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SOIL MECHANICS

CORRELATION BETWEEN DYNAMIC CBR AND COMPACTION AND BEARING CAPACITY OF PAVEMENT FOUNDATION LAYERS

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This paper presents a dynamic California Bearing Ratio (CBR_d) device that can be used on a prepared pavement foundation layer to obtain a certain parameter of the tested material in the laboratory and in situ in a direct and fast way. For the selected natural material (gravel), it is shown that the laboratory CBR_d can be used to estimate the compaction and bearing capacity, because it correlates well with the parameters of the standard and modified Proctor compaction tests. Comparative tests revealed that there is good correlation between the field CBR_d and the deformation modulus, and dynamic deformation modulus values obtained by field tests.

Introduction

The compaction and bearing capacity of natural materials are the most important indicators that must be satisfied during the construction of the foundation layers of pavements. Control procedures are used to ensure the quality of construction, in accordance with the criteria defined by certain design regulations, specifications, and standards. In addition to compaction control, the basic measure for ensuring the quality of the substrate is the bearing capacity of the final layer (subgrade) over which the pavement is built (upper bearing layers and asphalt and concrete layers).

The contributions of this study are as follows:

– the geotechnical properties of the selected material (gravel) were determined, and the physical-mechanical parameters are defined based on laboratory testing for incorporation into the substrate layer;

– the method of using a non-standardized dynamic California Bearing Ratio (CBR_d) device and the definitions of its values under laboratory and field conditions are proposed;

– the values of the modulus of deformation of the pavement foundation layer (subgrade) were determined at a certain location using the static plate load test (SPLT) and a lightweight deflectometer (LWD);

– the obtained data were analyzed and correlations between the CBR_d and the compaction and bearing capacity of the pavement foundation layers were established.

The results of CBR_d are extremely underrepresented in the literature, probably owing to the low prevalence of this method worldwide. The first CBR_d study considered mineral materials for roads [1] and reported good correlation between static and dynamic test results. A previous CBR_d study [2] has presented results for fine-grained soil under different compaction conditions. The study considered clay material with a water content of approximately ± 4% w_{opt} (maximum dry bulk density $\rho_{d\max}$ = 1.82 Mg/m^3, optimal water content w_{opt} = 15.6%). A comparison between the results of California Bearing Ratio (CBR) research on static (classic) and dynamic methods with ash samples in the unsaturated state has been presented [3], and the correlations of the parameters of the laboratory dynamic California Bearing Ratio (CBR_{LD}) with the compaction properties of sandy soil have been reported [4].

Owing to its short duration and ease, CBR_d testing using a LWD can become widespread as an alternative to the classic quality control method in the process of compaction or estimation of the substrate bearing capacity [5].

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Correlation dependencies have been established between the results of different studies on a pavement foundation layer (subgrade) built of gravel material, as follows:

The CBR_{LD} parameter is correlated with the parameters of the standard and modified Proctor compaction tests (ρ_d is dry bulk density, w is water content).

The field dynamic California Bearing Ratio (CBR_{TD}) parameter is correlated with the E_{v1}-E_{v2} and E_{vd} parameters obtained by field tests through a SPLT and LWD.

All experimental tests were performed in the TPA laboratory, and in situ at 'Batajnica' Intermodal Terminal in Belgrade. The tests were performed with adequate and modern equipment in accordance with applicable national and relevant standards, and the recommendations of other countries.

Problem Description

The CBR device, which has recently started being used in Serbia, has been in use worldwide for the last few years. As a device that can conduct tests in the laboratory and in the field, it allows the comparison of results obtained under different conditions, and the dependence between the parameters can be considered to evaluate the suitability of materials and the compaction and load capacity in road construction. In the present study, this device was used for measurements in the laboratory and at a specific field location. Based on the obtained results, certain correlations with the parameters obtained by standard procedures were observed and can be used to solve practical tasks.

Materials and Methods

All tests were performed on natural gravel material sampled at a temporary landfill at 'Batajnica' Intermodal Terminal in Belgrade. The same material was used for laboratory and in-situ testing. The grain size distribution was determined on the basis of three representative samples in accordance with SRPS EN ISO 17892-4:2017. The identification–classification analysis of the natural material samples in accordance with SRPS EN ISO 14688-2:2018 did not indicate significant differences in the grain size distribution, and it was determined that the material is natural mineral soil, sandy gravel (Sa-Gr), and non-plastic, where one grain size or a grain size range (0.1-0.5 mm) predominates, while some intermediate grain sizes are missing. The material's fine particle content that can pass through a 0.063-mm sieve is very low (less than 2.0%). The investigation identified the participation of individual fractions: 1.4%-1.8% clay and silt, 43.2%-46.2% sand, and 52.5%-55.4% gravel.

The basic compaction characteristics were determined by the standard and modified Proctor compaction tests in accordance with the SRPS EN 13286-2:2012 standard. The tests were performed by compacting the prepared samples in a cylindrical mold with a diameter of 150.0 mm. The following material characteristics were determined by testing. The maximum dry bulk density was determined as follows: $\rho_{d\max}$ (SP) = 1.97 Mg/m^3 and $\rho_{d\max}$ (MP) = 2.06 Mg/m^3 at the optimal water content w_{opt} (SP) = 9.5% and w_{opt} (MP) = 8.6%.

The CBR_d, SPLT, and LWD were used to estimate the compaction and bearing capacity properties of the selected natural material (gravel) embedded in the final layer of the substrate (subgrade).

CBR_d is a complex measure of the strength of a material, and depends on factors such as the grain size distribution, shape, and roughness of the grain, water content, and compaction, and can be expressed in the range of $20\% \leqslant CBR_d \leqslant 150\%$ [6].

A CBR_d test can be performed in the laboratory (CBR_{LD}) and in situ (CBR_{TD}) (Fig. 1). Additionally, in-situ CBR_d testing can be simulated in the laboratory by conducting the CBR test using cylinders. Other than static CBR, this is the only method that can be used in the laboratory to determine the required CBR_d values related to the compaction characteristics. Under field conditions, it is possible to estimate the soil compaction by comparing the in-situ CBR_d results with predefined minimum values. Particularly, CBR_d tests can be used for compaction control during the construction of the foundation layers of pavements (embankments). These tests offer the advantage of rapid investigation through the use of a LWD [7].

Such testing can be performed as an alternative to static CBR testing, particularly owing to the shorter duration of the CBR_d test. Compared with classic CBR testing, CBR_d has the advantage of not using a loading device, that is, a counterweight system as required for static testing (typically heavy construction machinery). Instead, the CBR_d test is performed by fixing the CBR attachment to the LWD device, where a falling weight is used to induce a defined impact load on the CBR piston. Then, the CBR_d can be calculated based on an empirical formula [8], as follows:

$$CBR_d = 24.26\ p / s^{0.59}. \quad (1)$$

With a force of 7070 N and a piston diameter of 50 mm (cross-section of 1963 mm²), Eq. (1) can be simplified to Eq. (2) (p = 3600 N/mm²), as follows:

$$CBR_d = 87.3 / s^{0.59}, \quad (2)$$

where s is the amplitude of the CBR_d piston settlement (mm), and p is the maximum amplitude of the dynamic load (N/mm^2).

Several factors can affect the measured CBR_d value, including the falling weight, height of fall, size (diameter) of the plate, plate contact stress, type and location of deflection transducer, use of load transducer, loading speed, and material strength [9, 10]. The tests with the CBR_d device were performed in accordance with TP BF-StB Teil B 7.1:2012.

Static plate load test

The counterweight system is not part of the device, but it is required to perform the test. A plate with a diameter of 300 mm was used to determine the modulus of deformation, and the load was increased until a normal stress of 0.5 MN/m^2 was reached below the plate.

Before the test started, the load transducer and the number gauge or transducer were set to zero. Subsequently, a preload corresponding to the pressure of 0.01 MN/m^2 for a plate diameter (d) of 300 mm was applied. The deformation modulus E_{v1}-E_{v2} was determined using the load-unload-load process according to the DIN 18134: 2012-04 standard [11]. Approximately 1 hour was required to prepare and perform one test. After performing SPLT and collecting the required data, the subgrade reaction modulus (K_s) was calculated for each station using the pressure–settlement curve [12]. In this process, certain items must be considered.

Light-weight deflectometer

The LWD is a portable device with a falling weight developed in Germany as an alternative to the SPLT, and measures the deformation (stiffness), that is, the level of compaction of the material, in situ and obtains the dynamic modulus of deformation (E_{vd}) [13, 14]. In Serbia, these devices are not widespread because the dynamic modulus is not considered in the quality assessment and quality control of pavement layers. The tests were performed using Zorn Instruments' ZFG 3.0 equipment [15]. A circular load plate with diameter D = 0.3 m was subjected to settlement owing to the maximum impact force of 7.07 kN (falling weight of 10 kg). The movement of the plate (settlement) was recorded using an electronic device, which prevented potential measurement errors. The LWD tests were performed in accordance with TP BF-StB Teil B 8.3 [16], and approximately five minutes were required for one test.

Research Results

To establish correlations between the compaction and bearing capacity parameters, the laboratory and field test results for the natural material (gravel) built into the lower layer of the pavement (subgrade) at 'Batajnica' Intermodal Terminal in Belgrade were analyzed. The results were used to define the values and method of use of CBR_d under laboratory and field conditions. In this regard, different correlations with the standard compaction and bearing capacity test parameters were observed.

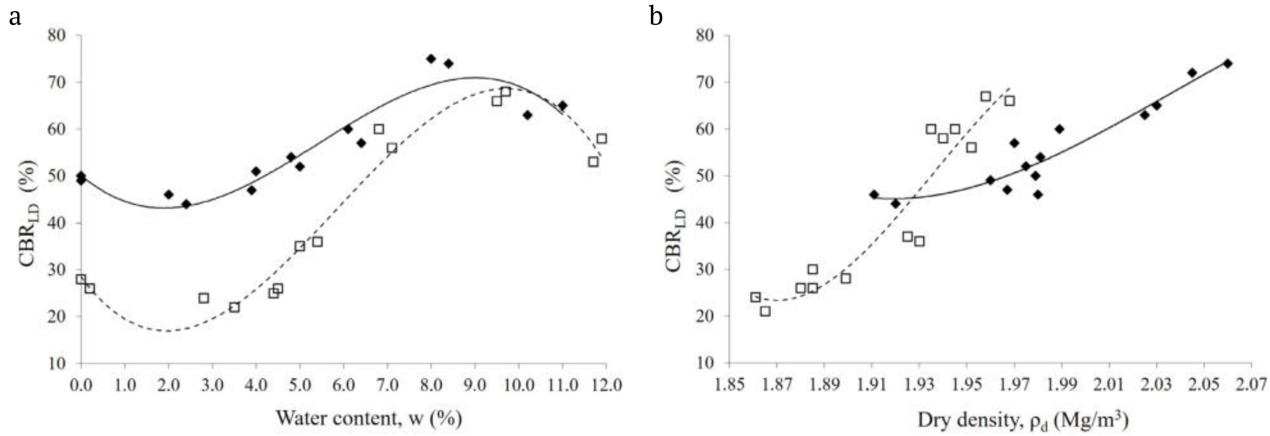

Fig. 2. Test results of $\mathrm{CBR_{LD}}$ in relation to: a) water content and b) dry bulk density; □) measured (SP), ◆) measured (MP), ---) predicted from Eq. (3), —) predicted from Eq. (4).

Laboratory tests

After evaluating the compaction properties of the tested material, $\mathrm{CBR_{LD}}$ testing was performed in the laboratory. The testing was performed by fixing the CBR attachment to the LWD device, and using a falling weight to induce a defined impact load on the CBR piston. The $\mathrm{CBR_{LD}}$ parameter was determined using Eq. (2). Different samples of gravelly material were prepared and compacted in the laboratory using the standard (SP) and modified (MP) compaction energy (Proctor compaction) with different water content in the range of 0-12. The water content range was selected such that unsaturated conditions could be represented, with the aim of replicating field conditions during the process of determining the compaction and bearing capacity parameters of the subgrade layer. The prepared samples were subjected to $\mathrm{CBR_{LD}}$ tests in the laboratory. Figure 2a shows the results obtained by the $\mathrm{CBR_{LD}}$ tests, depending on the water content for different compaction energies. Regarding the impact of water content on the formation of the gravelly material samples subjected to $\mathrm{CBR_{LD}}$ testing, it was observed that CBR_{LD} reached the highest value when the samples were compacted with water content close to w_{opt}. Additionally, it was observed that, when the water content for dry sample formation increased, CBR_{LD} decreased to 2.0% of the water content for formation, and then increased again as the water content increased from 2.0% to approximately 9.7% (SP) or 8.8% (MP), approaching w_{opt}. Increasing the water content for formation above w_{opt} resulted in a decreasing trend for the measured $\mathrm{CBR_{LD}}$ values. The impact of the water content for the formation of $\mathrm{CBR_{LD}}$ was successfully predicted using polynomial functions:

$$\mathrm{CBR_{LD}}\left(\mathrm{SP}\right) = -0.2216w^3 + 3.8763w^2 - 12.611w + 28.471, \quad R^2 = 0.9581\,, \tag{3}$$

$$\mathrm{CBR_{LD}}\left(MP\right) = -0.1547w^3 + 2.5276w^2 - 7.9066w + 50.122, \quad R^2 = 0.8999\,, \tag{4}$$

where w is the water content for sample formation.

The correlation between $\mathrm{CBR_{LD}}$ and the dry bulk density of the gravelly material is shown in Fig. 2b. The figure shows that $\mathrm{CBR_{LD}}$ increased nonlinearly with the dry bulk density of the tested samples. The polynomial functions describe the relationship between $\mathrm{CBR_{LD}}$ and the dry bulk density:

$$\mathrm{CBR_{LD}}\left(\mathrm{SP}\right) = -47805\rho_d^3 + 277599\rho_d^2 - 536707\rho_d + 345539, \quad \mathrm{R}^2 = 0.9046\,, \tag{5}$$

$$\mathrm{CBR_{LD}}\left(\mathrm{MP}\right) = -7066.6\rho_d^3 + 43156\rho_d^2 - 87562\rho_d + 59092, \quad \mathrm{R}^2 = 0.8903\,, \tag{6}$$

where ρ_d is the dry bulk density of the sample in $\mathrm{Mg/m^3}$.

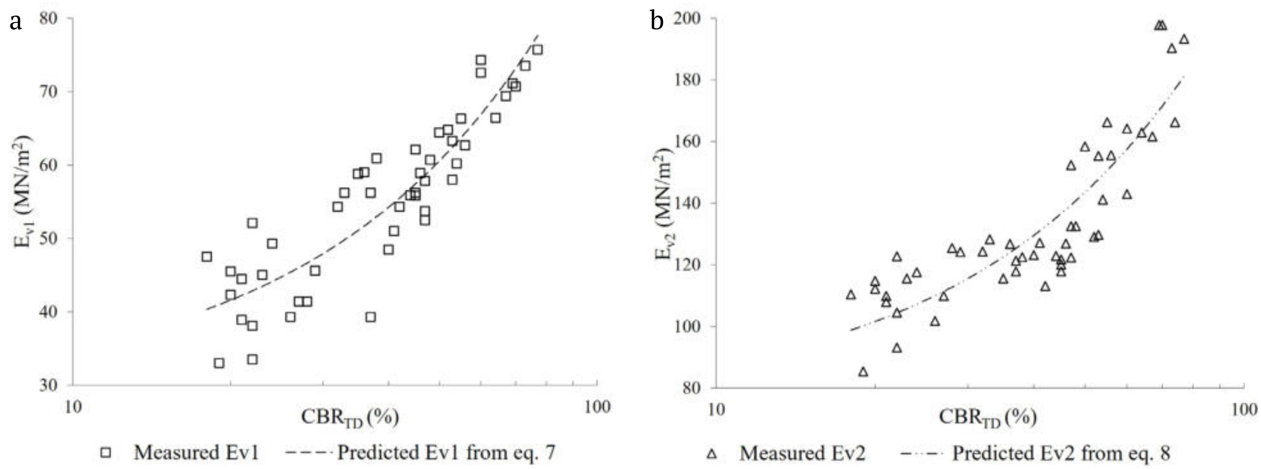

Fig. 3. Test results for CBR_{TD} in relation to deformation modulus: a) E_{v1} and b) E_{v2}.

The correlation coefficient is typically defined as a number, and provides an idea of how closely one variable is related to another [17]. The ratio of variables is reflected by the values of the determination coefficient. The high coefficient of determination of Eqs. (3), (4), (5), and (6) has good correlation with the CBR_{LD} values and compaction parameters (water content and dry bulk density).

Field tests

In addition to the laboratory dependencies discussed above, this paper also presents the correlations between the parameters obtained by the in-situ testing of the CBR_{TD}, modulus of deformation (E_{v1}–E_{v2}), and dynamic modulus of deformation (E_{vd}). The objective of regression analysis was to determine the parameters in the least-square error models, which are used to predict the conventional parameters of compaction and the bearing capacity of the pavement foundation layers (E_{v1}–E_{v2}, E_{vd}) from the CBR_{TD} value, and their respective coefficient of determination (r^2) and standard error. Notably, the parameters (E_{v1}–E_{v2}, E_{vd}) obtained from the reference test methods were used as dependent variables in the obtained regression model, while the CBR_{TD} parameter obtained by testing with the CBR_d device was used as an independent variable. A circular plate with a diameter of 300 mm was selected to investigate the correlation between the compaction parameters and the bearing capacity, because this plate diameter is extensively used in tests and can be facilitated by all three testing devices. The influence of the measurement depth was also identical, as required for correlation without unnecessary additional influencing factors. The tests were performed on a subgrade layer made of natural stone aggregate (gravel). The subgrade layer was constructed above the embankment layer, which consisted of natural material (sand) in three layers with a thickness of 0.3 m. Spreading was performed in a layer with a thickness of 0.35 m under a loose condition. Before compaction was carried out, the water content of the material was adjusted to an approximately optimal level, which was allowed by the site conditions. The compaction process was completely controlled such that the surface of the subgrade layer did not loosen during the preparatory work. The conditions within the depth range of the test location were assumed to be consistent and homogeneous. After five passes (two roller passes and three compactor passes), tests were performed on the subgrade layer with a thickness of 0.3 m under the compacted condition. Figure 3 shows the results obtained by the comparative measurement of CBR_{TD} and the modulus of deformation E_{v1}-E_{v2} on the compacted subgrade layer of gravel with known geotechnical characteristics at 50 measuring points:

$$E_{v1} = 0.6317\mathrm{CBR}_{TD} + 28.960\,, \quad R^2 = 0.8149, \tag{7}$$

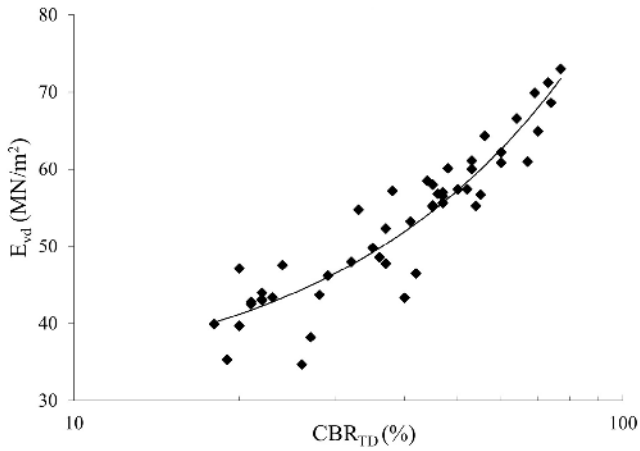

Fig. 4. Test results for CBR_{TD} in relation with deformation modulus E_{vd}: ◆) measured, ——) predicted from Eq. (9).

TABLE 1

Regression statistics – independent variable CBR_{TD}	Dependent variables		
	E_{v1}	E_{v2}	E_{vd}
Multiple R	0.902730052	0.882476039	0.930206737
R^2	0.814921546	0.778763959	0.865284574
Adjusted R^2	0.811065745	0.774154874	0.862478003
Standard error	5.062052668	12.52554984	3.552758725
Observations	50	50	50
P-value	2.19964E-19	7.42876E-20	9.69400E-27
Significance F	3.29677E-19	2.44039E-17	1.56729E-22

$$E_{v2} = 1.3976CBR_{TD} + 73.649, \quad R^2 = 0.7788, \tag{8}$$

$$E_{vd} = 0.5355CBR_{TD} + 30.476, \quad R^2 = 0.8653. \tag{9}$$

The modulus of deformation values, E_{vd} and E_{v1}, were obtained without major deviations within the range of approximately 35-75 MN/m^2. As can be seen, the values of the modulus of deformation E_{v2} are within the wide range of 90-200 MN/m^2, which indicates the diversity of the material's local bearing characteristics and moisture.

The relationship between the dynamic modulus of deformation E_{vd} and the CBR_{TD} index is described by a linear function. The correlation dependence is shown in Fig. 4 and is defined by Eq. (9). The correlation is based on the CBR_{TD} values measured in the range of 15%-80%.

The high correlation coefficient indicates good correlation between CBR_{TD} and the bearing capacity parameters (deformation modulus). Table 1 presents the results of regression analysis on the CBR_{TD} test data. The independent variable is CBR_{TD}, while E_{vd}, E_{v1}, and E_{v2} are the dependent variables, level of significance $\alpha < 0.05$. The correlations were evaluated using the coefficient of significance F and P-value.

As presented in Table 1, the significance value F of the correlation coefficient and P-value is less than 0.05. Therefore, the Pearson linear correlation coefficient is statistically significant. In other words, there is a statistically significant correlation between the CBR_{TD} parameter, E_{v1}–E_{v2}, and E_{vd}.

Conclusion

The primary objective of this study was to establish reliable correlations between the selected parameters of the gravel material so as to describe the compaction and bearing capacity of the substrate, and develop a method of using and defining the values of a CBR_d device. The following conclusions were drawn from this study.

1. Many parameters related to the compaction and bearing capacity of the gravel material were obtained by experimental tests performed in the TPA laboratory, and subsequently processed. Additionally, in-situ tests were conducted at 'Batajnica' Intermodal Terminal in Belgrade.

2. This study demonstrated that CBR_{LD} can be used as a method for estimating the compaction and bearing capacity of the selected natural material (gravel) and has good correlation with the parameters of the standard and modified Proctor tests.

3. The results obtained through comparative tests on a substrate layer (subgrade) made of gravel material revealed that there is good correlation between CBR_{TD} and the deformation modulus (E_{v1} – E_{v2}) and dynamic deformation modulus (E_{vd}) values obtained by field tests.

Owing to its speed and ease of use, CBR_d testing can become widespread as an alternative to the classic method of quality control in the process of compaction and estimation of the substrate bearing capacity. Additional research is required to establish more precise correlations, and other material types should be considered in future work. Correlation studies should be conducted for a limited set of material types, because the correlation predictions are only reliable for similar materials and the same standardized test equipment. Because the derived dependencies are only empirical correlations, which typically lack an adequate theoretical basis, deviations are possible in practice; therefore, caution must be exercised in their application. For this reason, it is not recommended to use these correlations in series, that is, by adding one correlation to another in sequence.

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