

Using Dynamic Cone Penetrometer (DCP) to Assess Geotechnical Properties of Basra Subbase Soils

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Abstract

The evaluation of subbase layers is essential for the performance of pavement structures, particularly in regions with variable soil conditions such as Basra, Iraq. The Dynamic Cone Penetrometer (DCP) test is widely used due to its simplicity, cost-effectiveness, and ability to provide continuous in-situ soil profiling without the need for sample extraction. This study investigates the relationship between the Dynamic Cone Penetration Index (DCPI), dry density, and moisture content for three commonly used subbase materials (Types B, C, and D) in Basra. A comprehensive experimental program was conducted using both DCP and Sand Replacement Method (SRM) tests under controlled laboratory conditions. Tests were performed at three moisture contents (4%, 6%, and 8.5%) and varying compaction efforts, resulting in a total of 270 test trials. The results revealed a clear inverse relationship between DCPI and dry density, while moisture content showed a significant influence on both parameters. A graphical method was developed to estimate in-situ dry density based on DCPI and moisture content. The proposed method demonstrated good agreement with SRM results, indicating its potential as a rapid and reliable alternative for field density estimation. This approach can significantly reduce testing time and cost in geotechnical site investigations.

Keywords

sand replacement method, dynamic cone penetration, dynamic cone penetration index, standard deviation, coefficient of variation

INTRODUCTION

The subbase layer plays a crucial role in road construction by distributing loads to the underlying layers and supporting subgrade stability. The performance of pavement systems depends strongly on the strength and stiffness of this layer. Owing to the diverse geological and climatic conditions in Basra, the Dynamic Cone Penetrometer (DCP) has become a practical tool for soil evaluation because of its simplicity, portability, and efficiency in the field. The test is performed by dropping a standard hammer onto a cone that penetrates the soil, and the resulting penetration rate provides useful information about soil density and bearing resistance.

Pen (1990) emphasized that the most important properties of the subgrade in pavement design are its ability to sustain applied loads and its resistance to deformation. Scala (1956) developed the dynamic cone penetrometer in Australia, and the device was later used to evaluate pavement-layer properties. Since then, it has been applied in the United Kingdom, New Zealand, Australia, and many parts of the United States for shallow subsurface investigation and for the assessment of subgrade, base, and subbase materials in both existing and new flexible pavements. It has also been used for compaction quality control. Early DCP devices used a 30° cone angle; however, the 60° cone has become more common because of its greater durability in materials with relatively high resistance, as reflected in ASTM D6951. Clegg (1979) investigated the use of the DCP in Perth sands and reported a relationship between DCPI and dry density for sandy soils. In addition, a minimum resistance of about 8 blows per 300 mm was considered indicative of well-compacted soil.

MATERIALS AND METHODS

The DCP test is widely used to evaluate soil quality and properties because it provides continuous profiling with depth. It is favored for its speed, low cost, and operational simplicity. The device consists of an 8 kg steel hammer dropped from a height of 575 mm, a 20 mm diameter cone with a 60° apex angle, a base plate, and a 600 mm driving rod. A striker ensures a consistent drop height, and the rod diameter is slightly reduced to minimize friction. The test specifications adopted in this study follow ASTM D6951-03 (2009). Table 1 shows the characteristics of commonly used DCP devices.

Table 1 Characteristics of commonly used (DCP)

(DCP)	Hammer mass (kg)	Height of drop (mm)	Potential energy per drop (J)	Cone angle (degree)
Scala 1956	8	575	45.1	60
Glick and Clegg (1965)	9	600	52.9	30
Sowers and Hedges (1966)	7	508	45.0	30
Van Vuuren 1969	10	460	45.0	60
ASTM D6951-03	8	575	45.1	60
AS 1289.6.3.2	9	510	45.0	30
Mohammadi et al. (2008)	8	575	45.1	60

In this research, soil samples were collected from Basra Governorate. The materials consisted of three subbase types: B, C, and D. These subbase types are among the most commonly used materials in road construction projects in Basra. Laboratory tests were carried out on the three samples, and the soils were classified according to ASTM D2487. Table 2 presents the results of the laboratory tests.

Table 2 Physical properties of subbase soil

	Test result of soil samples			Specification
	Type B	Type C	Type D	
USCS Classification	GP	SP	SP	
D ₁₀	0.12	0.09	0.075	ASTM D 2487
D ₃₀	1	0.52	0.26	
D ₆₀	15	8	4.85	
Coefficient of uniformity (Cu)	125	88.88	64.66	
Coefficient of curvature (Cc)	0.56	0.38	0.19	
Max. Dry Unit weight, g/cm ³	2.155	2.143	2.113	ASTM D 698
Optimum moisture content (OMC %)	8.50	8.7	9.1	
Specific Gravity G _s	2.62	2.61	2.60	ASTM D 854

Soil Preparation

The main objective of the field simulation tests was to determine the dry unit weight and the degree of compaction. This was achieved through dry density testing. In this research, special equipment was manufactured in the laboratory to simulate field soil conditions, as shown in Figure 1. A soil chamber with a diameter of 60 cm and a height of 70 cm was constructed. Figure 2 shows a schematic view of the test container. The dimensions of the container were selected carefully to ensure that the walls and bottom did not influence the results, especially during the DCP tests. According to Bolton et al. (1999), the container should be at least 35 times wider than the penetrometer for dense sand and 20 times wider for loose sand to avoid distortion of the test results. In this study, the container width was approximately 37.5 times the penetrometer diameter, which satisfies the recommendation for dense sand. In addition, the lateral distance from the test point to the wall was more than 9 times the cone diameter, which is also consistent with recommendations for dense sandy soils. Moreover, the vertical clearance below the cone tip exceeded 6 times the cone diameter, as recommended by Garnier et al. (2007), thereby avoiding bottom interference. An electric compaction hammer (36 kg, 1800 W, 230 V, 50 Hz) was designed and modified locally, with a circular steel plate of 2 mm thickness welded to its rod. This setup provided controlled laboratory compaction conditions.



Fig. 1 Manufactured components: (a) soil chamber; (b) electric hammer

System Layout

In this study, three subbase types were used. Laboratory tests, including sieve analysis, specific gravity, and the Proctor compaction test, were conducted to determine the soil properties and density before performing the tests in the manufactured soil chamber.

The work was carried out in three stages. In each stage, one specific subbase type (B, C, or D) was used. For each stage, water was added to the subbase at three moisture contents (4%, 6%, and 8.5%) in order to simulate different site conditions and to explore a wider range of DCP applications.

After the required amount of water was added, the soil was mixed in an electric mixer to obtain uniform moisture distribution. The soil was then placed in the chamber in five layers, each weighing 50 kg. The compaction time for each layer was varied in successive trials. The tested durations were 5, 4, 3, 2, and 1 minute, and each layer was compacted for the selected duration using the electric hammer to ensure consistent energy application. In each trial, a sand replacement test was carried out to determine the soil density and moisture content. The DCP test was then performed at the same point, and the number of blows required to penetrate 145–155 mm into the soil was recorded. For a layer weight of 50 kg and a compaction time of 5 minutes, the layer thicknesses were 120 mm for subbase type B, 100 mm for type C, and 90 mm for type D.

The test procedure was repeated following the same sequence described above by using moisture contents of 4%, 6%, and 8.5% and conducting the same five compaction attempts for each soil type (B, C, and D) (Figure 3).

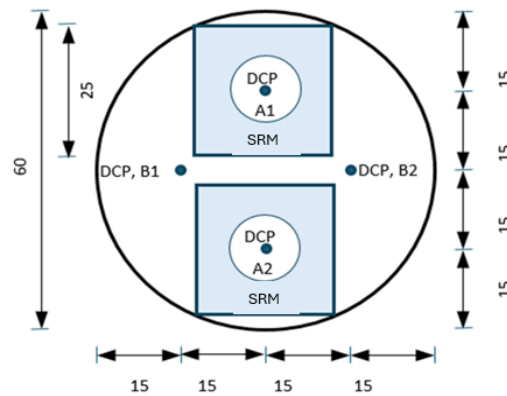


Fig. 2 Layout of testing points (all dimensions in cm)

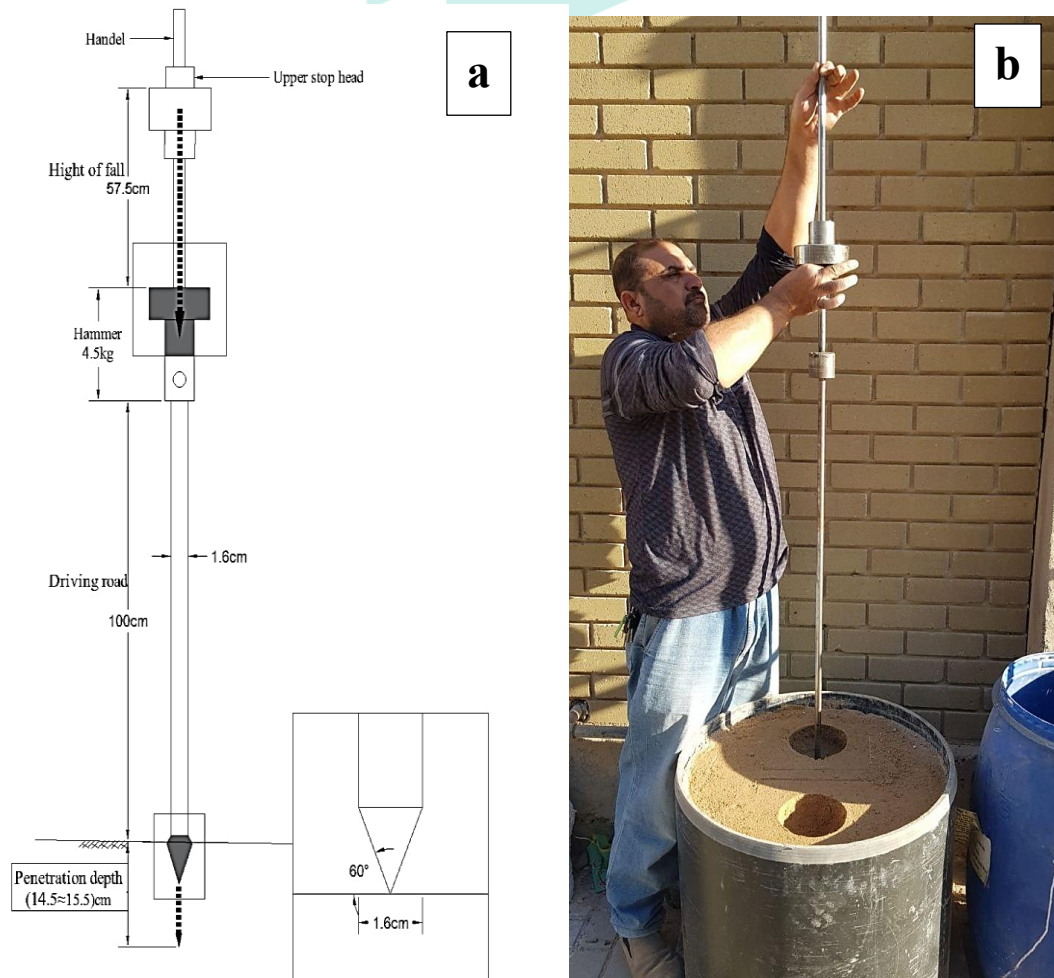


Fig. 3 DCP device: (a) DCP components; (b) application of the DCP test

RESULTS AND DISCUSSION

Sand Replacement Test

This section presents the results of the sand replacement test used to determine dry density and moisture content. The test was conducted in the soil chamber with systematic layer placement and varying compaction times while keeping the layer thickness constant. The results show that increasing the compaction time leads to higher dry density because of reduced voids between particles and improved particle arrangement.

For subbase type B, with a constant layer weight of 50 kg and a moisture content of 4%, the dry density reached 2.054 g/cm³ at 5 minutes of compaction and decreased to 1.807 g/cm³ at 1 minute. For subbase type C, the dry density varied from 2.038 g/cm³ to 1.761 g/cm³, while for type D it ranged from 2.028 g/cm³ to 1.748 g/cm³ (Das, 2002).

When the compaction time and layer thickness were kept constant, an increase in moisture content significantly affected the dry density. For subbase type D, the dry density increased from 2.028 g/cm³ at 4% moisture content to 2.090 g/cm³ at 8.5% moisture content, with an intermediate value of 2.051 g/cm³ at 6% moisture content, this consists with (Craig, 2004).

Overall, subbase type B showed the highest average dry density (2.054 g/cm³), followed by subbase type C (2.038 g/cm³) and type D (2.028 g/cm³). The standard deviation and coefficient of variation were below 10%, indicating acceptable repeatability and limited variability in the test results (Table 3, 4, and 5).

Table 3 Results of SRM tests for three types of subbases and M.C ≈4%

	Time of compaction (min.)	Subbase type B		Subbase type C		Subbase type D	
		M.C %	ρ_d g/cm ³	M.C %	ρ_d g/cm ³	M.C %	ρ_d g/cm ³
Average	5	4.130	2.054	4.180	2.038	3.995	2.028
STD		0.071	0.020	0.099	0.006	0.035	0.006
COV		1.712	0.964	2.368	0.312	0.885	0.279
Average	4	4.225	1.980	4.195	1.946	4.205	1.922
STD		0.134	0.035	0.106	0.006	0.064	0.014
COV		3.180	1.786	2.528	0.291	1.513	0.736
Average	3	4.020	1.922	4.190	1.895	4.210	1.850
STD		0.156	0.037	0.064	0.043	0.113	0.033
COV		3.870	1.950	1.519	2.277	2.687	1.758
Average	2	4.180	1.868	4.180	1.837	4.165	1.829
STD		0.127	0.022	0.057	0.017	0.049	0.030
COV		3.045	1.174	1.353	0.924	1.188	1.624
Average	1	4.040	1.807	4.065	1.761	4.210	1.748
STD		0.184	0.028	0.219	0.007	0.042	0.027
COV		4.551	1.565	5.392	0.402	1.008	1.537

Table 4 Results of SRM tests for three types of subbases and M.C ≈6%

	Time of compaction (min.)	Subbase type B		Subbase type C		Subbase type D	
		M.C %	ρ_d g/cm ³	M.C %	ρ_d g/cm ³	M.C %	ρ_d g/cm ³
Average	5	6.090	2.093	5.920	2.087	6.375	2.051
STD		0.127	0.060	0.014	0.054	0.177	0.024
COV		2.090	2.872	0.239	2.610	2.773	1.158
Average	4	6.210	2.012	6.140	1.994	5.980	1.962
STD		0.014	0.037	0.113	0.045	0.028	0.042
COV		0.228	1.863	1.843	2.235	0.473	2.162
Average	3	6.250	1.947	6.285	1.930	6.170	1.889
STD		0.099	0.040	0.177	0.035	0.170	0.037
COV		1.584	2.071	2.813	1.796	2.750	1.947
Average	2	6.165	1.868	6.170	1.857	6.090	1.829
STD		0.163	0.022	0.071	0.040	0.071	0.030
COV		2.638	1.174	1.146	2.132	1.161	1.624
Average	1	6.130	1.782	6.105	1.761	6.305	1.748
STD		0.028	0.049	0.049	0.021	0.233	0.027
COV		0.461	2.778	0.811	1.205	3.701	1.537

Table 5 Results of SRM tests for three types of subbases and M.C \approx 8.5%

	Time of compaction (min.)	Subbase type B		Subbase type C		Subbase type D	
		M.C %	ρ_d g/cm ³	M.C %	ρ_d g/cm ³	M.C %	ρ_d g/cm ³
Average	5	8.470	2.155	8.740	2.132	8.415	2.090
STD		0.170	0.028	0.099	0.033	0.262	0.026
COV		2.004	1.312	1.133	1.559	3.109	1.252
Average	4	8.350	2.117	8.510	2.079	8.320	2.022
STD		0.297	0.040	0.156	0.033	0.127	0.037
COV		3.557	1.904	1.828	1.599	1.530	1.854
Average	3	8.340	2.042	8.440	2.030	8.430	1.989
STD		0.297	0.062	0.170	0.050	0.368	0.037
COV		3.561	3.013	2.011	2.474	4.362	1.849
Average	2	8.510	1.982	8.695	1.950	8.360	1.930
STD		0.396	0.054	0.177	0.035	0.255	0.057
COV		4.653	2.748	2.033	1.813	3.045	2.931
Average	1	8.635	1.881	8.380	1.860	8.575	1.850
STD		0.163	0.062	0.297	0.049	0.262	0.049
COV		1.883	3.308	3.544	2.661	3.051	2.676

Dynamic Cone Penetration Test

Dynamic Cone Penetrometer (DCP) tests were conducted on the three subbase types under varying moisture contents (4%, 6%, and 8.5%) and different compaction durations (1–5 minutes) to assess penetration resistance. The Dynamic Cone Penetration Index (DCPI) was measured for each test condition.

The results revealed an inverse relationship between compaction time and DCPI; increasing the compaction time led to lower DCPI values, indicating greater penetration resistance. For example, at a moisture content of approximately 4% and a compaction time of 5 minutes, subbase type B exhibited a DCPI value of 5.128 mm/blow, whereas at 1 minute the value increased to 23.018 mm/blow. In contrast, DCPI values increased with increasing moisture content at a constant compaction time of 5 minutes. For subbase type B, the recorded DCPI values were 5.128, 7.160, and 9.020 mm/blow at moisture contents of approximately 4%, 6%, and 8.5%, respectively. This trend is consistent with previous observations that wetter soils tend to show lower penetration resistance because the increase in moisture reduces effective stress and interparticle friction (Eshan, 2014).

The granular distribution of the subbases also influenced the DCPI values. Subbase type B, which had a coarser and better graded granular structure, showed greater resistance to cone penetration and therefore lower DCPI values than subbases C and D. At 5 minutes of compaction and approximately 4% moisture content, the DCPI values were 5.128 mm/blow for type B, 8.213 mm/blow for type C, and 10.283 mm/blow for type D. This result highlights the influence of particle-size arrangement and gradation on soil resistance, which is consistent with the well-established understanding that well-graded soils exhibit greater interlocking and friction than uniformly graded soils (Bowles, 1970) (Table 6, 7, and 8).

Table 6 Results of DCP tests for three types of subbases and M.C \approx 4%

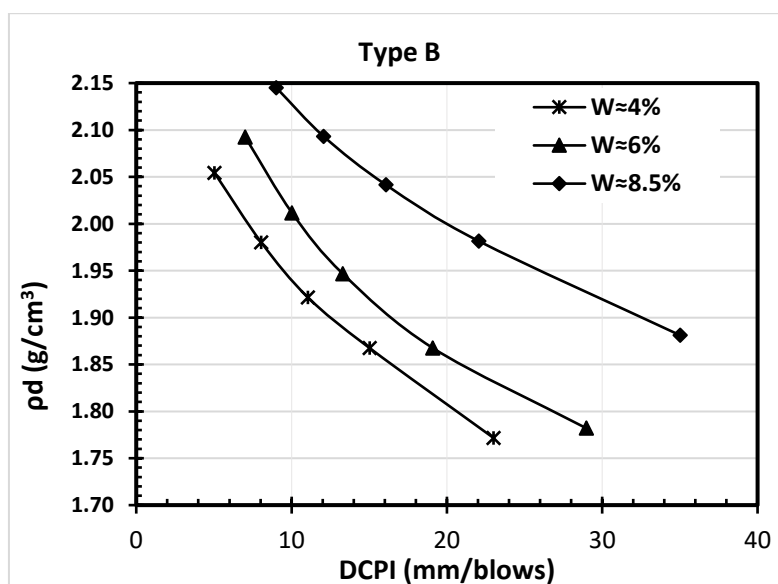
	Time of compaction (min.)	Subbase type B		Subbase type C		Subbase type D	
		M.C %	DCPI(mm /Blows)	M.C %	DCPI(mm /Blows)	M.C %	DCPI(mm /Blows)
Average	5	4.130	5.128	4.180	8.213	3.995	10.283
STD		0.071	0.109	0.099	0.161	0.035	0.223
COV		1.712	2.121	2.368	1.959	0.885	2.166
Average	4	4.225	8.265	4.195	11.228	4.205	15.168
STD		0.134	0.175	0.106	0.129	0.064	0.224
COV		3.180	2.120	2.528	1.151	1.513	1.479
Average	3	4.020	11.293	4.190	14.175	4.210	20.253
STD		0.156	0.196	0.064	0.165	0.113	0.106
COV		3.870	1.736	1.519	1.167	2.687	0.522
Average	2	4.180	15.383	4.180	19.330	4.165	24.253
STD		0.127	0.335	0.057	0.215	0.049	0.156
COV		3.045	2.175	1.353	1.111	1.188	0.642
Average	1	4.040	23.018	4.065	26.070	4.210	36.073
STD		0.184	0.448	0.219	0.504	0.042	0.924
COV		4.551	1.945	5.392	1.935	1.008	2.560

Table 7 Results of DCP tests for three types of subbases and M.C $\approx 6\%$

	Time of compaction (min.)	Subbase type B		Subbase type C		Subbase type D	
		M.C %	DCPI(mm /Blows)	M.C %	DCPI(mm /Blows)	M.C %	DCPI(mm /Blows)
Average	5	6.090	7.160	5.920	9.275	6.375	12.013
STD		0.127	0.187	0.014	0.130	0.177	0.329
COV		2.090	2.605	0.239	1.404	2.773	2.736
Average	4	6.210	10.238	6.140	13.125	5.980	17.163
STD		0.014	0.120	0.113	0.278	0.028	0.179
COV		0.228	1.170	1.843	2.120	0.473	1.041
Average	3	6.250	14.038	6.285	17.126	6.170	21.978
STD		0.099	0.345	0.177	0.270	0.170	0.255
COV		1.584	2.455	2.813	1.574	2.750	1.161
Average	2	6.165	15.398	6.170	19.270	6.090	24.205
STD		0.163	0.324	0.071	0.138	0.071	0.097
COV		2.638	2.106	1.146	0.714	1.161	0.403
Average	1	6.130	28.976	6.105	34.110	6.305	41.905
STD		0.028	0.357	0.049	0.401	0.233	0.392
COV		0.461	1.232	0.811	1.176	3.701	0.937

Table 8 Results of DCP tests for three types of subbases and M.C $\approx 8.5\%$

	Time of compaction (min.)	Subbase type B		Subbase type C		Subbase type D	
		M.C %	DCPI(mm /Blows)	M.C %	DCPI(mm /Blows)	M.C %	DCPI(mm /Blows)
Average	5	8.470	9.020	8.740	12.048	8.415	15.935
STD		0.170	0.331	0.099	0.352	0.262	0.205
COV		2.004	3.671	1.133	2.924	3.109	1.287
Average	4	8.350	12.078	8.510	15.055	8.320	22.103
STD		0.297	0.360	0.156	0.434	0.127	0.082
COV		3.557	2.984	1.828	2.885	1.530	0.370
Average	3	8.340	16.078	8.440	20.008	8.430	25.188
STD		0.297	0.350	0.170	0.161	0.368	0.257
COV		3.561	2.179	2.011	0.804	4.362	1.021
Average	2	8.510	22.055	8.695	28.163	8.360	33.110
STD		0.396	0.488	0.177	0.215	0.255	0.900
COV		4.653	2.215	2.033	0.764	3.045	2.719
Average	1	8.635	38.030	8.380	42.183	8.575	48.080
STD		0.163	0.657	0.297	0.535	0.262	0.521
COV		1.883	1.728	3.544	1.268	3.051	1.083



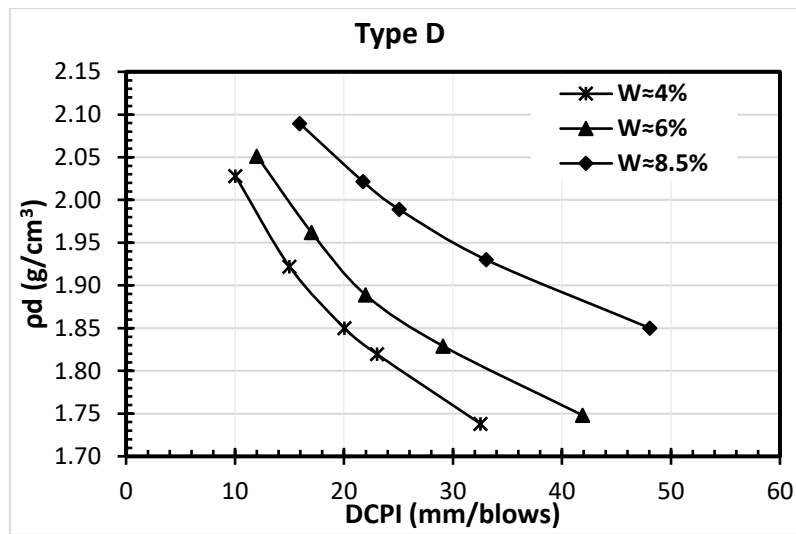
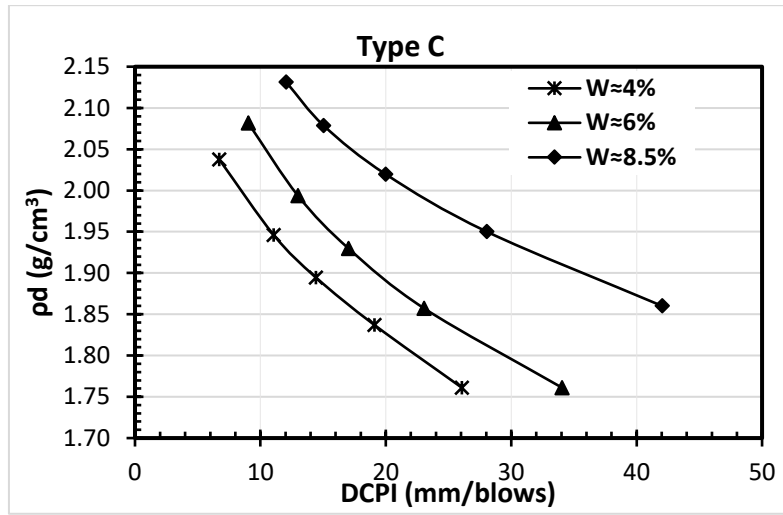
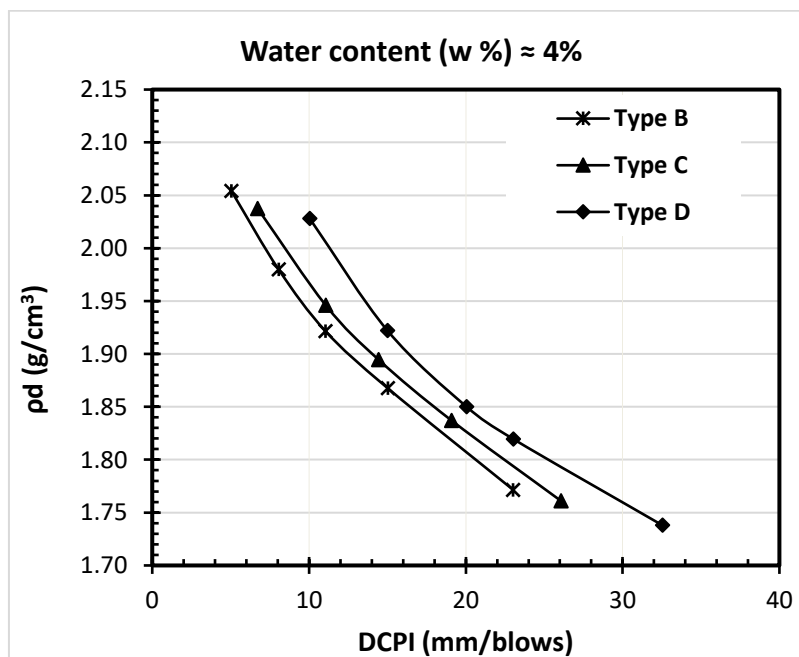


Fig. 4 Effect of moisture content on subbase types B, C, and D

Figure 4 illustrates the differences among the three subbase types. As the moisture content increases, both dry density and DCPI also increase within the tested range.



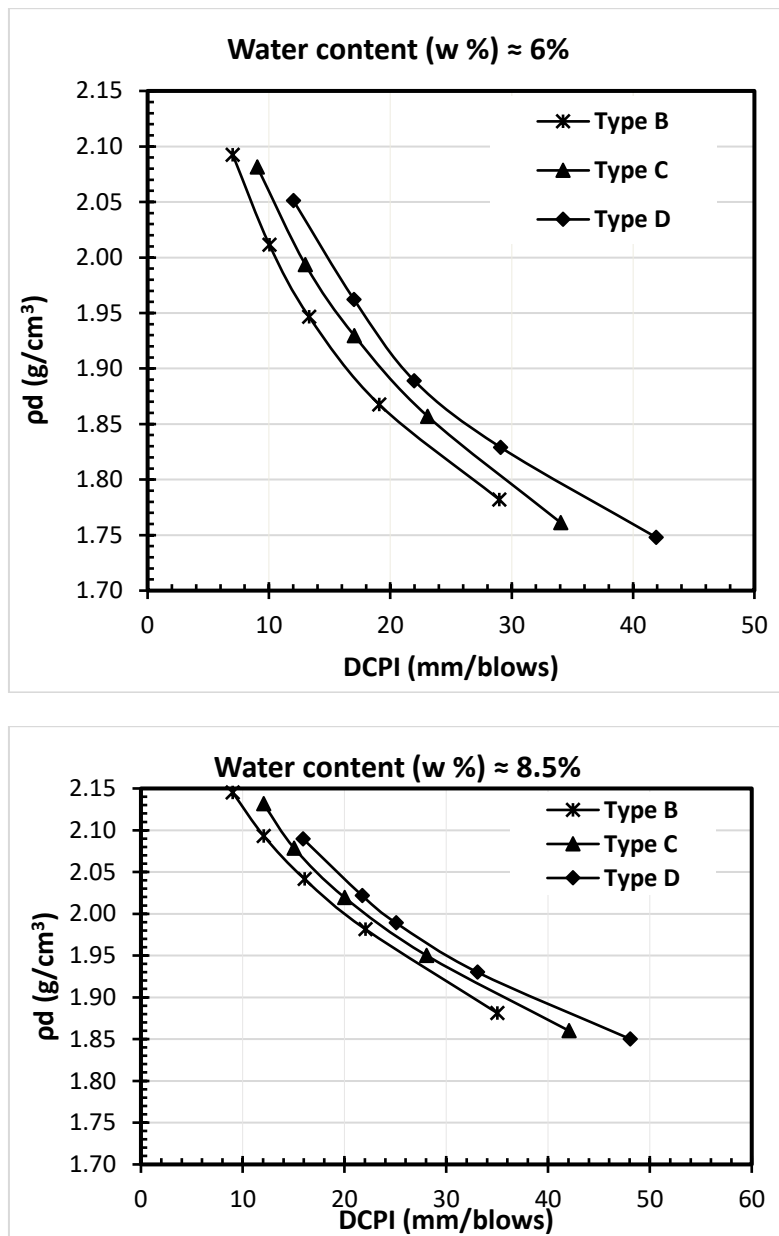


Fig. 5 Relationship between DCPI and dry density at moisture contents of 4%, 6%, and 8.5%

Figure 5 shows that, at a constant moisture content, subbase type B has a higher dry density than subbase types C and D. The graphs for soil types B, C and D clearly illustrate an inverse relationship between dry density (ρ_d) and the Dynamic Cone Penetration Index (DCPI). As DCPI increases, the dry density consistently decreases. This trend aligns with the well-established understanding that soils with lower compaction tend to exhibit higher penetration indices due to their reduced resistance to cone penetration. At a moisture content of 4%, the soils exhibit the highest dry densities and the lowest DCPI values, indicating a higher degree of compaction and resistance to penetration. As the moisture content increases to 6% and 8.5%, a gradual increase in dry density is observed, accompanied by a corresponding increase in DCPI. This behavior can be attributed to the lubricating effect of water, which reduces interparticle friction and shear strength, making the soil more susceptible to penetration. Although the general trend remains similar for three soil types, slight variations in the rate of change across the curves suggest that soil composition—such as grain size distribution or fine content—may influence the sensitivity of dry density to change in moisture and penetration resistance (Bowles, 1996).

Determination of Field Dry Density Using the Graphical Method

Based on the field-measured values of the Dynamic Cone Penetration Index (DCPI) and moisture content, the field dry density of compacted subbase layer can be estimated using the graphical method. This is achieved by utilizing the Figures (1, 2, and 3). The method involves the following steps:

1. Select the appropriate chart according to the type of subbase used in the compacted layer.
2. Determine the DCPI value from field measurements.
3. Determine the field moisture content of the compacted layer.
4. If the measured moisture content does not correspond to any of the three standard curves (each representing a specific moisture content) shown in the original figures, an additional interpolated curve is drawn to represent the measured moisture content.

5. From the measured DCPI value on the x-axis, draw a vertical line upward until it intersects the curve corresponding to the measured moisture content. Mark the point of intersection as point A.
6. From point A, draw a horizontal line toward the vertical axis which is representing dry density. The intersection point, labeled as point B, indicates the estimated field dry density corresponding to the measured DCPI and moisture content.

CONCLUSION

The experimental investigation using the Dynamic Cone Penetration (DCP) test on commonly used subbase materials in road projects in Basra led to the following conclusions:

1. Identifying the subbase type is essential when using DCP tests in site investigations in order to ensure correct use and interpretation of the corresponding graph.
2. The laboratory results revealed that DCPI values are inversely related to compaction effort; increasing the compaction effort leads to lower DCPI values, which indicates improved soil resistance.
3. Moisture content has a direct influence on DCPI values. As the moisture content increases, DCPI also increases, indicating lower penetration resistance within the tested range.
4. When moisture content and compaction effort are held constant, subbase type remains a critical factor. Subbase type B demonstrated higher dry density and lower DCPI values than types C and D, which may be attributed to its more favorable granular gradation.

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