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Strong correlation between the laboratory dynamic CBR and the compaction characteristics of sandy soil

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Abstract

Construction of earth structures involves the use of compacted soils. In roads construction quality controls like the bearing capacity of the subgrade, base and subbase layers, CBR values and compaction characteristics are primarily important. In Sweden, it has become interesting to correlate new testing parameters collected by simple tests to the conventional compaction parameters collected from modified Proctor tests. This action will help in assessing the bearing capacity of the selected material simply and quickly using the recent developed techniques instead of the conventional techniques which have been considered as time consuming methods. The aim of this study is to demonstrate that the laboratory dynamic California bearing ratio (CBR_{LD}) test can be used as a method of compaction assessment of selected subgrade soil. Moreover, it has been demonstrated in this study that the CBR_{LD} can strongly be correlated to the compaction densities and molding water contents using polynomial correlation and a best-fit multiple regression model for a wide range of molding water contents. In addition, the repeatability of the dynamic laboratory CBR test was examined as discussed in the current article.

Keywords: Compaction, Dynamic CBR test, Dry density, LWD, Subgrade soil, Water content

Introduction

Soil compaction is the process whereby soil is mechanically compressed through a reduction in the air voids [22]. It is one of the basic construction procedures used in building subgrades and bases for roads and airport pavements, embankments, earth-fill dams, and other similar structures [13, 15, 20]. Since, compaction helps to decrease the susceptibility of the unbound materials to environmental changes [7], a proper compaction of unbound materials is considered as one of the most important components in the construction of pavements, and embankments to ensure their adequate performance over time.

The impact compaction laboratory methods are the ones most commonly used to establish the compaction characteristics of unbound materials. These methods involve compacting a sample of the material to be used in the field in a standard mold using a drop hammer [11].

Although impact compaction using Proctor tests are commonly used to assess soil compaction and quality control during road construction, but the design of pavements and embankments is based on stiffness, strength parameters, or both [9]. Thus, there is a missing link between the design process and construction quality control practices of unbound materials. Yet few DOTs have developed such specifications. This was attributed mainly to the need for new and quick testing equipment, and the unfamiliarity of contractors with such specifications or both [9].

To address this problem and to speed up the construction process and reduce costly construction oversight, the Swedish transport administration has adopted the plate loading test which is based on stiffness and strength criterion used in the design. However, the static plate loading test is also costly as compared to lighter equipment used nowadays to control the bearing capacity of the compacted unbound materials. Moreover, the Swedish transport administration is interested in using the light weight deflectometer and the corresponding dynamic California bearing ratio test for compaction control of unbound materials and to develop further the current stiffness and strength-based specifications and roads design software.

Correspondingly, this study was conducted to assess the efficacy of the light weight deflectometer devise (LWD) to compute the laboratory dynamic California-bearing ratio (CBR_{LD}) and to assess the relationship between the computed CBR_{LD} and the compaction characteristics of the tested soil. This test is an easy add-on to the routine Proctor test and can be used to determine the target LWD modulus. It also provides valuable insights into the soil's response to water and density that can be used to tailor the compaction criteria in the field.

Different CBR sandy soil samples were prepared and compacted in the laboratory using modified Proctor compaction for a wide range of molding water contents. Then the compacted CBR soil samples were subjected to the laboratory dynamic California-bearing ratio tests. Furthermore, for each testing sample the dynamic CBR measurements were repeated for up to six times on each tested CBR sample in order to evaluate the repeatability of the test. The test results were statistically analyzed and discussed in the following paragraphs.

Literature review

Impact compaction laboratory method

Stanton [18] was the first who used soil compaction tests to determine optimum water content and maximum dry density. Later, Proctor [14] contributed significantly to the development of the standard laboratory compaction test, commonly known as the Proctor tests.

The compaction energy can be varied by changing the number of hammer's blows per layer as well as the weight and drop height of the hammer. Based on the compaction energy applied during the test, the procedure is either a "standard" or "modified" compaction procedure.

The modified compaction test uses a compaction effort approximately 4.5 times greater than that of the "standard" test and was developed by the U.S. Army Corps of Engineers to better represent the compaction effort required for airfields to support heavy aircraft [7]. During the modified Proctor test, a soil at a selected molding water content is placed in

five layers into a mold of given dimensions, with each layer compacted by 56 blows of a 44.48-N rammer dropped from a distance of 457.2 mm subjecting the soil to a total compaction effort of about 2700 kN-m/m^3 [2]. The resulting dry unit weight is determined, and the procedure is repeated for a sufficient number of molding water contents to establish a relationship between the dry unit weight and the molding water content for the soil. Nevertheless, only modified proctor compaction is of focus in this paper.

Dynamic CBR test

The dynamic CBR test is carried out by attaching CBR extension to the Light Weight Deflectometer, where a falling weight is used to generate a defined load pulse on the CBR piston. According to Zorn [23], the laboratory dynamic CBR value (CBR_{LD}) is calculated by employing an empirical equation, of relating piston settlement(s) as shown in Eq. (1) below:

$$CBR_{LD} = \frac{24.26 * p}{S^{0.59}} (\%) \tag{1}$$

where S is the settlement amplitude (in mm) of the CBR stamp and p is the peak pulse load amplitude (in N/mm^2). The peak pulse load is 7070 N and the diameter of the stamp is 50 mm (cross section area − 1963 mm^2). Hence p is 3.6 N/mm^2. Therefore:

$$CBR_{LD} = \frac{87.3}{S^{0.59}} (\%) \tag{2}$$

The dynamic CBR test can be performed both in the laboratory and in situ. However, only laboratory dynamic CBR test is of focus in this paper.

Several factors may influence the measured dynamic CBR value, including falling mass, drop height, plate size, plate contact stress, type and location of deflection transducer, usage of load transducer, loading rate, and buffer stiffness [5, 21].

Due to the speed of research execution of the dynamic CBR test, it could be used for running compaction control during embankment erection rapidly. The test results obtained from the tests carried out on sandy subgrade soil during this study revealed that the dynamic CBR could be recommended in the cases of embedded sandy soil with a wide range of molding water contents.

With respect to the repeatability of the dynamic CBR test, as far as the author know, no published research has been found discussing the repeatability of the LWD in terms of dynamic CBR values. The repeatability of the dynamic CBR test can by examined by measuring the percent error or sometimes called the coefficient of variation (COV) among the CBR_{LD} values computed from the deformations caused by successive drops of the falling weight.

Because the LWD is used to determine the dynamic CBR, it has become necessary to highlight some research done to evaluate the repeatability of the field LWD in terms of the measured deformation surface moduli. Petersen et al. [12] and Hossain [8] reported a relatively high coefficient of variation (COV), ranging from 22 to 77% for LWD-measured modulus when testing various types of unbound materials. Nazzal et al. [10]

evaluated the repeatability of the LWD by using the COV of five measurements taken at the same testing point. The COV of the LWD measurements ranged from 2.1 to 28.1%. In terms of the repeatability of the LWD in terms of the dynamic surface moduli, Steinart et al. [19] studied the influence of the number of load drops on the measured LWD modulus and found that the measurements from the first drop typically were smaller than those derived from subsequent ones. Therefore, they recommended that the first value be excluded in calculating the average LWD moduli value. Davich et al. [4] suggested using three LWD seating drops followed by three drops at each test location to produce consistent LWD data.

Since the LWD gains popularity day after day and some transport agencies use it in quality control of the compacted soil, it has become necessary to evaluate the repeatability of the LWD test in terms of the computed laboratory dynamic CBR values.

Tested soil properties

Material used

The soil tested in this study was brought from Linköping city at Östergötland region in Sweden.

Index properties such as specific gravity, SS-EN 1097-6 [17], and percent finer than [16] were carried out to characterize the soil, see Table 1.

The classification testing reveled that tested soil is a poorly graded sand (SP) according to ASTM D2487 [3].

Compaction test

The compaction properties were determined by modified Proctor test as per ASTM D1557 [2]. The test was performed by compacting several CBR soil samples using cylindrical molds of 152.4 mm diameter.

The CBR soil samples were compacted at different molding water contents ranging between 0 and 14% to determine the water-density relationship and the corresponding CBR_{LD} for each CBR soil sample after assessing the compaction properties.

Table 1 Physical parameters of the tested sandy soil

Grain size (mm)	% Finer than
8	100
5.6	100
4	100
2	100
1	98
0.5	69
0.25	27
0.125	8
0.063	2.2
$C_U = 3.14$	
$Cc = 1.183$	
Gs (specific gravity) = 2.664	

The results of the compaction tests revealed that the compaction curve of the tested soil is a one-and-one-half-peak curve with two optimum water contents and two maximum dry densities. One of the maximum dry densities lies on the dry side (at W = 0%) and the other one lies at the wet side (at around W = 12%), as shown in Fig. 1. The maximum dry densities are 1.8 and 1.72 g/cm^3 at 0 and 12% water content respectively.

Results and discussions

Repeatability of the laboratory dynamic CBR test

As mentioned previously, the dynamic CBR values were determined for each CBR soil sample after assessing the compaction properties. The test was performed when a falling weight produced a defined force pulse on the CBR piston, see Fig. 2. Then the dynamic CBR values were determined by using either Eqs. 1 or 2 as described previously. Note that in order to correlate the CBR_{LD} to the compaction characteristics, it has become necessary to examine first the repeatability of the laboratory dynamic CBR test in order to decide which CBR_{LD} value will be chosen for the correlation analysis. To reach the goal of the study, the repeatability of the laboratory dynamic CBR test, was checked up to six drops on each tested soil sample.

The test results showed that the CBR_{LD} increased significantly with increasing the number of drops. The measurements from the first drop typically were smaller than those derived from subsequent ones, as shown in Fig. 3. It is clear from this figure that the highest increase is found between the CBR_{LD} conducted from the first drop and the CBR_{LD} conducted from the second drop for all the tested CBR samples at different molding water content.

Moreover, with respect to Fig. 3, it can be noticed that for soil samples compacted at relatively high densities (i.e. the curves for W = 0%, 0.6%, 1.6%, 10.2%, 12.4% and 13.8% water contents), the differences between the CBR_{LD} computed from the first and second drops are large but then the differences die out with increasing the numbers of drops. In contrast, for CBR samples compacted at relatively low densities (e.g. for W = 2.8%, 4.8% and 8), the CBR_{LD} curves still have a sharp increasing trend with

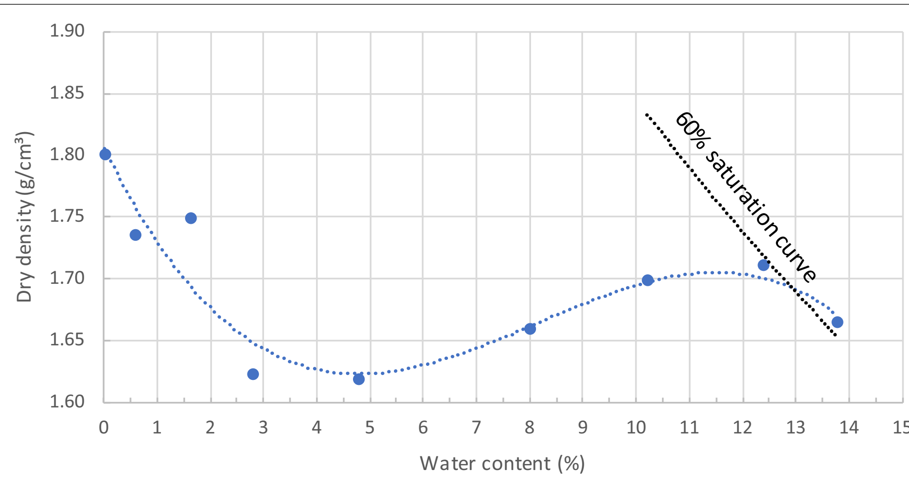

Fig. 1 Compaction curve of the tested sandy soil using modified compaction method

Fig. 2 Laboratory dynamic CBR test on sandy CBR soil samples prepared using modified compaction method

increasing the numbers of drops even when the sixth drops are reached for these samples. This rising trend indicates that samples compacted at lower densities have higher ability to exhibit compaction by successive falling weight drops. This observation goes well with the results presented in Fig. 4 which illustrated that for highly compacted soil samples of higher CBR_{LD} measured from the first drop, the coefficient of variation (COV), sometimes called the percent error, between CBR_{LD} measured from the first and second drops reduced.

Correlating the COV to the molding water content, as shown in Fig. 5, it can be noticed that the general trend of the COV curve is a sharp increase of the COV with increasing the molding water content. After reaching 8% molding water content, this trend dies out with further increase in the molding water content.

With respect to Figs. 4 and 5, the percent error is between 17.9 and 54.8% for the CBR_{LD} computed from the first and second drops. This high COV values can be attributed to the high compaction induced by the dropping weight to the tested soil sample caused by the falling weight (even for those compacted at high densities).

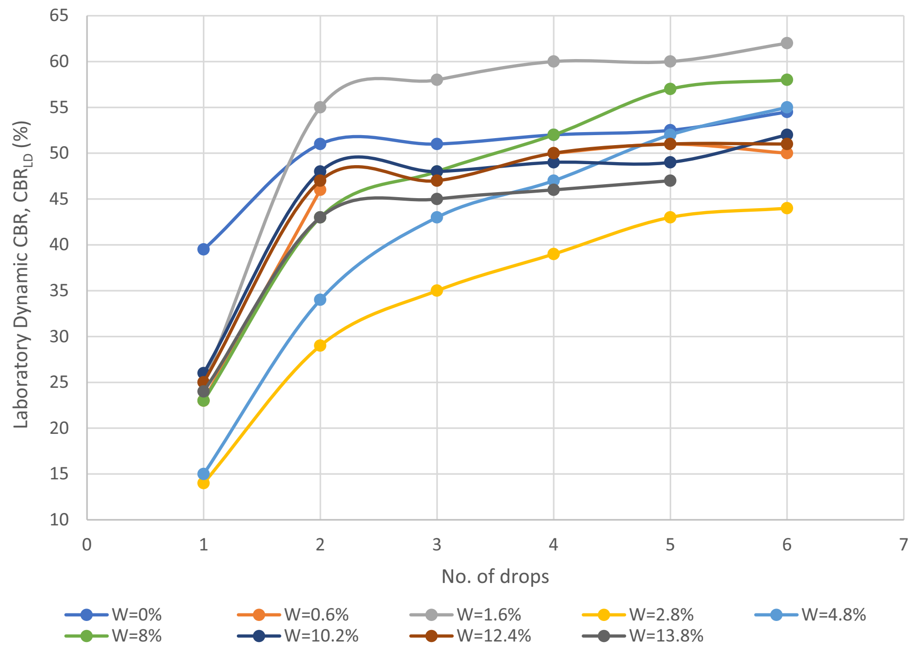

Fig. 3 Effect of consecutive drops on the laboratory dynamic CBR values at different molding water contents

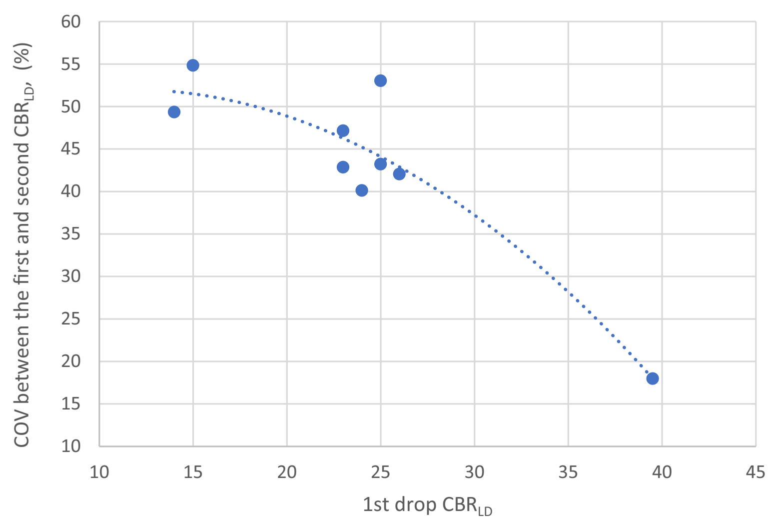

Fig. 4 The COV versus the CBR_{LD} computed from the first drop

Therefore, it can be concluded that the laboratory dynamic CBR test is not a repeatable test and for many considerations, as discussed below, one should consider the laboratory CBR_{LD} resulted from the first drop only. Since the laboratory CBR soil samples are usually prepares under controlled compaction and water content conditions, it is not recommended to exclude the first drop CBR and consider the second drop CBR nor applying seating drops when calculating the dynamic CBR at laboratory. This consideration is important to avoid any over estimation of the laboratory dynamic CBR when the second drop CBR_{LD} is considered.

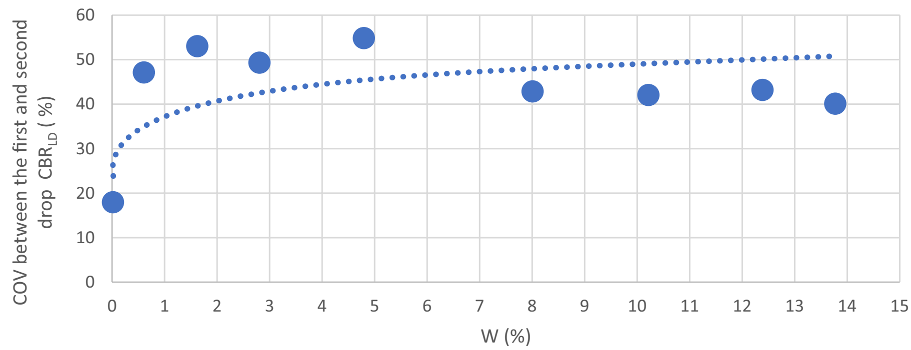

Fig. 5 Effect of water content on percent error resulted from the 1st and 2nd drop dynamic CBR values

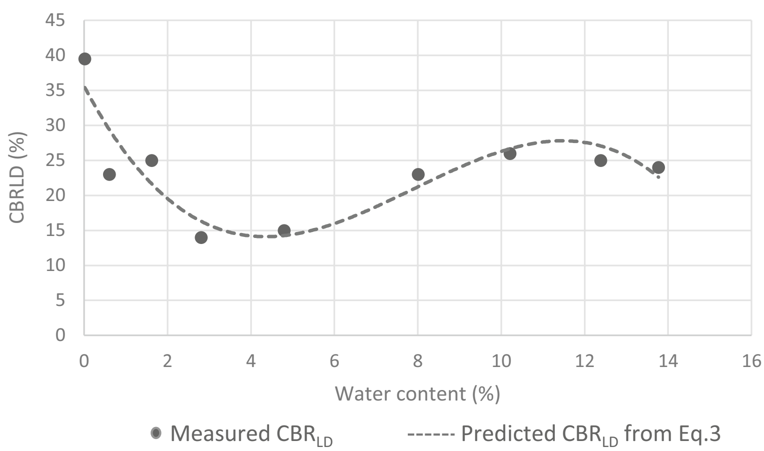

Fig. 6 Dynamic CBR test results versus molding water content

Of course, the COV between the first and second drop CBR$_{LD}$ is related to the type of the soil and its ability to exhibit further compaction by additional drops, but for safety reasons and to avoid over estimation of the measured dynamic CBR values and hence the bearing capacity of the tested soil, it is recommended to consider only the dynamic CBR values resulted from the first drop when the laboratory dynamic CBR is measured. Regarding, the repeatability of the dynamic CBR test in the field, which is beyond the scope of this paper, one may consider the evenness and uniformity of the contact soil surface and the dynamic CBR loading plate in judging the repeatability of the dynamic CBR test in the field.

Due to the non-repeatability of the laboratory dynamic CBR test, as discussed previously, the CBR$_{LD}$ values computed from the first drops have been considered in the correlation analysis and all the following predictive Eqs. 3 to 5 and Figs. 6, 7, 8.

Effect of water contents and densities on CBR$_{LD}$

Regarding the effect of molding water content on the CBR$_{LD}$ of the tested soil samples, it can be seen from Fig. 6 that the CBR$_{LD}$ reach the highest value in the case of specimens compacted at the dry optimum water content of 0%.

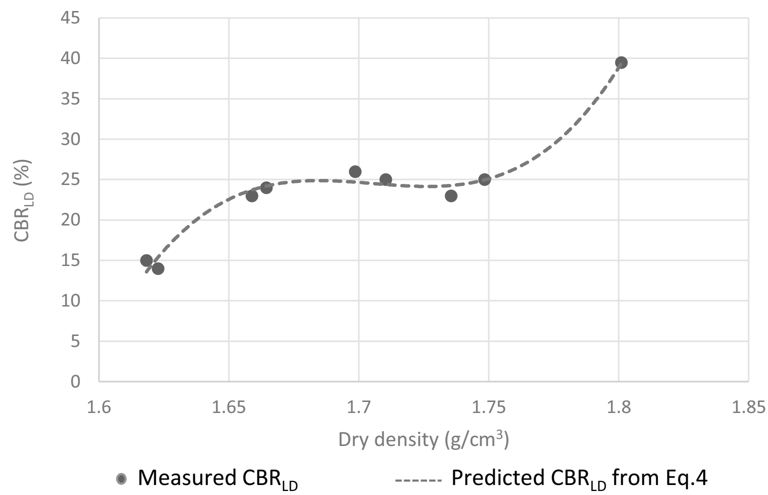

Fig. 7 Dynamic CBR values versus the dry densities of the tested CBR soil samples

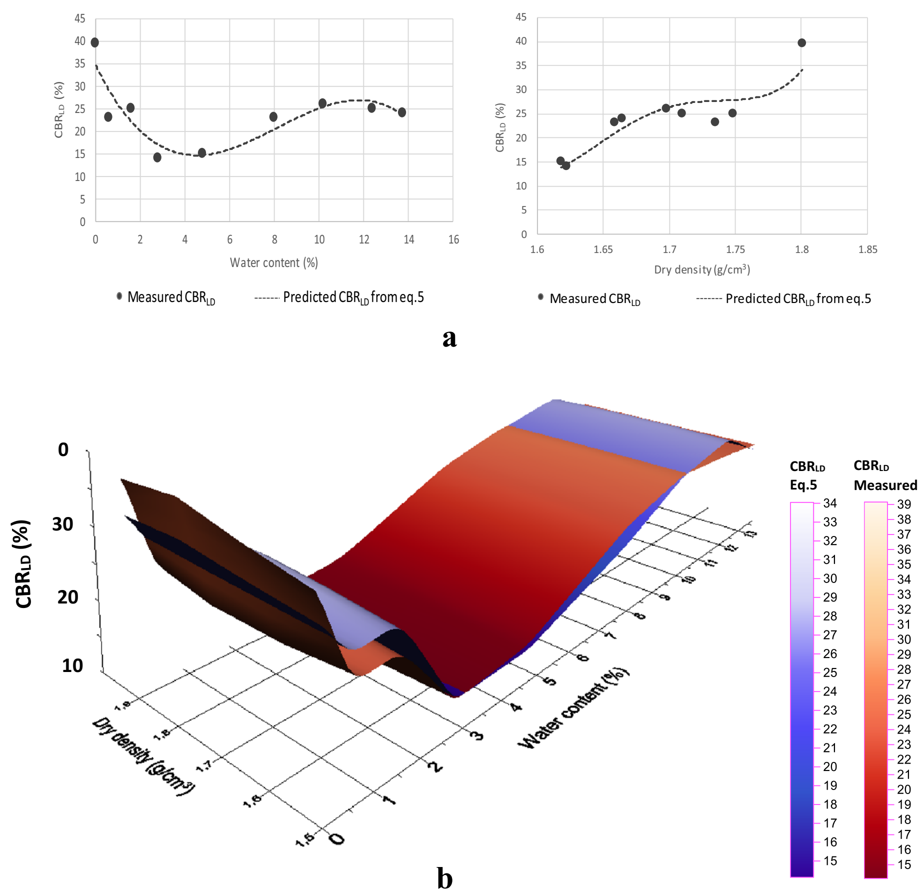

Fig. 8 **a** 2D and **b** 3D comparison of the laboratory and predicted CBR_{LD} for soil samples of different compaction densities and molding water contents

It can be noticed also from Fig. 6 that when the molding water content increases above the dry condition, the CBR_{LD} decreases, up to 5% molding water content, and then increases again with increasing the water content from 5% to about 12% (the wet side optimum water content). At w = 12%, another peak CBR_{LD} is reported. Increasing the molding water content above 12% has resulted in a decreasing trend of the measured CBR_{LD} values. The trend of the CBR_{LD} curve shown in Fig. 6 is almost like the trend of the compaction curve given in Fig. 1 something which confirm the strong dependence of the laboratory CBR_{LD} on the compaction characteristics of the tested soil. Predicting the effect of molding water content on the CBR_{LD} was performed successfully using a polynomial relationship, see Eq. (3).

$$CBR_{LD}(\%) = -0.0757\ W^3 + 1.7955\ W^2 - 11.318\ W + 35.589 \tag{3}$$

where W is the molding water content in %.

A high correlation coefficient (R) of 0.896 was observed from Eq. (3). The correlation coefficient is usually defined as a single summary number that gives you a good idea about how closely one variable is related to another variable [6]. Note that the strength of the relationship varies in degree based on the value of the correlation coefficient. According to Anderson and Sclove [1], the reported R of 0.896 indicating a strong correlation.

Moreover, Fig. 6 shows how close are the predicted CBR_{LD} from Eq. (3) to the measured CBR_{LD} values for a wide range of the molding water contents.

Furthermore, Fig. 7 shows the developed relationship between the CBR_{LD} values and the dry densities of the tested sandy soil. It can be seen from Fig. 7 that the CBR_{LD} increased nonlinearly with increasing the dry densities of the tested soil samples.

Similarly, a polynomial Eq. (4) with a high correlation coefficient (R) of 0.99, has been found to predict best the correlation between the dynamic CBR and the dry density of the tested soil samples.

$$CBR_{LD}(\%) = 19915\rho_d^3 - 101897\rho_d^2 + 173760\rho_d - 98729 \tag{4}$$

where ρ_d is the dry density of the tested soil samples in g/cm^3.

The high coefficient of correlations of Eqs. (3) and (4) indicating the strong dependency of the laboratory dynamic CBR to the main compaction parameters (i.e. the molding water content and the dry density) and hence it is possible to correlate the measured CBR_{LD} values to these two main compaction parameters in one predicting equation using multiple regression analysis as discussed in the following paragraph.

Multiple regression analysis

As the main aim of this study is to predict a simple and strong correlation between the CBR_{LD} values and the main compaction parameters namely the dry densities and the molding water contents, a multiple linear regression model was developed, and the mathematical relationship is illustrated in Eq. (5) below.

$$CBR_{LD}(\%) = 0.3546\ W + 118.3\rho_d - 178.866 \tag{5}$$

where W is the molding water content in % and ρ_d is the compaction dry density in g/cm^3

The comparison of the values of CBR_{LD} measured from the laboratory tests and those predicted from Eq. (5) is shown in Fig. 8. Note that a multiple correlation coefficient (R) of 0.913 was observed indicating a very strong correlation between the measured CBR_{LD} and the CBR_{LD} predicted from Eq. (5).

The 2D and 3D comparisons between the measured and predicted CBR_{LD} values shown in Fig. 8a, b respectively.

It can be shown from Fig. 8 that for many tested soil samples, the measured and predicted CBR_{LD} values were almost the same. The maximum observed difference was 5.3% but, in most cases, the absolute differences were less than 3.6%.

Conclusions

This investigation was undertaken with the primary objective to correlate the laboratory dynamic California bearing ratio (CBR_{LD}) to the compaction characteristics of chosen sandy soil. The CBR_{LD} and compaction data were statistically analyzed to develop predictive models that are reliable and capable of estimating the CBR_{LD} values from the main two compaction parameters namely (the dry densities and the molding water contents). To fulfill this objective, several laboratory CBR soil samples were compacted at different molding water content using modified Proctor compaction method and tested using the dynamic CBR testing approach. In addition, the repeatability of the conducted laboratory dynamic CBR tests were examined for up to six successive LWD drops. Based on the findings of experimental and regression analyses, the following main conclusions can be withdrawn:

- The results of the compaction tests revealed that the compaction curve of the tested sandy soil is a one-and-one-half-peak curve with two optimum water contents and two maximum dry densities. The maximum dry densities are 1.8 and 1.72 g/cm^3 at 0 and 12% water content respectively.
- In order to correlate the CBR_{LD} to the compaction characteristics, it has become necessary to examine first the repeatability of the laboratory dynamic CBR test in order to decide which CBR_{LD} value will be chosen for the correlation analysis. The test results showed that the CBR_{LD} increased significantly with increasing the number of drops. A maximum COV of 54.8% and a minimum of 17.9% have been reported for the CBR_{LD} measured from the first and second drops. The repeatability tests have indicated that the laboratory dynamic CBR test is not a repeatable test. This consideration is important to avoid any over estimation of the laboratory dynamic CBR when the second drop CBR_{LD} is considered.
- The maximum dynamic CBR values for the laboratory tested sandy soils observed at the optimum water contents (the dry side and wet side optimum water content).
- Regarding the effect of water contents and densities on the CBR_{LD} values, it has been found that when the molding water content increased above the dry condition, the CBR_{LD} decreased up to 5% molding water content, and then increased again with increasing the water content from 5% to about 12% (the wet side optimum water content). At $w = 12\%$, another peak CBR_{LD} was reported. Increasing the molding water content above 12% showed a decreasing trend of the measured CBR_{LD} values. Moreover, the CBR_{LD} increased nonlinearly with increasing the dry densities of the

tested sandy soil samples. The measured CBR_{LD} could be separately correlated to the molding water contents and the dry densities using polynomial equations of strong coefficient of correlations (R) of 0.896 and 0.99 respectively.

- Based on the results developed in this investigation, a general best-fit multiple regression model was developed that can reliably predict the CBR_{LD} values from the molding water contents and the dry densities data with high multiple correlation coefficient of 0.913 for the tested soil. This model can be used in predicting laboratory dynamic CBR for similar soil types and compaction conditions.

Recommendations

The laboratory dynamic California bearing ratio (CBR_{LD}) test can be widely used because it can be performed quickly and easily and hence it can be considered as an alternative method to the classic quality control methods in compaction process or assessment of subgrade resistance to failure and load carrying capacity.

The quality control of soil compaction conducted with CBR_{LD} test methodologies and a loading system employing the light weight deflectometer, is recommended to be used on compacted CBR soil samples for a wide range of molding water content. Keeping in mind that the laboratory dynamic test is not a repeatable test according to the current study and the CBR_{LD} collected from the first drop has been considered.

Moreover, the multiple regression CBR_{LD} model involving dry density and molding water content is recommended to be used in predicting the laboratory CBR_{LD} values for fine grained sandy soils compacted at similar conditions as in that developed for.

Furthermore, a database for target values of laboratory and in situ stiffness/strength measurements needs to be established for different soil types and water contents to facilitate the use of these devices in compaction control specifications. This database should be verified for local materials in each county before using it in quality control.

Nevertheless, the type of soil used in this study is a fine sandy soil. Future studies on other types of soils are recommended.

Acronyms

CBR_{LD}: laboratory dynamic California bearing ratio; COV: coefficient of variation, percent error; DOT: Department of transportation; LWD: light weight deflectometer; p: peak pulse load amplitude (in N/mm^2); S: settlement amplitude (in mm) of the CBR stamp; W: molding water content (%); Pd: compaction dry density in g/cm^3.

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Authors' contributions

The author read and approved the final manuscript.

Competing interests

The author declares no competing interests.

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