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THE ROLE OF DYNAMIC CONE PENETROMETER TESTING IN ASSESSING PAVEMENT SUBGRADE STRENGTH: A LITERATURE REVIEW

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ABSTRACT: In-situ tests for predicting geotechnical parameters related to shear strength, such as California Bearing Ratio (CBR), typically require drilling boreholes and manual cone driving, which can be time-consuming, expensive, and labor-intensive. The Dynamic Cone Penetrometer Test (DCPT) has emerged as a simpler, faster, and less expensive alternative for predicting CBR and other geotechnical parameters. This systematic review uses Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to examine relevant literature on DCP testing for accurately predicting CBR and other geotechnical parameters. After trimming 111 relevant studies to 55, the review discusses various research questions, including the correlation between DCP and CBR, factors such as water content and seasonal variations, and recent advances in DCP testing. The review emphasizes the importance of considering unsaturated soil behavior, such as soil suction, in pavement subgrade design to ensure the longevity and quality of the pavement. The findings provide compelling evidence for the utilization of DCP testing as an essential tool for predicting geotechnical parameters and designing high-performance pavements. By demonstrating the DCPT's remarkable convenience, reliability, and cost-effectiveness in CBR and geotechnical parameter prediction, this study paves the way for significant advancements in pavement design efficiency and economic viability.

Keywords: California bearing ratio, Cone penetration test, Dynamic cone penetrometer, Matric suction, Standard penetration test

1. INTRODUCTION

Assessing soil characteristics is crucial in geotechnical, foundation, and road engineering. The disturbance caused during collection, transportation, and testing of soil specimens complicates determining their mechanical properties accurately. In-situ tests have been developed to address this challenge, offering a non-disruptive means of evaluating soil properties. Two commonly used in-situ tests are the Standard Penetration Test (SPT) and Cone Penetration Test (CPT). SPT involves counting hammer blows to penetrate soil in boreholes, while CPT measures the force required to push a cone into cohesive soils. However, these tests, conducted with cone penetrometers, can be time-consuming, expensive, and labor-intensive [1]. To address prevailing challenges, a novel in-situ testing approach, the Dynamic Cone Penetration Test (DCPT), has been introduced. Unlike traditional methods like the SPT, the DCPT eliminates the need for boreholes while providing cone resistance data similar to the CPT. Widely used in geotechnical and pavement design, the portable DCPT apparatus includes an 8 kg sliding hammer, a 57.5 cm drop height, and a 111 cm driving shaft with a 60-degree angle cone tip. During testing, the hammer drives the cone into the ground, with penetration depth recorded after each drop. Numerous correlations have been established in the literature linking DCPT results with key soil properties such as the California Bearing Ratio (CBR), undrained shear strength (Su), elastic modulus (E), and resilient modulus (Mr), facilitating informed decision-making in engineering applications [2]. The most common correlation for DCP is its correlation with CBR. Where the material type of each pavement layer was determined using the correlation in accordance to ASTM, except lean clay soil [3]. Correlating the DCPI with geotechnical parameters provides rapid, cost-effective, and reliable results compared to other soil exploration methods. Crucial for engineering, geotechnical, and agricultural purposes, this test informs the design of structures like buildings, bridges, roads, and other infrastructure [4-5].

The Dynamic Cone Penetrometer (DCP) test is highly versatile for evaluating subgrade materials' engineering properties in geotechnical engineering. It is cost-effective, convenient, and provides precise data on bearing capacity and compaction characteristics of subgrade layers and pavements. Despite variations in DCP equipment, they share the same testing principle, as indicated in previous studies [6]. Some researchers have proposed using DCP in field trials to determine the mechanical properties of subgrade layers and road pavements, citing its simplicity, speed, and affordability compared to other geotechnical tests [7].

The Dynamic Cone Penetration Index (DCPI) is influenced by soil resistance to cone penetration. Decreased cohesive strength can lead to easier cone penetration, resulting in a higher DCPI and a lower California Bearing Ratio (CBR), potentially diverging from the actual CBR value [1]. Variations in water content can also affect DCPI-based predictions of soil properties. Soil attributes within the active layer, such as water content, chemical properties, strength, and stiffness, fluctuate due to seasonal moisture changes, impacting hydrological aspects like infiltration and distribution [8]. Consequently, predicted CBR using the Dynamic Cone Penetrometer (DCP) may vary based on soil moisture content even within the same soil sample. In highway subgrade construction, using soil with higher water content than optimum can hinder achieving target compaction [9]. Seasonal moisture fluctuations can also cause swelling in expansive clay subgrades, leading to pavement top layer uplift [10].

In the construction of granular pavement layers and earthworks, assessing the quality of compacted layers like subgrade, subbase, and base is crucial. With the transition from empirical to mechanistic-empirical pavement design methods, there's a need to shift QC/QA procedures from unit weight-based to stiffness/strength-based criteria. Unit weight-based criteria lack sufficient information about the engineering properties of granular layers, leading to a disconnect between design and quality control [11].

Although researchers have made adjustments to the Dynamic Cone Penetrometer (DCP) to resolve issues such as inaccurate penetration depth readings and tilted DCP orientation, while others have introduced equipment to measure moisture content during testing. Including parameters from unsaturated soil mechanics in the empirical formulas developed by several researchers for DCP testing remains pending. This field of soil mechanics is essential as it pertains to the influence of moisture variation and volumetric changes on soil behavior.

This literature review offers a comprehensive analysis of the Dynamic Cone Penetrometer (DCPT), covering its components, the relationship between DCP and CBR equations, apparatus improvements, and key knowledge gaps like the integration of unsaturated soil mechanics principles. It highlights formulas developed by previous researchers to guide future investigations aiming to enhance the reliability of DCPT without compromising its portability and effectiveness.

2. RESEARCH SIGNIFICANCE

In recent years, the use of Dynamic Cone Penetrometer Test (DCPT) as an alternative to traditional in-situ tests for predicting subgrade design parameters has gained attention. This review provides an in-depth analysis of DCP's advantages and recent advances that address its limitations. It emphasizes considering unsaturated soil behavior. The research is significant for addressing knowledge gaps and incorporating unsaturated soil mechanics in pavement construction, design and maintenance.

3. METHODOLOGY

Recent studies extensively used DCP to predict CBR values, establishing correlations through lab and in-situ testing. This study builds on that groundwork, investigating DCP's role in pavement design and analysis and aims to answer these specific research questions: 1) How can DCPT and CBR testing be used for the prediction of pavement performance? 2) What are the recent advances in DCP testing methods and data interpretation techniques? 3) How can the connection between DCP and CBR values be leveraged to create faster and more reliable ways to assess soil properties and design better pavements? 4) To what extent does soil moisture influence the outcomes of the DCP test?

The methodology rigorously followed the PRISMA guidelines, as depicted in Figure 1. A thorough search was conducted across prominent databases such as ScienceDirect and Google Scholar, using refined keywords including "Dynamic Cone Penetrometer," "California Bearing Ratio," and "emerging technology." This systematic search was limited to English language publications, with a focus on recent contributions, resulting in the identification of 111 relevant papers. Each paper underwent meticulous screening, including evaluation of title, abstract, introduction, and conclusion, resulting in the refinement of the initial selection to 79 papers. Following this, a thorough examination of the full texts led to the retrieval and review of 55 papers meeting the predetermined inclusion criteria. These carefully selected papers were included in the comprehensive review, ensuring a robust synthesis of contemporary literature on the subject.

4. DYNAMIC CONE PENETROMETER

The Dynamic Cone Penetrometer Test (DCPT) is commonly used in preliminary investigations to assess critical soil parameters for pavements, subgrades, and lightweight structures through empirical correlations[1,8,12,13]. It measures factors like bearing capacity, stiffness, cohesion, and more. It also evaluates the compaction of pavement materials [2, 6,7,9,11–25]. DCPT ensures quality control and is widely employed for site investigation in preliminary design.

4.1 DCP History

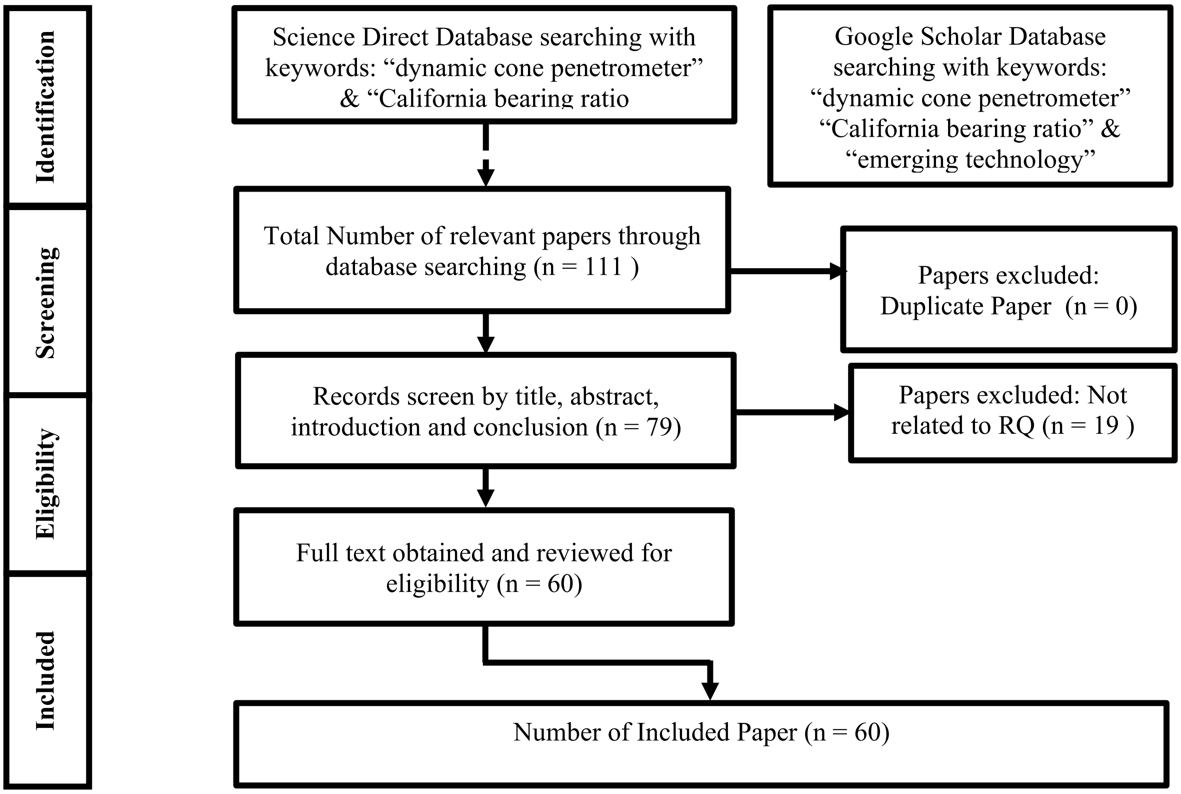
DCPT was developed in 1956 by Scala[21,26–28] and enhanced in 1969 by Dr. D.J. Van Vuuren and South Africa's Transvaal Roads Department. It estimates in-situ support capacity for subgrade materials and pavement layers[16,28]. Many countries, including the US, UK, Australia, New Zealand, and South Africa, adopted DCPT for soil characterization[7,26,29]. The US Air Force uses it to evaluate soil strength parameters like bearing capacity[30]. The cone tip can be modified from 30 to 60 degrees until ASTM developed a standard for its use[31] [32].

4.2 DCP Method and Apparatus

DCPT uses a portable dynamic cone penetrometer (DCP) operated by two technicians. One raises and drops an 8-kilogram (17.6 lb) hammer to push the cone into the soil, while the other records penetration depth and blows [27]. The DCP apparatus includes a cone-shaped probe with a flat bottom, a coupler assembly, a handle, a steel drive rod, and a vertical graduated scale for measuring depth (Fig. 2).

The DCP cone has a 20 mm (0.79 in) diameter 60-degree angle and provides 144 kN-m/m^2 theoretical energy per blow unit cone area. It is driven into the soil using a 17.6 lb (8 kg) hammer dropped from 22.6 in (575 mm). Soil shear strength is reported as the Dynamic Cone Penetration Index (DPI) in mm per blow at selected intervals[1–3,7,9–13,21–24,26,28,30,33–46]. Equation 1 determines the drive rod movement based on hammer blows (Fig.3). It considers two variables such as z1 for initial penetration depth and z2 for final penetration depth. The second variable, the hammer blow factor (h), adjusts the distance covered between the two points. A value of 1 and 2 is assigned to the heavy and lighter assembly, respectively [5].

Plotting penetration depth in millimeters against the number of blows on a graph reveals the DPI (mm/blow) slope. This test offers a quick and straightforward estimate of in-situ support capacity for subgrade materials and pavement layers.[3,4,23,27,29,47].



$$DPI(z) = \left(\frac{z_1 - z_2}{b}\right) x\ h \qquad (1)$$

The standard DCP apparatus is economical, portable, and highly mobile. However, accuracy depends on precise testing procedures. Factors like inconsistent driving energy and friction loss can affect results. Modified DCP apparatuses have been developed to address specific testing needs [16,38,48].

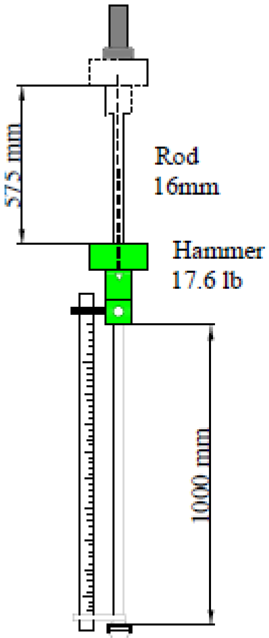


Fig.2 Schematic diagram of DCP [21]

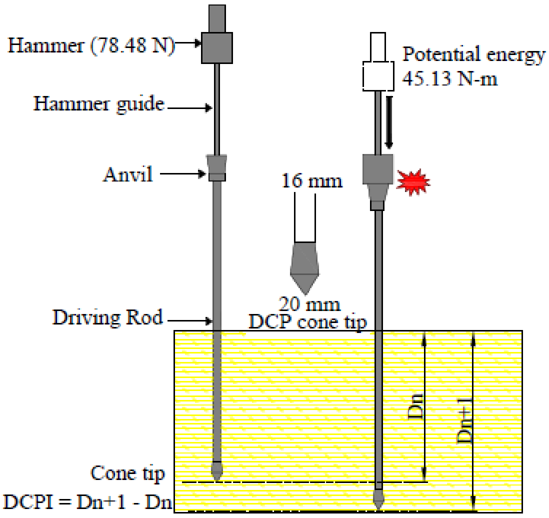


Fig.3 DCP Penetration depth measurement [38]

5. ADVANCES IN DCP

The DCP apparatus has seen improvements in addressing issues like predicted result variability in laboratory testing due to limited mold diameters[26], observer's penetration depth readings, tilted DCP orientation, and rod-anvil friction. Modifications have enhanced accuracy by eliminating potential sources of error[6], making DCP more reliable and versatile for soil characterization in geotechnical and foundation engineering fields[7,47,48].

5.1 Automated Dynamic Cone Penetrometer

The US Army Corps of Engineers developed an automated Dynamic Cone Penetrometer (DCP) system called RAVEN (road assessment vehicle - engineer) for soil strength testing. The system allows fully automated testing from inside a vehicle. The DCP attachment lifts and lowers the hammer using auxiliary hydraulics, providing precise results with sensors measuring cone penetration and hammer location. The system requires only one technician, reducing manual labor and offering instantaneous, secure results without post-processing[16].

5.2 Dynamic Lightweight Penetrometer (DLP)

In 2012, researchers introduced the Dynamic Lightweight Penetrometer (DLP) as an improved apparatus for Dynamic Cone Penetration (DCP) testing. The DLP test is conducted in a laboratory using a standard CBR mold and a lighter 2.25 kg hammer dropped from 510mm height (Fig.4). DLP results were comparable to DCP field tests, making it suitable for situations with access limitations or unsubstantial soil for the standard DCP[15,27,47,49,50].

5.3 Instrumented Dynamic Cone Penetrometer

The Instrumented Dynamic Cone Penetrometer (IDCP) assesses in-situ soil strength. A 24mm diameter cone tip with a 60° apex angle, equipped with an accelerometer and a load cell, enables quantification of soil strength. The IDCP (Fig.5) includes a driving rod, donut hammer (117.7 N), and hammer guide, with larger dimensions than a regular Dynamic Cone Penetrometer (DCP) to accommodate sensors. Each blow yields 67.7 N-m potential energy, higher than the conventional DCP's 47.7 N-m (Fig.2)[8,38,48].

5.4 Instrumented Dynamic Cone Penetrometer incorporated with TDR (IDPT)

The integrated IDPT apparatus uses TDR to predict water content, improving soil testing accuracy and efficiency. The instrument (Fig. 6) utilizes a combination of a probe, driving rod, energy module, and hammer equipped with accelerometers, load cells, and a cone energy tip module to estimate soil strength and water content simultaneously. Signals from the sensors are analyzed using a computer, significantly improving in situ soil testing[38].

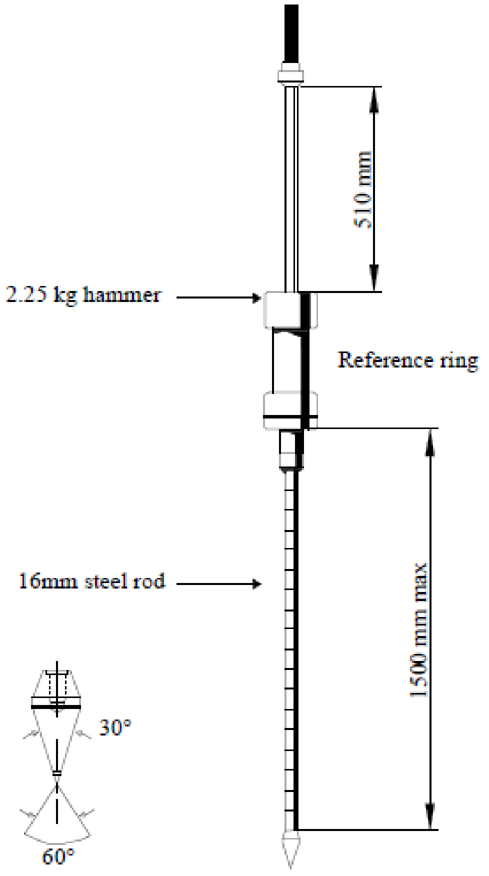


Fig.4 Schematic drawing of DLCP [49]

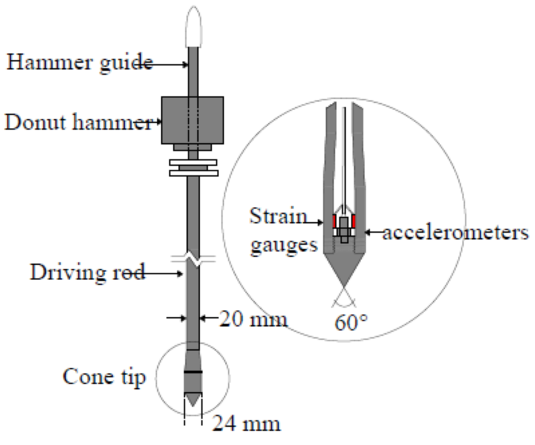


Fig.5 Schematic drawing of IDCP [8]

6. CALIFORNIA BEARING RATIO

The CBR test evaluates subgrade, subbase, and base materials for pavement design suitability, measuring soil's resistance to shearing under controlled moisture and density conditions. Developed by the California Division of Highways in 1929, it categorizes soils for use in highway construction. This method also assesses material stiffness and resistance to permanent deformation[11,30,34,39,41,42,46,47,51,52].

CBR is an empirical measure of subgrade behavior used in low-volume road design[4,5,11,34,44,50]. It represents soil resistance as a percentage of good-quality crushed rock, with CBR 20 indicating 20% lower resistance at 2.54 mm penetration with a 1360.8 kg load.

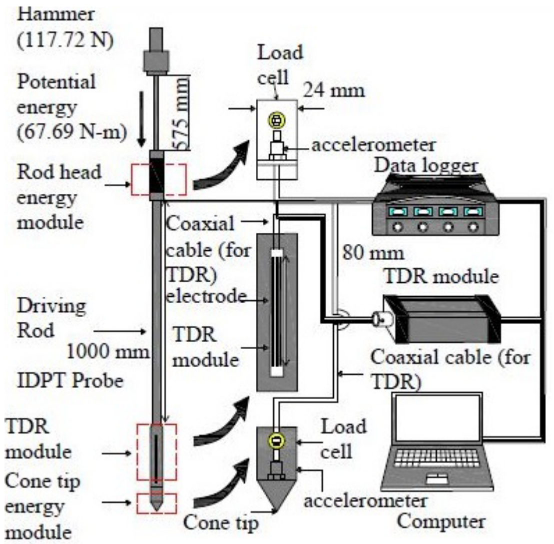


Fig.6 Schematic diagram of IDPT[38]

6.1 CBR Procedures and Apparatus

AASHTO and ASTM prescribe CBR test procedures for subgrade, subbase, and base course materials used in pavement construction. It evaluates materials with a maximum particle size of less than 3/4 in. (19 mm). The test equipment includes a cylindrical mold (Fig.7) with a volume of 2315.15 cm^3, a spacer disc, special weights, a metal penetration piston, and a loading machine with a capacity of at least 5000 kg traveling at 1.25 mm/min.[1,8,11,39,48,53]

6.1.1 Compaction of Specimens

Samples were dry compacted using a 10 lbs (4.54 kg) rammer dropped from 18 inches (457mm) in accordance with ASTM D1557/AASHTO T-180. The number of hammer blows (10, 25, or 56) depended on the desired density. Then, specimens were immersed in water with a metal surcharge as per ASTM D1883/AASHTO T-193.[28,47,48,53-54]

6.1.2 Soaking and Swelling Computation

After four days of soaking, CBR test penetration was performed on samples in a mold with perforated plates, allowing water access. Swelling properties were measured with an adjusted metal stem and a dial indicator. The swelling rate was calculated using Eq. (2)[33,39,41].

$$\delta = \frac{H_1 - H_O}{H_O} \tag{2}$$

6.1.3 Penetration

CBR values are calculated for soaked compacted specimens at penetration depths of 2.54 mm and 5.08 mm with reference loads of 6.9 MPa and 10.3 MPa[11,28,34], respectively. Testing is done on a CBR machine at 1.25 mm/min penetration rate, and division readings at required penetrations are recorded.

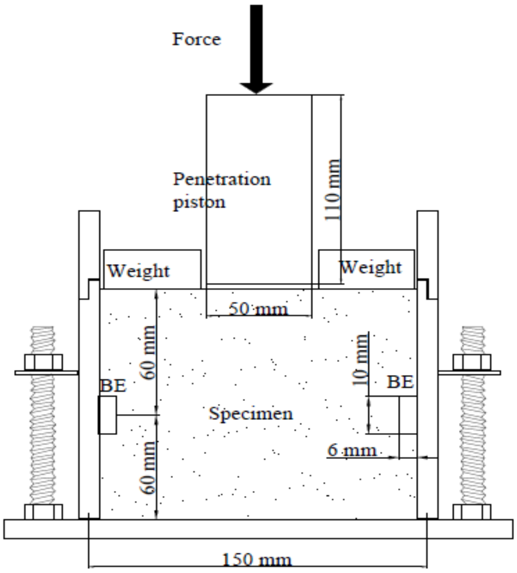


Fig.7 CBR mold [8]

Moisture content is calculated per ASTM D2216[55] and compared to optimum moisture content. Load-penetration curves are graphed to obtain CBR values. Failing to handle the equipment carefully can lead to inaccurate results, jeopardizing the entire experiment. [28].

For design purposes, use the CBR value at 2.5 mm if it is greater than the value at 5 mm. Repeat the test if the 5 mm value is greater. If the results are identical, use the CBR at 5 mm for design[11].

7. DCP-CBR RELATIONSHIP

Pavement design considers parameters like performance period, design traffic (computed using CESAL), and Effective Roadbed Resilient Modulus (Mr) based on CBR value, as per the AASHTO pavement design procedure[52,56].

The DCP test is a quick, in-situ method for measuring soil characteristics, providing a valuable tool for pavement design. Several researchers have developed DCP-CBR correlations for different soil types, see Table 1, making it widely used worldwide. Logarithmic equations (log CBR = A + log B) are prevalent for predicting the DCPI-CBR relationship in pavement engineering. The most preferred equation is the one initially proposed by USACE and ASTM in the exponential form[3,5,6,33, [35–37,40,57-59]. The exponential equation is preferred due to its simplicity and ease of interpretation. It predicts the inverse relationship between CBR and DCPI.

Table 1. DCP-CBR Correlation developed by previous researchers

References	DCP-CBR Correlation Equation	(R^2)	Materials
ASTM 6951	$\mathbf{CBR = \frac{292}{DCPI^{1.12}}}$ CBR = $\mathbf{\frac{1}{(0.017019\ DCPI)^2}}$ CBR = $\mathbf{\frac{1}{(0.002871\ DCPI)^2}}$		All soils except soft CL and CH soils CL soils with CBR < 10 CH soils
Khalid [1]	$\mathbf{CBR = \frac{383}{DCPI^{1.127}}}$	0.89	Fine grained soil(alluvial deposit)
Zhang [6]	log CBR = 2.16-0.65 log DCPI log CBR = 2.29-0.96 log DCPI log CBR = 2.04-0.61 log DCPI	0.74 0.79 0.78	Lignin-based by-product stabilized silty soil
Vakili [7]	$\mathbf{CBR = \frac{41.21}{e^{0.077DCPI}}}$	0.89	Marl soil stabilized with lime
Yan Jung-Du [9]	log CBR = 2.59-1.13 log DCPI log CBR = 2.61-1.21 log DCPI	0.75 0.73	Subgrade materials stabilized with CCR
Chang Seon [37]	log CBR=2.465-1.12 log DCPI		Soil stabilized with modified drilling waste materials
Gunde [24]	log CBR =2.48-1.057 log DCPI		SW, SC, and clayey sands
Al-Refeai [28]	log CBR = 2.50-1.07 log DCPI		Sand, silty sand, and clay
Sagar [41]	log CBR = 1.55-0.55 log DCPI		Clayey soil
Patel [42]	0.2235DCPI-0.29716WLL-0.34399MC+18.59709	0.89	Silty sand and clay (SM), silty soil (CL)
Wang [20]	$\mathbf{CBR = \frac{405.3}{DCPI^{1.259}}}$		Silty soil
Kim [8]	log CBR=2.09-0.38 log EDCPI log CBR =1.93-0.26 log IDCPI	0.71 0.45	Frozen thawed arctic soil
Lee [21]	log CBR =3.93-1.47 log DCPI	0.93	Gravelly and silty sand, (SP & SM)

8. EFFECT OF WATER IN DCP TEST

For reliable prediction of soil's physical and mechanical characteristics with practical significance, employing the DCPI requires incorporating the critical parameter of natural water content (w_n). The DCPI is highly sensitive to changes in soil water content, even when the dry density is constant, and there is a strong correlation between natural water content and other geotechnical characteristics of soil[1,23]

Rainfall can cause the natural water content of the soil to fluctuate, leading to significant changes in soil volume and varying volumetric water content[38]. As soil moisture increases, the soil begins to expand due to swelling. With further water addition, the pore pressure in the soil decreases, resulting in a reduction in cohesive strength and a subsequent apparent reduction in cohesive strength[5].

Since the DCPI relies heavily on soil resistance to cone penetration, a decrease in cohesive strength can make the cone penetrate more easily, resulting in a high DCPI and low CBR (California Bearing Ratio), which may differ from the actual CBR value of the soil. Previous studies have suggested that changes in water content can affect the DCPI-based prediction of the physical and mechanical properties of soil. Thus, integrating w_n into DCPI-based predictive models could improve the models' reliability and performance.[1]

Khalid [1], used natural water content (w_n) and the Dynamic Cone Penetrometer Index to develop predictive models for the physical and mechanical properties of undisturbed soils (DCPI). Their DCPI-CBR predictive model, which combines the two variables, demonstrates a strong correlation with a coefficient of determination of 0.62. When tested on a 3D response surface, the predictive model improves accuracy by 31%. This study emphasizes the significance of including natural water content when predicting the physical and mechanical properties of soils. However, the proposed model may not be applicable to dry soils, soils with no water content, or soils with seasonal moisture variations.

In a soil trafficability study, Sion [5] concluded that increased soil moisture levels reduce soil strength properties such as compressive strength, shear strength, and CBR. The effects of saturation on these properties were systematic. However, the study emphasizes the importance of taking environmental factors like vegetation, thawing, and land use into account when analyzing the effects of soil moisture on dynamic soil properties.

Ampadu [23] has found that the variation in average and optimum moisture content follows an analogous pattern to the soil-water characteristic curve (SWCC) and its influence on shear strength. They believe that further studies are required to identify the soil-water characteristics of the soil to develop a more thorough understanding of the effect of moisture on DCPI in terms of matric suction.

9. DISCUSSION

The research gaps identified in the literature can be categorized into several themes.

9.1 Soil Specificity and Applicability of Models/Equations

These gaps highlight the need for specific equations or models tailored to certain soil types or conditions. Issues such as soil moisture variations, soil swelling, site-specific characteristics, and regional variations call for more targeted research to improve the applicability and accuracy of existing models [1,6,7,8,22,35,60-62].

9.2 Testing Methods and Protocols

Gaps exist in testing methods, protocols, and correlations, especially concerning stabilized soils, gaining strength over time, and the effects of water on material properties. Further research is needed to refine testing protocols, including more diverse and comprehensive field tests and consideration of matric suction [23,28,33,37].

9.3 Long-term and Environmental Considerations

These gaps emphasize the importance of long-term monitoring, understanding the impact of environmental factors (such as rainfall during curing periods), and considering the evolution of treatments over time. Research focusing on seasonal moisture changes, durability, and the effects of combined treatments versus single treatments is necessary [5,9,12,30,63,64].

9.4 Validation and Validation Techniques

Validation of equations, models, or correlations through appropriate techniques like micro-coring or excavation with material sampling is necessary. Ensuring the presence of hydraulic binders and understanding soil-water characteristics for validation are crucial aspects [3,21].

The USACE and ASTM equation predicts CBR value for various soils. Specific equations for different soil types are also available. Moisture content and soil suction's impact on subgrade strength remain unclear and controversial. Compacted subgrade should be considered unsaturated due to seasonal moisture variations and underlying soil suction [5,23].

More research is needed to explore soil suction's influence on subgrade moisture content during DCP testing and incorporate the soil-water characteristic curve (SWCC) to understand the impact of unsaturated soil parameters like volume change [38] and matric suction [23].

In conclusion, the literature review reveals multifaceted gaps in soil mechanics research. Bridging these knowledge gaps demands a collaborative push to craft dedicated models tailored to diverse soil types, enhance testing methodologies and protocols with greater precision, integrate long-term environmental influences into our calculations, and leverage rigorous validation techniques to ensure accuracy.

10. CONCLUSIONS

The DCP has revolutionized preliminary soil assessment, providing a faster and more convenient alternative to traditional methods. It efficiently determines design parameters, including CBR and bearing capacity, making it an essential tool for pavement and building design.

DCP technology has improved soil testing, but understanding moisture content and soil suction on subgrade strength remains challenging. Soil swelling due to water content fluctuations affects strength [5,38]. Khalid's predictive model includes water content but has limitations [1]. Environmental factors also impact soil properties [5]. Ampadu's findings highlight the importance of considering water content for improved predictive models [23]. Field subgrades should be assessed in an unsaturated state for realistic behavior. While modified DCPs exist, they may not align with the portable and effective nature of the DCP.

This review emphasizes the importance of considering unsaturated soil behavior, including soil suction, in pavement subgrade design using DCP. Further research is needed to enhance DCP's reliability and performance, particularly in regions where unsaturated soil mechanics are not fully embraced. Addressing these gaps will improve pavement construction quality and longevity.

11. ACKNOWLEDGEMENT

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