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Influence of Degree of Saturation and Degree of Compaction on Unsoaked CBR Values

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I. Introduction

For the satisfactory performance of soil structures, it is conventional to control soil compaction by focusing on the dry density (ρ_d) and water content (w) relative to the maximum dry density (ρ_d) max and optimum water content (w_{opt}) determined by standard laboratory compaction tests at a specific compaction energy level (CEL)[1]. However, both $(\rho_d)_{max}$ and w_{opt} are significantly affected by variations in soil type and CEL, which are often difficult to accurately estimate or control in the field. Importantly, the resultant stress-strain, stiffness, and hydraulic properties of compacted soil, such as the California Bearing Ratio (CBR), are controlled not merely by ρ_d and w , but fundamentally by the ρ_d and the degree of saturation (S_r) achieved during compaction[1]. This is because the physical properties are governed by the effective stress state and the micro-structure, both of which are strongly influenced by the matric suction during compaction, a function of S_r[1] . This study investigates the fundamental variation of CBR values concerning the degree of compaction and under conditions of constant moisture content, thereby clarifying the mechanisms that govern soil strength under coupled density-saturation changes.

II. Literature Review

Strength and stiffness are closely tied to the compacted state defined by dry density (ρd) and to properties influenced by matric suction, which depends on the degree of saturation (Sr)[2].

There is a trade-off relationship between dry density and degree of saturation in controlling the CBR value when compaction increases under constant water content. Increasing compaction produces two simultaneous but opposing effects on CBR. As compaction increases, the void ratio decreases and dry density rises, creating a denser soil structure with closer particle contact. This improves load-bearing capacity and increases the CBR value due to enhanced inter-particle friction. At the same time, the reduced void ratio raises the degree of saturation because the same amount of water fills a larger proportion of the pore space. Higher saturation lowers matric suction, reducing apparent cohesion and stiffness in the unsaturated soil, which tends to decrease the CBR. The resulting CBR at any compaction level reflects the balance between these two mechanisms. At lower compaction, the benefit of increased dry density dominates; at higher compaction or near saturation, the loss of matric suction may offset or exceed this benefit, causing the CBR to plateau or decline.

This research evaluates these influences and aims to predict key compaction parameters to guide compaction methods, reducing the need for extensive field trials. Instead of dry density (ρd), the degree of compaction (Dc) is used for easier field interpretation.

III. Materials and Methods

This study analyzed CBR and compaction data consistent with full-scale compaction testing methods. The original full-scale tests, conducted by Nemoto and Sasaki (1994), used a large concrete pit to replicate field conditions. A 30 cm sandy loam test layer was placed over a 60 cm fixed base and compacted using vibratory and pneumatic tire rollers, with up to 16 roller passes (N). In-situ dry density (ρd) was measured by the sand-replacement method at N = 0, 2, 4, 8, and 16 within the top 10 cm, and corresponding CBR values were recorded to track stiffness development. For the current analysis, digital plot digitization software was employed to extract a total of 149 data points representing the unsoaked CBR, Degree of Saturation (S_r) and Degree of Compaction (Dc) from the published graphical data from the research article *"Compaction Characteristics and Physical Properties of Compacted Soil Controlled by the Degree of Saturation"* by Prof. Fumio Tatsuoka of the Tokyo University of Science, Japan[2].

IV. Results and Discussion

The empirical modeling aimed to quantify the opposing effects of densification and saturation on soil stiffness. The

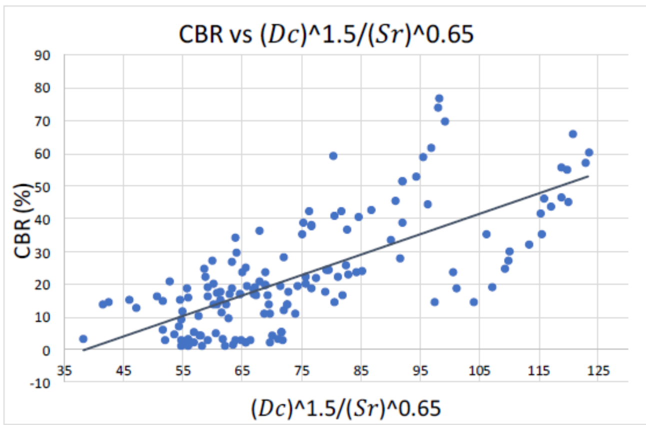

Fig. 1. Linear variation analysis of CBR vs. Optimized Compaction-Saturation Ratio

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analysis yielded a best-fit linear regression model where the Degree of Compaction (Dc) is raised to a positive power, and the Degree of Saturation (S_r) appears in the denominator.

$$CBR \approx 0.65 \frac{Dc^{1.5}}{Sr^{0.65}} - 22.5$$

The model achieved a coefficient of determination (R^2) of approximately 0.51, with exponents of 1.5 and 0.65 quantifying the respective contributions of density and saturation. Fig. 1. illustrates the clear positive trend between measured CBR and this combined index, validating the model's ability to capture the general governing relationship. However, the scatter of data points around the regression line reflects inherent variability in soil micro-structure that extends beyond simple density-saturation effects.

Fig. 2. shows the variation of CBR with degree of compaction (Dc) for two constant moisture contents (w = 11% and 13%), based on 65 data points. The graph identifies an optimum compaction range where particle packing and matric suction together maximize the CBR, followed by a decline as saturation increases and suction decreases.
CBR increases with Dc up to an intermediate peak, then declines even with further compaction. At low compaction, the loose structure and high void ratio create high matric suction, increasing apparent cohesion and strength. As compaction rises, particle packing improves, also increasing CBR. Beyond the peak, however, the reduced void ratio raises the degree of saturation (Sr), lowering matric suction and weakening particle bonding, which decreases CBR.

Analysis of Sr shows that CBR becomes inversely related to saturation beyond the optimum range. The highest CBR occurs when strong particle interlock from compaction is balanced with moderate suction from partial saturation. As Sr approaches full saturation, suction-induced strength is lost and bearing capacity drops despite higher density.

This trend aligns with findings in [2] and [3], which report that CBR and stiffness depend on both ρ_d and Sr, and that increasing Sr beyond the optimum (Sr)_opt reduces suction, leading to lower strength and stiffness.

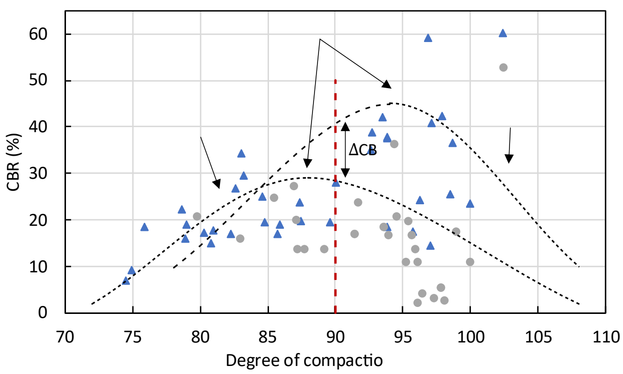

Fig. 2. CBR vs Dc for different constant w values

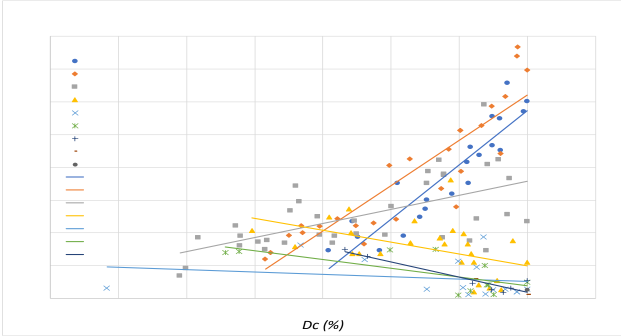

Fig. 3. Variation of California Bearing Ratio (CBR) against Degree of compaction (Dc) at different constant levels of Saturation *(Sr)*

Fig. 3 shows how the California Bearing Ratio (CBR) varies with dry density at different constant saturation levels. At low saturation, CBR increases sharply with dry density because the denser particle arrangement and partially filled pores generate strong capillary suction. As saturation rises (e.g., around 35%), this suction effect weakens, and the CBR–density relationship becomes less pronounced. At higher saturation levels, such as 45%, many fine pores are filled and water begins to act as a lubricant, limiting further stiffness gains. At very high saturation, the density–CBR curve may even plateau or slightly decline as lubrication reduces overall soil stiffness.

Field compaction control should evolve from relying solely on dry density to a dual-strategy monitoring both Dc and S_r. To optimize bearing capacity, operations must aim for high Dc while strictly maintaining S_r below the critical 80% threshold to leverage matric suction and avoid lubrication-induced strength loss. In practice, this means establishing a 'stiffness acceptance zone' where density requirements are paired with maximum saturation limits. Designers can also utilize the proposed empirical model to predict field performance more accurately by accounting for inevitable variations in saturation.

V. Conclusion

This study shows that compacted soil stiffness depends on the balance between densification and saturation. The empirical model indicates that while CBR increases with the Degree of Compaction (Dc), it decreases with the Degree of Saturation (Sr). Stiffness is highest at low saturation due to matric suction but declines at high saturation as pore water reduces particle friction. Thus, maximizing bearing capacity requires achieving high density while keeping saturation below critical levels. Future laboratory experiments are planned to validate these results.

References

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