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Correlation of Penetration Index of Dynamic Cone Penetrometer with Laboratory Dry Density and Moisture Content of Lateritic Gravel Soils

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Abstract - *The satisfactory performance of road pavements built with lateritic gravel largely depends on the compaction quality assurance and control measures undertaken during the construction phase. The sand replacement method is a destructive in-situ test that has been widely used as a compaction verification method in the field. However, this method is time consuming, tedious and tends to weaken the pavement layers if not properly executed. The dynamic cone penetrometer (DCP) is on the other hand, a simple portable device that provides a rapid, easy to operate, easy to understand and a non-destructive method for determining the strength parameters and profile of pavement layers. The compaction quality assurance and control process could be simplified by using the DCP as a compaction verification tool. This requires the establishment of correlation equations between the in-mould DCP penetration index (DPI) and the dry density/moisture contents from laboratory compaction tests. In this research, a lightweight DCP device was used to evaluate the correlation between the DPI and the dry density/moisture content of nine (9) lateritic gravel soils in the laboratory. By AASHTO classification system, eight (8) of the soil samples are granular materials in group A-2 and A-3. Only one sample is silt clay material from group A-7. The DCP device consisted of an 8-kg hammer that drops over a height of 575 mm, driving a 60° cone tip with 20 mm base diameter into the compacted samples. The results indicate very good model equations with very high coefficient of determination greater than 90% for R^2 and more than 80% for adjusted R^2.*

***Key Words*:** Dynamic cone penetration index (DPI), Dynamic Cone Penetrometer (DCP), Sand Replacement Method, Non-destructive method, Compaction verification, Maximum dry density (MDD), Optimum moisture content (OMC), Minimum DPI (DPImin).

1. INTRODUCTION

Lateritic gravel has been widely used as a good source of material for pavement construction especially in Ghana because they are readily available and relatively economical [1, 2]. However, the satisfactory performance of the road pavement built with this material largely depends on the quality assurance and control measures taken during the construction phase. High level of compaction is associated with high strength and minimum deformation, which leads to durable pavement layers. The level of compaction achieved is usually determined by measuring the dry density and water content of the compacted soil. In road pavement design, compaction quality assurance and control is typically performed based on the ASTM Test Method for Laboratory Compaction Characteristics of Soil. The procedure for verifying the level of compaction is done by determining the in-place dry density achieved in the field and then comparing this value with the maximum dry density obtained in the laboratory using the AASHTO T 180 specification [3, 4]. Several test methods are used to determine the in-place dry density and water content. These include sand replacement or sand cone method, ASTM D 1556-07 [5]; the rubber balloon, ASTM D 2167-08 [6]; drive cylinder, ASTM D 2937-10 [7], and nuclear-moisture density gauge, ASTM D 6938-10 [8].

For pavement quality assurance and control testing, the sand replacement test and the nuclear gauge tests are the most common method and specified for use in Ghana [3]. The nuclear gauge test, conducted according to BS 1377 [3, 9], is mostly used on large projects that are well funded because it is hazardous and requires the use of highly trained personnel in protective clothing to operate. The sand replacement method, however, is simple to operate and the commonest method preferred on low-volume road works. However, it has many key disadvantages such as:

- it is destructive to the pavement layers;
- it is tedious;
- it is time consuming; and
- It requires determination of the water content of the compacted material scooped out.

As a result, the compaction quality assurance and control is considerably slowed down beyond the desirable rate and consequently, the number of compaction quality assurance and control operation may be reduced or not even performed at all. However, the whole compaction quality assurance and control process may be simplified by introducing the Dynamic Cone Penetrometer (DCP) as a verification tool for the levels of compaction being achieved both on site and in the laboratory.

The DCP is a simple device that provides a rapid, easy-to-operate, easy-to-understand and a non-destructive method for determining the strength profile of flexible pavements or the subgrade due to its ability to provide a continuous record of relative soil strength with depth. The DCP has been widely used by many agencies primarily to estimate the California

Bearing Ratio (CBR) in-situ [10, 11]. The DCP was also proposed for use in the design and performance evaluation of road pavements [11-13]. Quadros and Jacobsz [14] used the DCP to estimate the elastic modulus back calculated from the falling weight deflectometer test. George, Rao [15] and Jjuuko, Kalumba [16] applied the DCP to predict the dry density achieved in lateritic soils in-situ. Gabr, Hopkins [11] and Ampadu and Arthur [17] proposed the DCP as a compaction verification tool. The Effect of Confinement on the Dynamic Cone Penetration Index of a Lateritic Soil for Field Compaction Verification was examined by Ackah [18].

This present research aims at determination of correlation equations for use with the DCP equipment and their reliability, which can aid in the compaction quality assurance and control of lateritic gravels with focus on Northern Ghana. The developed equations correlate the laboratory compacted dry density with in-mould DCP values (DPI) that can be applied in the field for compaction verification.

2. MATERIALS AND METHODS

To achieve the suitable correlations between the DCP test results and compaction characteristics of lateritic gravel soils, it was essential to select suitable samples. The appropriate sampling areas were selected based on convenience and proximity to the lab. Sampling was executed according to standard methods. The samples were then transported to the laboratory and prepared for the tests as explained in the later sections.

2.1 Location of Sample Area

The laterite soil samples for the study were collected within the Tamale metropolis and its surroundings. The samples were taken to the materials laboratory of Ghana Highways Authority of the Tamale Metropolis where they were tested. Figure 1 shows locations on a Google earth map of Tamale Metropolis where some of the samples were collected.

Fig -1: Layout of Samples Collection Points

2.2 Geology of Sample Area

The Tamale Metropolitan area lies within the Voltaian system, which is one of the geotectonic units in which Ghana can be delineated over the whole history of the geological time scale. The main rock types underlying the metropolis are sandstone, mudstone and shale, which over time, have been weathered to different degrees [19]. The main soil types that have resulted from the weathering of the above rocks include sand, clay and laterite ochrosols. Serious erosion may occur in these soil types during the rainy season due to scarce protection by vegetation [20].

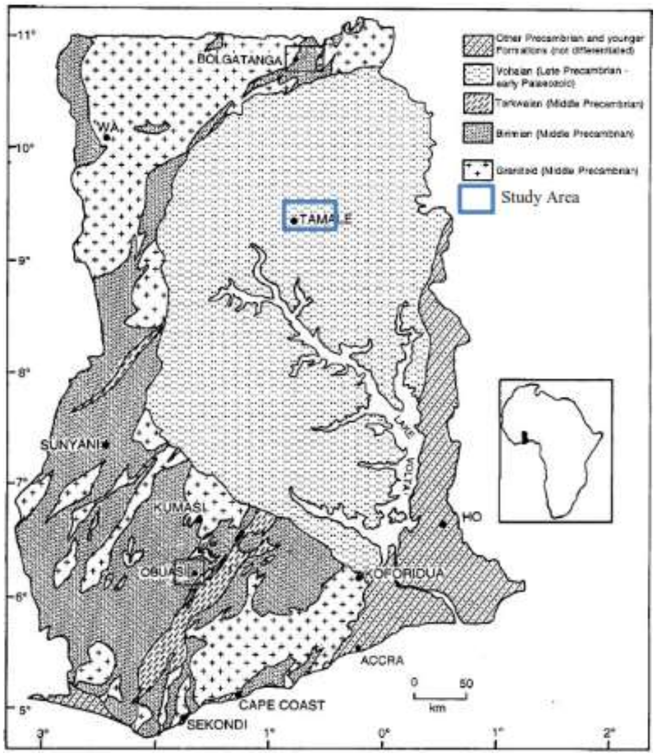

Fig -2: Geological map of Ghana showing Sampling Area within the Voltaian System [21]

2.3 Sampling and Sample Preparation

2.3.1 Sampling

A total of nine (9) disturbed soil samples were collected and tested. Depth of samples excavation was ranging from 0.3m – 0.5m after removing the top soil of 0.15m. The samples were labelled and transported to the laboratory. Each sample was air dried for about two days at room temperature and bagged for use.

2.3.2 Sample Preparation

The data used in this paper were obtained from laboratory tests conducted at the Materials Engineering Laboratory of Ghana Highways Authority, Tamale, Ghana, on soil samples collected from Tamale Metropolis. To prepare the soil samples for testing, air dried lateritic soil samples were quartered to a suitable quantity and then used for the various tests.

To prepare the soil for grading analysis, the air-dried sample was quartered until an appropriate quantity was obtained and used for the particle distribution test. To prepare the soil samples for Atterberg limit tests, the air-dried samples were quartered until an appropriate quantity is achieved. This quantity was then sieved through the 19mm sieve and then through the 0.425mm sieve. The material passing the 0.425mm sieve was used for the consistency tests.

To prepare the soil sample for compaction tests, the air dried soil sample was quartered until an appropriate quantity of about 12kg was obtained. The soil was then sieved over the 19mm sieve and the material passing the 19mm sieve was used for the compaction tests to determine the dry density of the soil. The in-mould DCP tests were then carried out on the compacted soils.

2.4 Testing Procedures

Several tests were conducted on the soil samples taken from the various locations within the Tamale Metropolis. These include atterberg limit tests (liquid limit and plastic limit), grading, compaction tests and DCP tests. The grading and atterberg limits tests were carried out to determine the type of soil and classify the soil sample accordingly. The compaction tests were carried out to determine the optimum moisture content and the maximum dry density of the soil samples. The DCP tests were also carried out to determine the dynamic cone penetration index (DPI) of the compacted soil samples.

2.4.1 Compaction tests

Compaction tests were performed on the soil sample to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for each sample. The test procedure was done in accordance with GHA S1 which is equivalent to AASHTO T 180 [3]. The test was performed on the portion of the sample that passed through the 19mm sieve. Soil was mixed thoroughly with water at water content increments of 2% on a tray. The mixture was compacted using different moulds of the same diameter and height of 152 mm and 127 mm respectively in five equal layers. Fifty-six (56) blows were applied over the entire surface to each layer using the Modified Proctor rammer of mass 4.5 kg, falling freely over a height of 457mm. The moisture content for each cycle of compaction was determined.

2.4.2 Dynamic Cone Penetrometer Test (DCP)

The description of the Dynamic Cone Penetrometer (DCP) can be found in ASTM 6951-09 [22]. The DCP comprises an 8kg hammer, which is lifted and dropped over a height of 575 mm. This produces a hypothetical energy of 45J, to drive a 60° cone tip vertically into the soil. The base diameter of the cone tip is usually 20 mm and the steel rod attached to the cone has a diameter of 16mm, which is smaller than the cone diameter. This ensures the reduction of the effect of skin friction. Typical depth of investigation using DCP is up to 2m, though greater depths can be achieved in some areas. Figure 3 shows a diagram of the dynamic cone penetrometer used in this study.

During operation, the number of blows that results in particular depth of penetration is recorded together with the depth of penetration it yields. A plot of penetration depth against number of blows gives a curve relationship. The DCP penetration index (DPI), measured in millimeters per blow, is the slope of the curve defining the relationship between penetration depth and number of blows at a given linear depth segment. According to Embacher [23], the DPI (mm/blow) for each depth can also be calculated using the equation:

$$DPI = \frac{P_{i+1} - P_i}{B_{i+1} - B_i}$$

Where

P Penetration at *i* or *i+1* hammer drops (mm); and

B Blow count at *i* or *i+1* hammer drops

Mohammadi, Nikoudel [24] emphasis the need to adhere to a standard procedure in the analysis and interpretation of DCP data. This will ensure that a characteristic value of penetration per blow for the material being tested is obtained. This characteristic value is obtained by determining the DPI across the entire penetration depth for each test specimen. For calculating the characteristic DPI value for the entire penetration depth of the compacted samples, the entire depth of the compacted samples were divided by the cumulative number of blows for each specimen.

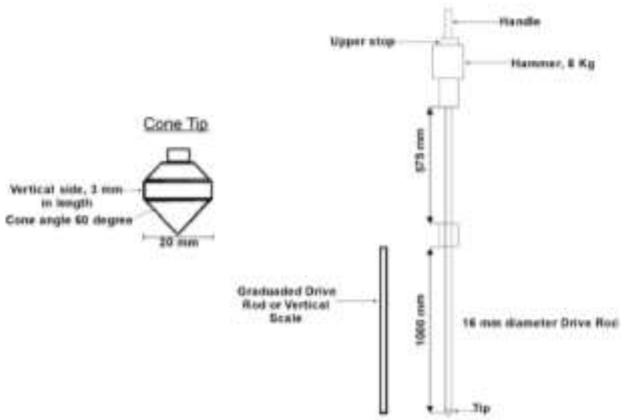

Fig -3: Dynamic Cone Penetrometer (DCP) Schematic [25]

The main advantages of the DCP include:

- low cost of the equipment
- high speed of operation

- applicability in difficult terrains where access is poor
- minimal equipment and personnel requirement
- simplicity of the operation and data recording/analysis
- easy to generate correlations with other expensive and time consuming tests
- large amounts of data gathering possible

As previously mentioned, the DCP tests were carried out in a mould with a diameter and height of 152 mm and 127mm, respectively. The DCP tests were conducted at the centre of the test mould for all the samples to eliminate excessive side wall friction effects from the mould and to ensure uniformity of results.

3. RESULTS AND DISCUSSIONS

In the subsequent sections, the results of the classification tests are first presented. These are followed by the results of compaction tests and the DCP tests. The model equations arrived at between the DPI and the dry density and the DPI and the moisture content of the soil samples considered are also discussed.

3.1 Sample Classification Results

Results of the soil classification tests have been summarized and presented in table 1. The soil samples were observed to be reddish brown to dark brown in colour. Using the AASHTO classification system, the eight out of the nine soils samples were silty or clayey gravel and sand belonging to groups, A – 2 – 4, A – 2 – 6 and A – 3 while the remaining one was clayey soil belonging to group A – 7 – 6. Soils belonging to group A – 4 and A – 7 – 6 are generally rated as fair to poor as a subgrade material while soils belonging to group A – 2 – 4 and A – 2 – 6 are also generally rated as excellent to good as a subgrade material. The numbers in brackets attached to the group classification indicates Group Index, GI that further denotes the suitability of the soil to be used as subgrade material.

Table -1: Summary of soil sample classification

Sample No	Sieve Analysis		Atterberg Limits			Classification	Soil Type
	Sieve Sizes (mm)	% Passing	LL	PL	PI		
1	2.0	28	21	13	8	A - 2 - 4(0)	Silty or clayey gravel and sand
	0.425	27					
	0.075	26					
2	2.0	39	22	11	10	A - 2 - 4(0)	Silty or clayey gravel and sand
	0.425	30					
	0.075	27					
3	2.0	54	41	13	28	A - 7 - 6(6)	Clayey soil
	0.425	43					
	0.075	41					
4	2.0	30	27	15	12	A -2 - 6(0)	Silty or clayey gravel and sand
	0.425	19					
	0.075	17					
5	2.0	42	26	19	7	A - 2 - 4(0)	Silty or clayey gravel and sand
	0.425	26					
	0.075	19					
6	2.0	81	34	18	17	A - 2 - 6(0)	Silty or clayey gravel and sand
	0.425	76					
	0.075	28					
7	2.0	38	39	20	19	A - 2 - 6(0)	Silty or clayey gravel and sand
	0.425	20					
	0.075	14					
8	2.0	41	20	14	6	A - 2 - 4(0)	Silty or clayey gravel and sand
	0.425	32					
	0.075	21					
9	2.0	15	24	-	-	A – 3(0)	Silty or clayey gravel and sand
	0.425	11					
	0.075	4					

3.2 Dry Density versus moisture content

Charts 1 (a – i) give the compaction curves for the various lateritic soil samples. They represent the dry density – moisture content relationship for the various soil samples for which the optimum moisture content, OMC and maximum dry density, MDD are determined. Optimum moisture content for samples range from a minimum of 8.2% for sample no. 2, to a maximum of 14.6% for samples no. 1 and 6. Maximum dry densities for samples on the other hand range from a minimum of 1302kg/m^3 for sample no. 6, to a maximum of 1635kg/m^3 for sample no. 2. On the average, samples with higher OMC yields lower maximum dry densities as compared to samples with lower OMCs, which yield higher maximum dry densities.

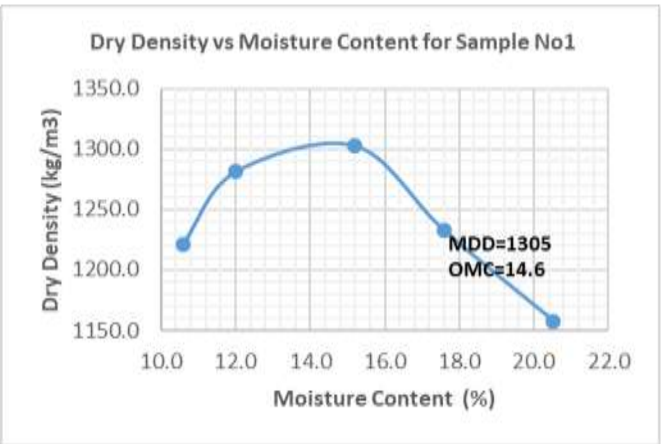

Chart -1(a): Dry Density and Moisture content relationship for Sample 1

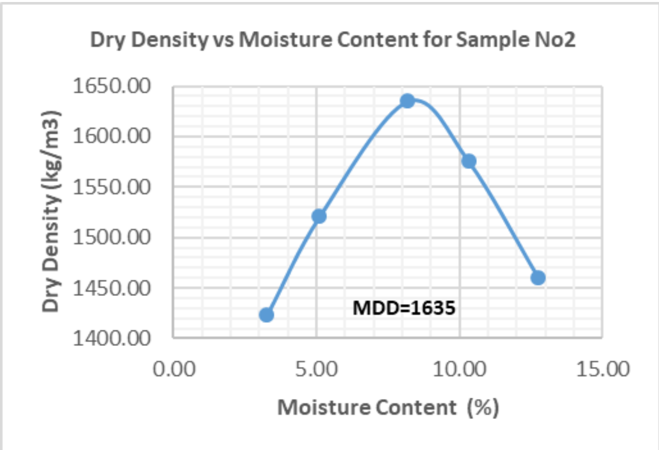

Chart -1(b): Dry Density and Moisture content relationship for Sample 2

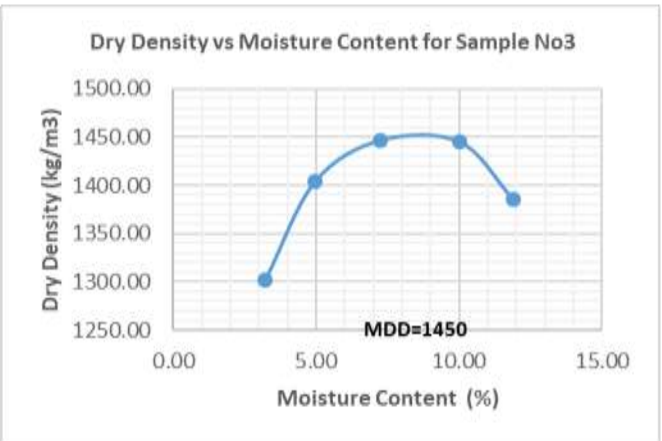

Chart -1(c): Dry Density and Moisture content relationship for Sample 3

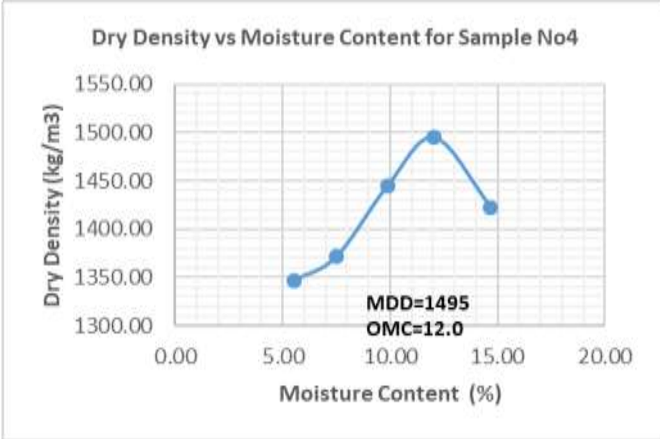

Chart -1(d): Dry Density and Moisture content relationship for Sample 4

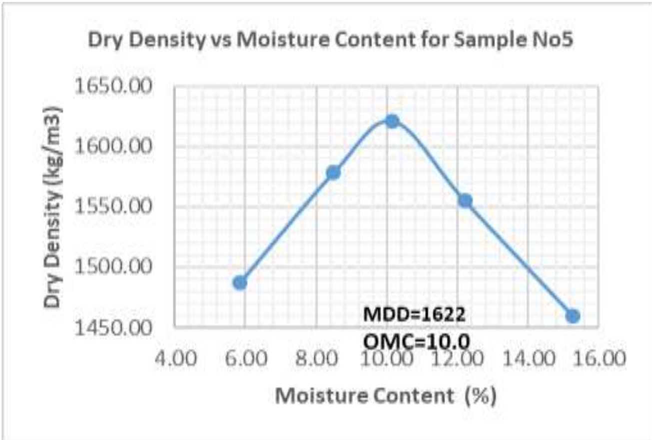

Chart -1(e): Dry Density and Moisture content relationship for Sample 5

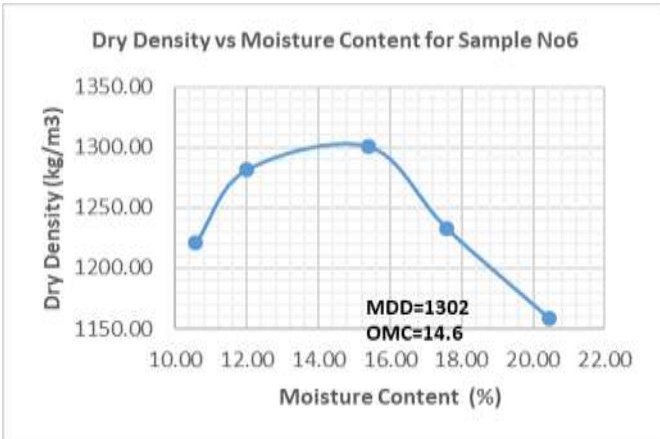

Chart -1(f): Dry Density and Moisture content relationship for Sample 6

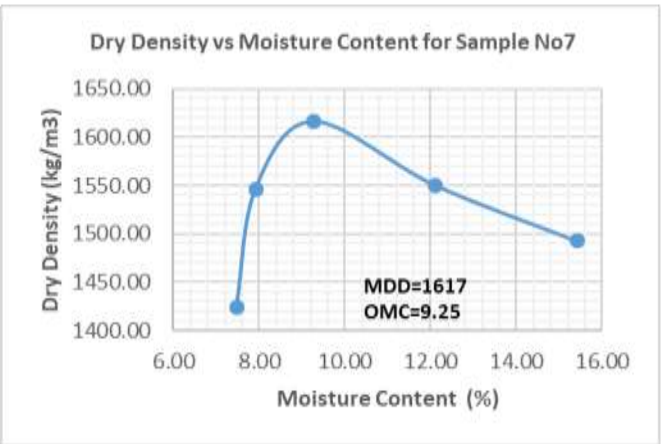

Chart -1(g): Dry Density and Moisture content relationship for Sample 7

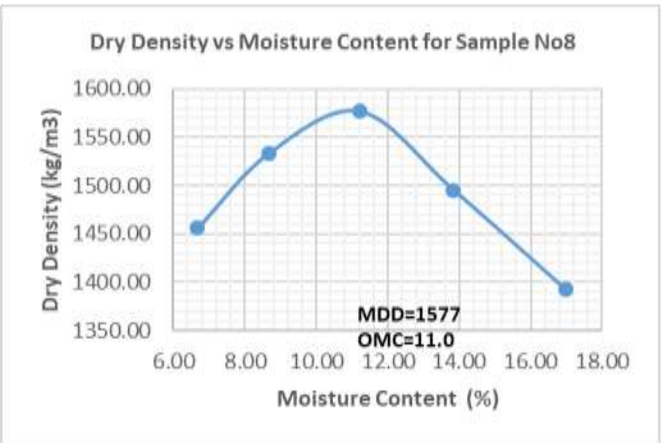

Chart -1(h): Dry Density and Moisture content relationship for Sample 8

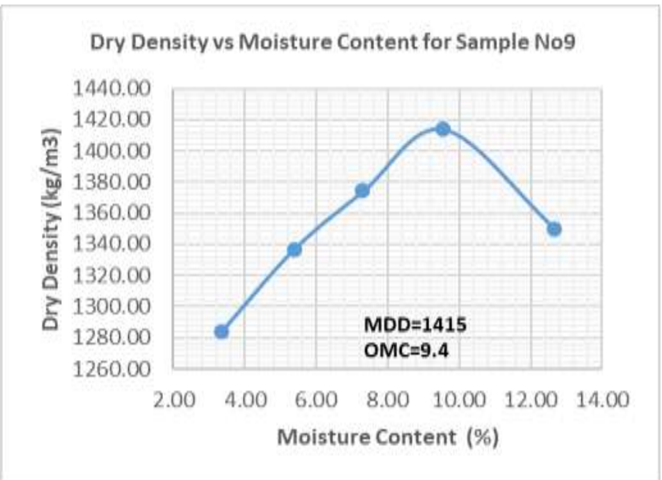

Chart -1(i): Dry Density and Moisture content relationship for Sample 9

The dry density corresponding to compaction moisture content, air – dry moisture content and percentage of water added as well as the corresponding maximum dry density and optimum moisture content for each soil sample as read from the graphs are also presented in table 2.

Table -2: Summary of Compaction Test Results

Sample No	Compacted moisture content (%)	OMC (%)	Dry Density (kg/m^3)	MDD (kg/m^3)
1	10.58	14.6	1220.69	1305
	11.99		1281.17	
	15.20		1303.04	
	17.59		1232.81	
	20.53		1157.75	
2	3.27	8.2	1423.23	1635
	5.10		1521.06	
	8.18		1634.96	
	10.31		1575.30	
	12.75		1460.11	
3	3.22	8.4	1302.44	1450
	4.95		1403.52	
	7.26		1446.24	
	10.02		1444.57	
	11.89		1385.77	
4	5.53	12.0	1346.74	1495
	7.48		1371.32	
	9.87		1444.85	
	12.05		1494.62	
	14.69		1422.46	
5	5.86	10.0	1487.68	1622
	8.50		1578.65	
	10.17		1620.95	
	12.21		1554.99	
	15.27		1459.21	
6	10.58	14.6	1220.69	1302
	11.99		1281.17	
	15.40		1300.77	
	17.59		1232.81	
	20.44		1158.57	
7	7.48	9.25	1423.73	1617
	7.92		1546.43	
	9.26		1616.72	
	12.11		1550.30	
	15.42		1492.35	
8	6.69	11.0	1455.78	1577
	8.68		1532.93	
	11.22		1576.30	
	13.84		1495.21	
	17.00		1391.88	
9	3.35	9.4	1284.12	1415

Sample No	Compacted moisture content (%)	OMC (%)	Dry Density (kg/m³)	MDD (kg/m³)
	5.38		1337.00	
	7.30		1374.20	
	9.56		1414.12	
	12.67		1350.14	

3.3 Dynamic Cone Penetration Results

Results of DCP test are presented in table 3. The DPI values were obtained by dividing the depth of penetration by the total number of blows required to attain the total penetration of 150mm. It can be observed that lowest DPI values corresponds to maximum dry density values occurring at optimum moisture content.

Table -3: DCP Test Results

Sample No	DPI (mm/blows)	Compaction moisture content (%)	Dry Density (kg/m³)
1	8.82	10.58	1220.69
	5.17	11.99	1281.17
	3.75	15.20	1303.04
	7.50	17.59	1232.81
	12.50	20.53	1157.75
2	16.67	3.27	1423.23
	11.54	5.10	1521.06
	4.84	8.18	1634.96
	30.00	10.31	1575.30
	150.00	12.75	1460.11
3	9.38	3.22	1302.44
	7.50	4.95	1403.52
	4.55	7.26	1446.24
	16.67	10.02	1444.57
	30.00	11.89	1385.77
4	7.89	5.53	1346.74
	7.50	7.48	1371.32
	5.36	9.87	1444.85
	3.95	12.05	1494.62
	10.00	14.69	1422.46
5	11.54	5.86	1487.68
	6.25	8.50	1578.65
	3.95	10.17	1620.95
	7.89	12.21	1554.99
	15.00	15.27	1459.21
6	9.38	10.58	1220.69
	4.41	11.99	1281.17

Sample No	DPI (mm/blows)	Compaction moisture content (%)	Dry Density (kg/m³)
	3.57	15.40	1300.77
	6.25	17.59	1232.81
	12.50	20.44	1158.57
7	8.33	7.48	1423.73
	6.00	7.92	1546.43
	4.69	9.26	1616.72
	6.25	12.11	1550.30
	10.00	15.42	1492.35
8	5.36	6.69	1455.78
	5.00	8.68	1532.93
	4.29	11.22	1576.30
	8.82	13.84	1495.21
	18.75	17.00	1391.88
9	8.33	3.35	1284.12
	7.14	5.38	1337.00
	6.52	7.30	1374.20
	5.56	9.56	1414.12
	15.00	12.67	1350.14

3.4 DPI versus Moisture Content

Results of DCP test are presented in table 3.3 above. The DPI values were obtained by dividing the depth of penetration by the total number of blows.

Plots of DPI versus moisture content of compacted samples are shown in Charts 2 (a – i). The graphs show that DPI decreases with increasing moisture content for compaction on the dry side of the optimum moisture content and DPI increases with increasing moisture content for compaction on the wet side of the optimum moisture content. This is in contrast to increasing density with increasing moisture content on the dry side of OMC and decreasing dry dry density on the wet side of OMC. For every sample, there is a minimum DPI (DPImin) corresponding to the OMC on the DPI – moisture content curve as compared to the maximum dry density MDD on the dry density versus moisture content curve which also occurs at the optimum moisture content.

Results essentially show that the DPI versus moisture content exhibits the inverse of the compaction curve for dry density vs. moisture content. Thus when using the DCP equipment, the DPImin could be seen as reflecting the material with highest density and by extension, higher strength. Each sample exhibits a particular equation that relates the DPI to the moisture content. These equations were subjected to statistical analysis. Statistical analysis shows that the DPI – moisture content relationship for the samples is either a quadratic or a cubic relationship. The coefficient of determination R^2, for all the test samples gave very strong correlation values of greater than 96%. The least adjusted R^2 values were determined to be 87.1% and 89.1 for samples 7 and 5 respectively for the cubic function. The quadratic function for sample 5 however gave a higher adjusted R^2 value of 93.3%. All other samples gave adjusted R^2 values of greater than 95%. These results indicate very strong correlation between the DPI and the moisture content.

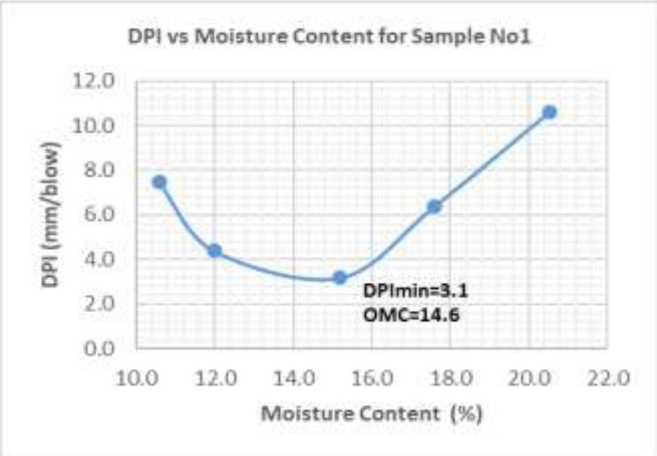

Chart -2(a): DPI and Moisture content relationship for Sample 1

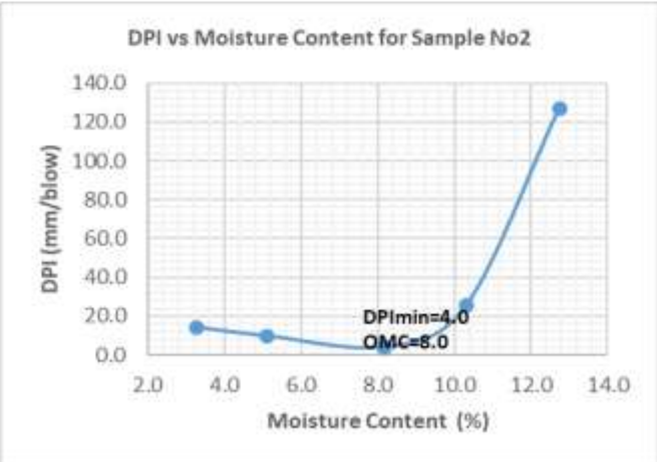

Chart -2(b): DPI and Moisture content relationship for Sample 2

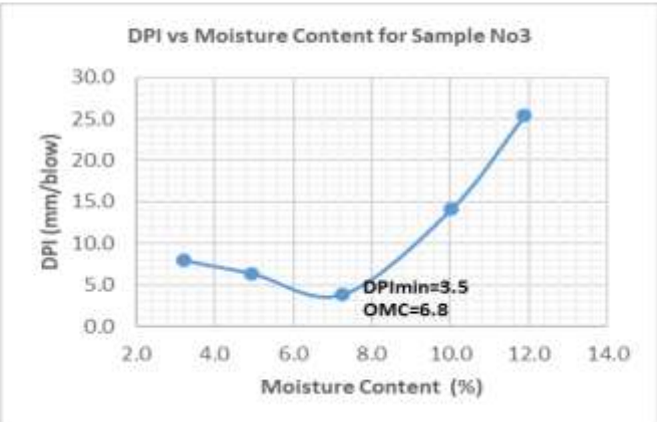

Chart -2(c): : DPI and Moisture content relationship for Sample 3

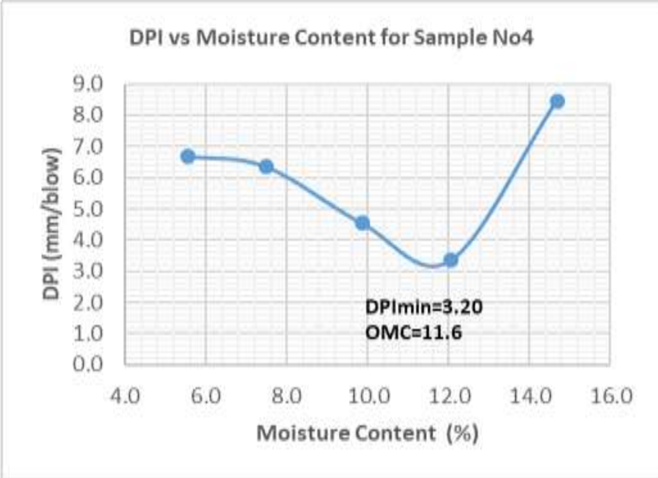

Chart -2(d):: DPI and Moisture content relationship for Sample 4

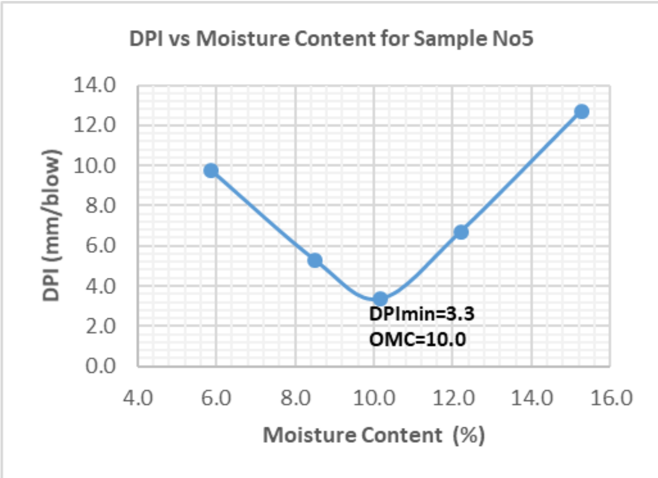

Chart -2(e): DPI and Moisture content relationship for Sample 5

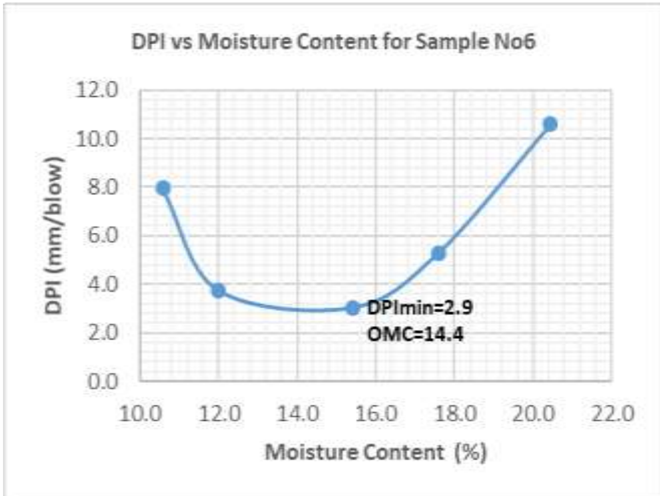

Chart -2(f): DPI and Moisture content relationship for Sample 6

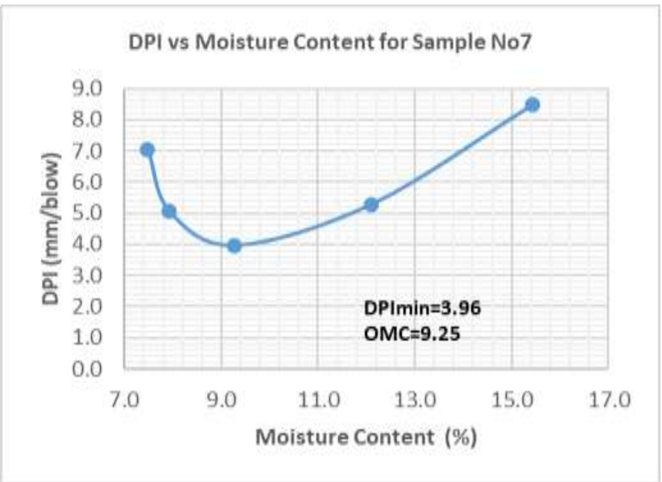

Chart -2(g): DPI and Moisture content relationship for Sample 7

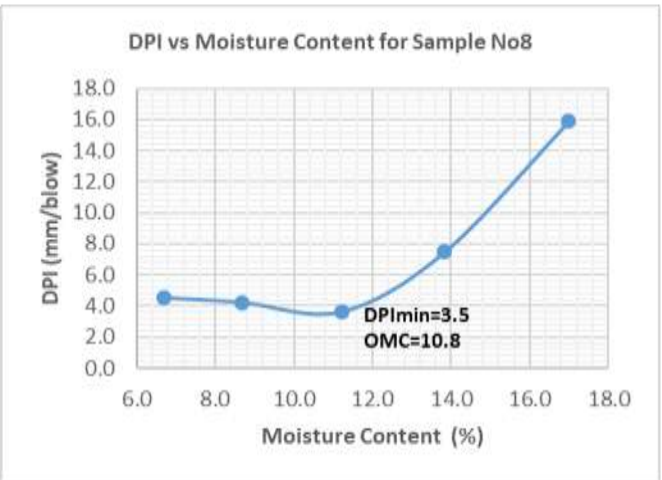

Chart -2(h): DPI and Moisture content relationship for Sample 8

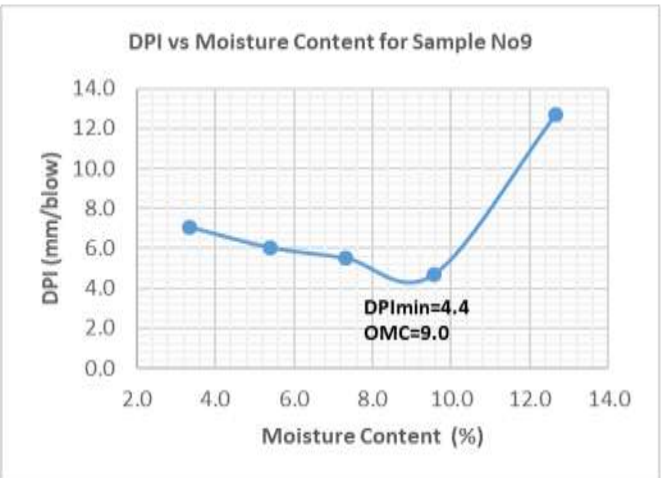

Chart -2(i): DPI and Moisture content relationship for Sample 9

3.5 DPI versus Dry Density

Plots of DPI versus dry density of samples are shown in Charts 3 (a – i). The graphs depicts clearly the relationship between the dry density (DD) and the DPI of the samples. In all the graphs, two distinct arms of the curve can be identified. The lower left arm and the upper right arm with both arms meeting at the DPImin and the MDD. The lower left arm can be seen as the values of DPI and MDD on the dry side of OMC. The upper right arm depicts the values of DPI and MDD on the wet side of the OMC.

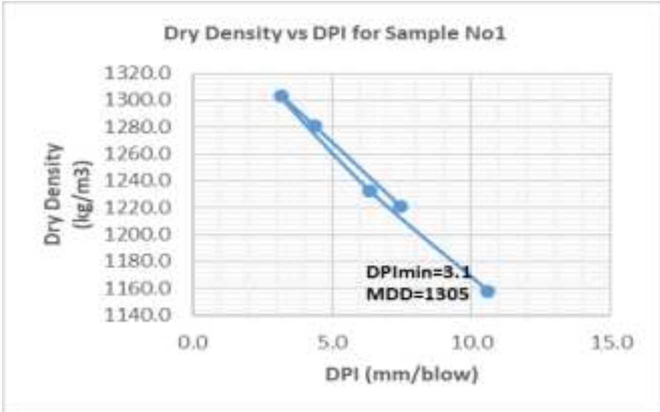

Chart -3(a): DPI and Dry Density relationship for Sample 1

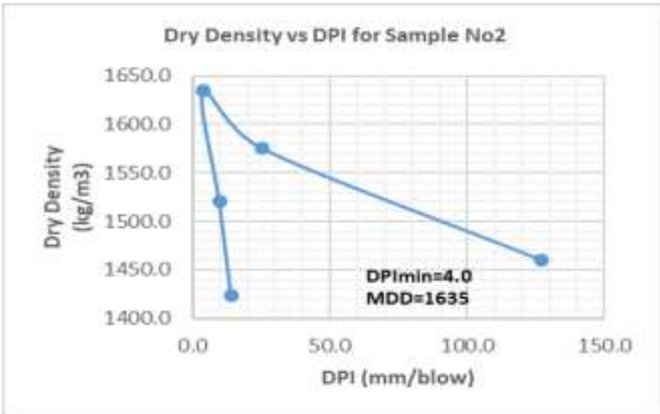

Chart -3(b): DPI and Dry Density relationship for Sample 2

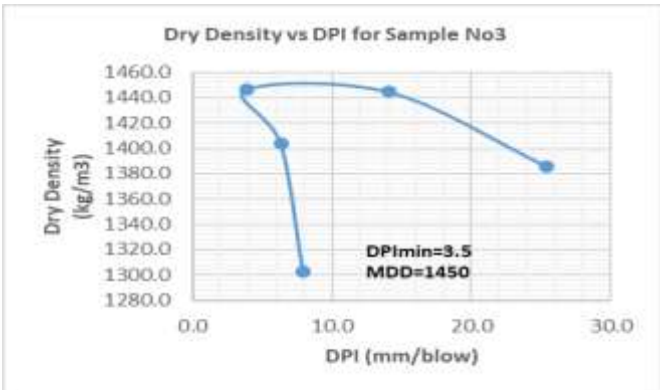

Chart -3(c): DPI and Dry Density relationship for Sample 3

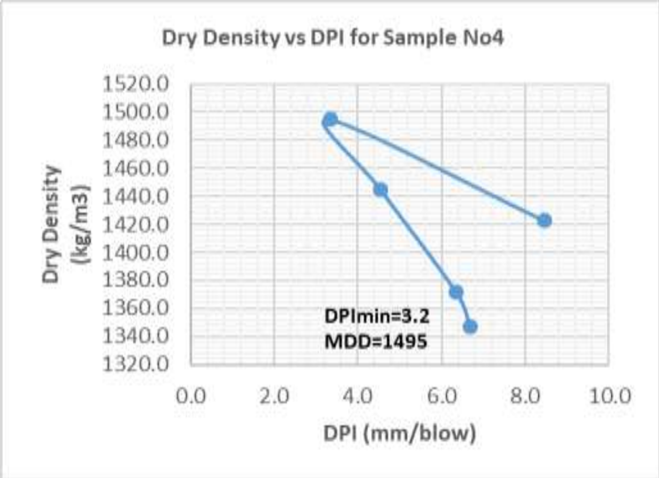

Chart -3(d): DPI and Dry Density relationship for Sample 4

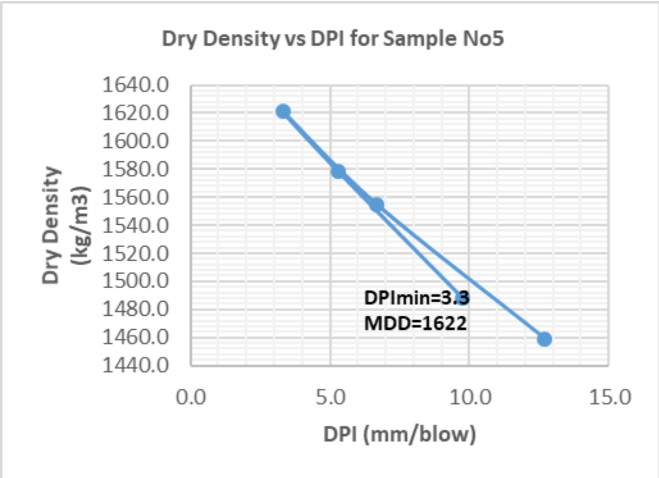

Chart -3(e): DPI and Dry Density relationship for Sample 5

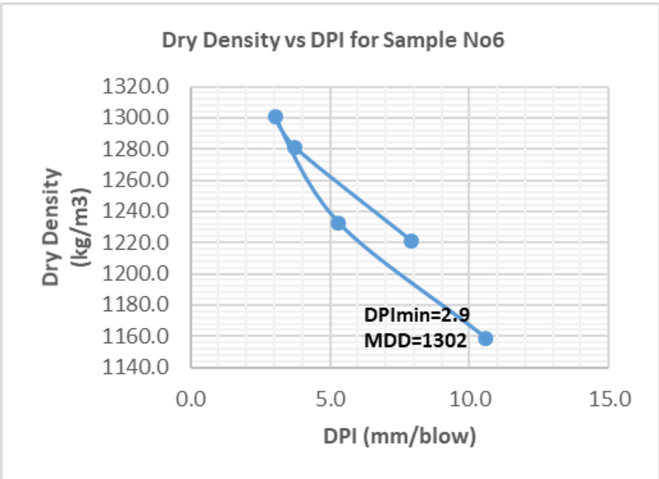

Chart -3(f): DPI and Dry Density relationship for Sample 6

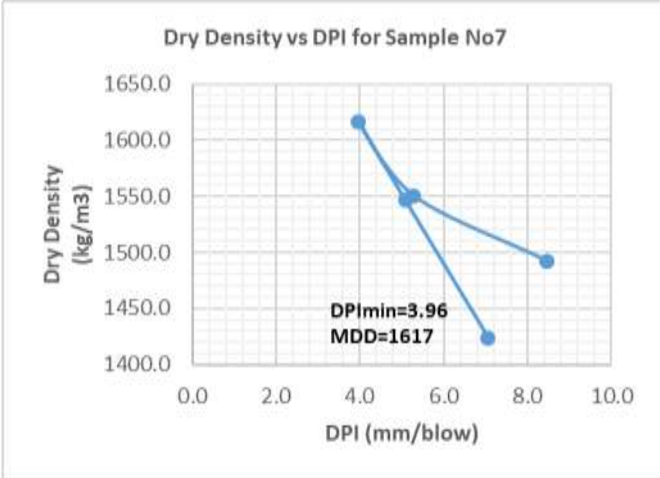

Chart -3(g): DPI and Dry Density relationship for Sample 7

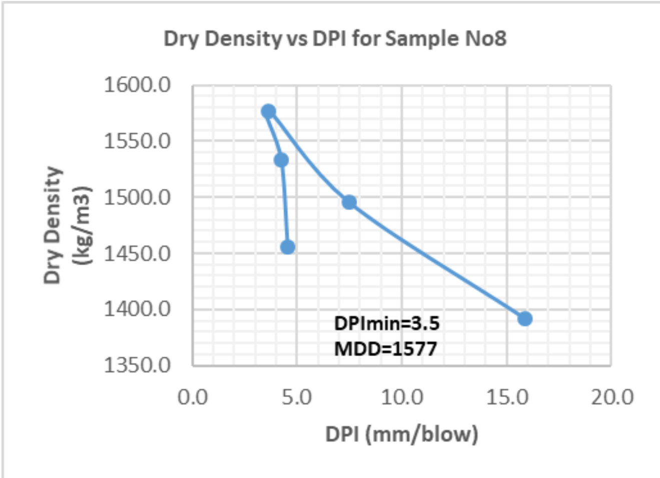

Chart -3(h): DPI and Dry Density relationship for Sample 8

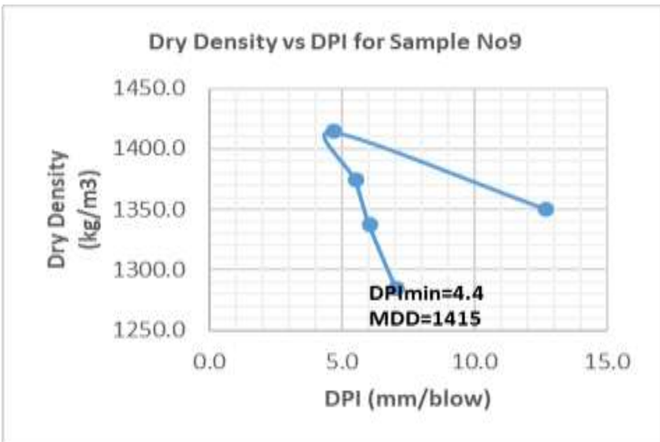

Chart -3(i): DPI and Dry Density relationship for Sample 9

Statistical analysis shows that the DPI – dry density relationship for the samples could be linear, quadratic or cubic relationship. Each sample exhibits a distinct equation that relates the DD to the DPI. When these equations were subjected to statistical analysis, it was found out that the DD

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– DPI relationship for the samples is best described by the cubic function. The coefficient of determination R^2, for all the test samples gave very strong correlation values of greater than 90% except that of sample 3, which gave the least value of 75%. The adjusted R^2 values all indicate very strong correlation equations for all the samples except again that of sample number 3. Six out of the nine samples have adjusted R^2 values higher than 95% whilst two samples have adjusted R^2 values between 74% and 80%. The adjusted R^2 values for sample 3 was very low (0.6%). A closer look at sample number 3 however indicates that the soil is a clayey soil and not a silty or clayey gravel as with the other samples tested. This could be the reason for lowest values of R^2 and adjusted R^2 values obtained for this sample number. These results indicate that for gravelly soils, very strong correlation exists between the DD and the DPI.

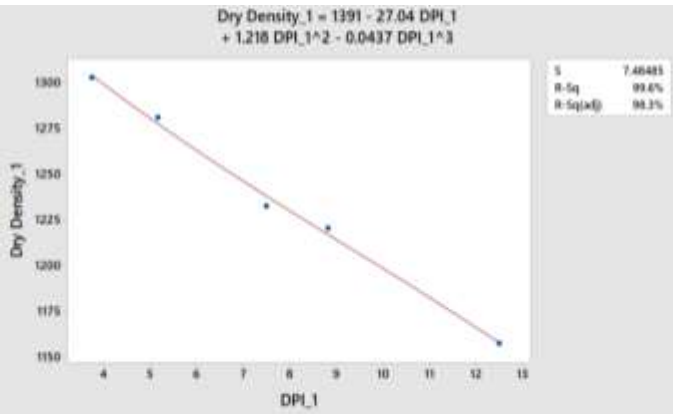

Chart -4(a): Dry Density and DPI Correlation for Sample 1

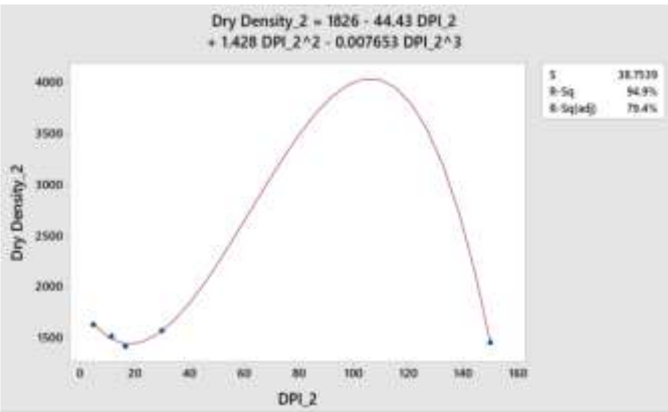

Chart -4(b): Dry Density and DPI Correlation for Sample 2

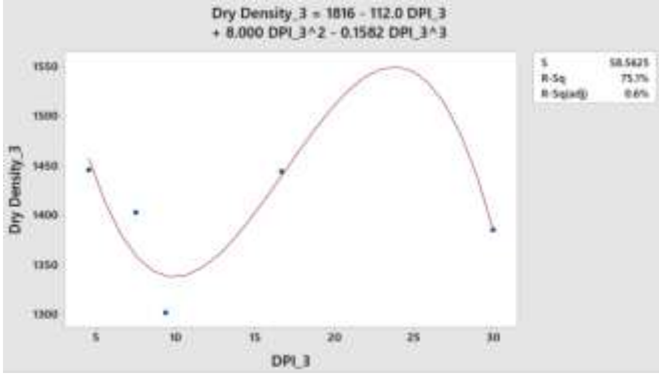

Chart -4(c): Dry Density and DPI Correlation for Sample 3

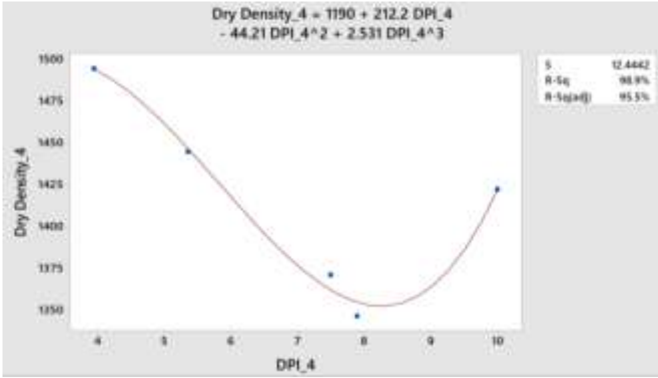

Chart -4(d): Dry Density and DPI Correlation for Sample 4

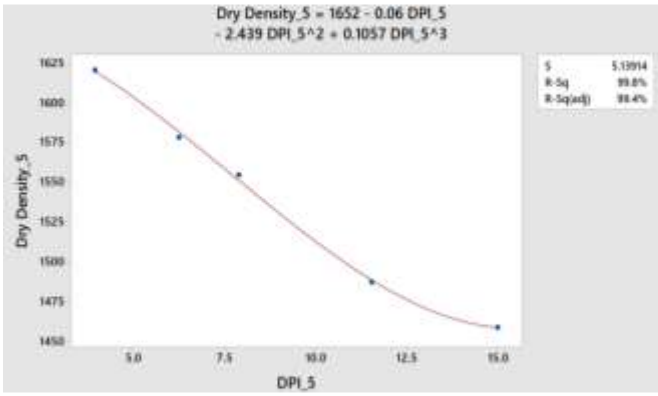

Chart -4(e): Dry Density and DPI Correlation for Sample 5

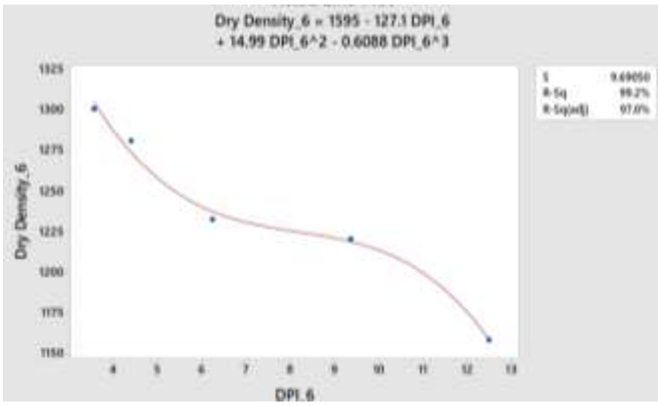

Chart -4(f): Dry Density and DPI Correlation for Sample 6

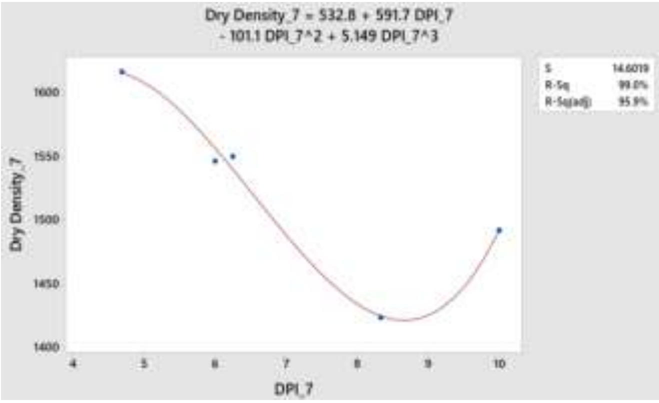

Chart -4(g): Dry Density and DPI Correlation for Sample 7

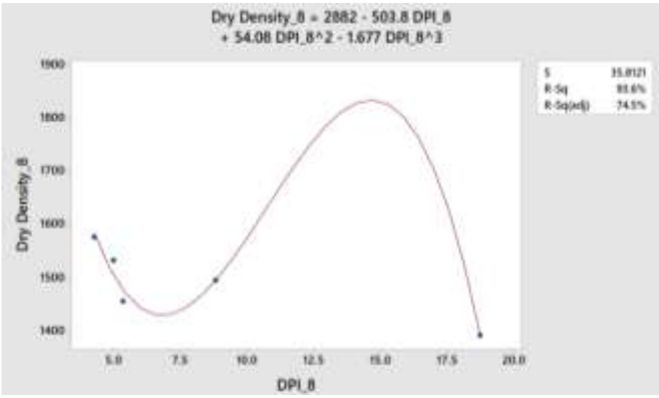

Chart -4(h): Dry Density and DPI Correlation for Sample 8

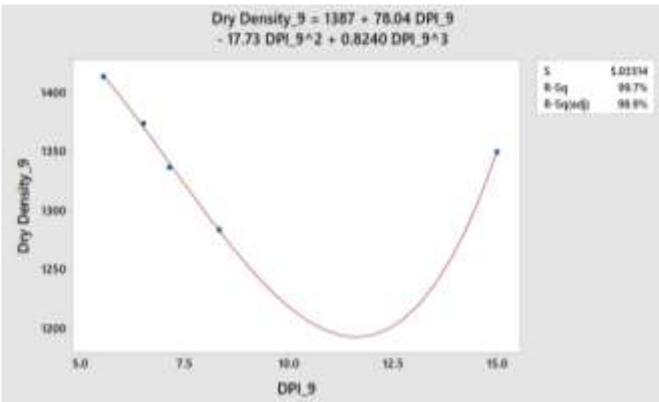

Chart -4(i): Dry Density and DPI Correlation for Sample 9

4. SUMMARY AND CONCLUSIONS

Due to the lightweight nature of the DCP device, it suitable for soil investigation in difficult terrains with poor access and up to a depth of 2m. The results of DCP testing can be used to promptly assess variability of soil conditions, permitting different layers to be identified.

Based on the results of the present research, correlations can be established between

1. The DPI and the dry density of lateritic gravel soils
2. The DPI and the moisture content of lateritic gravel soils.

Statistical approach has been applied to find the best correlations of the results with a high coefficient of determination (R^2). For the results obtained, the determination coefficients (R^2) between DPI and the engineering parameters (dry density and moisture content) were mostly greater than 0.90. Tables 4 and 5 show summary of the equations obtained in this study. To ensure that the terms in the equations developed actually models the variations within the system and not noise, the adjusted R^2 values were computed. The high values of more than 0.90 attained in most of the samples shows that the models predict with high accuracy the dry density and moisture content of the samples. Thus the DCP can be used as a compaction verification tool and as an alternative to the sand replacement method as previously stated by De Beer and Van der Merwe [12], Gabr, Hopkins [11], Ampadu and Arthur [17], and Sawangsuriya and Edil [25] among others.

It is however noteworthy that model equations to generalize the use of the DPI to estimate the engineering properties (moisture content and dry density) for all samples tested gave very weak correlation results. The individual soil samples gave very strong correlation results between the DPI and the engineering parameters with coefficient of determination (R^2) generally more than 0.90. Conversely, all the samples together gave very weak correlation results with coefficient of determination (R^2) of 0.09. The adjusted R^2 value for all samples was 0.023 indicating very weak results.

Therefore, from results this study, it is not prudent to generalise the DPI and MDD or DPI and MC relationship from different sources due to weak correlation between the results. The DPI – MDD or DPI – MC relationship on case-by-case basis however shows very strong correlation and can be employed to determine the dry density and moisture content for effective compaction verification in the field. Consequently, it is recommended that a model equation be determined for a particular sample source in the laboratory and then used in the field for compaction verification.

Table -4: Summary of Model Equations for Dry Density versus DPI

Sample No	R^2 (%)	R^2 adj (%)	Standard Error	Function type	Function
1	99.60	98.30	7.48485	Cubic	Dry Density_1 = 1391 - 27.04 DPI_1+ 1.218 DPI_1^2 - 0.0437 DPI_1^3
2	94.90	79.40	38.7539	Cubic	Dry Density_2 = 1826 - 44.43 DPI_2+ 1.428 DPI_2^2 - 0.007653 DPI_2^3

Sample No	R^2 (%)	R^2 adj (%)	Standard Error	Function type	Function
3	75.10	0.60	58.5625	Cubic	Dry Density_3 = 1816 - 112.0 DPI_3+ 8.000 DPI_3^2 - 0.1582 DPI_3^3
4	98.90	95.50	12.4442	Cubic	Dry Density_4 = 1190 + 212.2 DPI_4- 44.21 DPI_4^2 + 2.531 DPI_4^3
5	99.80	99.40	5.13914	Cubic	Dry Density_5 = 1652 - 0.06 DPI_5- 2.439 DPI_5^2 + 0.1057 DPI_5^3
6	99.20	97.00	9.6905	Cubic	Dry Density_6 = 1595 - 127.1 DPI_6+ 14.99 DPI_6^2 - 0.6088 DPI_6^3
7	99.00	95.90	14.6019	Cubic	Dry Density_7 = 532.8 + 591.7 DPI_7- 101.1 DPI_7^2 + 5.149 DPI_7^3
8	93.60	74.50	35.8121	Cubic	Dry Density_8 = 2882 - 503.8 DPI_8+ 54.08 DPI_8^2 - 1.677 DPI_8^3
9	99.70	98.90	5.03314	Cubic	Dry Density_9 = 1387 + 78.04 DPI_9- 17.73 DPI_9^2 + 0.8240 DPI_9^3
All Samples	9.00	2.30	125.359	Cubic	Dry Density = 1546 - 25.74 DPI+ 0.9633 DPI^2 - 0.005303 DPI^3

Table -5: Summary of Model Equations for DPI versus Moisture Content

Sample No	R^2 (%)	R^2 adj (%)	Standard Error	Function type	Function
1	99.80	99.20	0.297025	Cubic	DPI_1 = 161.9 - 28.57 Moisture Content_1+ 1.649 Moisture Content_1^2 - 0.02977 Moisture Content_1^3
2	99.90	99.60	3.78554	Cubic	DPI_2 = - 59.53 + 47.89 Moisture Content_2- 9.339 Moisture Content_2^2 + 0.5389 Moisture Content_2^3
3	98.80	95.20	2.23988	Cubic	DPI_3 = 20.26 - 3.506 Moisture Content_3- 0.027 Moisture Content_3^2 + 0.03310 Moisture Content_3^3
3	98.40	96.80	1.8221	Quadratic	DPI_3 = 30.48 - 8.603 Moisture Content_3+ 0.7193 Moisture Content_3^2
4	99.40	97.50	0.369675	Cubic	DPI_4 = - 24.82 + 12.70 Moisture Content_4- 1.546 Moisture Content_4^2 + 0.05735 Moisture Content_4^3
5	97.30	89.10	1.44613	Cubic	DPI_5 = 56.62 - 12.12 Moisture Content_5+ 0.8486 Moisture Content_5^2 - 0.01524 Moisture Content_5^3
5	96.60	93.30	1.13534	Quadratic	DPI_5 = 41.96 - 7.359 Moisture Content_5+ 0.3673 Moisture Content_5^2
6	99.30	97.30	0.609833	Cubic	DPI_6 = 172.3 - 29.97 Moisture Content_6+ 1.690 Moisture Content_6^2 - 0.02964 Moisture Content_6^3
7	96.80	87.10	0.753554	Cubic	DPI_7 = 114.5 - 28.49 Moisture Content_7+ 2.371 Moisture Content_7^2 - 0.06246 Moisture Content_7^3
8	99.50	97.80	0.889131	Cubic	DPI_8 = 9.74 - 0.033 Moisture Content_8- 0.1693 Moisture Content_8^2 + 0.01192 Moisture Content_8^3
8	99.10	98.10	0.821694	Quadratic	DPI_8 = 26.46 - 4.793 Moisture Content_8+ 0.2549 Moisture Content_8^2
9	99.00	95.90	0.765017	Cubic	DPI_9 = 0.219 + 4.995 Moisture Content_9- 0.9488 Moisture Content_9^2 + 0.05103 Moisture Content_9^3
All Samples	3.00	0.00	22.2495	Cubic	DPI = 22.10 - 5.82 Moisture Content+ 0.707 Moisture Content^2 - 0.02247 Moisture

Sample No	R^2 (%)	R^2 adj (%)	Standard Error	Function type	Function
					Content^3

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