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Stabilization of Expansive Soil for Highway Pavement Using Portland Cement As The Stabilizing Agent

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Abstract: *Expansive soils are problematic soil which are extensively found worldwide, where there are natural deposited abundantly. Due to the ability of the expansive soil to swell when exposed to moisture and shrink when the moisture is lost, there are sources of great damage to infrastructure and buildings. These problems posed by the expansive soils are mitigated by stabilization using Portland cement at varying percentage, which shows improvement in the engineering properties of the expansive soil. Two sample where collected for laboratory tests from pit 1 and pit 2, result obtained showed a similar improvement of the properties of the expansive soil. The liquid limit of the expansive soil when tested with 0% additive is 104.47% which decreased to 58.2% as the cement content is increased 2% to 10% for pit 1 sample. The plastic limit is on the increase with increase percentage of the cement content from 32.6% to 36.01%. The maximum dry density increased with the increase in the percentage cement content. There is a reduction in the specific gravity values due the presence of cement in the expansive soil. The CBR value shows improvement when the Portland cement is added to the expansive soil. 5% to 10% Portland cement content has a greater improvement on the expansive clay soils.*

Keyword: *Expansive soils, CBR value, Portland cement, Stabilization.*

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I. Introduction

Expansive soils are soils that have the ability to swell and soften when their water content is increased or shrink and crack when the water content is decreased. These soils containing a clay mineral known as montmorillonites is usually exhibit such properties (Nelson & Miller, 1992). Expansive soil is a term generally applied to any soil or rock material that has a potential for shrinking or swelling under changing moisture conditions (Nelson & Miller, 1992).

In civil engineering structures, various kinds of soils are used; however, some soil deposits in their natural form are suitable for construction purposes, whereas others are unsuitable without treatment, such as the problematic soils. These soils need to be excavated and then replaced, or their properties should be modified before they can sustain the applied loads by the upper structures. Typical of problematic soils are the expansive soils, which are frequently observed due to their existence worldwide, except the arctic regions (Steinberg, 2000).This kind of soil has caused a significant amount of damage in the United States (Jones Jr & Holtz, 1973), due to its high susceptibility to volume change, sensitive to moisture content. The inherent volume change characteristics of expansive soils are mainly resulting from their fine-grained clay mineral content. Due to cost implication, geotechnical engineers often prefer modifying the properties of fine-grained soils in situ via stabilization in comparison with the soil replacement in practice (Bastasa, Joy, Sagayap, Rafael, Sampayan, & Taniñas, 2019). Generally, the typical expansive soils can be easily identified from their high plasticity, excessive heave, and high swell-shrink potential which are made up of clay, shale or marl (Steinberg, 2000). A well-known expansive soil with high volume change tendency is the black cotton soil (BCS), which occurs mainly in areas with lacustrine and basaltic geologic origin like the Lake Chad basin and India (Ikeagwuani & Nwonu, 2019), stated that the expansive nature of BCS is due to the presence of montmorillonite group, which dominates its clay fraction.

Severe damages occur to structures like light building, pavements, retaining walls, canal beds and linings etc. founded on the expansive soils. Soil stabilization may be defined as any process by which a soil material is improved and made more stable resulting in improved bearing capacity, increase in soil strength, and durability under adverse moisture and stress conditions (Manasseh & Isaac, 2011). Clay minerals such illites, vermiculites and chlorites can be regarded as expansive soil, but there are less problematic to the soil. Clay soils exhibit, sometimes, a significant volume change due to the variation of water content in the mass of the soil, in response to climatic conditions and the action of vegetation. These volume changes affect the function of the constructions and foundations in contact with the soil and they represent the causes of damage, especially intense, during periods of drought.

One of the methods of controlling the volume changes of expansive soil is chemical stabilization. It is the process of adding admixtures that can prevent such change in volume or effectively modify the volume changes characteristics and as such reducing the effects of cracks and shrinkages of the soil. Its practice includes the use of lime and/or other chemicals, both organic and inorganic to stabilize expansive soils. Portland cement and lime have been used to stabilize expansive soils to relatively shallow depth under footing and subgrade. Through soil stabilization, unbound materials can be stabilized with cementitious materials (cement, lime, fly ash, bitumen or combination of these). The stabilized soil materials have a higher strength, lower permeability and lower compressibility than the native soil (Keller brochure 32-01E).

In general soil stabilization is a practice used in the field of highway construction and road pavements, but has been used successfully in the stabilization of the subgrade soil for individual buildings.

Clays have been defined on the basis of an assembly of certain specific characters such as plasticity, small particle size, hardening on firing, and chemical constitution (i.e. as consisting largely of silica, alumina and water). This definition is applied in a broad sense.

The definition of clays that has been given in terms of the relative proportion of the clay fraction in rocks or soils (Clay-area designated on the triangular diagram with the component proportions of sand and silt) to the fractions of sand and silt is, however, inconsistent from Sudo et. al point of view.

The most important grain property of fine-grained soils is the mineralogical composition. If the soils particles are smaller than 0.002mm, the influence of the gravitational force on the particles is insignificant compared to the electrical force acting on the surface of the particle (Terzaghi, Ralph, & Gholamreza, 1996). All the clay minerals are crystalline hydrous aluminosilicates having a lattice structure, similar to the pages of a book, in which the atoms are arranged in several layers. The colloidal particles of soil consist primarily of clay minerals that were derived from rock minerals by erosion, but that have differing mineralogical structure from those of the initial minerals.

Three important structural groups of clay minerals are described for engineering purposes as follows: Kaolinite group, Mica-like group and Smectite group (Nelson & Miller, 1992).

II. Sampling And Testing Methodology

General

The detailed procedures of the different laboratory tests conducted on the expansive soil in order to accomplish the objectives of this thesis are presented in this chapter.

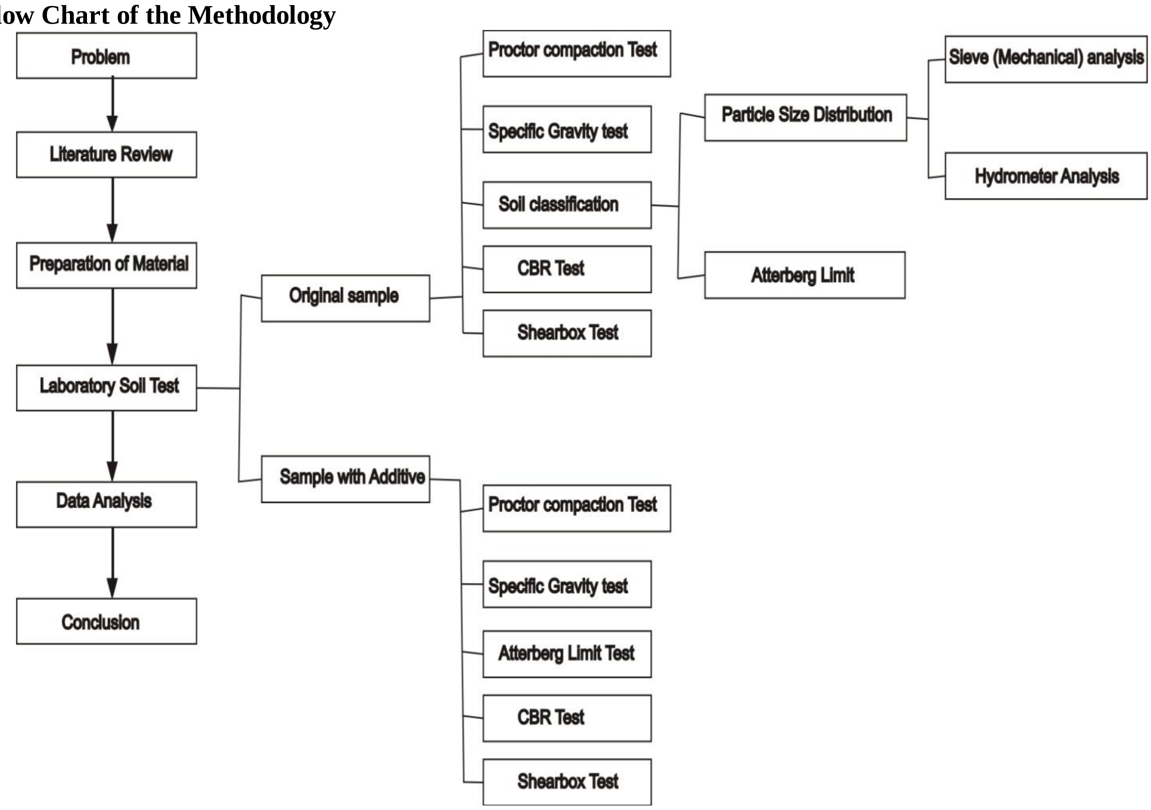
All the tests were done in Material and Research Laboratory Ministry of Works Enugu and all the results were recorded and a comparison was made on the two samples (soil).

Methodology Description

To study the effect of Portland cement on expansive soil, the various proportions of 2%, 5%, 8% and 10% were mixed with clay soil and laboratory tests were conducted to study the index and engineering properties. The index properties of the natural soil are obtained prior to stabilization, such as: Particle size distribution, Specific gravity test, Atterberg limit test, free swell index test, and Standard proctor compaction test. The engineering properties tests were also carried out such as: Direct shear test and California bearing ratio test.

All laboratory tests performed on both the natural and stabilized soils throughout this thesis is based on the British Standard (BS 1377, 1990).

Flow Chart of the Methodology



LABORATORY TEST

Particle Size Distribution

Soil particles also referred to as grains are classified to determine the physical properties of soil. Grain-size analysis is used in soil classification and as part of the specifications of soil for airfield, roads, earth dams, and soil embankment construction to determine the relative proportions of different grain sizes as they are distributed among certain size ranges. The particle-size or grain-size distribution is accomplished in two steps:

- A screening process (a sieve analysis, which is also called the mechanical analysis) for particle sizes retained on the no. 200 sieve.
- A sedimentation process (a hydrometer analysis) for particle sizes smaller than the No. 200 sieve.

Sieve Analysis (Mechanical Analysis)

The accurate completion of sieve analysis test will produce the percent of gravel, sand, and fines of the material. The most accurate process for this test method is wet sieving over the No. 200 sieve; this will give more accurate percent of fines. The particles retained in the No. 200 sieve are use to determine the grain-size distribution or the gradation curve of the soil by the mechanical analysis; determining the percentage retained in each sieve, after shaking.

Hydrometer Analysis

Hydrometer method combined with the dry sieving enables a continuous particle size distribution curve of a soil to be plotted from the size of the coarsest particle down to clay sizes. It covers the quantitative determination of the particle size distribution in a soil from the coarse sand size to the clay size by means of sedimentation. The test is normally not required if less than 10% of the material passes the 75micro meter test sieve in wet or dry sieving analysis.

Moisture Content Determination

To determine the amount of water present in a soil expressed as a percentage of the mass of dry soil. This is termed the moisture content of the soil.

The moisture content of the soil is assumed to be amount of water within the pore space between the soil grains which is removable by oven-drying at a temperature not exceeding 110 ^{0}C. The moisture content has a profound effect on soil behavior. The oven drying method is regarded as standard laboratory practice.

Atterberg Limit

I. Liquid Limit

The liquid limit is the empirically established moisture content at which a soil passes from the liquid state to the plastic state. The liquid limit provides a means of identifying fine-grained cohesive soils especially when also the plastic limit is known. Variation in the moisture content in a soil may has significant effect on its shear strength, especially on fine-grained soils.

II. Plastic Limit

The Plastic Limit is the empirically established moisture content at which a soil becomes too dry to be plastic. It is used together with the Liquid Limit to determine the Plasticity Index which plotted against the Liquid Limit on the plasticity chart provides a means of classifying cohesive soils. The Plasticity Index is the difference between the Liquid Limit and the Plastic Limit. The Plasticity Index is the range of moisture content in which a soil is plastic; the finer the soil, the greater the Plasticity Index.

III. Plasticity Index

The plasticity Index (I_P) is defined as the difference between the liquid limit (w_L) and the plastic limit (w_P), and the is calculated from the equation:

$I_P = w_L – w_p$

IV. Linear Shrinkage

Due to the expansive nature of clay soil shrinkage caused by drying of the moisture is significant, but less so in silts and sand. If the drying process is prolong after the plastic limit has been reached, the soil will continue to decrease in volume, which is also relevant to the converse condition of expansion due to wetting. The linear shrinkage value is a way of quantifying the amount of shrinkage likely to be experienced by clayey material. Such a value is also relevant to the converse condition of expansion due to wetting.

Linear shrinkage method covers the determination of the total linear shrinkage from linear measurement on a bar of soil of the fraction of a soil sample passing a $425\ \mu m$ test sieve, originally having the moisture content of the liquid limit.

Specific Gravity Determination – Small Pycnometer Method

Specific gravity of particles also known as the particle density of particle is essential in relation to other tests, especially for calculating porosity and voids and for computation of particle size analysis from a sedimentation procedure (Hydrometer analysis). It is also vital when compaction and consolidation properties are considered.

The small Pycnometer method is suitable for soil consisting of particles finer than 2 mm. larger particles may be ground down to smaller than 2 mm before testing.

Standard Proctor Compaction (Light Compaction)

The objective of this test is to determine relationship between compacted dry density and soil moisture content, using two magnitudes of manual compactive effort. The test is used to provide a guide for specifications on field compaction. A compaction mould of 1 L internal volume and a 2.5 kg rammer is used for light compaction. The moisture content which gives the highest dry density is called the optimum moisture content for that type of compaction. Generally the plastic limit is greater than the optimum moisture content.

Modified Proctor Compaction for Stabilized Material

Compaction of stabilized material is the process by which the solid particles are packed more closely together by mechanical means, thereby increasing the dry density of the material. A 4.5 kg rammer with a 450 mm drop compacting material in a CBR mould in 5 equal layers (Modified Proctor) is adopted as the compactive effort. A range of moisture contents is observed in a special manner in the determination of the dry density of the stabilized sample during compaction. The range includes the optimum moisture content (OMC) at which the maximum dry density (MDD) for this degree of compaction is obtained. The test is used for soil in which all particles pass a 20 mm test sieve. It is also used for coarser soils containing up to 15% material coarser than 37.5 mm.

CBR- California Bearing Ratio Test- One Point Method

The strength of the subgrade is the main factor in determining the required thickness of flexible pavements for roads and airfields. The strength of the subgrade, subbase and base course materials are expressed in terms of their California Bearing Ratio (CBR) value. The CBR-value is a requirement in design for pavement materials of natural gravel.

The CBR value is the resistance to penetration of 2.5 mm of a standard cylindrical plunger of 50 mm diameter, expressed as a percentage of the known resistance of the plunger to 2.5 mm in penetration in crushed aggregate.

Shear Box Test-Drained shear strength

The shear Box allows a direct shear test to be made by relating the shear stress at failure to the applied normal stress. The objective of the test is to determine the effective shear strength parameters of the soil, the cohesion and the angle of internal friction. These values may be used for calculating the bearing capacity of the soil and the stability of slopes.

In the direct shear test a square prism of soil is laterally restrained and sheared along a mechanically induced horizontal plane while subjected to a pressure applied normal to that plane. The shearing resistance offered by the soil as one portion is made to slide on the other is measured at regular intervals of displacement. Failure occurs when the shearing resistance reaches the maximum value which the soil can sustain.

III. Analysis and Results

Representative moisture content test results

Table 3.1: Determination of moisture content for test pit 1

Depth (m)	3m	
Container no.	Tin 1	Tin 2
Mass of container (g): (M_1)	15.70	15.40
Mass of container + wet soil (g): (M_2)	57.40	50.30
Mass of container + dry soil (g): (M_3)	44.60	39.50
Mass of water (g): (M_2 - M_3)	12.80	10.80
Mass of dry soil (g): (M_3 - M_1)	28.90	24.10
Moisture content (%): (w)	44.29	44.81
Average moisture content (%)	44.55	

Table 3.2: Determination of moisture content for test pit 2

Depth (m)	3m	
Container no.	Tin 1	Tin 2
Mass of container (g): (M_1)	15.60	15.50
Mass of container + wet soil (g): (M_2)	39.60	38.50
Mass of container + dry soil (g): (M_3)	33.00	32.20
Mass of water (g): (M_2 - M_3)	6.60	6.30
Mass of dry soil (g): (M_3 - M_1)	17.40	16.70
Moisture content (%): (w)	37.93	37.72
Average moisture content (%)	37.83	

Representative of the Specific Gravity test results

Table 3.3: Determination of specific gravity for test pit 1 for 0% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	91.15	91.15
Mass of bottle + dry soil (g): (M_2)	28.50	28.55
Mass of bottle full of water (g): (M_4)	84.80	84.85
Mass of density bottle (g): (M_1)	18.50	18.55
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.30	66.30
Mass of water used (g): (M_3-M_2)	62.65	62.60
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	3.65	3.70
Specific gravity	2.74	2.70
Average specific gravity	2.72	

Table 3.4: Determination of specific gravity for test pit 1 for 2% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	91.06	91.12
Mass of bottle + dry soil (g): (M_2)	28.52	28.50
Mass of bottle full of water (g): (M_4)	84.82	84.82
Mass of density bottle (g): (M_1)	18.52	18.50
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.30	66.32
Mass of water used (g): (M_3-M_2)	62.54	62.62
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	3.76	3.70
Specific gravity	2.66	2.70
Average specific gravity	2.68	

Table 3.5: Determination of specific gravity for test pit 1 for 5% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	90.99	91.03
Mass of bottle + dry soil (g): (M_2)	28.51	28.50
Mass of bottle full of water (g): (M_4)	84.84	84.82
Mass of density bottle (g): (M_1)	18.51	18.50
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.33	66.32

Mass of water used (g): (M_3-M_2)	62.48	62.53
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	3.85	3.79
Specific gravity	2.60	2.64
Average specific gravity	2.62	

Table 3.6: Determination of specific gravity for test pit 1 for 8% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	90.92	90.98
Mass of bottle + dry soil (g): (M_2)	28.48	28.50
Mass of bottle full of water (g): (M_4)	84.80	84.83
Mass of density bottle (g): (M_1)	18.48	18.50
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.32	66.33
Mass of water used (g): (M_3-M_2)	62.44	62.48
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	3.88	3.85
Specific gravity	2.58	2.60
Average specific gravity	2.59	

Table 3.7: Determination of specific gravity for test pit 1 for 10% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	90.84	90.83
Mass of bottle + dry soil (g): (M_2)	28.50	28.51
Mass of bottle full of water (g): (M_4)	84.81	84.83
Mass of density bottle (g): (M_1)	18.50	18.51
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.31	66.32
Mass of water used (g): (M_3-M_2)	62.34	62.32
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	3.97	4.00
Specific gravity	2.52	2.50
Average specific gravity	2.51	

Table 3.8: Determination of specific gravity for test pit 2 for 0% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	91.05	91.08
Mass of bottle + dry soil (g): (M_2)	28.50	28.50
Mass of bottle full of water (g): (M_4)	84.80	84.80
Mass of density bottle (g): (M_1)	18.50	18.50
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.30	66.30
Mass of water used (g): (M_3-M_2)	62.55	62.58
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	3.75	3.72
Specific gravity	2.67	2.69
Average specific gravity	2.68	

Table 3.9: Determination of specific gravity for test pit 2 for 2% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	90.89	90.95
Mass of bottle + dry soil (g): (M_2)	28.50	28.50
Mass of bottle full of water (g): (M_4)	84.80	84.80
Mass of density bottle (g): (M_1)	18.50	18.50
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.30	66.30
Mass of water used (g): (M_3-M_2)	62.39	62.45
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	3.91	3.85
Specific gravity	2.56	2.60
Average specific gravity	2.58	

Table 3.10: Determination of specific gravity for test pit 2 for 5% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	90.89	90.83
Mass of bottle + dry soil (g): (M_2)	28.50	28.50
Mass of bottle full of water (g): (M_4)	84.80	84.80
Mass of density bottle (g): (M_1)	18.50	18.50

Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.30	66.30
Mass of water used (g): (M_3-M_2)	62.39	62.33
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	3.91	3.97
Specific gravity	2.56	2.52
Average specific gravity	2.54	

Table 3.11: Determination of specific gravity for test pit 2 for 8% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	90.78	90.78
Mass of bottle + dry soil (g): (M_2)	28.50	28.50
Mass of bottle full of water (g): (M_4)	84.80	84.80
Mass of density bottle (g): (M_1)	18.50	18.50
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.30	66.30
Mass of water used (g): (M_3-M_2)	62.28	62.28
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	4.02	4.02
Specific gravity	2.49	2.49
Average specific gravity	2.49	

Table 3.12: Determination of specific gravity for test pit 2 for 10% Portland cement

Depth, m	3m	
Pycnometer no.	1	2
Mass of bottle + water + soil (g): (M_3)	90.78	90.72
Mass of bottle + dry soil (g): (M_2)	28.50	28.50
Mass of bottle full of water (g): (M_4)	84.80	84.80
Mass of density bottle (g): (M_1)	18.50	18.50
Mass of soil (g): (M_2- M_1)	10.00	10.00
Mass of water in full bottle (g): (M_4-M_1)	66.30	66.30
Mass of water used (g): (M_3-M_2)	62.28	62.22
Volume of soil particle (ml): (M_4-M_1)-(M_3-M_2)	4.02	4.08
Specific gravity	2.49	2.45
Average specific gravity	2.47	

Representative Liquid Limit and Plastic Limit test results

Table 3.13: Liquid limit and Plastic Limit for test pit 1 for 0% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		56	99	22	21	32	38
Mass of container (M_1), g		09	09	13	12	10	10
Mass of container + wet soil (M_2), g		27.09	29.34	35.32	40.59	24.70	24.58
Mass of container + dry soil (M_3), g		19.23	19.34	23.45	22.43	20.33	20.31
Mass of water (M_2 - M_3), g		7.86	10.00	11.87	18.16	4.37	4.27
Mass of dry soil (M_3 - M_1), g		10.23	10.34	10.45	10.43	10.33	10.31
Moisture content (w), %		76.83	96.71	113.59	174.11	42.30	41.42
Number of blows, N		34.0	27.0	23.0	15.0	-	-
Results, %		106				41.86	

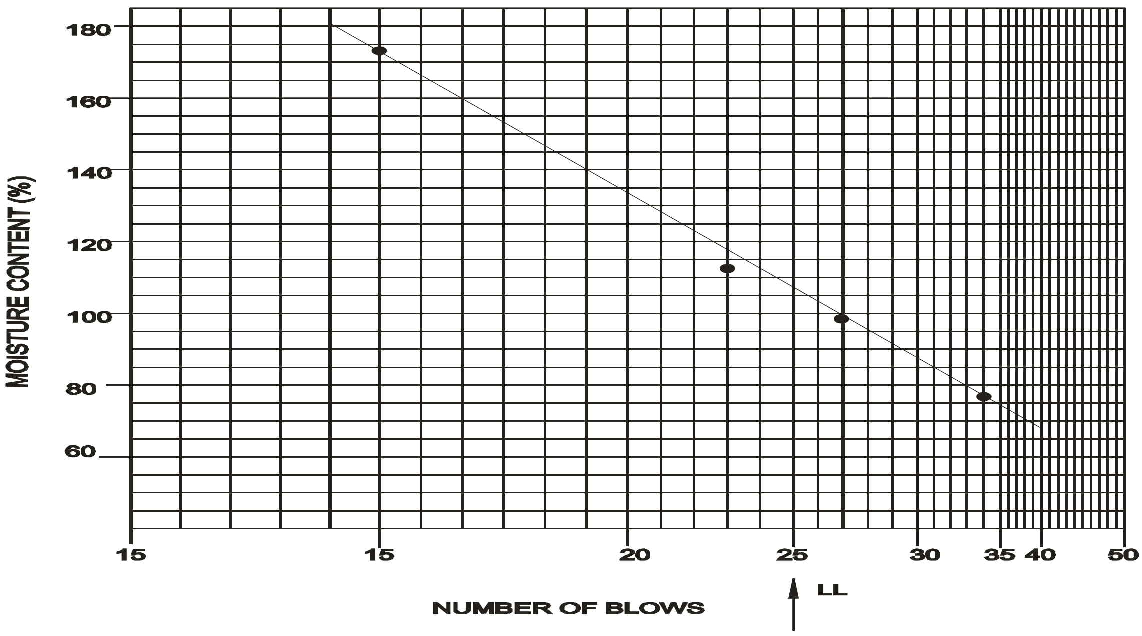


Figure 3.1: Liquid Limit of soil sample with 0% cement content for test pit 1

Table 3.14: Liquid limit and Plastic Limit for test pit 1 for 2% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		180	182	176	145	176	23
Mass of container (M_1), g		08	08	09	10	10	10
Mass of container + wet soil (M_2), g		26.66	28.29	30.65	37.68	23.57	23.98
Mass of container + dry soil (M_3), g		20.30	20.32	21.34	22.54	20.22	20.56
Mass of water (M_2 - M_3), g		6.36	7.97	9.31	15.14	3.35	3.42
Mass of dry soil (M_3 - M_1), g		12.30	12.32	12.34	12.54	10.22	10.56
Moisture content (w), %		51.70	64.69	75.44	120.73	32.78	32.39
Number of blows, N		34.0	28.0	24.0	16.0	-	-
Results, %		74				32.59	

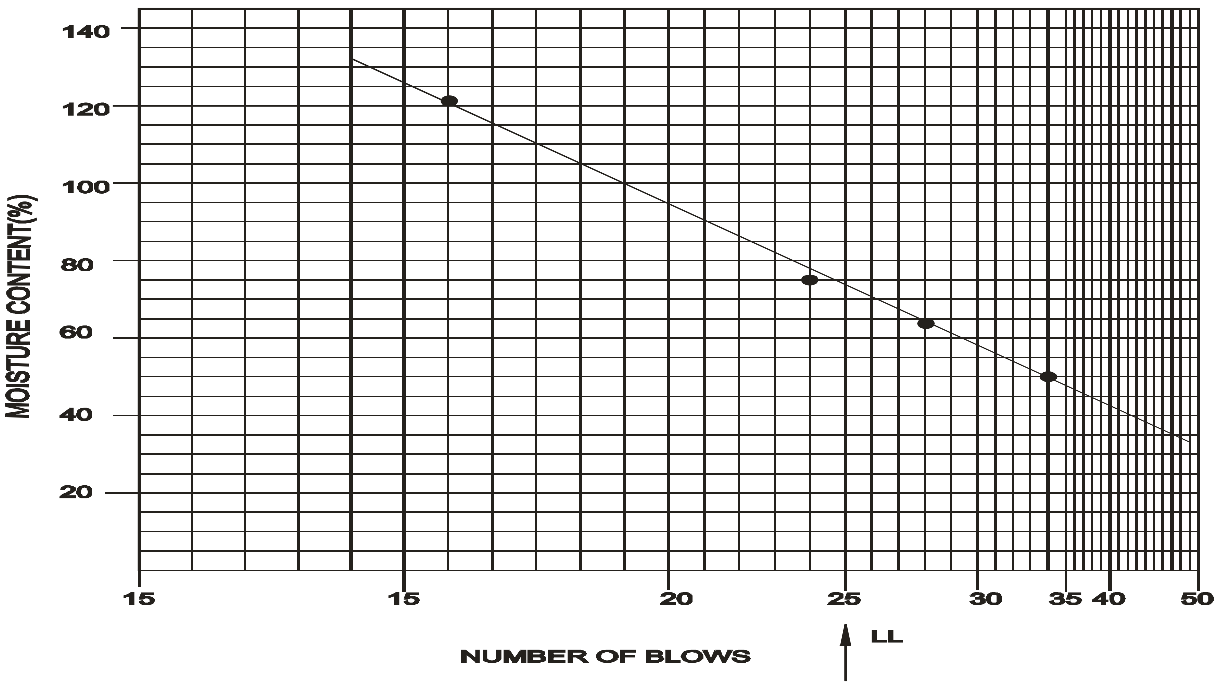


Figure 3.2: Liquid Limit of soil sample with 2% cement content for test pit 1

Table 3.15: Liquid limit and Plastic Limit for test pit 1 for 5% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		129	130	231	234	43	101
Mass of container (M_1), g		10	10	10	10	10	12
Mass of container + wet soil (M_2), g		25.12	31.78	30.30	38.79	18.93	20.91
Mass of container + dry soil (M_3), g		21.22	22.23	20.78	22.23	16.66	18.64
Mass of water (M_2 - M_3), g		3.90	9.55	9.52	16.56	2.27	2.27
Mass of dry soil (M_3 - M_1), g		11.22	12.23	10.78	12.23	6.66	6.64
Moisture content (w), %		34.76	78.09	88.31	135.40	34.08	34.19
Number of blows, N		34.0	26.0	22.0	16.0	-	-
Results, %		69				34.14	

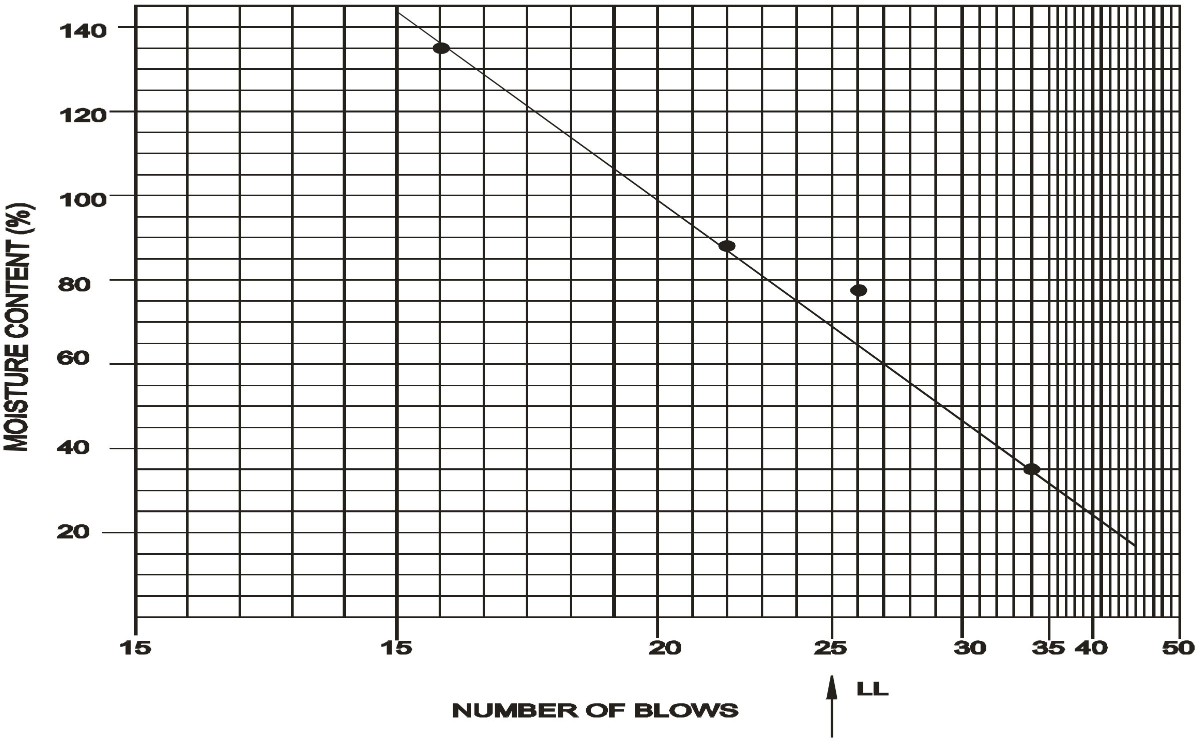


Figure 3.3: Liquid Limit of soil sample with 5% cement content for test pit 1

Table 3.16: Liquid limit and Plastic Limit for test pit 1 for 8% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		50	61	62	93	94	98
Mass of container (M_1), g		07	11	15	12	10	10
Mass of container + wet soil (M_2), g		23.49	28.62	34.04	34.36	17.67	18.13
Mass of container + dry soil (M_3), g		18.30	22.31	26.34	23.32	15.67	16.01
Mass of water (M_2 - M_3), g		5.19	6.31	7.70	11.04	2.00	2.12
Mass of dry soil (M_3 - M_1), g		11.30	11.31	11.34	11.32	5.67	6.01
Moisture content (w), %		45.93	55.79	67.90	97.53	35.27	35.27
Number of blows, N		34	28	23	16	-	-
Results, %		64				35.27	

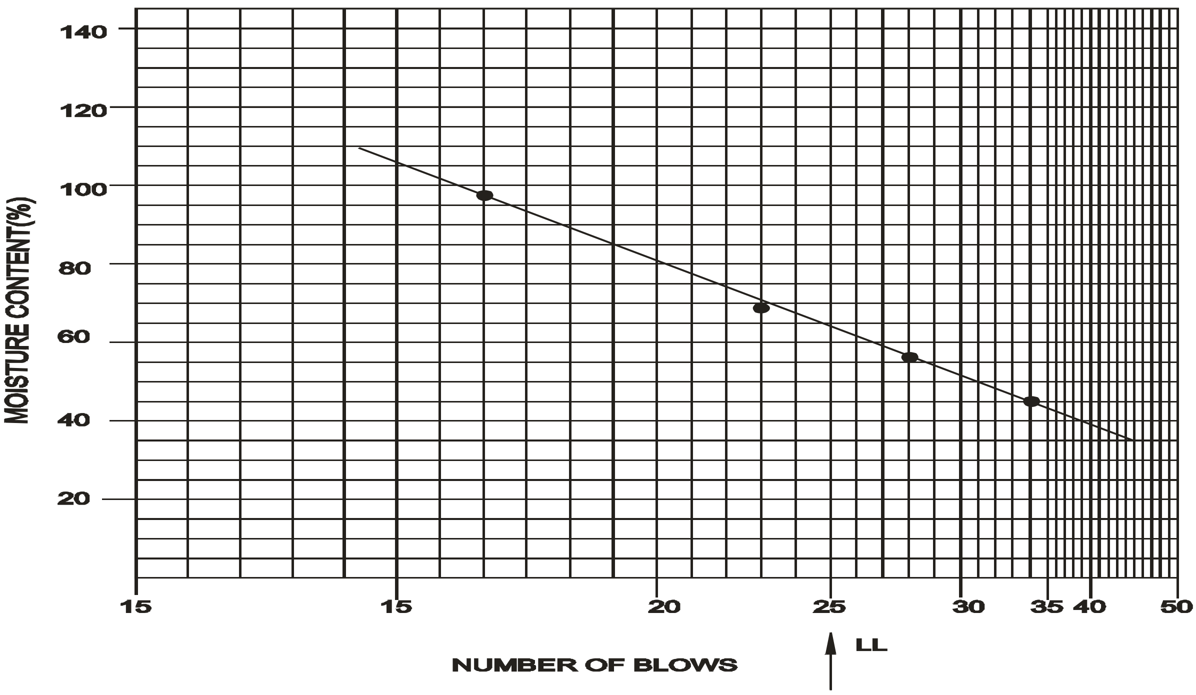


Figure 3.4: Liquid Limit of soil sample with 8% cement content for test pit 1

Table 3.17: Liquid limit and Plastic Limit for test pit 1 for 10% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		01	100	121	122	30	80
Mass of container (M_1), g		10	09	10	10	08	08
Mass of container + wet soil (M_2), g		24.50	24.40	26.6	29.22	15.70	15.54
Mass of container + dry soil (M_3), g		20.23	19.24	20.32	20.34	13.66	13.54
Mass of water (M_2 - M_3), g		4.27	5.16	6.28	8.88	2.04	2.00
Mass of dry soil (M_3 - M_1), g		10.23	10.24	10.32	10.34	5.66	5.54
Moisture content (w), %		41.74	50.39	60.85	85.88	36.04	36.10
Number of blows, N		35	29	24	17	-	-
Results, %		58				36.07	

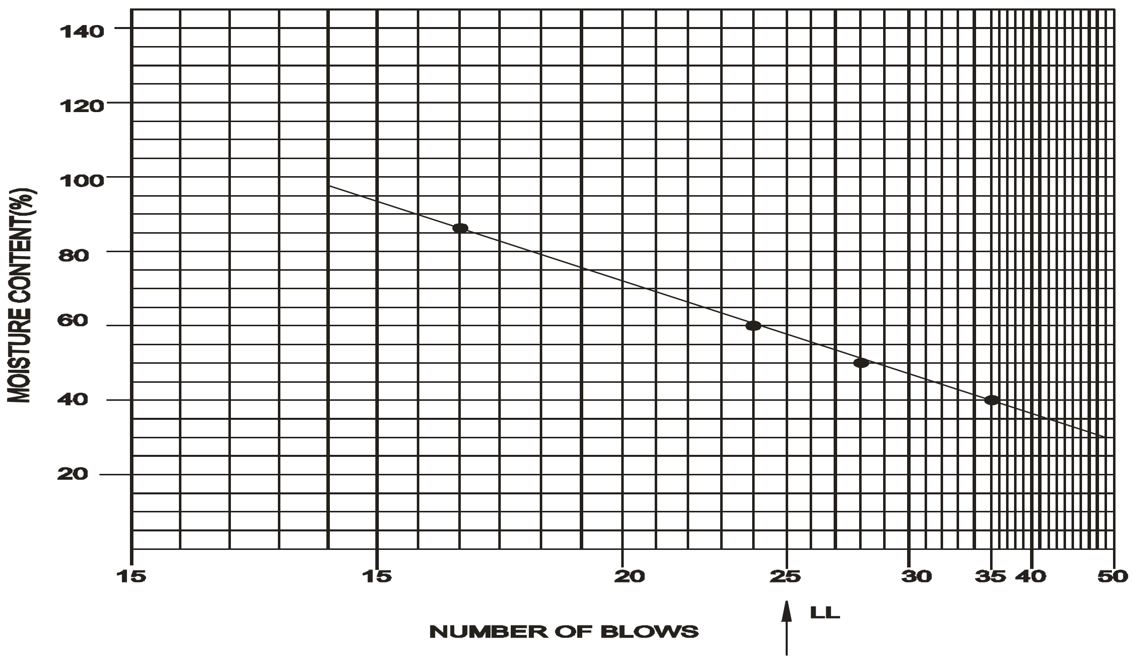


Figure 3.5: Liquid Limit of soil sample with 10% cement content for test pit 1

Table 3.18: Liquid limit and Plastic Limit for test pit 2 for 0% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		23	13	25	67	87	77
Mass of container (M_1), g		10	09	09	10	05	07
Mass of container + wet soil (M_2), g		31.29	32.87	34.12	42.21	18.75	21.07
Mass of container + dry soil (M_3), g		22.22	21.34	20.98	22.01	14.98	17.21
Mass of water (M_2 - M_3), g		9.07	11.53	13.14	20.20	3.77	3.86
Mass of dry soil (M_3 - M_1), g		12.22	12.34	11.98	12.01	9.98	10.21
Moisture content (w), %		74.22	93.44	109.68	168.19	37.78	37.81
Number of blows, N		33.0	27.0	23.0	15.0	-	-
Results, %		102				37.80	

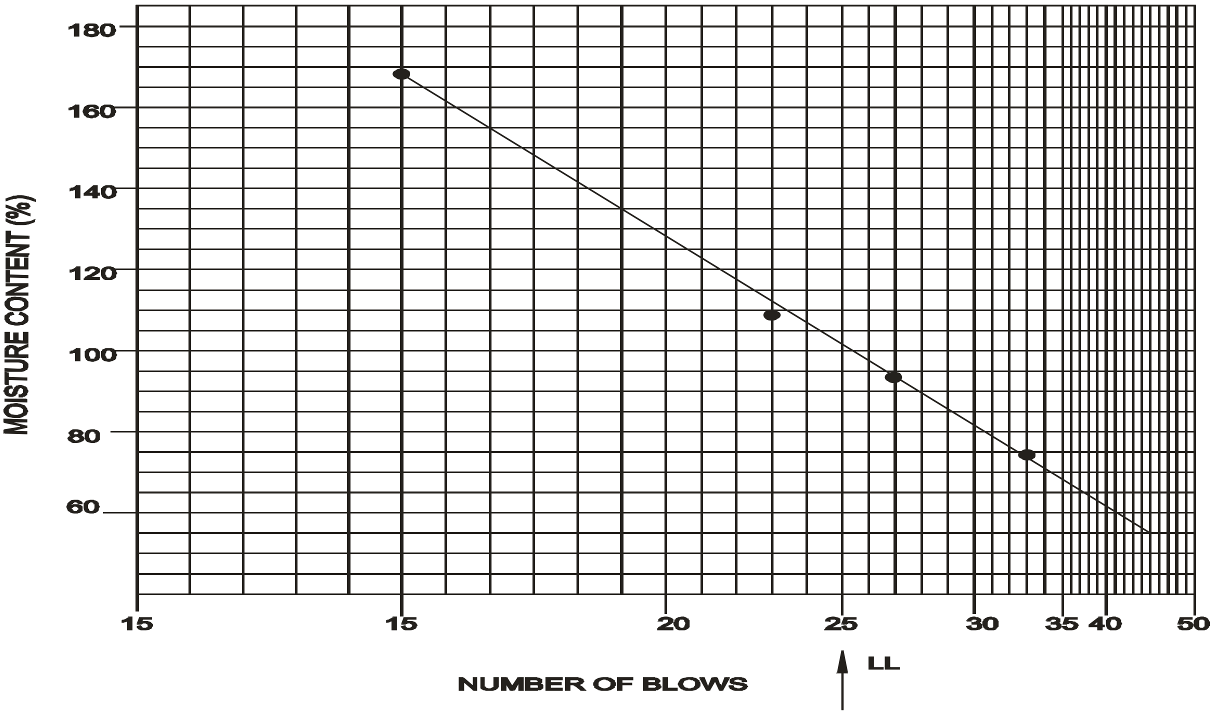


Figure 3.6: Liquid Limit of soil sample with 0% cement content for test pit 2

Table 3.19: Liquid limit and Plastic Limit for test pit 2 for 2% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		22	13	54	38	67	55
Mass of container (M_1), g		10	11	11	09	07	07
Mass of container + wet soil (M_2), g		29.25	31.74	34.02	36.34	17.17	17.46
Mass of container + dry soil (M_3), g		22.23	23.22	23.45	21.31	14.89	15.12
Mass of water (M_2 - M_3), g		7.02	8.52	10.57	15.03	2.28	2.34
Mass of dry soil (M_3 - M_1), g		12.23	12.22	12.45	12.31	7.89	8.12
Moisture content (w), %		57.40	69.72	84.90	122.10	28.90	28.82
Number of blows, N		34	28	23	16	-	-
Results, %		77				28.86	

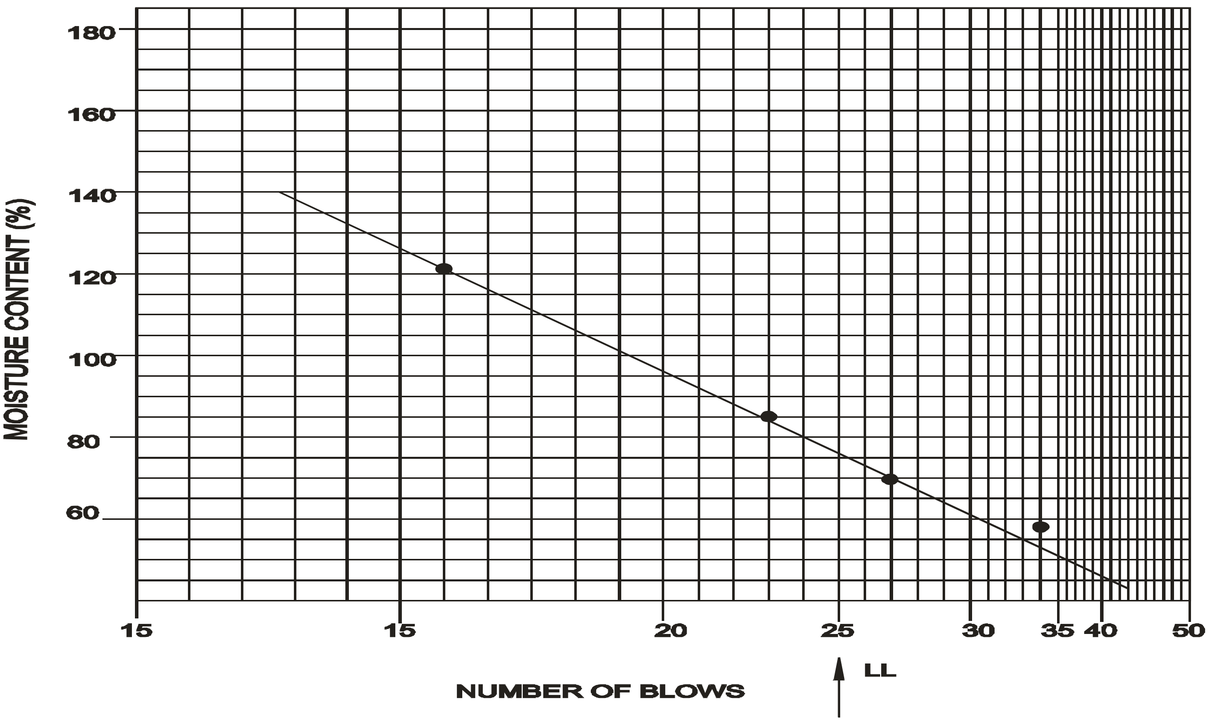


Figure 3.7: Liquid Limit of soil sample with 2% cement content for test pit 2

Table 3.20: Liquid limit and Plastic Limit for test pit 2 for 5% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		78	89	06	05	33	22
Mass of container (M_1), g		10	10	10	10	10	10
Mass of container + wet soil (M_2), g		25.35	26.42	27.87	31.00	19.54	19.52
Mass of container + dry soil (M_3), g		20.12	20.23	20.32	20.33	17.32	17.31
Mass of water (M_2 - M_3), g		5.23	6.19	7.55	10.67	2.22	2.21
Mass of dry soil (M_3 - M_1), g		10.12	10.23	10.32	10.33	7.32	7.31
Moisture content (w), %		51.68	60.51	73.16	103.29	30.33	30.23
Number of blows, N		34	29	24	17	-	-
Results, %		69				30.28	

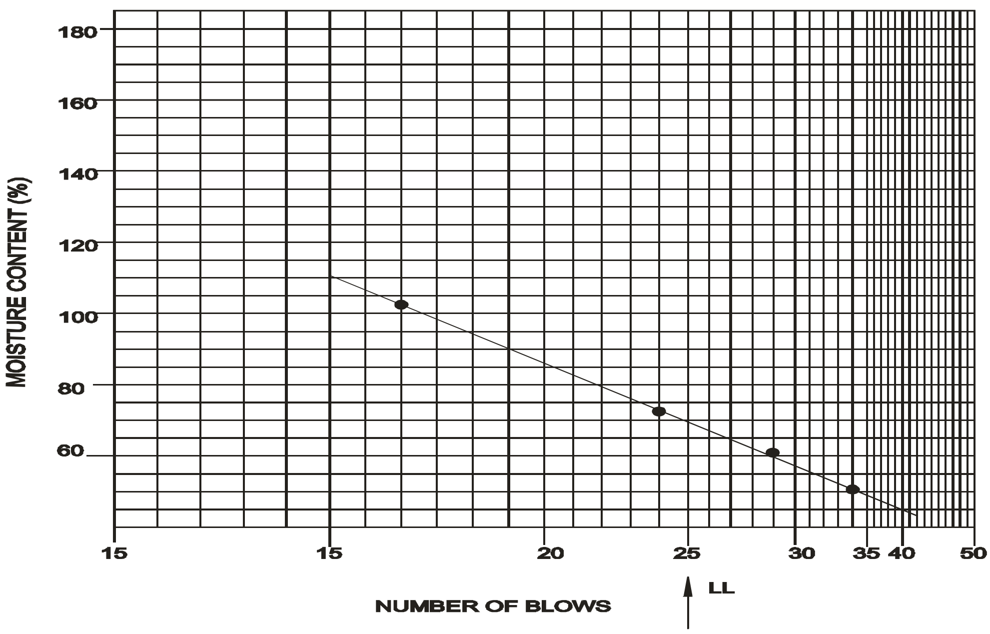


Figure 3.8: Liquid Limit of soil sample with 5% cement content for test pit 2

Table 3.21: Liquid limit and Plastic Limit for test pit 2 for 8% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		23	04	40	113	112	11
Mass of container (M_1), g		10	10	10	10	05	06
Mass of container + wet soil (M_2), g		24.59	25.49	26.75	28.89	13.90	14.94
Mass of container + dry soil (M_3), g		20.21	20.21	20.31	20.30	11.75	12.78
Mass of water (M_2 - M_3), g		4.38	5.28	6.44	8.59	2.15	2.16
Mass of dry soil (M_3 - M_1), g		10.21	10.21	10.31	10.30	6.75	6.78
Moisture content (w), %		42.90	51.71	62.46	83.40	31.85	31.86
Number of blows, N		35	29	24	18	-	-
Results, %		59				31.86	

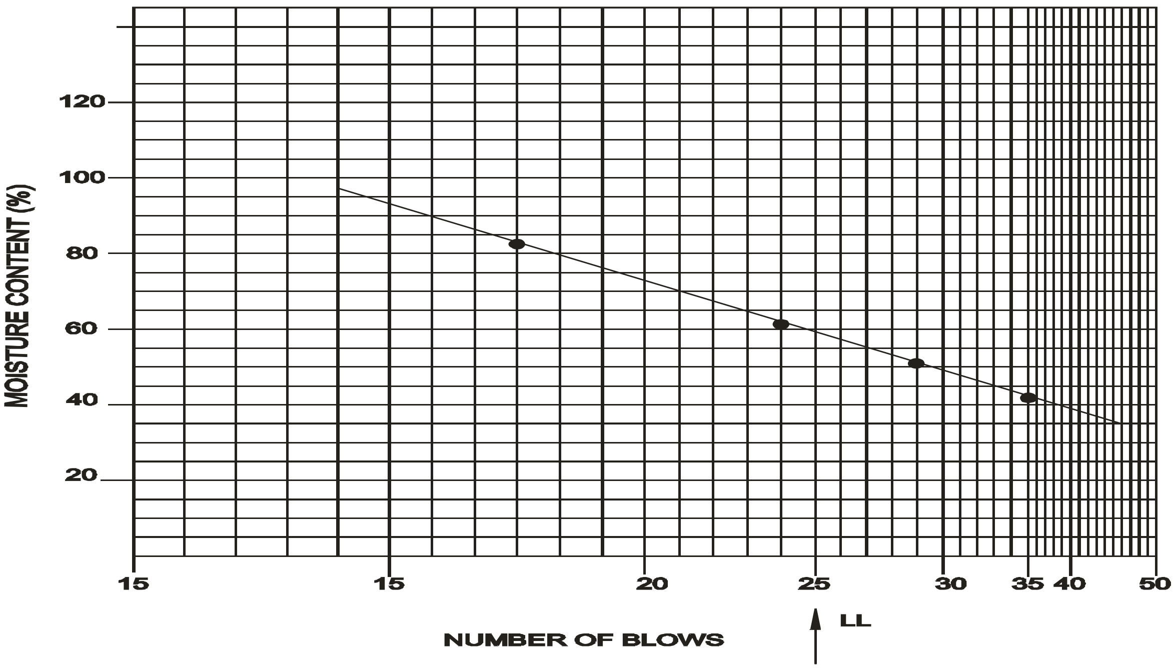


Figure 3.9: Liquid Limit of soil sample with 8% cement content for test pit 2

Table 3.22: Liquid limit and Plastic Limit for test pit 2 for 10% Portland cement

Depth, m	3m	Liquid Limit				Plastic Limit	
Trial No.		1	2	3	4	1	2
Container No.		24	56	46	50	33	32
Mass of container (M_1), g		10	10	12	11	10	10
Mass of container + wet soil (M_2), g		27.38	28.46	31.42	32.72	19.84	19.87
Mass of container + dry soil (M_3), g		22.31	22.33	24.32	23.35	17.32	17.34
Mass of water (M_2 - M_3), g		5.07	6.13	7.10	9.37	2.52	2.53
Mass of dry soil (M_3 - M_1), g		12.31	12.33	12.32	12.35	7.32	7.34
Moisture content (w), %		41.19	49.72	57.63	75.87	34.43	34.47
Number of blows, N		35	29	25	19	-	-
Results, %		58				34.45	

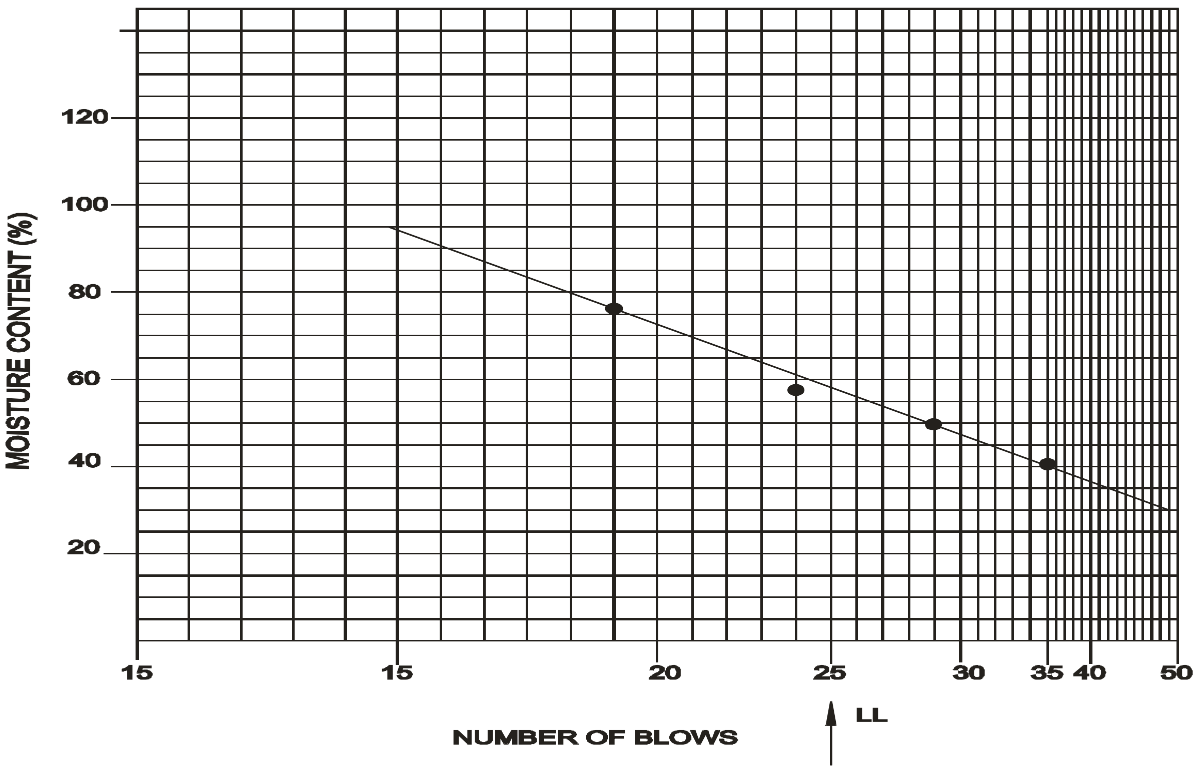


Figure 3.10: Liquid Limit of soil sample with 10% cement content for test pit 2

4.4 Representative Free Swell test results

Table 3.23: Free Swell test result for test pit 1 for 0% Portland cements

Depth, m	3	
Sample No.	1	2
Initial volume, ml	10	10
Final volume, ml	24	26.5
Free Swell, %	140	165
Average Free Swell, %	152.5	

Table 3.24: Free Swell test result for test pit 2 for 0% Portland cement

Depth, m	3	
Sample No.	1	2
Initial volume, ml	10	10
Final volume, ml	27	26
Free Swell, %	170	160
Average Free Swell, %	165	

3.5 Representative Grain size Analysis test results

Table 3.25a: Sieve analysis for test pit PT_1 @ 3m depth

Sieve size (mm)	Mass retained (g)	Percentage retained (%)	Cumulative percentage retained (%)	Percentage passing (%)
12.500	0.0	0.00	0.00	100.00
9.500	0.0	0.00	0.00	100.00
4.750	1.4	0.12	0.12	99.88
2.360	4.1	0.34	0.46	99.54
2.000	4.2	0.35	0.81	99.19
1.180	5.5	0.46	1.27	98.73
0.600	6.1	0.51	1.78	98.23
0.425	4.1	0.34	2.12	97.88
0.300	5.4	0.45	2.57	97.43
0.150	5.5	0.46	3.03	96.98
0.075	4.4	0.37	3.39	96.61
Pan	0.2	-	-	-

Table 3.25b: Hydrometer analysis for test pit 1 @ 3m depth

Elapse time (T)	Actual Hydrometer reading	Comp. correction	Corrected Hydrometer reading	Effective depth, cm	Test temp.	Coefficient (K)	Grain size (D), mm	Percentage finer (P), %	Combined percentage finer,%
0.75	1.0320	0.00308	1.02892	7.835	18.1	0.01376	0.04448	91.61	88.50
1	1.0315	0.00308	1.02842	7.968	18.1	0.01376	0.03885	90.02	86.97
2	1.0305	0.00308	1.02742	8.232	18.1	0.01376	0.02792	86.86	83.91
4	1.0295	0.00308	1.02642	8.497	18.1	0.01337	0.01949	83.69	80.85
8	1.0285	0.00312	1.02538	8.761	17.9	0.01380	0.01444	80.39	77.67
15	1.0275	0.00314	1.02436	9.026	17.8	0.01382	0.01072	77.16	74.55
30	1.0270	0.00312	1.02388	9.158	17.9	0.01380	0.00762	75.64	73.08
60	1.0260	0.00306	1.02294	9.422	18.2	0.01375	0.00545	72.67	70.20
120	1.0250	0.00300	1.02200	9.687	18.5	0.01370	0.00389	69.69	67.32
240	1.0240	0.00276	1.02124	9.952	19.7	0.01349	0.00275	67.28	65.00
480	1.0230	0.00266	1.02034	10.216	20.2	0.01341	0.00196	64.43	62.24
1440	1.0220	0.00340	1.01860	10.481	16.5	0.01405	0.00120	58.92	56.92

Table 3.26a: Sieve analysis for test pit 2 @ 3m depth

Sieve size (mm)	Mass retained (g)	Percentage retained, (%)	Cumulative percentage retained (%)	Percentage passing (%)
9.500	0.0	0.00	0.00	100.00
4.750	4.2	0.35	0.35	99.65
2.360	3.2	0.27	0.62	99.38
2.000	4.3	0.36	0.97	99.03
1.180	5.3	0.44	1.42	98.58
0.600	5.8	0.48	1.90	98.10
0.425	4.0	0.33	2.23	97.77
0.300	4.1	0.34	2.57	97.43
0.150	2.4	0.20	2.77	97.23
0.075	6.6	0.55	3.32	96.68
Pan	0.4	-	-	-

Table 3.26b: Hydrometer analysis for test pit 2 @ 3m depth

Elapse time (T)	Actual Hydrometer reading	Comp. correction	Corrected Hydrometer reading	Effective depth, cm	Test temp.	Coefficient (K)	Grain size (D), mm	Percentage finer (P), %	Combined percentage finer,%
0.75	1.03300	0.00288	1.03012	7.571	19.1	0.013403	0.0426	94.80	91.65
1	1.03250	0.00294	1.02956	7.703	18.8	0.013454	0.0373	93.03	89.94
2	1.03150	0.00292	1.02858	7.968	18.9	0.013437	0.0268	89.95	86.96
4	1.03050	0.00292	1.02758	8.232	18.9	0.013437	0.0193	86.80	83.92
8	1.02900	0.00296	1.02604	8.629	18.7	0.013471	0.0140	81.96	79.23
15	1.02750	0.00294	1.02456	9.026	18.8	0.013454	0.0104	77.30	74.73
30	1.02600	0.00294	1.02306	9.422	18.8	0.013454	0.0075	72.58	70.16
60	1.02450	0.00294	1.02156	9.819	18.8	0.013454	0.0054	67.86	65.60
120	1.02350	0.00288	1.02062	10.084	19.1	0.013403	0.0039	64.90	62.74
240	1.02200	0.00288	1.01912	10.481	19.1	0.013403	0.0028	60.18	58.18
480	1.02100	0.00270	1.01830	10.745	20.0	0.013250	0.0020	57.60	55.68
1440	1.02000	0.00338	1.01662	11.010	16.6	0.013832	0.0012	52.31	50.57

3.6 Representative Bulk and Dry Density Test Results

Table 3.27a: Bulk Density test result for pit 1 for 0% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5031	5030	5176	5299	5234
Weight of mold + sample (g)	6512	6692	6908	6992	6807
Weight of sample (g)	1481	1662	1732	1693	1573
Wet density (g/cm^3)	1.48	1.66	1.73	1.69	1.57

Table 3.27b: Dry Density test result for pit 1 for 0% Portland cement

Moisture Content tin number	31	3	8	7	89	90	67	34	12	33
Weight of tin + wet soil (g)	23.85	23.88	24.12	24.00	24.44	23.98	25.64	24.61	25.89	26.17
Weight of tin + dry soil (g)	21.21	21.23	21.22	21.12	21.25	20.89	22.01	21.22	22.01	22.22
Weight of tin (g)	10	10	10	10	10	10	10	10	10	10
Weight of water (g)	2.64	2.65	2.90	2.88	3.19	3.09	3.63	3.39	3.88	3.95
Weight of dry soil (g)	11.21	11.23	11.22	11.12	11.25	10.89	12.01	11.22	12.01	12.22
Moisture content (%)	23.55	23.60	25.85	25.90	28.36	28.37	30.22	30.21	32.31	32.32
Average moisture content (%)	23.58		25.88		28.37		30.22		32.32	
Dry density of soil (g/cm^3)	1.20		1.32		1.35		1.30		1.19	

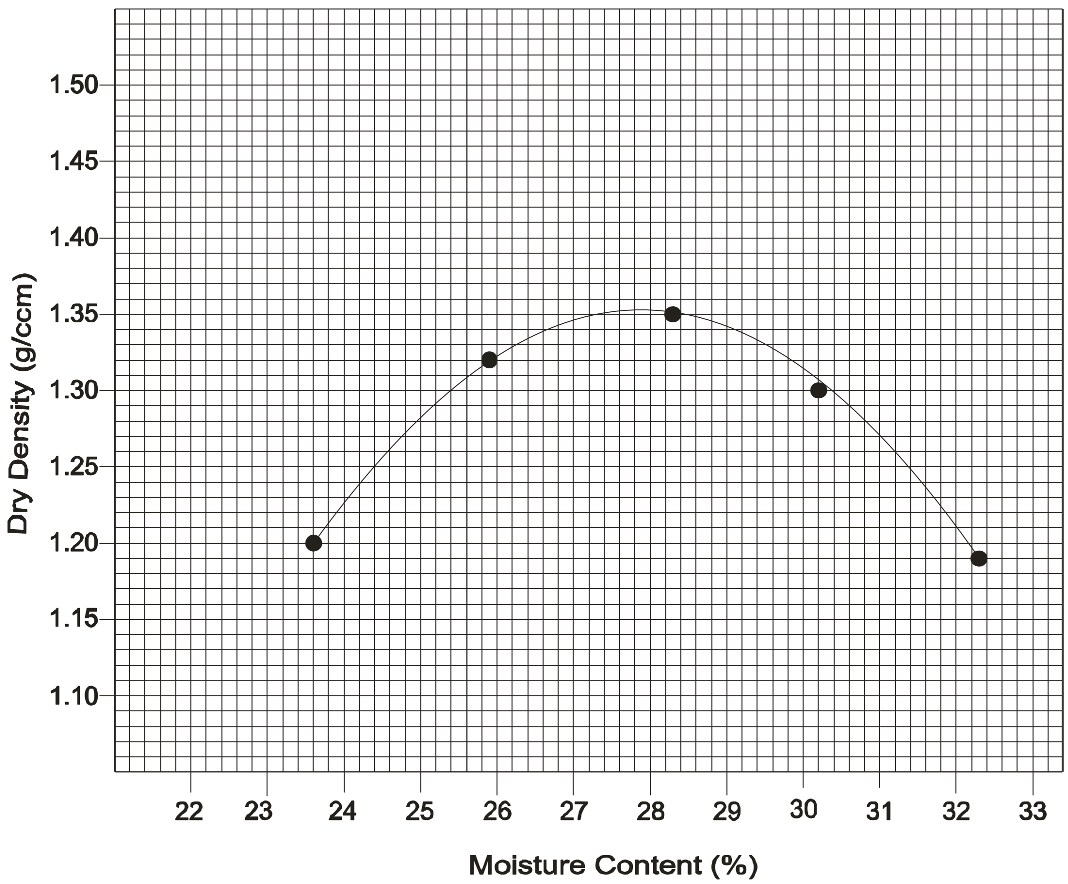


Figure 3.13: dry density-moisture content relation of 0% cement content for test pit 1

Table 3.28a: Bulk Density test result for pit 1 for 2% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5031	5030	5234	5299	5176
Weight of mold + sample (g)	6652	6799	7144	7189	7018
Weight of sample (g)	1621	1769	1910	1890	1842
Wet density (g/cm^3)	1.62	1.77	1.91	1.89	1.84

Table 3.28b: Dry Density test result for pit 1 for 2% Portland cement

Moisture Content tin number	11	23	34	55	67	87	56	69	09	22
Weight of tin plus wet soil (g)	24.36	24.32	24.70	24.74	25.09	24.97	26.09	25.82	26.81	26.78
Weight of tin plus dry soil (g)	22.34	22.31	22.33	22.34	22.32	22.22	22.76	22.54	23.01	22.98
Weight of tin (g)	10	10	10	10	10	10	10	10	10	10
Weight of water (g)	2.02	2.01	2.37	2.40	2.77	2.75	3.33	3.28	3.80	3.80
Weight of dry soil (g)	12.34	12.31	12.33	12.34	12.32	12.22	12.76	12.54	13.01	12.98
Moisture content (%)	16.34	16.32	19.22	19.40	22.52	22.52	26.12	26.12	29.22	29.24
Average moisture content (%)	16.33		19.31		22.52		26.12		29.23	
Dry density of soil (g/cm^3)	1.39		1.48		1.56		1.50		1.42	

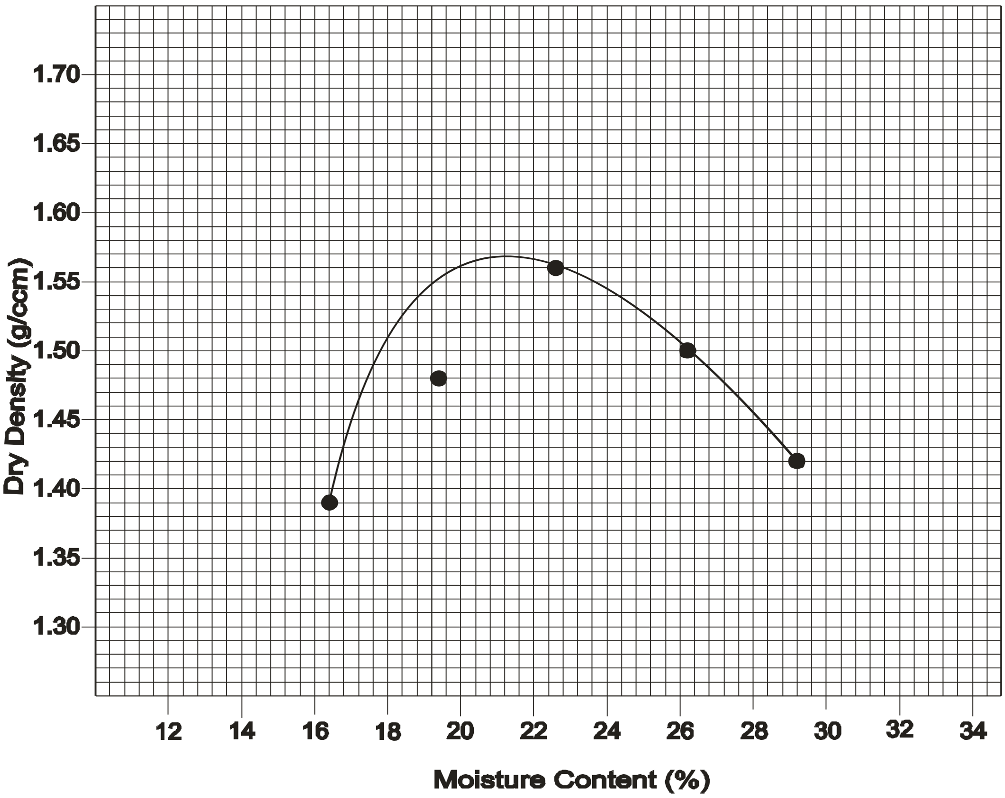


Figure 3.14: dry density-moisture content relation of 2% cement content for test pit 1

Table 3.29a: Bulk Density test result for pit 1 for 5% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5030	5031	5233	5290	5173
Weight of mold + sample (g)	6702	6792	7143	7209	6995
Weight of sample (g)	1672	1761	1910	1919	1822
Wet density (g/cm^3)	1.72	1.78	1.88	1.80	1.75

Table 3.29b: Dry Density test result for pit 1 for 5% Portland cement

Moisture Content tin number	11	13	45	67	89	09	65	54	32	12
Weight of tin plus wet soil (g)	19.86	22.08	23.00	20.26	24.54	24.14	24.63	23.61	22.75	25.22
Weight of tin plus dry soil (g)	18.21	20.21	21.23	18.45	22.21	21.87	22.06	21.22	20.33	22.33
Weight of tin (g)	08	09	11	08	10	10	10	10	10	10
Weight of water (g)	1.65	1.82	1.77	1.81	2.33	2.27	2.57	2.39	2.42	2.89
Weight of dry soil (g)	10.21	11.21	10.23	10.45	12.21	11.87	12.06	11.22	10.33	12.33
Moisture content (%)	16.20	16.24	17.32	17.30	19.09	19.13	21.34	21.32	23.46	23.44
Average moisture content (%)	16.22		17.31		19.11		21.33		23.45	
Dry density of soil (g/cm^3)	1.48		1.52		1.58		1.48		1.42	

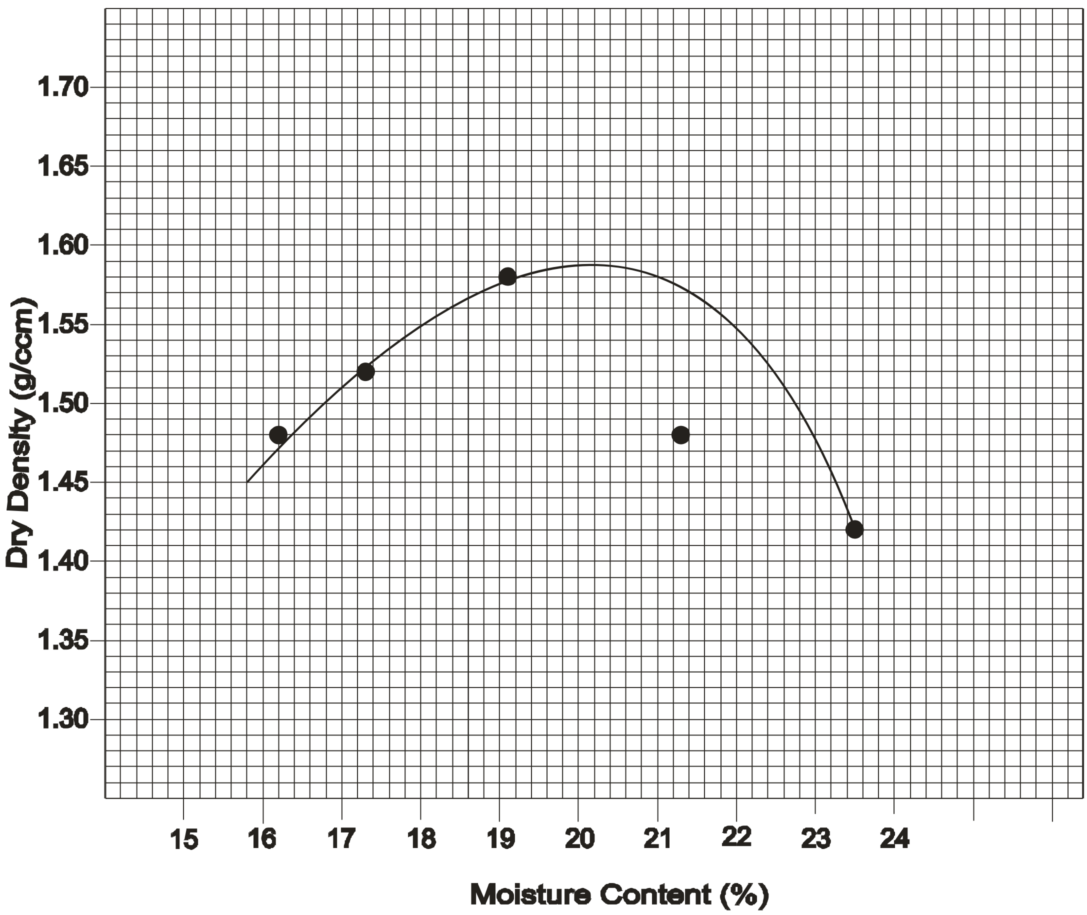


Figure 3.15: dry density-moisture content relation of 5% cement content for test pit 1

Table 3.30a: Bulk Density test result for pit 1 for 8% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5030	5031	5233	5233	5290
Weight of mold + sample (g)	6722	6853	7153	7143	7209
Weight of sample (g)	1692	1822	1920	1910	1919
Wet density (g/cm^3)	1.69	1.82	1.92	1.88	1.80

Table 3.30b: Dry Density test result for pit 1 for 8% Portland cement

Moisture Content tin number	76	23	22	09	12	13	02	01	88	98
Weight of tin plus wet soil (g)	22.89	21.79	22.34	24.47	24.60	24.44	24.54	24.14	24.63	23.61
Weight of tin plus dry soil (g)	21.31	20.22	20.45	22.56	22.45	22.33	22.21	21.87	22.06	21.22
Weight of tin (g)	09	08	08	10	10	10	10	10	10	10
Weight of water (g)	1.58	1.57	1.89	1.91	2.15	2.11	2.33	2.27	2.57	2.39
Weight of dry soil (g)	12.31	12.22	12.45	12.56	12.45	12.33	12.21	11.87	12.06	11.22
Moisture content (%)	12.81	12.83	15.18	15.20	17.27	17.15	19.09	19.13	21.34	21.32
Average moisture content (%)	12.82		15.19		17.21		19.11		21.33	
Dry density of soil (g/cm^3)	1.50		1.58		1.64		1.58		1.48	

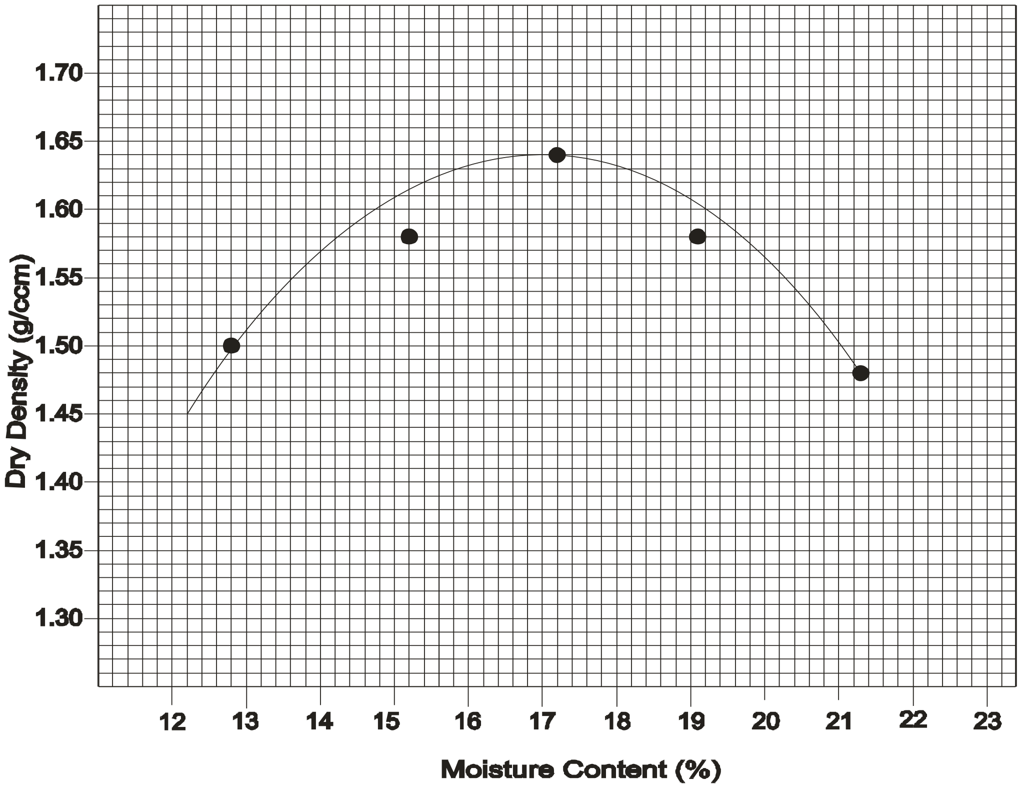


Figure 3.16: Dry Density-Moisture Content Relation of 8% cement content for test pit 1

Table 3.31a: Bulk Density test result for pit 1 for 10% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5056	5030	5289	5332	5222
Weight of mold + sample (g)	6647	6782	7280	7204	7013
Weight of sample (g)	1591	1752	1991	1872	1791
Wet density (g/cm^3)	1.59	1.75	1.99	1.98	1.79

Table 3.31b: Dry Density test result for pit 1 for 10% Portland cement

Moisture Content tin number	90	98	74	23	45	67	112	165	123	20
Weight of tin plus wet soil (g)	23.92	23.92	24.46	23.79	24.22	24.49	20.91	21.04	24.72	25.55
Weight of tin plus dry soil (g)	22.35	22.34	22.56	21.98	22.22	22.45	19.10	19.21	21.89	22.56
Weight of tin (g)	10	10	10	10	10	10	10	10	10	10
Weight of water (g)	1.57	1.58	1.90	1.81	2.00	2.04	1.81	1.83	2.83	2.99
Weight of dry soil (g)	12.35	12.34	12.56	11.98	12.22	12.45	9.10	9.21	11.89	12.56
Moisture content (%)	12.75	12.79	15.11	15.15	16.37	16.37	19.88	19.86	23.79	23.83
Average moisture content (%)	12.77		15.13		16.37		19.87		23.81	
Dry density of soil (g/cm^3)	1.41		1.52		1.71		1.65		1.45	

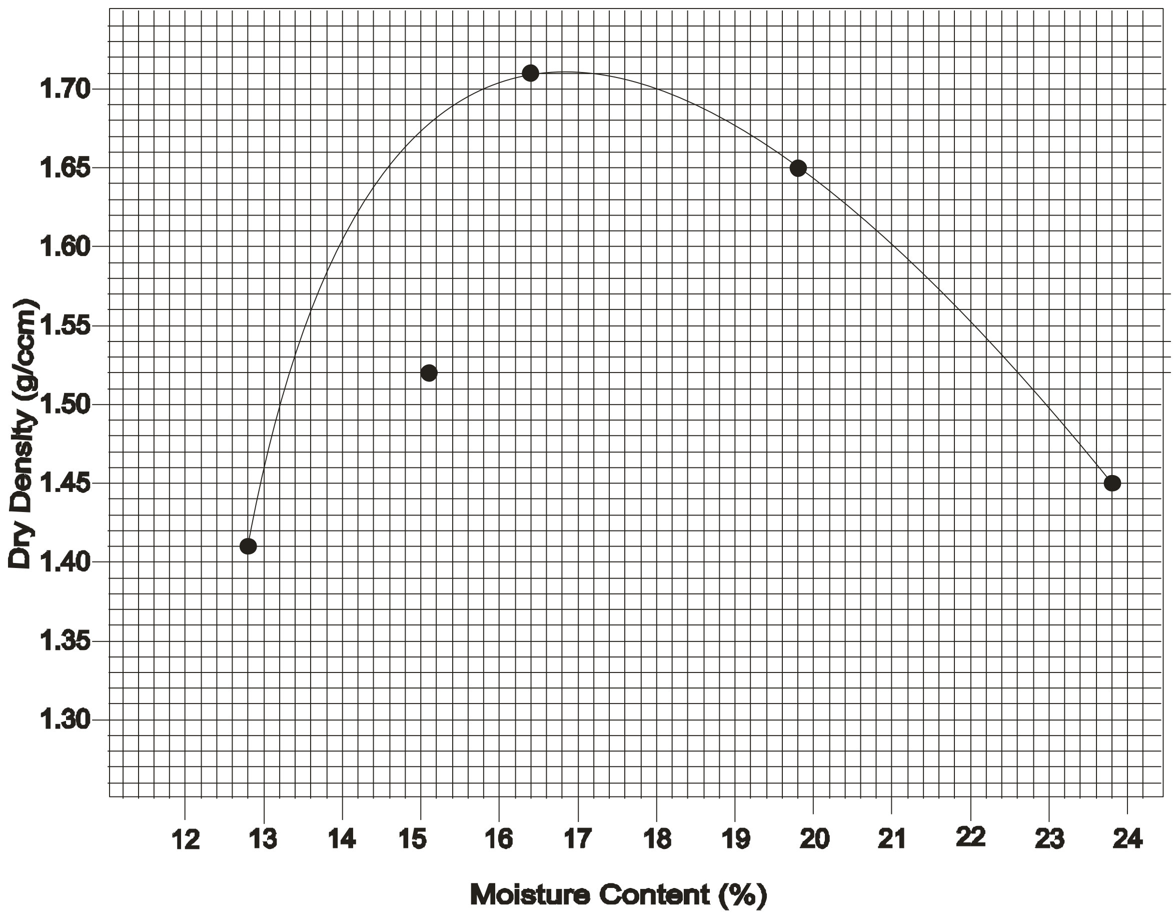


Figure 3.17: Dry Density-Moisture Content Relation of 10% cement content for test pit 1

Table 3.32a: Bulk Density test result for pit 2 for 0% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5056	5030	5289	5270	5180
Weight of mold + sample (g)	6427	6569	6891	6852	6709
Weight of sample (g)	1371	1539	1602	1582	1529
Wet density (g/cm^3)	1.37	1.54	1.60	1.58	1.53

Table 3.32b: Dry Density test result for pit 2 for 0% Portland cement

Moisture Content tin number	23	56	78	95	55	44	67	65	43	09
Weight of tin plus wet soil (g)	21.94	22.59	23.39	22.80	23.47	24.71	23.71	23.47	23.55	23.91
Weight of tin plus dry soil (g)	20.31	20.86	21.10	20.83	21.22	22.25	21.23	21.02	20.91	21.21
Weight of tin (g)	10	10	10	10	10	10	10	10	10	10
Weight of water (g)	1.63	1.73	2.02	1.97	2.25	2.46	2.48	2.45	2.64	2.70
Weight of dry soil (g)	10.31	10.86	11.10	10.83	11.22	12.25	11.23	11.02	10.91	11.21
Moisture content (%)	15.81	15.93	18.20	18.19	20.05	20.08	22.08	22.23	24.20	24.09
Average moisture content (%)	15.87		18.20		20.07		22.16		24.15	
Dry density of soil (g/cm^3)	1.18		1.30		1.33		1.29		1.23	

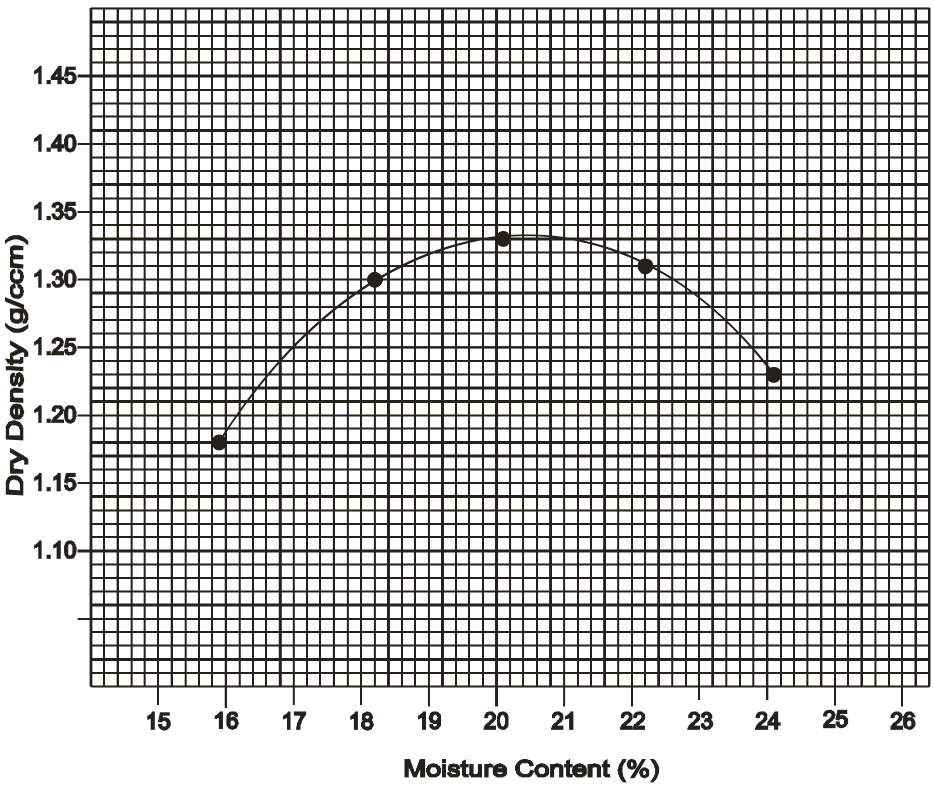


Figure 3.18: Dry Density-Moisture Content relation of 0% cement content for test pit 2

Table 3.33a: Bulk Density test result for pit 2 for 2% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5056	5030	5289	5270	5180
Weight of mold + sample (g)	6557	6781	7111	7043	6830
Weight of sample (g)	1501	1751	1822	1773	1650
Wet density (g/cm^3)	1.50	1.75	1.82	1.77	1.65

Table 3.33b: Dry Density test result for pit 2 for 2% Portland cement

Moisture Content tin number	23	45	6	7	8	78	95	56	21	99
Weight of tin plus wet soil (g)	23.95	24.10	24.34	24.23	24.57	24.61	24.86	24.81	24.95	24.82
Weight of tin plus dry soil (g)	22.20	22.34	22.33	22.23	22.32	22.35	22.36	22.32	22.22	22.11
Weight of tin (g)	10	10	10	10	10	10	10	10	10	10
Weight of water (g)	1.75	1.76	2.01	2.00	2.25	2.26	2.50	2.49	2.73	2.71
Weight of dry soil (g)	12.20	12.34	12.33	12.23	12.32	12.35	12.36	12.32	12.22	12.11
Moisture content (%)	14.34	14.26	16.30	16.35	18.26	18.30	20.23	20.21	22.34	22.38
Average moisture content (%)	14.30		16.33		18.28		20.21		22.36	
Dry density of soil (g/cm^3)	1.31		1.50		1.55		1.47		1.35	

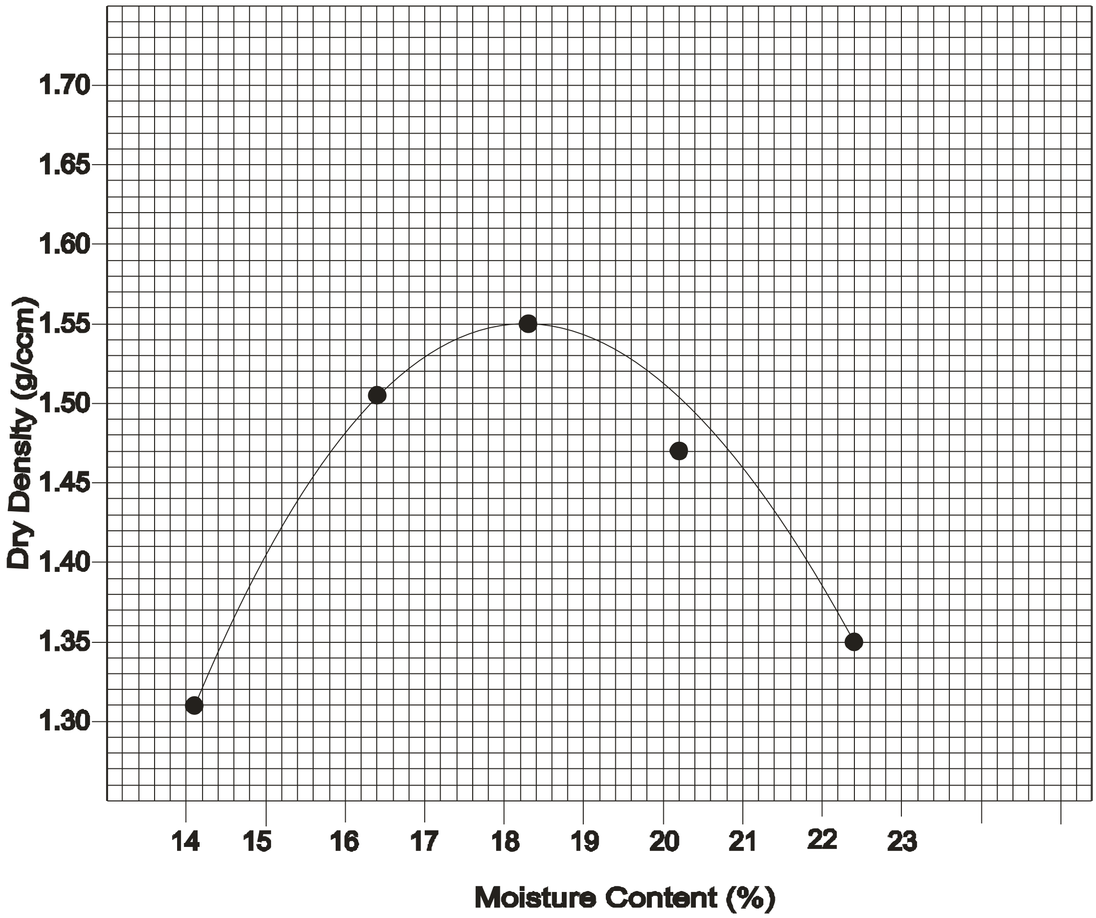


Figure 3.19: Dry Density-Moisture Content relation of 2% cement content for test pit 2

Table 3.34a: Bulk Density test result for pit 2 for 5% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5050	5032	5067	5034	5045
Weight of mold + sample (g)	6601	6864	6977	6886	6796
Weight of sample (g)	1551	1832	1910	1852	1751
Wet density (g/cm^3)	1.55	1.83	1.91	1.85	1.75

Table 3.34b: Dry Density test result for pit 2 for 5% Portland cement

Moisture Content tin number	12	22	23	67	46	89	65	49	08	88
Weight of tin plus wet soil (g)	20.17	19.95	20.39	21.53	20.56	20.31	19.52	20.56	21.39	20.87
Weight of tin plus dry soil (g)	18.98	18.78	19.01	20.00	18.97	18.76	18.01	18.88	19.45	19.02
Weight of tin (g)	10	10	10	10	10	10	10	10	10	10
Weight of water (g)	1.19	1.17	1.38	1.53	1.59	1.55	1.51	1.68	1.94	1.85
Weight of dry soil (g)	8.98	8.78	9.01	10.00	8.97	8.76	8.01	8.88	9.45	9.02
Moisture content (%)	13.30	13.34	15.36	15.32	17.70	17.74	18.86	18.90	20.56	20.56
Average moisture content (%)	13.32		15.34		17.72		18.88		20.56	
Dry density of soil (g/cm^3)	1.37		1.59		1.62		1.56		1.45	

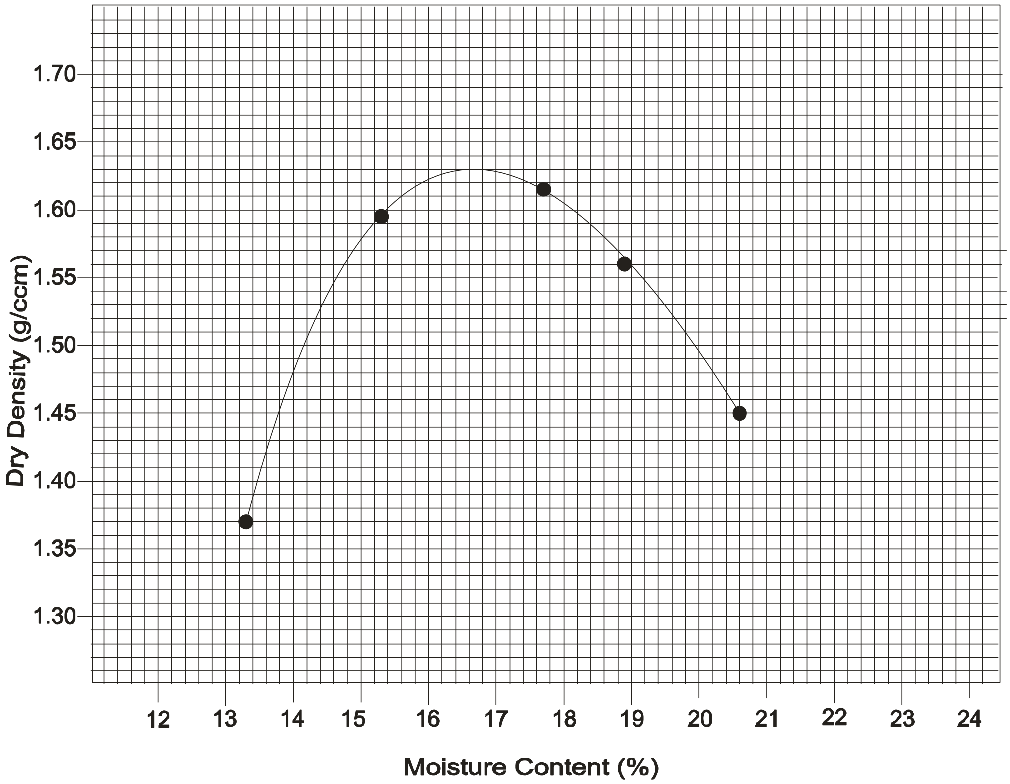


Figure 3.20: Dry Density-Moisture Content relation of 5% cement content for test pit 2

Table 3.35a: Bulk Density test result for pit 2 for 8% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5051	5031	5067	5034	5045
Weight of mold + sample (g)	6812	6953	7048	6967	6897
Weight of sample (g)	1761	1922	1981	1933	1852
Wet density (g/cm^3)	1.76	1.92	1.98	1.93	1.85

Table 3.35b: Dry Density test result for pit 2 for 8% Portland cement

Moisture Content tin number	66	09	112	181	78	143	115	67	43	22
Weight of tin plus wet soil (g)	21.64	21.65	22.93	22.82	22.68	22.67	23.21	22.05	22.08	22.59
Weight of tin plus dry soil (g)	20.31	20.32	21.31	21.21	20.88	20.87	21.21	20.22	20.13	20.56
Weight of tin (g)	10	10	10	10	10	10	10	10	10	10
Weight of water (g)	1.33	1.33	1.62	1.61	1.80	1.80	2.00	1.83	1.95	2.03
Weight of dry soil (g)	10.31	10.32	11.31	11.21	10.88	10.87	11.21	10.22	10.13	10.56
Moisture content (%)	12.87	12.85	14.30	14.34	16.55	16.57	17.90	17.88	19.21	19.21
Average moisture content (%)	12.86		14.32		16.56		17.89		19.21	
Dry density of soil (g/cm^3)	1.56		1.68		1.70		1.64		1.55	

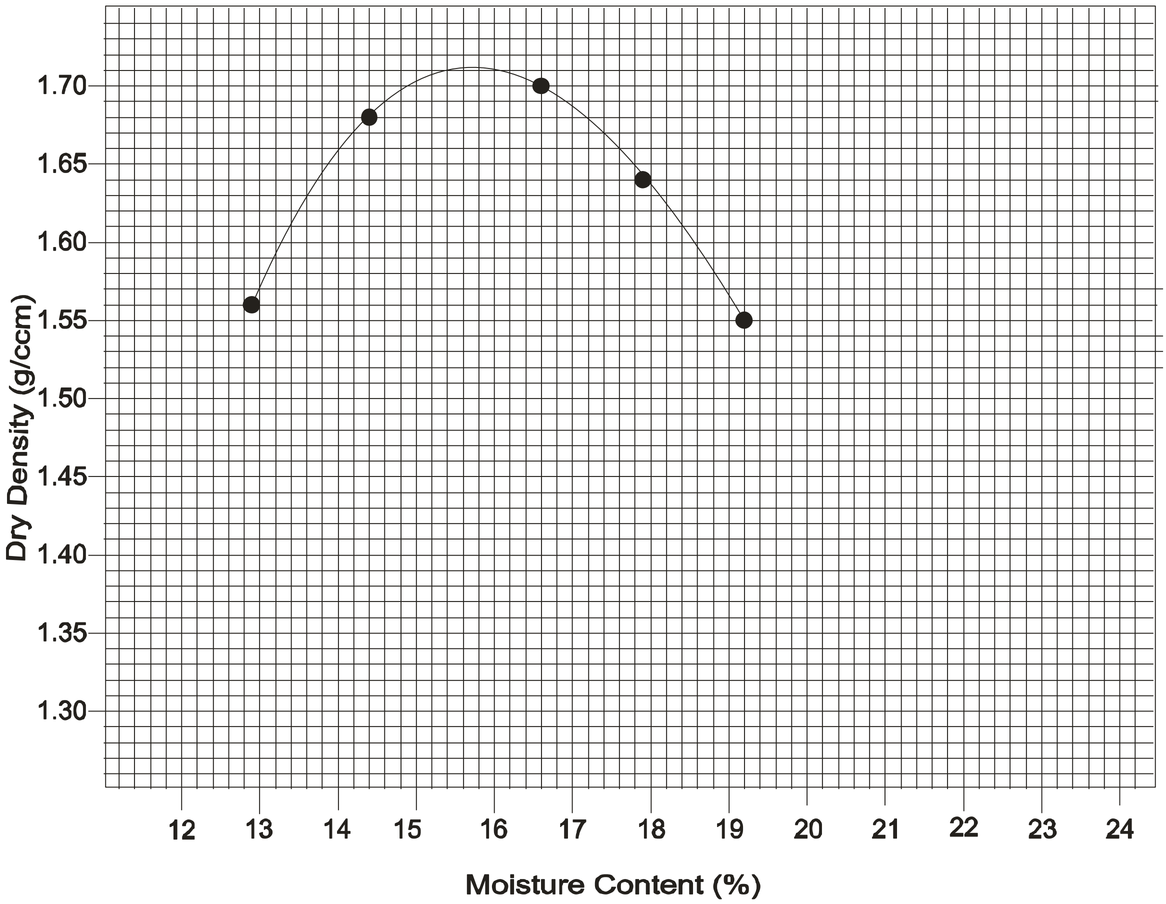


Figure 3.21: Dry Density-Moisture Content relation of 8% cement content for test pit 2

Table 3.36a: Bulk Density test result for pit 2 for 8% Portland cement

Sample No.	1	2	3	4	5
Weight of mold (g)	5051	5031	5067	5034	5045
Weight of mold + sample (g)	6792	6903	7056	6934	6776
Weight of sample (g)	1741	1872	1989	1900	1731
Wet density (g/cm^3)	1.74	1.87	1.99	1.90	1.73

Table 3.36b: Dry Density test result for pit 2 for 10% Portland cement

Moisture Content tin number	12	11	10	14	33	66	34	54	87	117
Weight of tin plus wet soil (g)	21.36	21.38	22.67	22.56	22.44	22.42	23.05	21.90	21.98	22.49
Weight of tin plus dry soil (g)	20.31	20.32	21.31	21.21	20.88	20.87	21.21	20.22	20.13	20.56
Weight of tin (g)	10	10	10	10	10	10	10	10	10	10
Weight of water (g)	1.05	1.06	1.36	1.35	1.56	1.55	1.84	1.68	1.85	1.93
Weight of dry soil (g)	10.31	10.32	11.31	11.21	10.88	10.87	11.21	10.22	10.13	10.56
Moisture content (%)	10.21	10.23	12.00	12.04	14.30	14.34	16.44	16.40	18.30	18.32
Average moisture content (%)	10.22		12.02		14.32		16.42		18.31	
Dry density of soil (g/cm^3)	1.58		1.67		1.74		1.63		1.46	

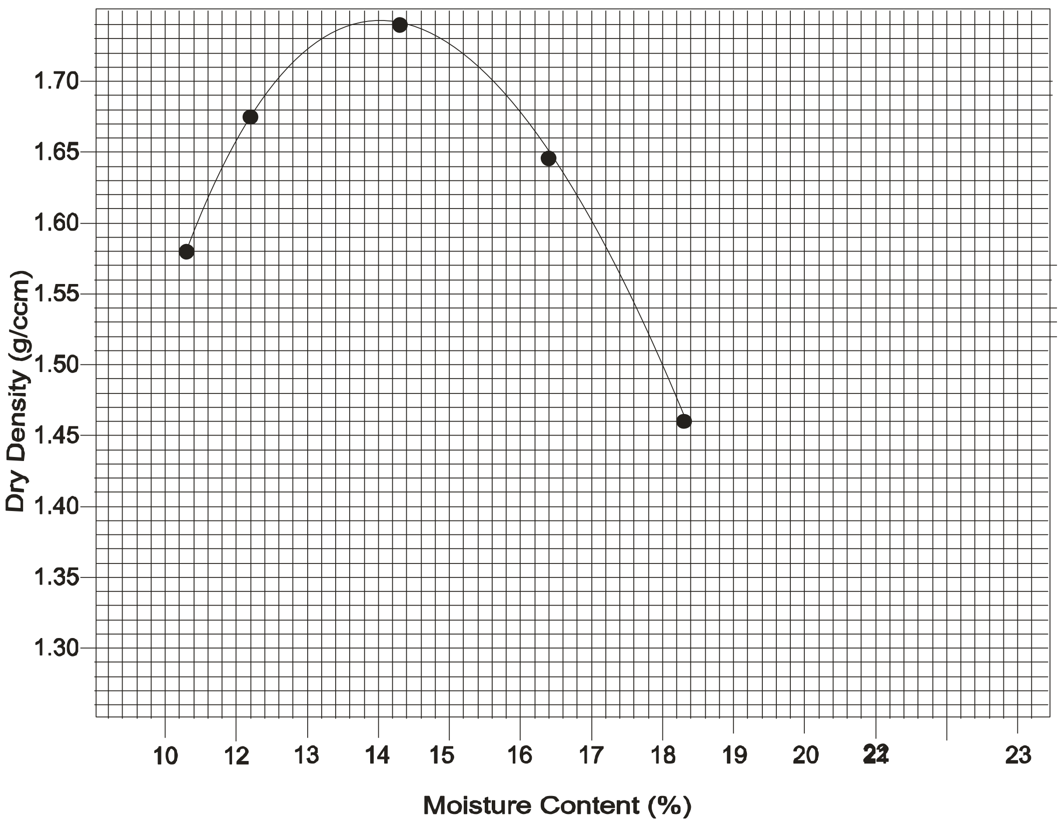


Figure 3.22: Dry Density-Moisture Content relation of 10% cement content for test pit 2

4.7 Representative California Bearing Ratio (CBR) Test Results

Table 4.37: CBR test result for pit 1 for 0% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	1	0.029
3	1.5	3	0.086
4	2.0	5	0.144
5	2.5 (0.1)	6	0.172
6	3.0	8	0.230
7	3.5	11	0.316
8	4.0	13	0.374
9	4.5	15	0.431
10	5.0 (0.2)	17	0.489
11	5.5	18	0.517
12	6.0	21	0.604
13	6.5	23	0.661
14	7.0	26	0.747
15	7.5 (0.3)	29	0.834
16	8.0	31	0.891

Note: Ring factor is 2.93

CBR Value $= \frac{0.489}{20} \times 100\% = 2.44\%$ @5mm

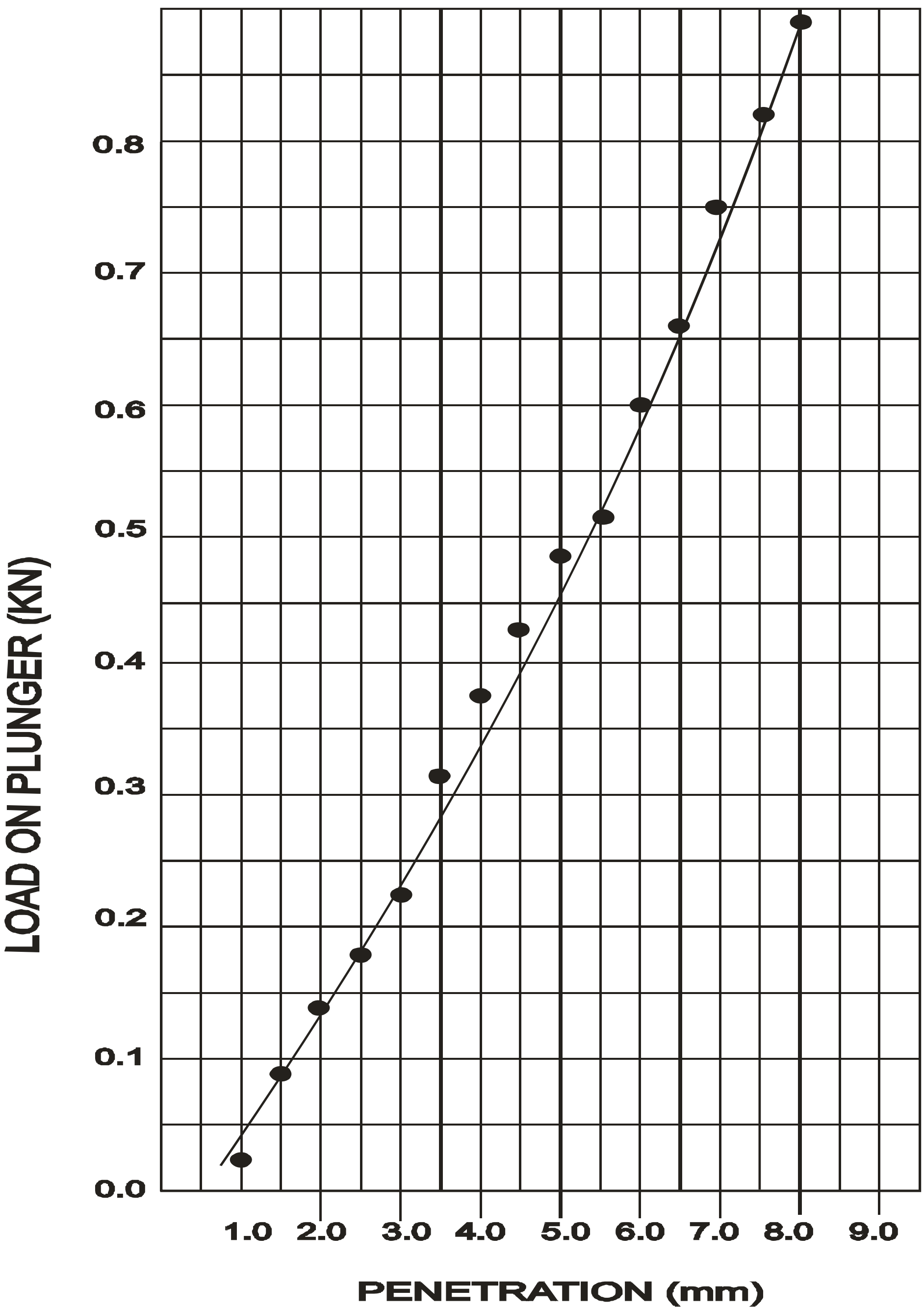


Figure 3.23: Penetration test of Soil sample with 0% cement content for test pit 1

Table 3.38: CBR test result for pit 1 for 2% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	5	0.144
3	1.5	9	0.259
4	2.0	12	0.345
5	2.5 (0.1)	15	0.431
6	3.0	17	0.489
7	3.5	19	0.546
8	4.0	21	0.604
9	4.5	23	0.661
10	5.0 (0.2)	25	0.719
11	5.5	28	0.805
12	6.0	31	0.891
13	6.5	33	0.949
14	7.0	37	1.064

15	7.5 (0.3)	39	1.121
16	8.0	42	1.207

Note: Ring factor is 2.93

CBR Value $= \frac{0.546}{13.2} \times 100\% = 4.14\%$ @2.5mm

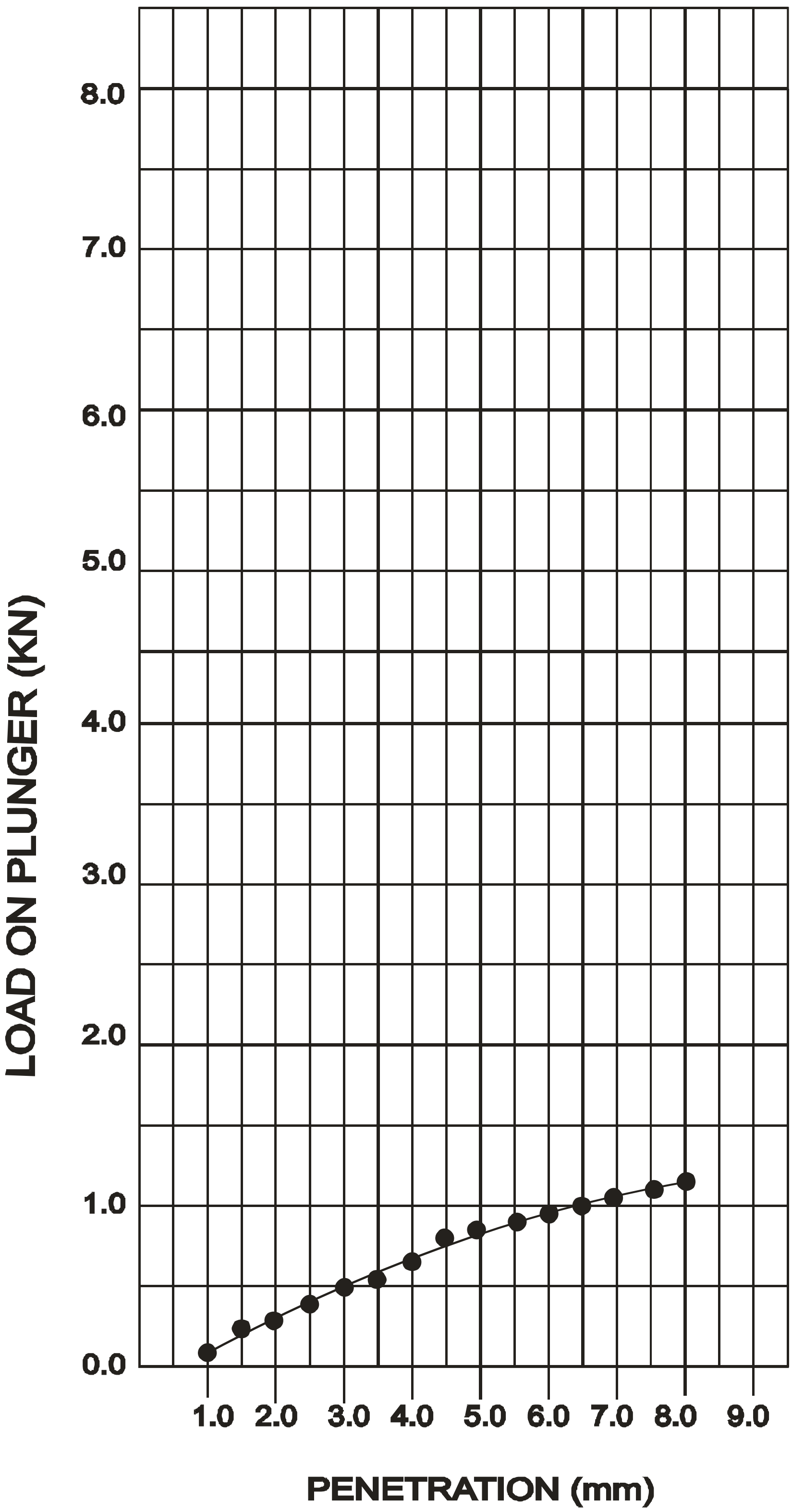


Figure 3.24: Penetration test of Soil sample with 2% cement content for test pit 1

Table 3.39: CBR test result for pit 1 for 5% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	14	0.402
3	1.5	23	0.661
4	2.0	34	0.977
5	2.5 (0.1)	46	1.322
6	3.0	55	1.581
7	3.5	63	1.811
8	4.0	72	2.070
9	4.5	80	2.299
10	5.0 (0.2)	88	2.529
11	5.5	99	2.846
12	6.0	107	3.076
13	6.5	115	3.305
14	7.0	123	3.535
15	7.5 (0.3)	130	3.737
16	8.0	137	3.938

CBR Value $= \frac{2.529}{20} \times 100\% = 12.65\%$ @5mm

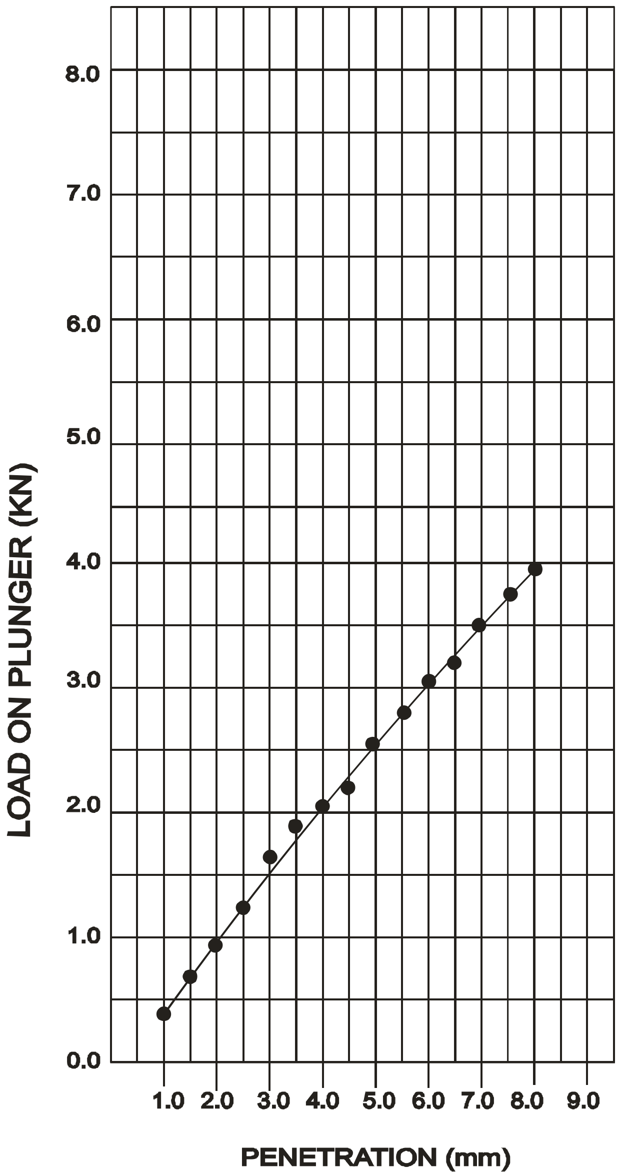


Figure 3.25: Penetration test of Soil sample with 5% cement content for test pit 1

Table 3.40: CBR test result for pit 1 for 8% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	32	0.920
3	1.5	47	1.351
4	2.0	59	1.696
5	2.5 (0.1)	74	2.127
6	3.0	83	2.386
7	3.5	92	2.644
8	4.0	99	2.846
9	4.5	105	3.018
10	5.0 (0.2)	112	3.219
11	5.5	123	3.535
12	6.0	128	3.679
13	6.5	134	3.852
14	7.0	140	4.024
15	7.5 (0.3)	143	4.110
16	8.0	149	4.283

CBR Value $= \frac{2.13}{13.2} \times 100\% = 16.14\%$ @2.5mm

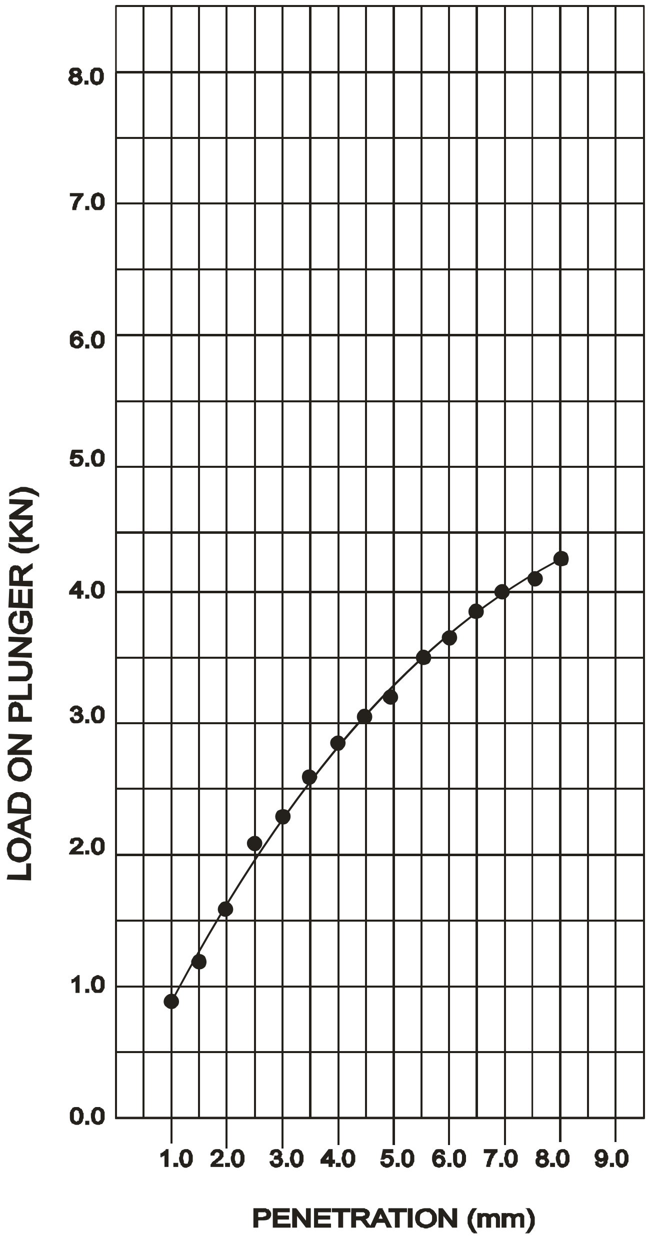


Figure 3.26: Penetration test of Soil sample with 8% cement content for test pit 1

Table 3.41: CBR test result for pit 1 for 10% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	38	1.092
3	1.5	56	1.610
4	2.0	75	2.156
5	2.5 (0.1)	96	2.759
6	3.0	105	3.018
7	3.5	113	3.248
8	4.0	120	3.449
9	4.5	129	3.708
10	5.0 (0.2)	139	3.995
11	5.5	146	4.197
12	6.0	153	4.398
13	6.5	159	4.570
14	7.0	166	4.771
15	7.5 (0.3)	171	4.915
16	8.0	176	5.059

CBR Value $= \frac{4.995}{20} \times 100\% = 25\%$ @5mm

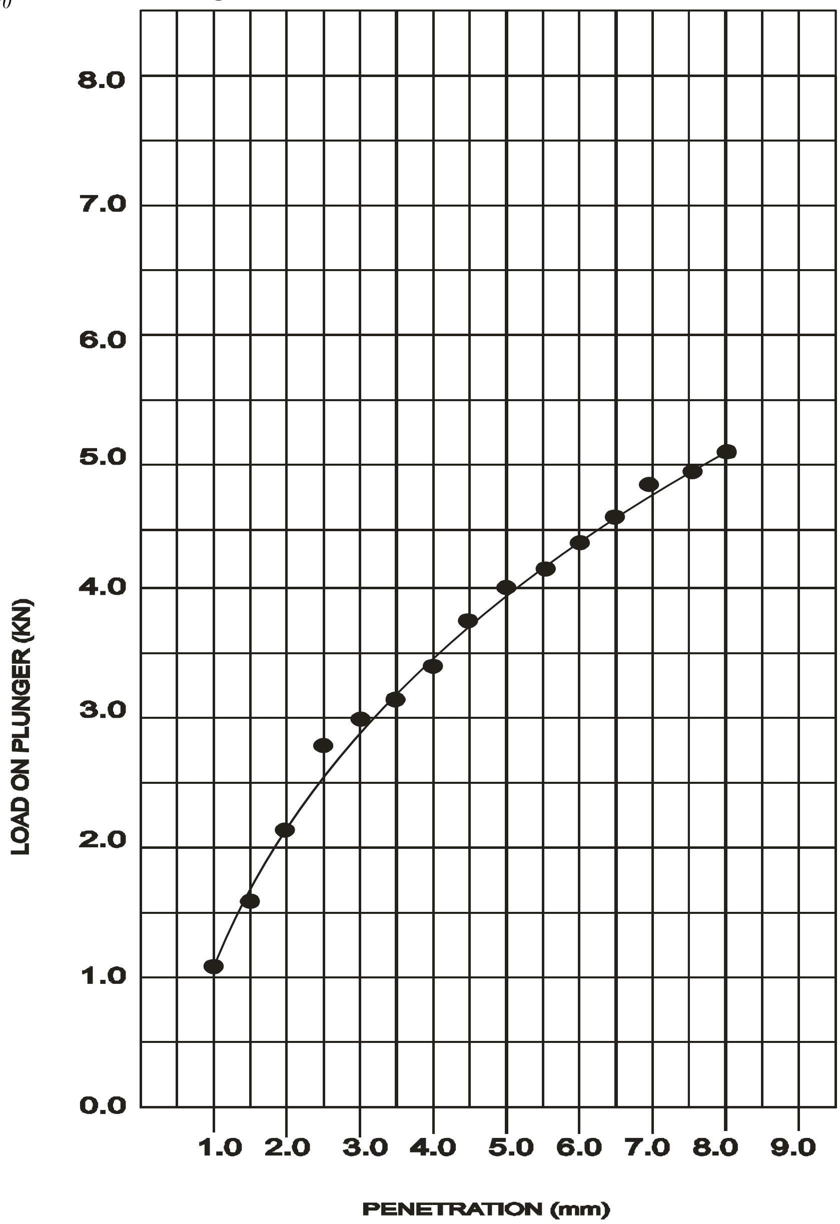


Figure 3.27: Penetration test of Soil sample with 10% cement content for test pit 1

Table 3.42: CBR test result for pit 2 for 0% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	2	0.057
3	1.5	5	0.144
4	2.0	6	0.172
5	2.5 (0.1)	8	0.230
6	3.0	11	0.316
7	3.5	13	0.374
8	4.0	14	0.402
9	4.5	16	0.460
10	5.0 (0.2)	17	0.489
11	5.5	19	0.546
12	6.0	22	0.632
13	6.5	26	0.747
14	7.0	28	0.805
15	7.5 (0.3)	32	0.920
16	8.0	35	1.006

CBR Value $= \frac{0.489}{20} \times 100\% = 2.44\%$ @5mm

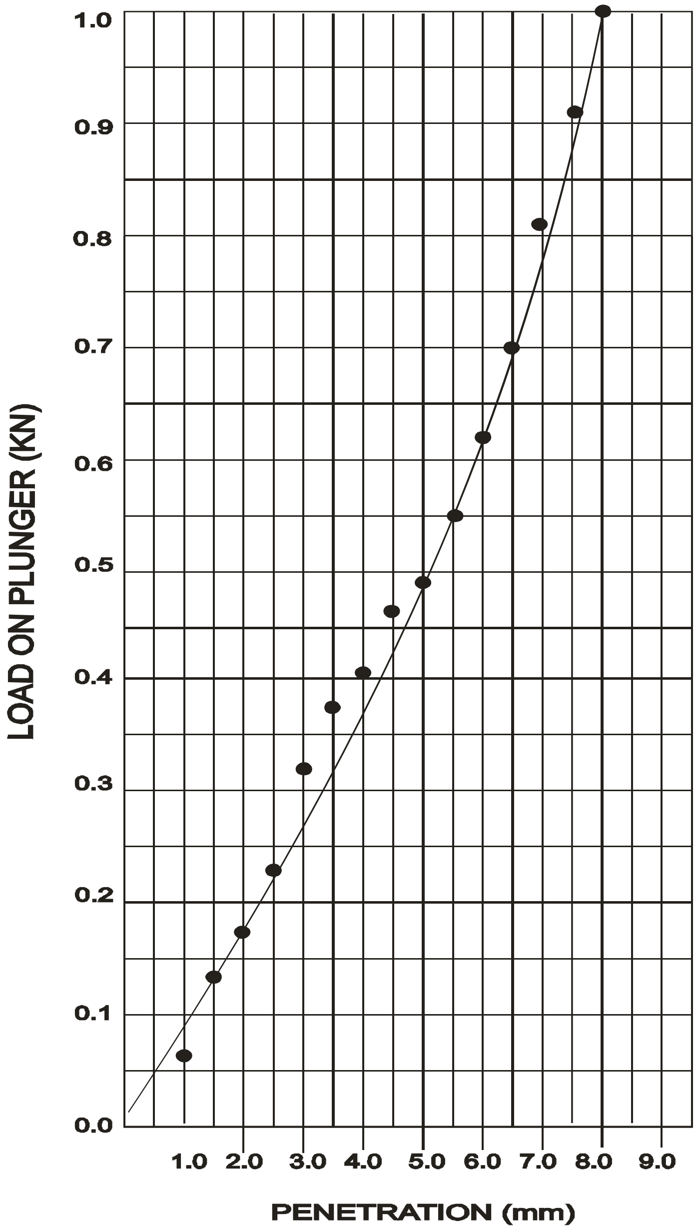


Figure 3.28: Penetration test of Soil sample with 0% cement content for test pit 2

Table 3.43: CBR test result for pit 2 for 2% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	7	0.201
3	1.5	10	0.287
4	2.0	14	0.402
5	2.5 (0.1)	17	0.489
6	3.0	21	0.604
7	3.5	24	0.690
8	4.0	29	0.834
9	4.5	33	0.949
10	5.0 (0.2)	37	1.064
11	5.5	41	1.178
12	6.0	44	1.267
13	6.5	49	1.408
14	7.0	54	1.552
15	7.5 (0.3)	58	1.667
16	8.0	61	1.753

CBR Value $= \frac{1.064}{20} \times 100\% = 5.32\%$ @5mm

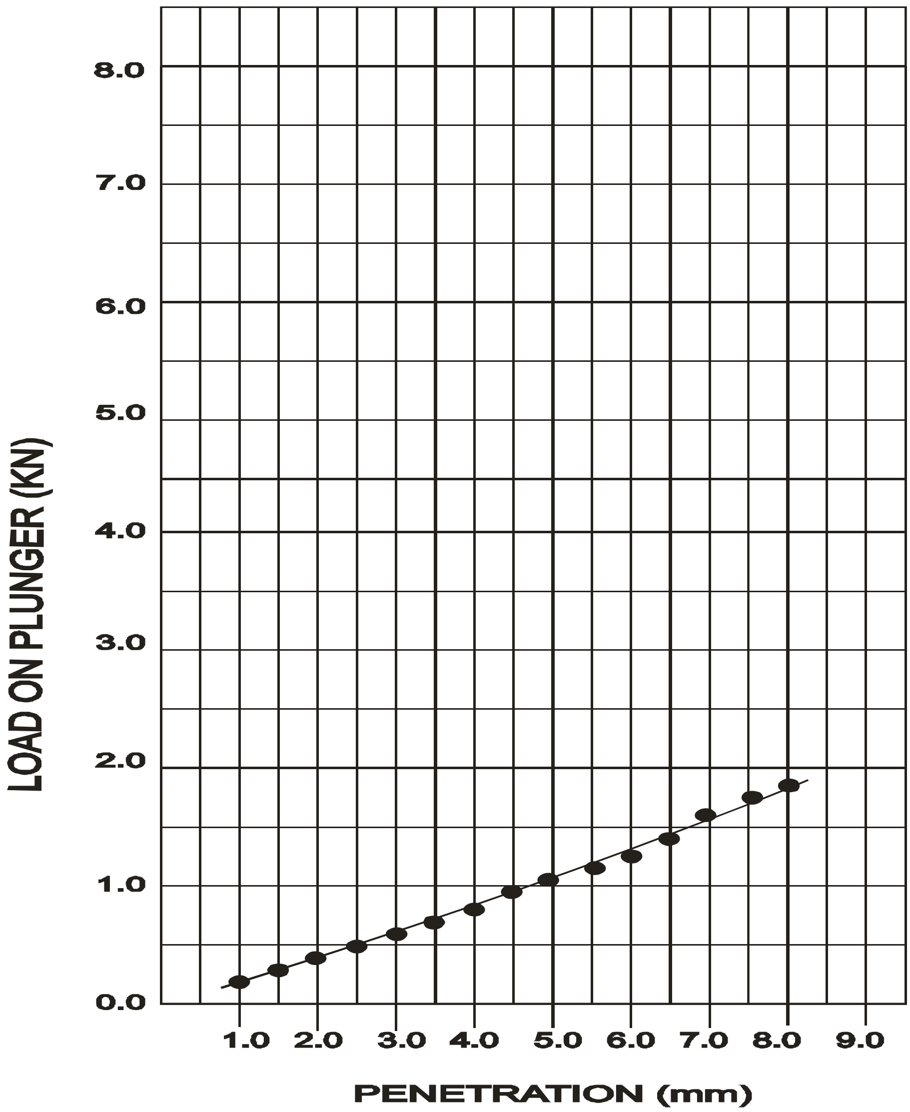


Figure 3.29: Penetration test of Soil sample with 2% cement content for test pit 2

Table 3.44: CBR test result for pit 2 for 5% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	19	0.546
3	1.5	27	0.776
4	2.0	37	1.064
5	2.5 (0.1)	48	1.380
6	3.0	56	1.610
7	3.5	62	1.782
8	4.0	70	2.012
9	4.5	79	2.271
10	5.0 (0.2)	87	2.501
11	5.5	95	2.731
12	6.0	103	2.961
13	6.5	108	3.104
14	7.0	116	3.334
15	7.5 (0.3)	123	3.535
16	8.0	131	3.765

CBR Value $= \frac{2.501}{20} \times 100\% = 12.51\%$ @5mm

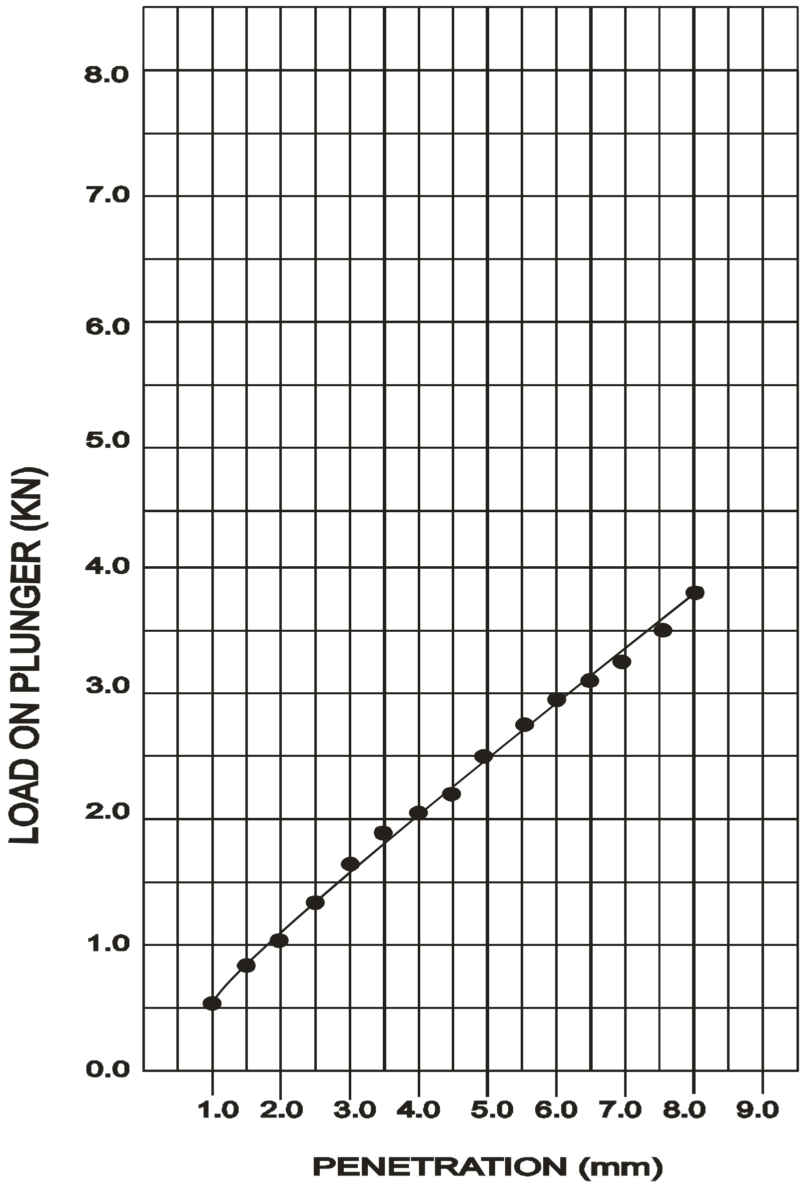


Figure 3.30: Penetration test of Soil sample with 5% cement content for test pit 2

Table 3.45: CBR test result for pit 2 for 8% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	32	0.920
3	1.5	49	1.408
4	2.0	67	1.926
5	2.5 (0.1)	80	2.300
6	3.0	92	2.644
7	3.5	105	3.018
8	4.0	114	3.277
9	4.5	123	3.308
10	5.0 (0.2)	131	3.765
11	5.5	140	4.024
12	6.0	148	4.254
13	6.5	155	4.455
14	7.0	163	4.685
15	7.5 (0.3)	171	4.915
16	8.0	180	5.174

CBR Value $= \frac{3.765}{20} \times 100\% = 18.83\%$ @5mm

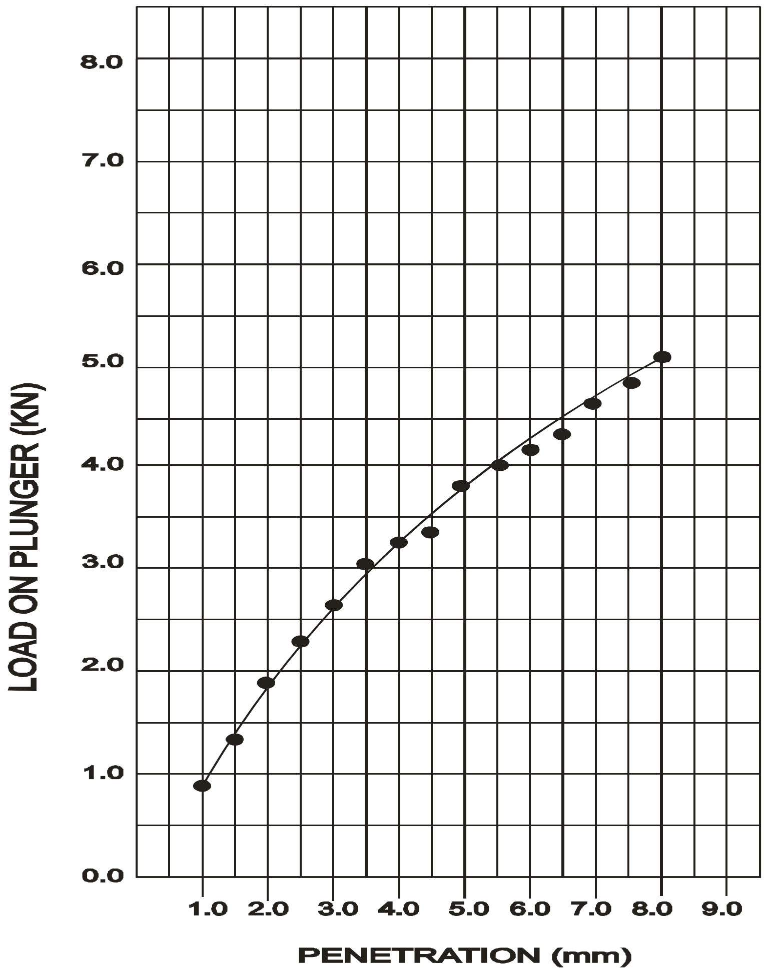


Figure 3.31: Penetration test of Soil sample with 8% cement content for test pit 2

Table 3.46: CBR test result for pit 2 for 10% Portland cement

S. No.	Penetration of plunger mm (inches)	Ring dial reading in divisions (top)	Load on plunger (KN)
1	0 (0)	0	0
2	1.0	40	1.150
3	1.5	58	1.667
4	2.0	79	2.271

5	2.5 (0.1)	98	2.817
6	3.0	113	3.248
7	3.5	129	3.708
8	4.0	142	4.082
9	4.5	158	4.541
10	5.0 (0.2)	176	5.059
11	5.5	191	5.490
12	6.0	207	5.950
13	6.5	225	6.467
14	7.0	244	7.013
15	7.5 (0.3)	259	7.445
16	8.0	272	7.818

CBR Value $= \frac{5.059}{20} \times 100\% = 25.29\%$ @5mm

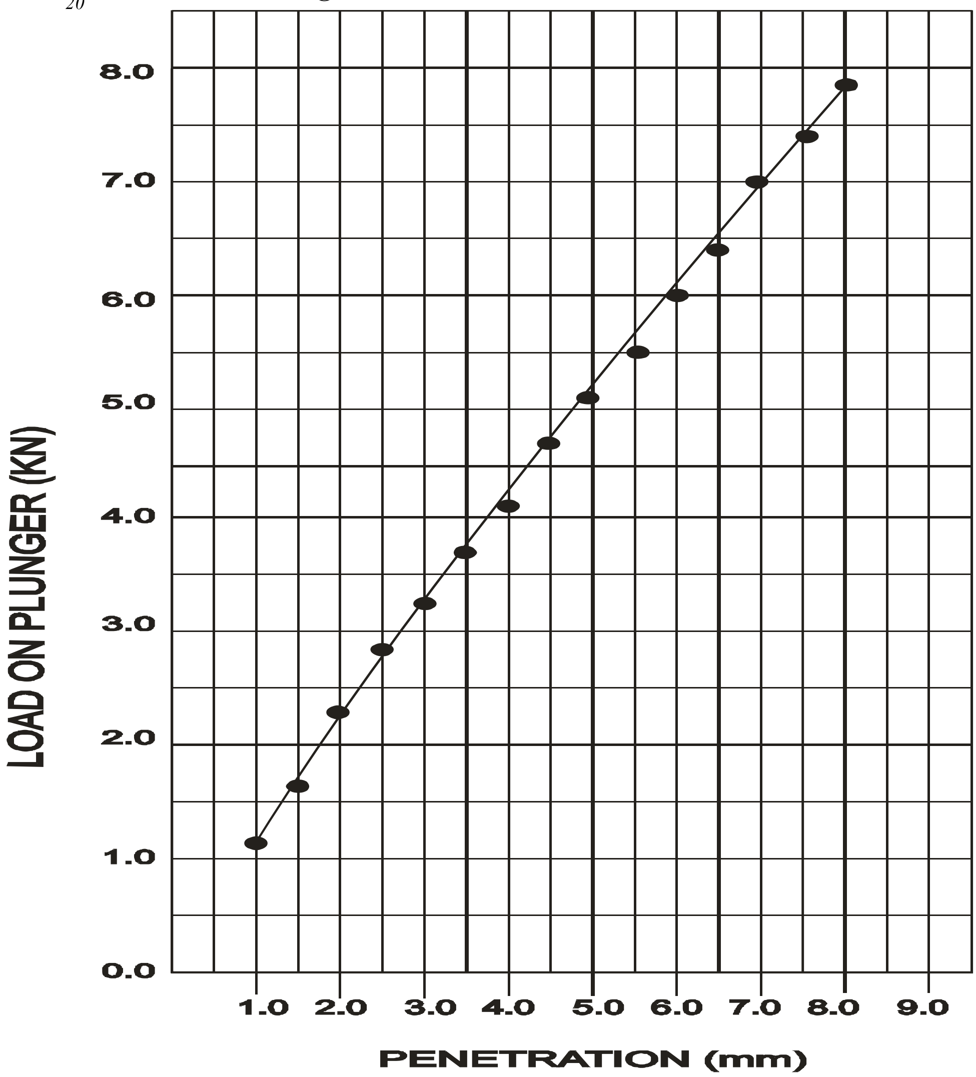


Figure 3.32: Penetration test of Soil sample with 10% cement content for test pit 2

3.8 Representative Direct Shear Test Results

Table 3.47: Shearbox test result for pit 1 for 0% Portland cement @5kg load

Horizontal Dial Reading	Horizontal Displacement, Δ□(mm) x 0.01	Load Dial Reading	Horizontal Shear Force, F(KN)	Shear Stress, □(□□/□□)
0	0	0	0	0
50	0.5	9	0.01935	5.375
100	1.0	15	0.03225	8.958
150	1.5	19	0.04085	11.347
200	2.0	27	0.05805	16.125
250	2.5	39	0.08385	23.292
300	3.0	52	0.1118	31.056

350	3.5	62	0.1333	37.028
400	4.0	72	0.1548	43.000
450	4.5	87	0.18705	51.958
500	5.0	98	0.2107	58.528
550	5.5	103	0.22145	61.514
600	6.0	116	0.2494	69.278
650	6.5	120	0.258	71.667
700	7.0	125	0.26875	74.653
750	7.5	126	0.2709	75.200
800	8.0	126	0.2709	75.200

PRC = 2.15N/div

Table 3.48: Shearbox test result for pit 1 for 0% Portland cement @10kg load

Horizontal Dial Reading	**Horizontal Displacement, Δ□(mm) x 0.01**	**Load Dial Reading**	**Horizontal Shear Force, F(KN)**	**Shear Stress, □(□□/□□)**
0	0	0	0	0
50	0.5	6	0.0129	3.583
100	1.0	14	0.0301	8.361
150	1.5	16	0.0344	9.556
200	2.0	18	0.0387	10.750
250	2.5	23	0.04945	13.736
300	3.0	29	0.06235	17.319
350	3.5	34	0.0731	20.306
400	4.0	45	0.09675	26.875
450	4.5	56	0.1204	33.444
500	5.0	67	0.14405	40.014
550	5.5	78	0.1677	46.583
600	6.0	87	0.18705	51.958
650	6.5	96	0.2064	57.333
700	7.0	102	0.2193	60.917
750	7.5	114	0.2451	68.083
800	8.0	122	0.2623	72.861
850	8.5	129	0.27735	77.042
900	9.0	130	0.27957	77.639
950	9.5	131	0.28165	78.236
1000	10.0	132	0.2838	78.672
1050	10.5	132	0.2838	78.672
1100	11.0	132	0.2838	78.672

Table 3.49: Shearbox test result for pit 1 for 0% Portland cement @15kg load

Horizontal Dial Reading	**Horizontal Displacement, Δ□(mm) x 0.01**	**Load Dial Reading**	**Horizontal Shear Force, F(KN)**	**Shear Stress, □(□□/□□)**
0	0	0	0	0
50	0.5	8	0.0172	4.778
100	1.0	11	0.02365	6.569
150	1.5	25	0.05375	14.931
200	2.0	34	0.0731	20.306
250	2.5	46	0.0989	27.472
300	3.0	57	0.12255	34.042
350	3.5	68	0.1462	40.611
400	4.0	76	0.1634	45.389
450	4.5	87	0.13705	51.958
500	5.0	92	0.1978	54.944
550	5.5	102	0.2193	60.917
600	6.0	116	0.2494	69.278
650	6.5	123	0.26445	73.458
700	7.0	129	0.27735	77.042
750	7.5	133	0.28595	79.431
800	8.0	134	0.288	80.028
850	8.5	136	0.292	81.222
900	9.0	137	0.295	81.819
950	9.5	138	0.2967	82.145
1000	10.0	138	0.2967	82.145

Table 3.50: Maximum value for Load of pit test 1 (0% Portland cement content)

Normal Load, N (KN)	0.09	0.14	0.19
Normal Stress, □□ (KN/m^2)	25.000	38.889	52.778
Maximum Shear Stress, □ (KN/m^2)	75.200	78.672	82.145
Cohesion, C (KN/m^2)	68.95		
Angle of internal friction, □(°)	14		

Table 3.51: Maximum value for Load of pit test 1 (2% Portland cement content)

Normal Load, N (KN)	0.09	0.14	0.19
Normal Stress, □□ (KN/m^2)	25.000	38.889	52.778
Maximum Shear Stress, □ (KN/m^2)	123.043	127.556	132.069
Cohesion, C (KN/m^2)	114.92		
Angle of internal friction, □(°)	18		

Table 3.52: Maximum value for Load of pit test 1 (5% Portland cement content)

Normal Load, N (KN)	0.09	0.14	0.19
Normal Stress, □□ (KN/m^2)	25.000	38.889	52.778
Maximum Shear Stress, □ (KN/m^2)	195.528	202.004	208.481
Cohesion, C (KN/m^2)	183.87		
Angle of internal friction, □(°)	25		

Table 3.53: Maximum value for Load of pit test 1 (8% Portland cement content)

Normal Load, N (KN)	0.09	0.14	0.19
Normal Stress, □□ (KN/m^2)	25.000	38.889	52.778
Maximum Shear Stress, □ (KN/m^2)	267.832	276.177	284.522
Cohesion, C (KN/m^2)	252.81		
Angle of internal friction, □(°)	31		

Table 3.54: Maximum value for Load of pit test 1 (10% Portland cement content)

Normal Load, N (KN)	0.09	0.14	0.19
Normal Stress, □□ (KN/m^2)	25.000	38.889	52.778
Maximum Shear Stress, □ (KN/m^2)	515.856	327.035	337.125
Cohesion, C (KN/m^2)	298.78		
Angle of internal friction, □(°)	36		

Graphical representation of the properties of Soil samples

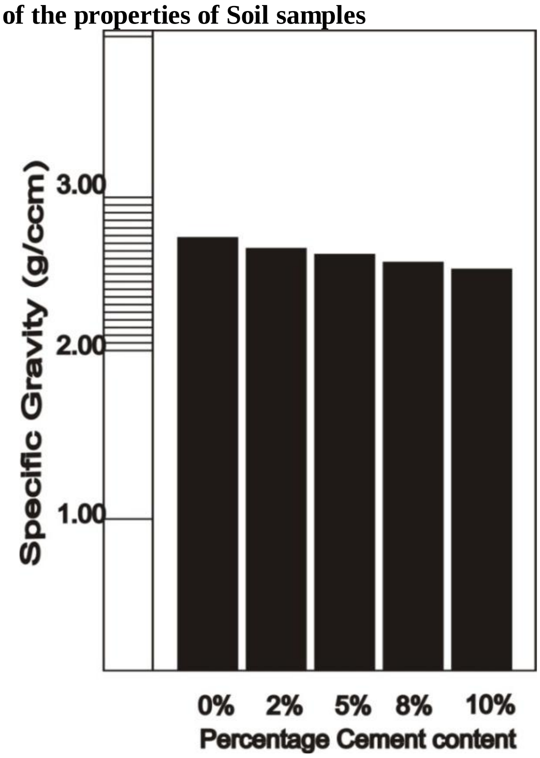


Figure 3.33: Influence of Cement Content on Specific Gravity (SG) for test pit 1

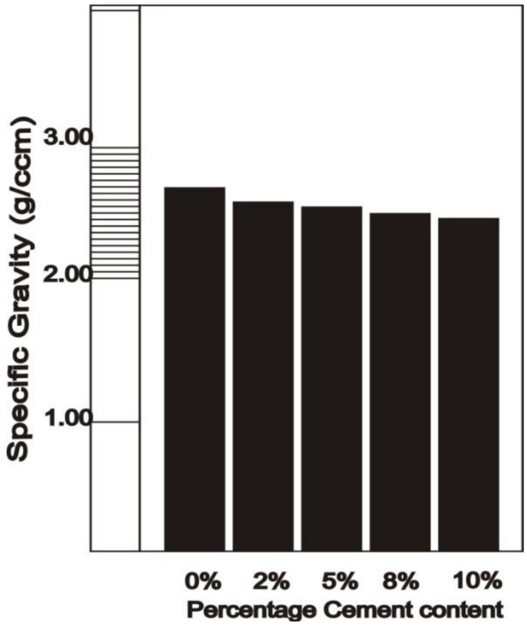


Figure 3.34: Influence of Cement Content on Specific Gravity (SG) for test pit 2

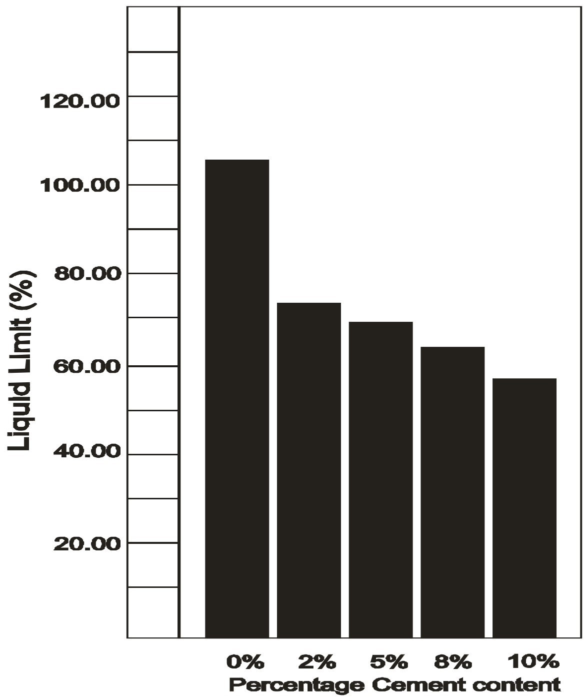


Figure 3.35: Influence of Cement Content on Liquid Limit (LL) for test pit 1

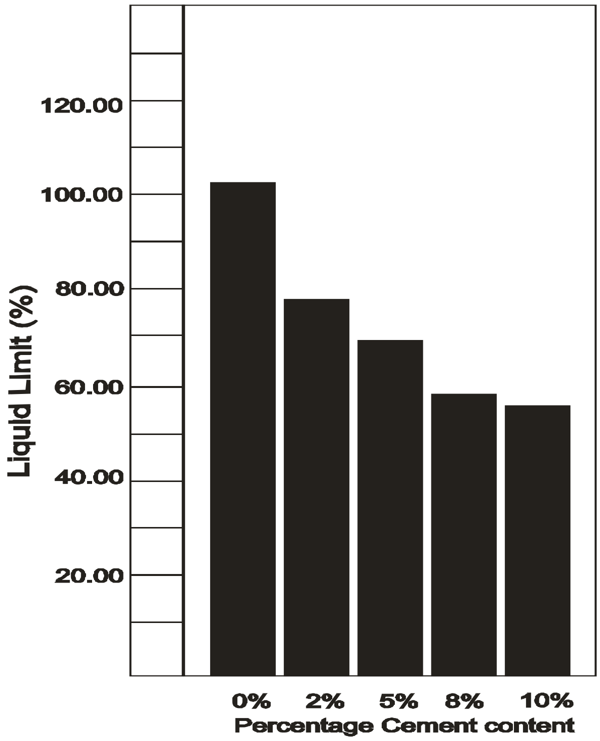


Figure 3.36: Influence of Cement Content on Liquid Limit (LL) for test pit 2

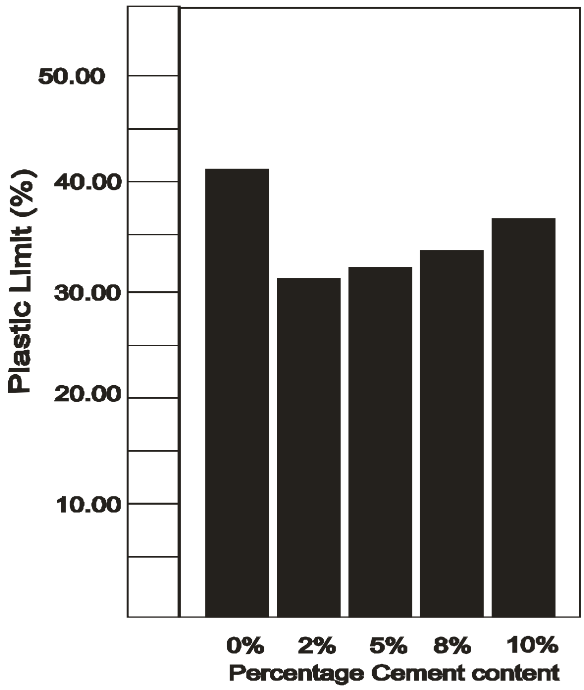


Figure 3.37: Influence of Cement Content on Plastic Limit (LL) for test pit 1

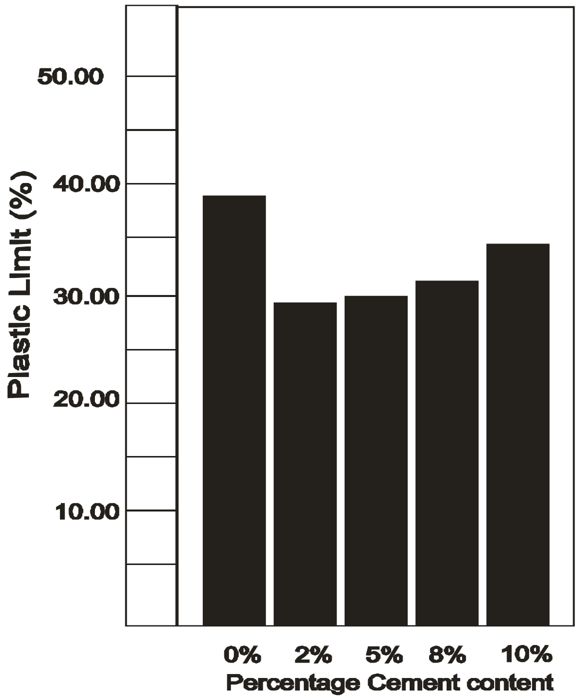


Figure 3.38: Influence of Cement Content on Plastic Limit (LL) for test pit 2

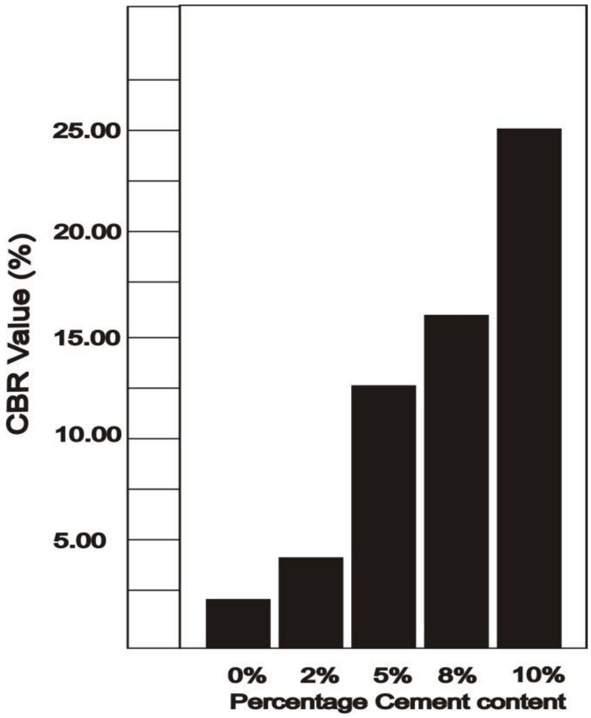


Figure 3.39: Influence of Cement California Bearing Ratio (CBR) for test pit 1

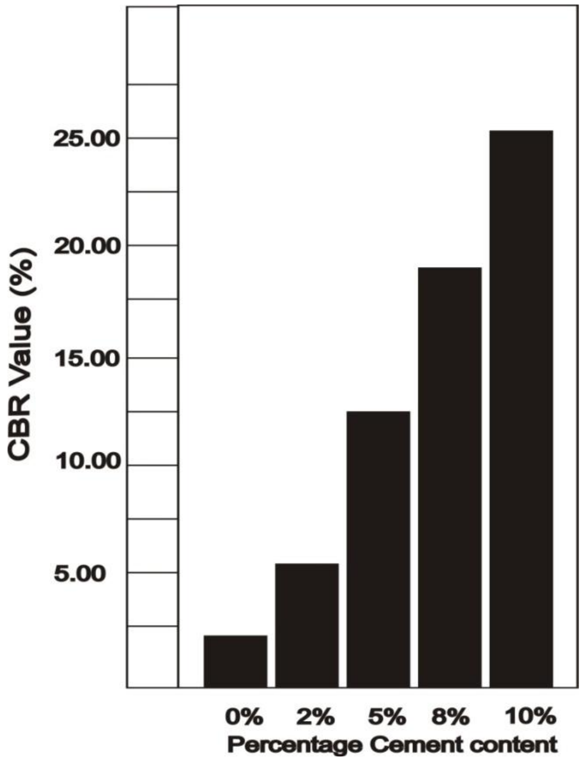


Figure 3.40: Influence of Cement California Bearing Ratio (CBR) for test pit 2

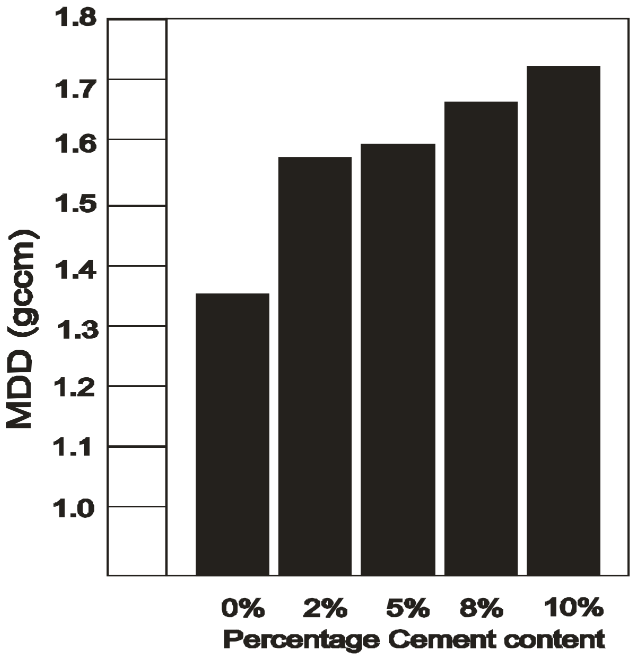


Figure 3.41: Influence of Cement Maximum Dry Density (MDD) for test pit 1

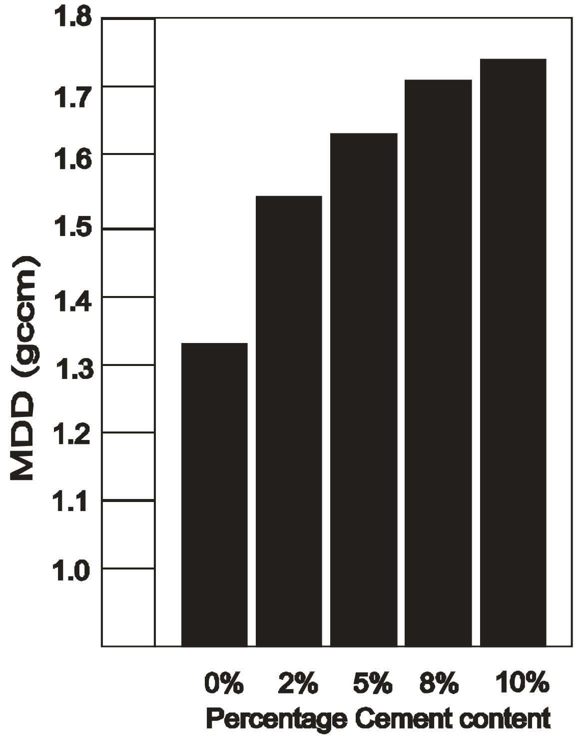


Figure 3.42: Influence of Cement Maximum Dry Density (MDD) for test pit 2

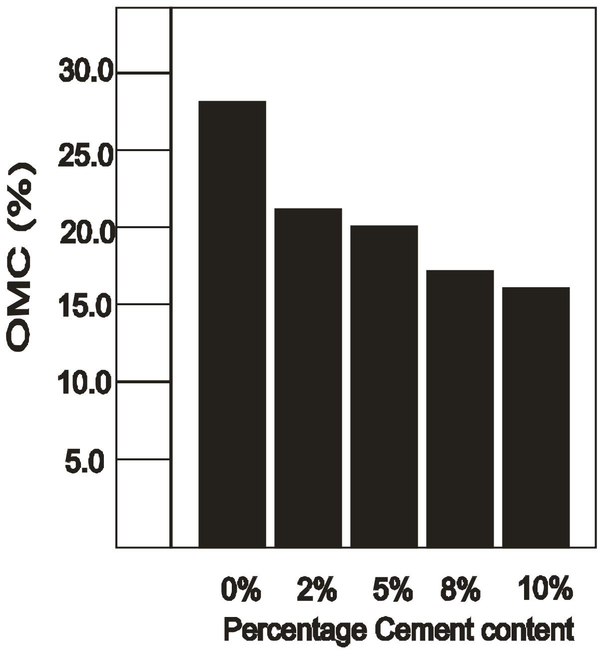


Figure 3.43: Influence of Cement Optimum Moisture Content (OMC) for test pit 1

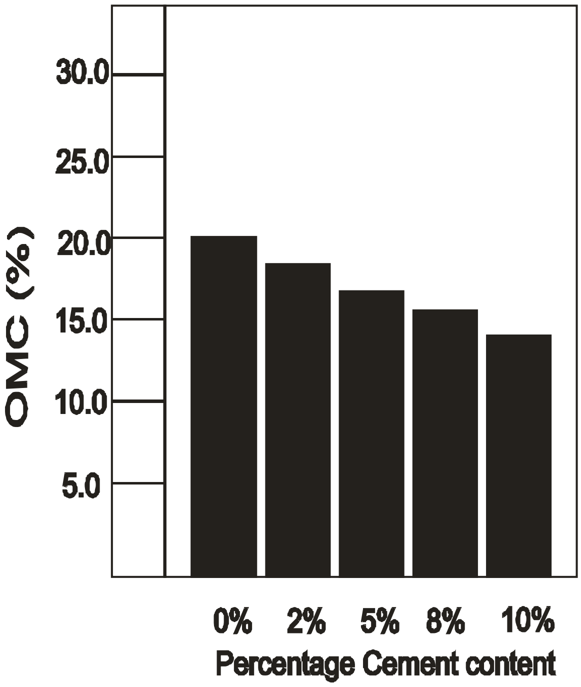


Figure 3.44: Influence of Cement Optimum Moisture Content (OMC) for test pit 2

IV. Conclusion

An investigation into the effect of stabilization of expansive soil for highway pavement using Portland cement on the Engineering properties of the expansive soil obtained from Emene in Enugu State in the Eastern part of Nigeria. The soil was collected by method of disturbed sampling from a depth of 3m. The soil sample was sealed to avoid loss of moisture during transportation. After various laboratory test was carried out on the soil sample the following conclusion were made:

- Portland cement provides strength and durability which is outstanding value a sub-base material. 5-10 percent of Portland cement is required to stabilize an expansive soil for highway pavement.
- The Portland cement provides a layer in the sub-base which distributes the loads on the pavement uniformly there by reducing the deflection and moisture content of the soil.
- The liquid limit of the expansive decreases as the percentage of the Portland cement is increased and also the plastic limit increases as percentage of Portland cement is increased.
- The OMC of the decreases with increase of cement content.
- The UCS of the stabilized soil increase with increase quantity of cement content in the mixture.
- The maximum dry density of the stabilized soil increase with increase cement content.
- The specific gravity of the stabilized soil decreases with increase in the cement content.
- The CBR value increases significantly as the cement content is gradually increasing.
- The cohesion and the angle of internal friction obtained from the direct shear test are found to be increased as the cement content is increased.

V. Recommendation

The followings are recommendation for the use of Portland cement as stabilizer of expansive soil.

- To obtain more accurate results on the engineering properties of stabilized soil, there is need to collect as many samples throughout the length of the construction site.
- Cement stabilized soil is a highly compacted mixture of soil/aggregate, cement, and water. It has a low cost pavement base for roads, residential streets, parking areas, airports, shoulders, and storage areas.
- Its advantages of great strength and durability combine with low cost to make it the outstanding value in its field.
- A thin bituminous surface is usually placed on the soil-cement to complete the pavement.
- Due to sudden hardening of the soil-cement mixture, there will be cracking of the layer when subjected to a heavy load. Portland cement stabilization is not suitable for all road construction.

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