determined by means of laboratory oedometer test on undisturbed samples based on Terzaghi’s consolidation theory. These parameters can be influenced from the quality of samples used in the tests. Conventional oedometer test comprises major disadvantages such as costliness, unwieldiness and time-consuming. In addition, the other important disadvantage of the estimation of the compressibility parameters is that the graphical method directly depends on the personal experience. Because of these factors, many researchers have been tried to develop practical and fast correlation solutions. The presence of relationships between the compressibility parameters and the basic soil properties has been investigated from past to present. Many different correlations based on multiple linear regression analysis have been proposed for determination of compression index (C<sub>c</sub>) soil by researchers (Skempton 1944; Terzaghi and Peck 1967; Azzouz et al. 1976; Nagaraj and Srinivas Murthy 1985; Lav and Ansal 2001; Yoon et al. 2004; Solanki et al. 2008; Dipova and Cangir 2010; Bae and Heo 2011; Akayuli and Ofosu 2013; [Kurnaz et al. 2016]).

Rakesh Kumar et al (2016) presents the method to predict the compression index (C<sub>c</sub>) for a soil specimen with the liquid limit. One equation is applicable for soils with activities higher than one and the other equation is applicable for soils with activities lower than one (Binod Tiwari and Beena Ajmera, 2012).

Solanki, (2009) observed that existing correlations depend purely upon one or two parameters only, whereas, the compressibility depends on other factors also, e.g. two different types of soil may have same value of liquid limit but different compressibility character. Also, the use of empirical correlations to find consolidation parameters cannot be generalized for all regions and all soils. Empirical model is prepared to predict the settlement of shallow foundations incorporating soil index and plasticity characteristics. The model incorporates the computation of over consolidation ratio, time rate settlement, magnitude of settlement and differential settlement of foundations.

In retrospect, numerous researchers have proposed empirical correlations to estimate compaction properties from index parameters. However, Atterberg limits are determined for the fraction passing 425 micron sieve size. It, therefore, becomes necessary to proportion the effect of these limits to represent the overall behaviour. Accordingly, the compaction and compressibility characteristics are examined in relation to modified Atterberg limits.

### 5. MATERIALS AND METHODS

Compaction of soils is a regular procedure in the development of infrastructure projects. The sub-grade, sub-base and other under lying soil layers in the Roads ways; Flyovers are subject to compaction in order to improve the strength and stability characteristics. Compaction is also an important process in the construction of earthen bunds, embankments and dams. An experimental programme is taken up in the present paper involving determination of basic properties, compaction and consolidation characteristics.

The soil samples are prepared passing 4.75 mm sieve in order to ensure uniform grain size in all the soil samples. The fraction greater than 4.75 mm is proportionately added between the grain size of 4.75 mm and 75 μ. All the test procedures adopted are as per Bureau of Indian Standards as indicated in the Table 1. The present investigation considered soil samples collected from eight different locations as shown in figure 1.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Description</th>
<th>IS Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific Gravity</td>
<td>IS: 2720 (Part. III) 1980</td>
</tr>
<tr>
<td>2</td>
<td>Sieve Analysis</td>
<td>IS:2720 (Part.IV) 1985</td>
</tr>
<tr>
<td>a</td>
<td>Dry Sieve Analysis</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>Wet Sieve Analysis</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Plasticity Characteristics</td>
<td>IS:2720 (Part.V) 1985</td>
</tr>
<tr>
<td>a</td>
<td>Liquid Limit</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>Plastic Limit</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>Plasticity Index</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Compaction Characteristics</td>
<td>IS: 2720 (Part. VII) 1980</td>
</tr>
<tr>
<td>a</td>
<td>Maximum Dry Density</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>Optimum Moisture Content</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Swelling Characteristics</td>
<td>IS: 2720 (Part. XL) 1977</td>
</tr>
<tr>
<td>a</td>
<td>Free Swell Index</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>Swelling Pressure</td>
<td>IS: 2720 (Part. XLI) 1977</td>
</tr>
<tr>
<td>c</td>
<td>Coefficient of Compressibility</td>
<td>IS: 2720 (Part. XV) 1986</td>
</tr>
<tr>
<td>6</td>
<td>Strength Characteristics</td>
<td>IS: 2720 (Part. X) 1991</td>
</tr>
<tr>
<td>a</td>
<td>Unconfined Compressive Stress</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>Triaxial Compressive Stress</td>
<td>IS: 2720 (Part. XI) 1993</td>
</tr>
</tbody>
</table>
These soil samples comprises of distinct variations in the properties such as grain size, liquid limit, plastic limit and specific gravity. The soil samples are designated as S1 (Renigunta), S2 (Chipllivage, Madanapalle), S3 (Yedugundlapadu, Ongole), S4 (Mungamur Canal Road, Ongole), S5 (Tirupati, Bypass), S6 (Tiruchanur, Tirupati), S7 (Annasampalli Road, Renigunta), S8 (YSR Kadapa). Table 2 depicts the basic properties of eight soils. The grain size distribution obtained from dry sieve analysis is integrated with hydrometer analysis and the particle size distribution curves thus obtained are presented in Figure 2. It may be seen that grain sizes and Atterberg limits represent wide spectrum in terms of soil classification ranging from Clayey Sand (SC) to Clay with high Compressibility (CH).

5.1 Compaction properties

The compaction properties are presented in Figure 3 for all the eight samples considered in the present investigation. Figure 3 also represents respective zero air void lines. It may be noticed that the compaction curves are spaced relatively closer to the zero air void lines. The values of maximum dry density and optimum moisture content for the soils are shown in Table 2. The values of maximum dry density ranges from 17.90 kN/m$^3$ to 19.50 kN/m$^3$ where as optimum moisture content ranges from 14% to 16.90%.

**Table 2: Basic Properties**

<table>
<thead>
<tr>
<th>S.No</th>
<th>Properties</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific Gravity</td>
<td>2.74</td>
<td>2.63</td>
<td>2.56</td>
<td>2.76</td>
<td>2.73</td>
<td>2.65</td>
<td>2.65</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>Gravel (%)</td>
<td>9.20</td>
<td>1.20</td>
<td>3</td>
<td>1.16</td>
<td>1.20</td>
<td>4.20</td>
<td>2.22</td>
<td>6.41</td>
</tr>
<tr>
<td></td>
<td>Sand (%)</td>
<td>47.00</td>
<td>24.00</td>
<td>19</td>
<td>63.47</td>
<td>62.10</td>
<td>47.40</td>
<td>47.17</td>
<td>14.90</td>
</tr>
<tr>
<td></td>
<td>Silt (%)</td>
<td>37.42</td>
<td>34.31</td>
<td>21.49</td>
<td>20.46</td>
<td>24.49</td>
<td>30.75</td>
<td>32.26</td>
<td>65.91</td>
</tr>
<tr>
<td></td>
<td>Clay (%)</td>
<td>6.38</td>
<td>40.49</td>
<td>56.51</td>
<td>14.91</td>
<td>12.21</td>
<td>17.65</td>
<td>18.34</td>
<td>12.78</td>
</tr>
<tr>
<td></td>
<td>% Passing 425 µ</td>
<td>66.2</td>
<td>86.74</td>
<td>93.51</td>
<td>52.25</td>
<td>58</td>
<td>68</td>
<td>85.43</td>
<td>82.62</td>
</tr>
<tr>
<td>3</td>
<td>Liquid Limit (%)</td>
<td>62.00</td>
<td>41</td>
<td>51.00</td>
<td>33</td>
<td>51</td>
<td>65</td>
<td>60.00</td>
<td>55.00</td>
</tr>
<tr>
<td></td>
<td>Plastic Limit (%)</td>
<td>20.4</td>
<td>21</td>
<td>19</td>
<td>25</td>
<td>21</td>
<td>20.6</td>
<td>17</td>
<td>21.54</td>
</tr>
<tr>
<td></td>
<td>Plasticity Index (%)</td>
<td>41.6</td>
<td>20</td>
<td>32</td>
<td>8</td>
<td>60</td>
<td>45</td>
<td>43</td>
<td>33.46</td>
</tr>
<tr>
<td>4</td>
<td><strong>IS Classification</strong></td>
<td><strong>SC</strong></td>
<td><strong>CI</strong></td>
<td><strong>CH</strong></td>
<td><strong>SM</strong></td>
<td><strong>SC</strong></td>
<td><strong>SC</strong></td>
<td><strong>SC</strong></td>
<td><strong>CH</strong></td>
</tr>
<tr>
<td>5</td>
<td>Maximum Dry Density (kN/m$^3$)</td>
<td>19</td>
<td>18.12</td>
<td>17.90</td>
<td>19.22</td>
<td>19.5</td>
<td>18.8</td>
<td>18.75</td>
<td>18.10</td>
</tr>
<tr>
<td></td>
<td>Optimum Moisture Content (%)</td>
<td>15</td>
<td>17</td>
<td>16.5</td>
<td>14.5</td>
<td>14</td>
<td>14.5</td>
<td>15.5</td>
<td>16.9</td>
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<td></td>
<td>Free Swell Index (%)</td>
<td>110</td>
<td>108</td>
<td>105</td>
<td>60</td>
<td>181</td>
<td>160</td>
<td>135</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>Swelling Pressure (kPa)</td>
<td>50</td>
<td>45</td>
<td>62</td>
<td>16</td>
<td>75</td>
<td>72</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Compression Index</td>
<td>0.21</td>
<td>0.19</td>
<td>0.23</td>
<td>0.13</td>
<td>0.23</td>
<td>0.22</td>
<td>0.26</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Unconfined Compressive Strength (kPa)</td>
<td>219</td>
<td>233</td>
<td>226</td>
<td>238</td>
<td>208</td>
<td>215</td>
<td>216</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td>Triaxial Compressive Strength (kPa)</td>
<td>84</td>
<td>98</td>
<td>92</td>
<td>101</td>
<td>80</td>
<td>82</td>
<td>86</td>
<td>81</td>
</tr>
</tbody>
</table>
5.2 Compressibility Behaviour

The soil samples which are compacted at respective optimum moisture content are transferred to Oedometer taking care to see that there is no loss of moisture in the process. The soil samples were consolidated with vertical stresses of 5, 10, 20, 40, 80, 160, 320 and 640 kPa. Further unloading was effected in the sequence of 640, 160, 40 and 10 kPa with load decrement ratio of 3. The consolidation curves on e - σ, plot...
are shown in figure 4. After each test was completed, the specimens were oven dried to obtain dry mass in order to evaluate void ratio of the specimen during the sequence of loading. The same procedure was adapted with regard to liquid limit and plastic limit of natural samples. It may be seen that the compression curves are varying in their paths in conformity with the grain size, mineralogy as reflected by Atterberg limits as also of the initial void ratio corresponding to maximum dry density. In order to obtain compression index and swelling index the consolidation behaviour is represented on e-logσv plot as shown in figure 5. It is indicative in figure 5 that the compression path is characterised by definite breaking point by to linear curves. Thus breaking point may be viewed as yield point representing the stress history.

![Figure 4: e – σv Plot](image1)

![Figure 5: e – Log σv Plot](image2)

### 6. ANALYSIS OF TEST RESULTS

An attempt has been made to examine the functional relationships with modified plastic limit (w\text{mpl}) and optimum moisture content, modified plastic limit (w\text{mpl}) and dry density as well as grain size index defined by \( CF/FF \), versus dry density. Further plastic limit is considered to represent minimum structural resistance at particulate level for particle re-adjustment leading to effective packing under a given compactive energy. It may be seen from figure 6 that the optimum moisture content(OMC) and modified plastic limit (w\text{mpl}) bears linear relationship with regression coefficient of 0.9507 reflecting a close agreement between the parameters.

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The relationship between optimum moisture content and modified plastic limit is found to be:

\[ \text{omc} = 0.4944(w_{mpl}) + 8 \]

\[ R^2 = 0.9507 \]

This equation turns out that if soil is devoid of plastic limit, the optimum moisture content would be of the order of 8.0%.

Similar attempt has been made to examine a relationship between modified plastic limit \( (w_{mpl}) \) and the respective dry density values. The modified plastic limit \( (w_{mpl}) \) chosen because it is at thus moisture content the density becomes maximum for each soil, the relationship is presented in figure 7. It is observed that the dry density is inversely proportional to modified plastic limit with a linear relationship as

\[ (\gamma_d)_{\text{max}} = -23.42(w_{mpl}) + 22.219, \ R^2 = 0.9554 \]
Another attempt also has been made to find out the possible relationship between grain size Index represented by CF/FF in relation to the maximum dry density. It may be seen in figure 8 that the correlation which is linear with \( R^2 \) of 0.965 as given in the following equation. Table 3 presents the data of maximum dry density values in relation to modified plastic limit (\( w_{mpl} \)) and grain size index (CF/FF).

\[
(\gamma_d)_{\text{max}} = 0.8705(CF/FF) + 17.845 \\
R^2 = 0.9654
\]

![Figure 8: Variation of maximum dry density with grain size index](image)

**Table 3: Maximum dry density versus \( w_{mpl} \) and CF/FF**

<table>
<thead>
<tr>
<th>( (\gamma_d)_{\text{max}} )</th>
<th>( w_{mpl} )</th>
<th>CF/FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.00</td>
<td>13.50</td>
<td>1.28</td>
</tr>
<tr>
<td>18.12</td>
<td>18.22</td>
<td>0.34</td>
</tr>
<tr>
<td>17.90</td>
<td>17.77</td>
<td>0.14</td>
</tr>
<tr>
<td>19.22</td>
<td>13.06</td>
<td>1.83</td>
</tr>
<tr>
<td>19.50</td>
<td>12.18</td>
<td>1.72</td>
</tr>
<tr>
<td>18.80</td>
<td>14.00</td>
<td>1.07</td>
</tr>
<tr>
<td>18.75</td>
<td>14.52</td>
<td>0.98</td>
</tr>
<tr>
<td>18.10</td>
<td>17.80</td>
<td>0.27</td>
</tr>
</tbody>
</table>

The multi linear regression analysis conducted with \( (\gamma_d)_{\text{max}} \) as dependent variable and \( w_{mpl} \), CF/FF as independent variables yields the following relationship with \( R^2 \) of 0.98

\[
(\gamma_d)_{\text{max}} = -0.10388(w_{mpl}) + 0.501206(CF/FF) + 19.76855 \\
R^2 = 0.98
\]

Compression Index is an important parameter in the design calculation of settlement of foundations for the structures. Though number of researchers have proposed different empirical relations with basic properties such as liquid limit, void ratio etc., It continues to attract the attention of the researchers to examine the possibilities of other meaningful functional relationships with Index properties. Once such attempt is made to examine the relation between Compression
Index and modified liquid limit \((\text{w}_{\text{mll}})\). [\text{w}_{\text{mll}} = \text{Liquid limit multiplied by percentage passing 425\(\mu\)]]. Figure 9 shows the variations of Compression Index with modified liquid limit. It is of interest of to know that the relationship is linear with a regression coefficient of 0.9604 as given by:

\[
\text{Cc} = 0.0037(\text{w}_{\text{mll}}) + 0.0659
\]

\[
R^2 = 0.9604
\]

**Figure 9**: Variation of Compression Index with modified liquid limit

Figure 10 represents the Swelling Index \((\text{Cs})\) and modified liquid limit \((\text{w}_{\text{mll}})\) having linear relationship given by \(\text{Cs} = 0.0015(\text{w}_{\text{mll}}) - 0.0069\). It turns out that the Swell Potential is directly proportional to modified liquid limit. As modified liquid limits increases the Swell Index increases.

\[
\text{Cs} = 0.0015(\text{w}_{\text{mll}}) - 0.0069
\]

\[
R^2 = 0.9574
\]

**Figure 10**: Variation of Compression Index with modified liquid limit
It has been further shown that the ratio of Cc/Cs with liquid limits having a linear relationship with the following expression as the ratio of Cc/Cs decreases the modified liquid limit increases. This is because of the fact that the Swelling Index rapidly increases with the liquid limit and hence the ratio of Cc/Cs correspondingly decreases as seen in figure 11.

\[ \frac{Cc}{Cs} = -0.082(w_{\text{ml}}) + 7.6501 \]
\[ R^2 = 0.9516 \]

Figure 11: Variation of ratio of Cc/Cs with modified liquid limit

Swell pressure for each sample is determined by allowing the sample to swell freely under nominal pressure and upon subsequent loading the sample brought back to original volume. The swell pressure thus evaluated is correlated with swell index (Cs). From the figure 12, the relationship thus obtained is given by the following expression with a reasonable value of regression coefficient.

\[ P_s = 1351.1(Cs) - 12.976 \]
\[ R^2 = 0.9357 \]

Figure 12: Variation of Swell pressure (Ps) with Swelling Index

\[ P_s = 1351.1(Cs) - 12.976 \]
\[ R^2 = 0.9357 \]
7. PROPOSED APPROACH TO FIND COMPACTION, COMPRRESSIBILITY AND SWELL CHARACTERISTICS OF COMPACTED SOILS

Based on detailed experimental investigation and analysis of test results the compaction, compressibility and swell characteristics of compacted soils can be obtained from the basic properties of modified plastic limit, modified liquid limit and ratio of grain size index as detailed in the Table 4.

Table 4: Proposed Correlations

<table>
<thead>
<tr>
<th>Engineering Property</th>
<th>Proposed Equation</th>
<th>Requisite basic parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum Moisture Content (%)</td>
<td>$OMC = 0.5(w_{mpl}+16)$</td>
<td>Modified plastic limit (%)</td>
</tr>
<tr>
<td>Maximum dry density (kN/m$^3$)</td>
<td>$(Y_d)<em>{max} = 22.219 - 23.42(w</em>{mpl})$</td>
<td>Modified plastic limit (%)</td>
</tr>
<tr>
<td>Maximum dry density (kN/m$^3$)</td>
<td>$(Y_d)_{max} = 0.8705 \left(\frac{CF}{FF}\right) + 17.845$</td>
<td>ratio of coarse faction and fine fraction (Grain size index)</td>
</tr>
<tr>
<td>Compression Index</td>
<td>$Cc = 0.0037(w_{mll} + 17.81)$</td>
<td>Modified liquid limit (%)</td>
</tr>
<tr>
<td>Swelling Index</td>
<td>$Cs = 0.0015(w_{mll} - 4.6)$</td>
<td>Modified liquid limit (%)</td>
</tr>
<tr>
<td>Ratio of compression index and swelling index</td>
<td>$\frac{Cc}{Cs} = 7.651 - 0.082(w_{mll})$</td>
<td>Modified liquid limit (%)</td>
</tr>
<tr>
<td>Swelling pressure (kPa)</td>
<td>$p_s = 1351.1(Cs - 0.0096)$</td>
<td>Swelling Index</td>
</tr>
<tr>
<td></td>
<td>(or) $p_s = 1351.1(Cs) - 12.96$</td>
<td></td>
</tr>
</tbody>
</table>

8. CONCLUDING REMARKS

Most field engineers look for independent methods of predicting the compaction soil behaviour for taking engineering decisions with regard to infrastructure development projects. These methods provide independent means of verification of test results for ensuring the reliability of measurements. A limited investigation considered in the present study involving eight different soil samples subjected to assessment of basic properties, compaction and compressibility characteristics and subsequent analysis of test results yield the following concluding remarks.

i. The optimum moisture content is a function of modified plastic limit.

ii. The maximum dry density obtained is dependent on modified plastic limit and representative grain size index.

iii. The compression index (Cc) is found to be linearly related to modified liquid limit.

iv. The swelling index is directly proportional to modified liquid limit.

v. The ratio of compression index and swelling index is inversely proportional to modified liquid limit.

vi. The swelling pressure is directly proportional to the swelling index.

These observations and empirical relations pertain to the soil samples considered in the present investigation. These observations give a definite lead for further scope involving more number of soils for possible refinement in the coefficient.

REFERENCES


