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Moisture Effects on Load-Penetration and Compaction Behavior of Well-Graded Granular Materials

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A B S T R A C T

In the current investigation, the soil sample was taken from Mukerian, Punjab, India. Initially, the index characteristics of the soil were examined using grain size distribution, moisture content, and specific gravity tests. Sieve analysis of the selected sample was also conducted as per the ISSC System to explore its type. A specific gravity test was performed using a pycnometer. The moisture level of the soil sample was measured under various conditions using the oven-dry method. The OMC of the soil sample was determined using a proctor test. In the last, the strength of subgrade-strength soil under different moisture conditions was also explored using the CBR test. The particle size curve formed after conducting sieve analysis revealed that the selected soil is "Well Graded Sand" (SW), and the obtained value of specific gravity was around 2.7. Also, the obtained value of OMC is equal to 10.22%. It has also been observed that CBR values increase from field moisture content to OMC conditions and then decrease rapidly. It has also been observed that under unsoaked and one-day soaking conditions, the moisture level is insignificant. Moreover, a longer soaking time results in more variations in moisture levels when taken from the top layer as compared to those in the lower layers.

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1. INTRODUCTION

Soil plays a vital role in many construction applications like highways, building structures, dams, etc. [1]. A hard layer of soil is required for strong and stable structures. The structure built on top of the failing and weak soil may also collapse. Proper analysis should be conducted to guarantee that the structures stay safe and free from settling and collapsing. In order to gain knowledge, soil samples from a construction site must be gathered and evaluated in order to quantitatively assess the soil's engineering qualities [2].

Since soil characteristics differ from place to place, there are very few construction sites with identical soil conditions. Soils are often

composed of a variety of particles with varying sizes, shapes, and compositions. Because of this, it is harder to forecast how soil will behave than how steel will behave. The possibility of significant variation in attributes within a single site can be highly significant. Consequently, before beginning a detailed design, the soil characteristics at each site need to be carefully examined. The behavior of soil conditions can be expected by experienced engineers by looking at soil samples. This is an advantage to them as they select the type of soil that is suitable for any certain project. But to get actual data, especially for design information, laboratory tests will be needed to analyze the soil condition. In highway construction, the CBR test is used to measure the strength of compacted soil for infiltration. The pavement's thickness that will be placed on the subgrade layer is designed using the results of this test [3]. Alayaki and Bajomo [4] investigated how changes moisture affected the laterite soil's strength properties in Abeokuta, Ogun State, Nigeria. The authors found that soaking the compacted soil sample for an additional one to five days decreased the soil's CBR and increased its bulk density. This reduction in CBR affects the soil's water-holding capacity, causing it to yield under load. In another study, Kumar et al. [5] studied 25 samples of red soil from various north coastal areas of Andhra Pradesh. The findings indicated that soil with a small proportion of fine particles and a wide range of particle sizes had high CBR values. Additionally, the models created by multiple linear regression analysis to correlate the soaked CBR value with gradation characteristics (S, F, D60, Cu, WL, and Ip) demonstrated comparatively high R2 values. Shirur et al. [6] found a correlation between the values of the CBR and the physical features of the soil subgrade and suggested a way to do the same for the LL, PL, SL, PI, OMC, and MDD. The plasticity index and CBR value have a linear relationship, with a coefficient of correlation of R2 = 0.72. According to the authors, there is no meaningful correlation between the plastic limit and liquid limit and the CBR value. The correlation analysis shows that there is a significant difference between the testing and forecast CBR values, especially when high-flexible clays are involved. Bello [7] explored using regression ered that the soil's clay content directly affected the CBR value, with greater or smaller clay content having an impact on it. Furthermore, a rise in the shrinkage limit was linked to a rise in the CBR value. A visual examination of the soil data revealed a constant ratio of 0.5 for the immersed-to-dry CBR value. Patel and Desai [8] suggested a method for determining the relationship between CBR values and cohesive soil parameters, primarily alluvium soil in different zones of Surat, India, the state of Gujarat, including the LL, PL, PI, MDD, and OMC. In the end, formulas were developed for CBR values in both drenched and dry conditions that were particular to the area in question and were within predetermined ranges of soil properties. Notably, it was discovered that the soil's clay content directly affected the CBR value, with a higher or lower clay level having an impact on it. Furthermore, a rise in the Shrinkage Limit was linked to a rise in the CBR value. A graphical examination of the soil data revealed a constant ratio of 0.5 for the drenched to dry CBR value. Laxumiet al. [9] conducted a study using soil samples from the Thiruporur District of Chennai and used the Modified Proctor Compaction Test (MPCT) with five different numbers of blows per layer in an attempt to establish a relationship between compaction energy, MDD, and OMC. In order to determine a relationship between the CBR values for silt clay (CL) soil under immersed and dry conditions, the authors of this study created regression equations based on the compaction properties of the soil. As the OMC dropped, and the MDD rose as a result of a decrease in voids, the soil became more compacted, and the CBR values increased for both immersed and dry conditions. Kumar [10] carried out a study to find a relationship between immersed CBR values and different soil characteristics, such as MDD, OMC, LL, PL, and PI. In the Nogaon District of Assam, India, soil samples were taken from various locations, and laboratory analyses were conducted. For every property's relationship to CBR, the study included determining correlation coefficients (r), and statistical t-tests were used to determine the importance of the results. The previously mentioned soil parameters were then used to create a linear multiple regression models in Microsoft Excel that predicted CBR values. Notably, there was a significant correlation found between PI, MDD, and OMC and fine-grained soils (ML and MI). It was discovered that the CBR value increased with an increase in MDD but decreased with an increase in PI and OMC. In a different study, Roy et al. [11] highlighted the efficiency of CBR tests, emphasizing their quick, cost-effective,

and time-saving nature. In light of this, previous researchers have explored and developed methods to determine CBR values using low-cost, time-efficient, and straightforward tests. However, it's worth noting that when dealing with non-plastic soils or soils with minimal sand content, there can be a significant discrepancy of over 20% between reported and predicted soaked CBR values when using the Nomograph of IRC:SP:72-2007. Razouki and Al-Azawi [12] conducted a study on the long-term soaking behavior of compacted Iraqi gypsiferous soil, which contained approximately 34% gypsum content. The findings indicated that the soil swelled at first before starting to settle. The process of settling persisted slowly, even after 180 days of immersion. The resilient modulus of the gypsiferous soil was estimated by subjecting each sample to compressive and shears wave tests using ultrasonic pulse velocity techniques after soaking. With longer soaking times, the tests showed a discernible drop in MR and, to a lesser degree, CBR. The research made it clear that soaking times as short as four days could produce dangerous and deceptive results when it comes to the toughness, rigidity, and distortion properties of gypsiferous soils.

In this study, soil samples were taken from Mukerian, District Hoshiarpur, Punjab, India, and their index properties were evaluated using grain size distribution tests, moisture level tests, and specific gravity tests. A sieve test was carried out as per the ISSC system to explore its type. A specific gravity test was conducted using a pycnometer. The moisture level of the soil sample was determined under various conditions using the oven-dry method. To confirm the OMC, a standard proctor test was conducted. In the end, soil samples were subjected to the CBR test in order to determine the subgrade soil's strength under various moisture levels.

2. MATERIALS AND METHODOLOGY

In the current study, a sample was chosen from Mukerian town in the district of Hoshiarpur, Punjab, and a variety of tests were performed on it. The following is an explanation of the methodology used.

2.1 Materials

Material plays a crucial role in the study, and soil is a fundamental component for this study. Whether soil is in its natural state as in situ subgrade material or transported and modified as embankment material, soil serves as a foundational material for all highways. Soil was collected from Mukerian, Punjab, and various experiments were performed on it. These experiments were carried out to find index properties of soil, in which initial identification and classification of the soil were tested. Natural soil has wide variations in properties and behavior, and soil is never homogenous. The classification relies on fundamental soil properties.

2.2 Testing of soil

In this study, different experiments were carried out on soil, including soil classification, specific gravity, and moisture content. Further, CBR was calculated at different moisture levels to examine the soil strength behavior. First, CBR was examined at field moisture content and then at optimum moisture content. After that, three samples were immersed in water for three days. Each sample was examined for CBR on day one, day two, and day three, and the moisture levels of the soil from the apparatus were checked to find the variations. Soil testing is a crucial process that helps analyze the composition and properties of soil. To evaluate the index properties, testing of soil was done, and details of the various tests performed are given as follows:

2.2.1 Identification of soil

In this study, the ISSC System was used for soil identification, and sieve analysis was carried out for its classification [13]. For this, the soil was passed through a 0.075-mm IS sieve. Based on these results, further testing is extended to identify the type of soil, i.e., very coarse soils, coarse soils, or fine soils. After identifying the type of soil, the sieve test was repeated to check whether the soil was “gravel” or "sand." Based on the observation, the “grain size distribution curve” was drawn for the gradation of the selected sample [13] as per Equations 1 and 2.

$$Cu = \frac{D_{60}}{D_{10}} \quad (1)$$

$$Cc = \frac{(D_{30})^2}{D_{10} * D_{60}} \quad (2)$$

Where Cu is the "Coefficient of Uniformity", Cc is the "Coefficient of curvature", D60, D30, D10 represent 60%, 30%, 10% particles are finer than the diameter D60, D30, and D10 respectively.

If the value of Cu is greater than 4 and the value of Cc lies between 1 and 3, then the soil is well-graded gravel. If the value of Cu is greater than 6 and the value of Cc lies between 1 and 3, then the soil is well-graded sand.

2.2.2 Specific gravity

Specific gravity is a fundamental soil property that provides insights into the density and composition of soil particles. It is described as the relationship between a substance's density and that of water, usually for soil testing purposes, measured by a pycnometer. In this technique, a measured quantity of dry soil is poured into the apparatus and weighed. After that, the apparatus is poured with water, and the weight is recorded. By comparing the weight of the apparatus with the soil and water, the value of the sample can be determined [14]

2.2.3 Moisture Content Test

The moisture level of a specimen is determined by dividing the weights of water and solids using an oven drying test. In this process, the sample is weighed, then heated at 105–110 °C for approximately 24 hours, causing the moisture to evaporate. After drying, the sample is reweighed, and the weight difference represents the moisture content [15].

2.2.4 Standard proctor test

This test is used to obtain the OMC and MDD of soil for compaction and involves air-drying, crushing, and passing the soil through a specific sieve. Then, a measured amount of soil is added with varying water contents to a compaction mold, and the moisture level is determined. After thorough compaction and testing at each moisture level, a moisture-density curve is drawn. The point of intersection of MDD and OMC signifies the desired compaction condition for the soil [15].

2.2.5 California Bearing Ratio Test

This test represents the soil specimen's ability to withstand a specific stress level during a 1.25 mm/min penetration, relative to the stress a standard soil can endure. This value serves as a display of the soil's strength. The procedure involves preparing a soil sample that is compacted at different moisture contents and subjecting the samples to a standard penetration test using a plunger. Therefore, the CBR test was carried out by measuring the load required to penetrate the selected soil sample at a rate of 1.25 mm/min and then comparing it with the standard reference value [16–18]. In addition to standard laboratory CBR testing, previous studies have used index properties, compaction parameters, soft-computing systems, and artificial-intelligence-based approaches to estimate CBR values [19–21].

3. RESULTS AND DISCUSSION

In the current investigation, the sample was selected from Mukerian, District Hoshiarpur, Punjab. After the collection of soil, its grade was classified using sieve analysis. Initially, a dry soil sample was taken, and a test was performed on a 0.075 mm IS sieve. It is observed that the weight retained on the sieve was more than 50% of the weight percentage. This revealed that the soil is coarse-grade soil. Now the grain size distribution was evaluated as per [13], and observations are listed in Table 1. In this table, the second column describes the different weight values of retained soil on the sieves, and the third column indicates the percentage weight of soil. In the last two columns, cumulative percentage weight and percentage weight are shown, from which a graph is formed between percentage passing and grain size. It has been observed that a greater percentage of coarse fraction passes through the 4.75 mm IS sieve, so the soil is coarse-grained sand.

Table 1. Observation of sieve analysis.

I.S Sieve no.	Wt. retained in Sieves	Wt. %	Cumulative Wt. % (x)	Wt. % (100-x)
4.75	135	27.21774	27.21774	72.78226
2.36	90	18.14516	45.3629	54.6371
1.18	90	18.14516	63.50806	36.49194
0.6	75	15.12097	78.62903	21.37097
0.3	55	11.08871	89.71774	10.28226
0.15	45	9.072581	98.79032	1.209677
0.075	5	1.008065	99.79839	0.201613
Pan	1	0.201613	100	0

Based on observation, a graph is drawn between percentage passing and grain size, as described in Figure 1, to explore the grading of soil. From this figure, it is found that D10=0.26, D30=0.9, and, according to the equation, the calculated values of Cu and Cc are equal to 10 and 1.03, respectively. This satisfied both conditions of well-graded sand, so this revealed that coarse-grained sand was well-graded sand [13].

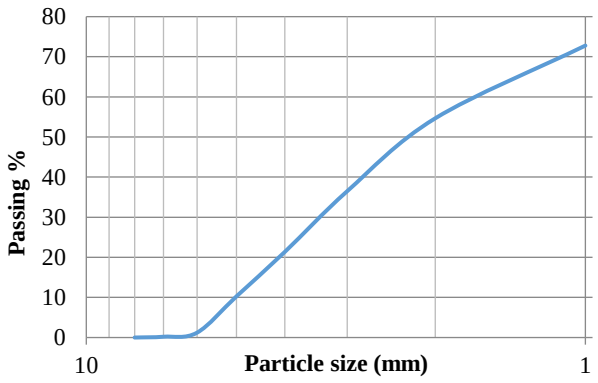


Fig. 1. Sieve analysis showing "Particle Size Distribution Curve" for Soil.

3.1 Specific gravity test

This test is performed with the help of a pycnometer as per [14], which yields a value of the specific gravity equal to 2.7.

3.2 Standard Proctor test

This is performed to determine the compaction of soil at different moisture levels. Moisture content was found by drying a soil sample in an oven using a mold weighing 4950 g, and the test observations are listed in Table 2. The soil was compacted using a hammer, and then the wet soil and wet density of the soil were calculated. Then, the moisture level of compacted soil was calculated as per [15].

Figure 2 indicates the variations of dry density with respect to moisture level for a given soil. It has been observed that initially, the density of the soil suddenly increased with increasing moisture levels and then decreased with further increasing moisture levels. From this figure, the obtained values of MDD and OMC are 1.93 g/cm3 and 10.22%, respectively.

Table 2. Observation of standard proctor test.

Mould weight + Compacted soil weight (g)	Wet soil weight (g)	Wet density (g/cm^3)	Wet sample weight (g)	Dry sample weight (g)	Moisture content %	Dry density (g/cm^3)
6800	1850	1.959746	40	36.69	9.021532	1.797577
6960	2010	2.129237	50.15	45.26	10.80424	1.921621
6990	2040	2.161017	50	41.97	19.13271	1.813958
6920	1970	2.086864	45	38.54	16.76181	1.787283
6900	1950	2.065678	40	33.77	18.44833	1.743949

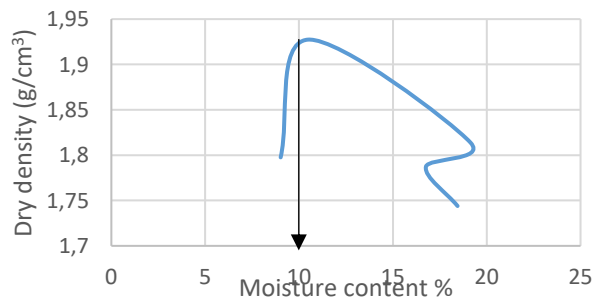


Fig. 2. Dry Density Vs Moisture Level graph.

3.3 Moisture Content

To determine the moisture level of the soil, the initial step involved weighing the soil sample. Subsequently, the sample was subjected to 24 hours of drying in an oven. Following the drying process, the soil sample was reweighed, and the variance in weight represented the moisture level in the soil sample. The analysis revealed that the soil had a field moisture content of 7%, while

the optimum moisture content was measured at 10.22%. Subsequently, a CBR test was conducted, and the moisture level was evaluated using the oven-drying method. The test results were then interpreted.

3.4 California Bearing Ratio Test

The observations of this test listed in *Table 3* are analyzed and interpreted.

Table 3. Observations of CBR test conducted under different moisture content.

Depth of Penetration (mm)	At Field Moisture Content (7%)			At Optimum Moisture Content (10.22%)			At Day one Soaking Condition (18.02%)			At Day second Soaking Condition (21.56%)			At Day third Soaking Condition (21.91%)		
	A	B	CBR %	A	B	CBR %	A	B	CBR %	A	B	CBR %	A	B	CBR %
0	0	0		0	0		0	0		0	0		0	0	
0.5	15	37.5		21	52.5		4	10		2	5		1	2.5	
1	28	70		45	112.5		6	15		5	12.5		4	10	
1.5	43	107.5		69	172.5		9	22.5		7	17.5		6	15	
2	56	140		87	217.5		13	32.5		9	22.5		8	20	
2.5	68	170	12.40876	101	252.5	18.43066	15	37.5	2.737226	11	27.5	2.007299	9	22.5	1.642336
3	77	192.5		114	285		16	40		12	30		10	25	
3.5	86	215		125	312.5		17	42.5		13	32.5		11	27.5	
4	93	232.5		134	335		19	47.5		14	35		11	27.5	
4.5	97	242.5		143	357.5		21	52.5		15	37.5		12	30	
5	101	252.5	12.2871	150	375	18.24818	22	55	2.676399	16	40	1.946472	13	32.5	1.581509
5.5	105	262.5		157	392.5		25	62.5		17	42.5		16	40	
6	110	275		164	410		27	67.5		17	42.5		17	42.5	
A = Proving ring Reading No. Divisions B= Test load*value of one division (kg)															

Table 3 indicates the observations of the CBR test performed under different moisture contents. The percentage of CBR was calculated at 2.5 mm and 5 mm of penetration. It has been observed that penetration follows a proportional trend up to approximately 200 kg with respect to penetration. After that, penetration rapidly increases with respect to load, as illustrated by Figure 3.

Figure 4 shows that at optimum moisture content curves follow the proportionality trends up to approx. 200 kg and then this trend was changed. It is also seen that at OMC condition more load is required to apply to penetrate as compared to field moisture content.

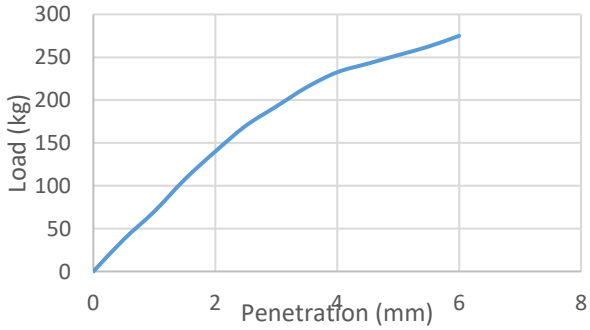


Fig. 3. Load Vs Penetration graph for un-soaked condition (At Field Moisture Content).

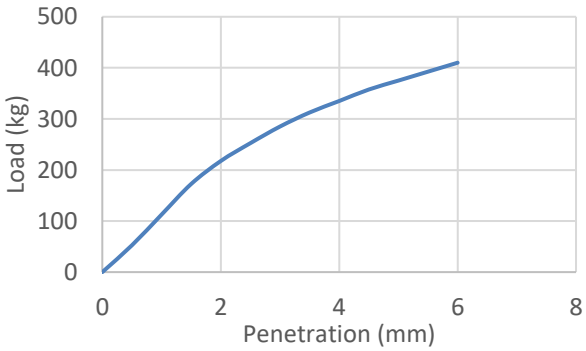


Fig. 4. Load Vs penetration graph for dry condition (At OMC).

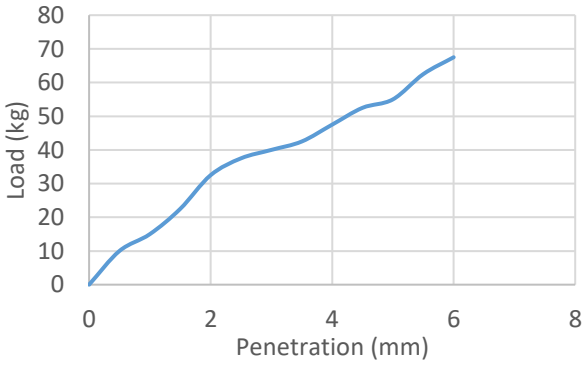


Fig. 5. Load Vs penetration graph for Day one soaked condition.

Figure 5 shows that curves do not follow the proportionality trend and it show variations in penetration with respect to load. It also reveals that for day one condition only less load required for penetration as compared to OMC as well as field conditions.

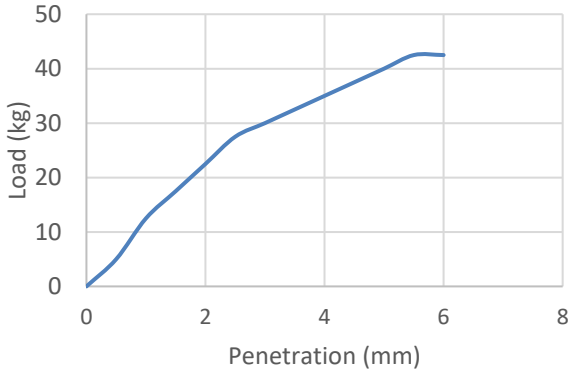


Fig. 6. Load Vs penetration graph for Day Second soaked condition.

Figure 6 shows that curves also do not follow proportionality trends and it look like parabola. Also, less load is required for the penetration.

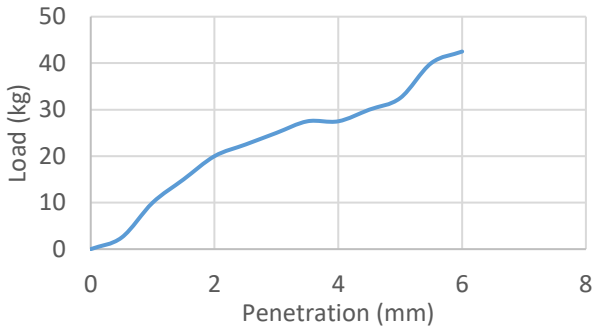


Fig. 7. Load Vs penetration graph for Day Third Soaked condition.

Figure 7 shows the curve varies in a such way initially penetration increases rapidly up to 5 kg and then it became slow up to 10 kg, again penetration varies un proportionality with respect to load.

From the above figures it has been observed that to penetrate the knob up-to 6mm deep, highest load (around 410 kg) is required in the case of OMC condition followed by field condition that requires 250 kg load. However, for other soaking conditions, a load about 40 to 70 kg is enough to penetrate the knob up-to specific depth. The results revealed that maximum strength is obtained at OMC condition and decreases by soaking the specimen in water following different trends.

At various locations throughout the mold, the soil sample's moisture content has been computed. The middle layer (vertical level) is almost at the center of the sample. The distances between the upper and bottom layers of a specimen are approximately 15 cm apart. For each layer (level), the east and west point to the left and right halves of the sample, respectively, while the north and south point to the observer and the tests that are directed in those directions.

The values are calculated by drying soil sample in the oven Table 4 illustrates the variation of moisture contents in all soaked samples at different positions.

Table 4. Observation of Moisture content at different soaking condition.

VP	Moisture Contents Percentage														
	Day – 1					Day – 2					Day – 3				
	Horizontal Position					Horizontal Position					Horizontal Position				
	E	W	N	S	C	E	W	N	S	C	E	W	N	S	C
T	17.94	18.53	18.75	19.91	19.65	27.49	27.93	25.27	24.37	26.13	25.53	25.29	25.79	25.89	24.99
M	17.78	17.57	17.66	17.51	17.71	19.85	19.58	19.77	19.55	19.50	20.71	21.04	21.45	21.89	20.64
B	17.63	18.81	16.66	17.50	17.74	18.35	18.67	18.84	19.18	18.97	18.76	18.87	19.33	18.79	19.73
E- East, W- West, N-North, S- South, C- Center, VP- Vertical Position, T- Top, M- Middle, B-Bottom															

4. CONCLUSIONS

In this study soil sample undergo different tests to investigate the soil type and later on to find the index properties as well as engineering properties. From the experimental results the following consequences are drawn.

1. The outcomes of sieve analysis revealed that the selected soil is “Well Graded Sand (SW)”.
2. The CBR values of selected soil increased slightly from field moisture content to optimum moisture content and then decreased with respect to soaking time. However, the reduction rate decreases as the number of soaking days increases.
3. It has also observed that under un-soaked and one day soaking condition the moisture level is insignificant. Moreover, a longer soaking time, results in more variations in moisture level when the taken from top layer from set up as compared to that in the lower layers.

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ABBREVIATIONS

OMC: Optimum Moisture Content
MDD: Maximum Dry Density
LL: Liquid Limit
PL: Plastic Limit
PI: Plasticity Index
ISSC: Indian Standard Soil Classification
CBR: California Bearing Ratio