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ABSTRACT

Earth structures require appropriate soil compaction, commonly assessed using the Proctor methods. In the case of cohesive soil and fly ash, whose permeability and mechanical properties depend on moisture content at compaction, compaction degree (% of maximum compaction) should not be the only parameter of estimation of soil compaction. Therefore, for such materials the California Bearing Ratio (CBR) could be used as a method of compaction assessment and an indicator of soil bearing capacity. Another and much more efficient method for the compaction control is the dynamic CBR (CBR_d). This methodology is conducted by using a loading system employing a light falling weight deflectometer (LFWD), consisting of a falling weight to produce a defined force pulse on the CBR piston. In this paper, the CBR research was done for both static (classic) and dynamic methods on fly ash specimens without soaking them to replicate field conditions. A force of 2.44 kPa was applied to all specimens subjected to penetrations. Due to the speed of research execution of the dynamic CBR test, it could be used for running compaction control during embankment erection. Test results obtained from the tests on fly ash revealed that dynamic CBR could be recommended in the cases of embedded fine-grained soil with moisture contents insignificantly greater or less than optimum water content.

Keywords

compaction, CBR, CBR_d, fly ash, compaction assessment

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Nomenclature

87.3 = number standing as a value of dynamic loading including empirical coefficient for CBR_d calculation

CBR = California Bearing Ratio

CBR_d = dynamic California Bearing Ratio, obtained by using LFWD

C_C = curvature coefficient for graining estimation

C_U = uniformity curvature for graining estimation

D_{50} = the equivalent grain diameter for which 50 % of the soil by weight is finer

DCP = dynamic cone penetrometer

G_s = specific gravity of soil

LFWD = light falling weight deflectometer

MP = the modified Proctor method of soil compaction

p = unit load during CBR test

p_s = standard load during CBR test

R^2 = coefficient of determination

s = piston settlement in millimeters during dynamic *CBR* test

SEE = standard error of estimation

SP = the standard Proctor method of soil compaction

Sr = degree of soil saturation ($0\ \% \leq Sr \leq 100\ \%$)

w = water content at compaction

w_{opt} = optimum water content

$w_{opt\ MP}$ = optimum water content by the modified Proctor method

$w_{opt\ SP}$ = optimum water content by the standard Proctor method

ρ_d = dry density of soil

$\rho_{d\ max}$ = maximum dry density

Introduction

In engineering practice, earth construction requires suitable soil compaction, usually relating to the standard and modified Proctor methods. Materials of the built-in road embankment and the subgrade have their own specifications, dependent on the kind of earth structure and soil plasticity characteristics. Care should be taken not to use compaction degree (% of maximum compaction) as the only parameter to assess compaction of material in embankments. This applies to both cohesive soil and fly ash. The permeability and mechanical properties of compacted fly ash are dependent on moisture content present during compaction, as are properties of cohesive mineral soils [1–3]. Consequently, different values of geotechnical parameters are obtained for water content on either side of the optimum water content on the compaction curve for the same dry densities. Thus for these types of soils, California Bearing Ratio (CBR) may be used as a method of compaction assessment because it is an indicator of ground bearing capacity broadly used in the design of civil engineering.

The laboratory CBR tests by means of both static (classic) and dynamic methods were carried out to establish the relationship between bearing ratio and fly ash compaction. Specimens, compacted by the standard or modified Proctor methods, were prepared without soaking them to replicate field conditions during earth structure erection. The dynamic CBR (CBR_d) tests were done using an impact generator and guide rod, which are the parts of light falling weight deflectometer (LFWD), with the addition of a cylindrical CBR piston. A falling weight produces a defined force pulse on the CBR piston that can be used both in laboratory and field tests.

The aim of this study was to demonstrate that CBR tests could be used as a method of road embankment or subgrade compaction assessment. This refers especially to the CBR_d test that may be used for running compaction control during embankment erection due to the speed of research execution, as well as LFWD, geogauge, or dynamic cone penetrometer (DCP) [4,5]. CBR_d is a much more efficient method because it is the only method, besides static CBR, that can be used initially in the laboratory for determination of the required values of CBR_d in relationship to the compaction characteristics. Under field conditions, it is possible to assess the soil compaction, comparing *in situ* CBR_d results with pre-defined required minimum values. Dynamic and classic (static) CBR are highly correlated to each other, which will be shown in this paper.

To better explain the advantages of the dynamic CBR test, the operating principles of the DCP, geogauge, and LFWD should be briefly recalled and the limitations of these methodologies ought to be indicated.

The DCP methodology [6] employs a falling mass dropped from a specified height to drive a cone into the compacted material. The penetration distance per drop is then used to estimate the shear strength and *in situ* CBR using empirical relationships. The geogauge is an alternative, non-destructive method for monitoring or controlling compaction [7]. Low strain cyclic loading (relating road static load) is applied by the apparatus to measure the soil layer stiffness. Another uncomplicated method is the LFWD that imparts a pulse force through a loading plate and measures (directly or indirectly) the movement under force of the ground. The surface modulus is computed at each tested point on the basis of the maximum deflection and device parameters. Deflections may be used to determine, *inter alia*, the quality assurance of compacted layers, and structural evaluation of force carrying capacity [8,9]. According to ASTM D6951/D6951M-09 [6]: “a field DCP measurement results in a field or *in situ* CBR and will not normally correlate with the laboratory /…/ CBR of the same material.” This statement concerns not only DCP but both other methods as well. Calibration of all the methods may be done on soil built-in earth construction.

In addition, the use of various LFWDs may lead to hard-comparable test results. Stamp and Mooney [10] conducted research to determine the impact of different LFWD design characteristics described by sensor type (accelerometer versus geophone), detecting configuration (measurement of plate versus ground surface), plate rigidity, and applied force pulse on the measured deflection and estimated dynamic modulus. They found that each of the LFWD configurations produced various values of ratio of peak deflection to the peak force and dynamic modulus for the same ground conditions and the relationship between these results was difficult to predict. For example, plate measured peak deflection normalized by the peak force for soils exceeded ground surface measurement by 44 %–203 %. The influences of the sensor type (accelerometer versus geophone), plate rigidity, and force pulse each led to smaller differences, lower than 10 %. Thus, each of the LFWDs should be calibrated separately for particular soil type to assess the compaction.

CBR Test Method—Classic and Dynamic

The *CBR* is expressed as the percentage ratio of unit force, *p*, that has to be applied so that a standardized circular piston may be pressed into a soil specimen to a definite depth at a rate of 1.25 mm/min and standard force, corresponding to unit force, p_s, necessary to press the piston at the same rate into the same depth of a standard compacted crushed rock:

$$CBR = \frac{p}{p_s} \cdot 100\% \tag{1}$$

CBR value is used for evaluation of the subgrade or sub-base strength, and may be applied to assess the resistance to failure or indicate the load-carrying capacity. It should be noted here that CBR values in pavement design do not reflect the shear stresses that are generated due to repeated traffic loading. The shear stress depends on many factors; none of them is fully controlled or modeled in CBR test [11,12]. Nevertheless, the CBR has been used widely to soil and granular material testing in highway laboratories from over seventy years. The CBR method continues to be used as the basic method of pavement design in many countries or even as the recommended method for characterizing subgrades [12]. CBR values are closely connected with the characteristics of compaction, so CBR test can be used as a method of earthwork assessment.

In the laboratory, CBR penetration tests are performed on material compacted in a specified mold and placed in a test machine equipped with a movable base that rises at a uniform rate used in forcing the penetration piston into the specimen. Tested specimens are penetrated directly after compaction or are to be previously soaked. CBR tests, *in situ*, are carried out with a mechanical screw jack for continuous increase of the applied force to the penetration piston. A reaction forcing the penetration piston into the soil is provided by a lorry equipped with a metal beam and attachments under its rear.

The CBR_d test can be performed both in the laboratory and *in situ*. The test can be conducted as an alternative to the static CBR test, especially due to the short period of time required. Compared with the classic CBR, one advantage of CBR_d is the elimination of a loading frame necessary in static loading. The CBR_d test is conducted using a loading system with a LFWD, where a falling weight is used to generate a defined force pulse on the cylindrical CBR piston. CBR_d is calculated employing an empirical equation [13], of relating piston settlement (*s*) as:

$$CBR_\text{d} = \frac{87.3}{s^{0.59}} (\%) \tag{2}$$

CBR_d is recommended to specify when it is greater or equaled 20 % and is equaled or lower than 150 %.

ASTM D4429-09 [14] recommends conducting the CBR test in-place if granular material is saturated ($Sr \geq 80$ %) or material is coarse grained and cohesionless, i.e., without consideration for variation caused by change in moisture content. Afterwards, field test data may be used to indicate the average load-carrying capacity. In the authors' opinion, CBR field test can be accomplished on unsaturated, fine-grained soils, provided the test is conducted immediately after earth works, before drying the material or wetting it by precipitation, especially if the test is used for running compaction control.

Literature Review

Turnbull and Foster [1] produced broad studies on CBR for compacted mineral soils. They determined penetration resistance of unsoaked specimens of lean clay, compacted by means of four different energy values and at different moisture contents. It was demonstrated that the CBR value for compacted clay is a function for both water content as well as dry density. Compacted specimens reached higher CBR values when greater energy values were applied. Moisture increase of compacted specimens decreased CBR value and in cases of compacted specimens with moisture contents greater than optimum water content, penetration resistance was near zero. Soaking of specimens caused a decrease of the CBR value: quite significant in specimens compacted: dry of optimum, less significant at optimum water content. The smallest decrease was observed in specimens compacted at wet of optimum. Rodriguez et al. [11] described CBR dependence on compaction parameters—moisture contents and dry densities, as well as on conditions of compaction—energy and methodology of compaction. The authors point to the fact that the CBR value of the soil compacted with higher energy value may be lower than that resulting from the compaction with lower energy value. CBR dependence on moisture in the process of compaction was confirmed in the course of studies conducted by Faure and Viana Da Mata [15]. The authors straightforwardly claim that dry density resulting from the compaction of a specimen does not have any impact on CBR value that, on the other hand, is influenced by moisture present in the process of compaction. CBR's relationship with moisture content was also observed in the case of compacted marl from Saudi Arabia [16], where marl was subjected to tests at moisture optimum as well as moisture contents on the dry and wet sides of optimum. Moisture–density curves and CBR(w) dependency curves were said to be similar; the greatest CBR values were obtained at optimum moisture. The studies of the specimens tested immediately after compaction and the soaked specimens confirmed that the effect of soaking is decreased when the specimens are compacted at moisture greater than optimum.

Zabielska-Adamska [3] concluded that the greatest CBR values for unsoaked specimens of fly ash (class F) appear in modified compaction—in case of moisture level below optimum, and in standard compaction—in case of moisture level within or slightly below optimum. In saturated specimens, the greatest values for bearing ratio CBR are present in the moisture level equal optimum for both compaction energy levels. Once optimum moisture is exceeded, CBR value drops dramatically, regardless of the compaction energy and method of preparation of specimens, soaked or unsoaked. High moisture results in the loss of contact among fly ash grains. Thus, CBR value dependence on the moisture level of fly ash is quite apparent. The CBR of specimens compacted by means of a modified method for optimum moisture is almost twice as great than in the case of optimum compaction by standard method, which points to a significant influence of compaction energy and dry density. It is interesting how compaction energy influences CBR in specimens of the same level of moisture, compacted, however, with the use of different energies. Fly ash specimens with moisture value w, compacted by the modified Proctor method, where $w > w_{\mathrm{opt\ MP}}$, show far lower CBR than specimens of the same moisture level w, but compacted by standard method where $w < w_{\mathrm{opt\ SP}}$. The lowest CBR values in the analysis of various specimens of fly ash was obtained in case of fly ash of the finest graining that influences increase of optimum moisture and decrease of density of solid particles. Zabielska-Adamska and Sulewska [17] studied the relationships between CBR and analyzed parameters of various specimens of fly ash by means of artificial neural networks and, as a result, concluded that the most relevant variables were ρ_d and relation w/w_{opt}, thus confirming the fact that optimum water content and moisture content at compaction are the most significant parameters in CBR. Dry density, as another significant parameter, should be considered as dominant when comparing CBR values for different fly ash shipments compacted with the use of different energies.

The results of the dynamic CBR are poorly represented in the literature, which is probably due to a low prevalence of this method in the world. The first study of CBR$_d$, done on the road mineral materials, was presented by Weingard et al. [18]. A good correlation between test results was obtained using static and dynamic methodologies. A study conducted by Schmidt and Volm [19] is the only one known to the authors of this paper that presents results of research with CBR$_d$ carried out on cohesive soil with different compaction. The studies were conducted for silty clay with moisture content grade from 11 to 18 %, and optimum water content established as 15.6 %. As a

TABLE 1 The basic chemical composition for tested fly ash.

Chemical	Content in Tested Fly Ash (%)
Si as SiO_2	44.28–47.44
Al as Al_2O_3	17.85–20.86
Fe as Fe_2O_3	5.18–5.43
Ca as CaO	3.04–4.48
Mg as MgO	0.73–2.01
S as SO_3	0.496–0.585
P as P_2O_5	0.082–0.430
Ti as TiO_2	1.04–1.40
Mn as Mn_3O_4	0.035–0.110
Na as Na_2O	0.093–0.202
K as K_2O	0.078–0.604
C as a loss of ignition	7.6–15.0

FIG. 1 Static (classic) CBR test.

result of laboratory studies, the researchers obtained two curves $CBR_d(w)$ and $CBR(w)$, shifted in relation to each other by approximately 5 %–7 %. In case of moisture content greater than optimum, the difference between static values and dynamic values changed to approximately 9 %. Higher bearing ratio was obtained in dynamic studies. CBR_d is recommended for control research in embankment erection with the use of fine-grained soils compacted at moisture contents less than optimum.

Attempts have been made to apply the dynamic CBR test to fly ash compaction assessment for standard and modified Proctor's methods, as described briefly in Ref. [20].

Laboratory Testing

TESTED MATERIAL

All the tests were conducted on the basis of fly ash and bottom ash mixture from hard coal burning at the Bialystok Thermal-Electric Power Plant in Poland, stored at a dry storage yard that are referred to as *fly ash* because there is only a vestige of bottom ash in the mix.

The basic composition for tested fly ash is given in **Table 1**. X-ray diffraction patterns of the fly ash indicate basic mineralogical composition as quartz SiO_2, mullite $3Al_2O_3 \cdot 2SiO_2$, and calcite $CaCO_3$.

The tested class F fly ash shipment corresponded in graining to sandy silt with an effective size D_{50} of 0.055–0.065 mm. According to the criterion that mineral soils are estimated by their uniformity and curvature coefficients, the tested fly ash qualifies as a material that responds poorly to compaction because its C_U ranges from 3.89 to 4.25–uniform (uni-fraction) soil, and C_C is 0.94–1.03. The G_s value obtained for an average sample was 2.11 ± 0.1. Fly ash optimum water content (w_{opt}) was equal to 45.5 and 37 % when maximum dry density (ρ_{dmax}) was 1.009 and 1.068 Mg/m^3, respectively, for the standard (SP) and modified Proctor (MP) compaction method. Each compaction curve point was designated on a separate specimen. During the compaction tests, individual specimens of fly ash were used only once; otherwise they could not be regarded as representative [21].

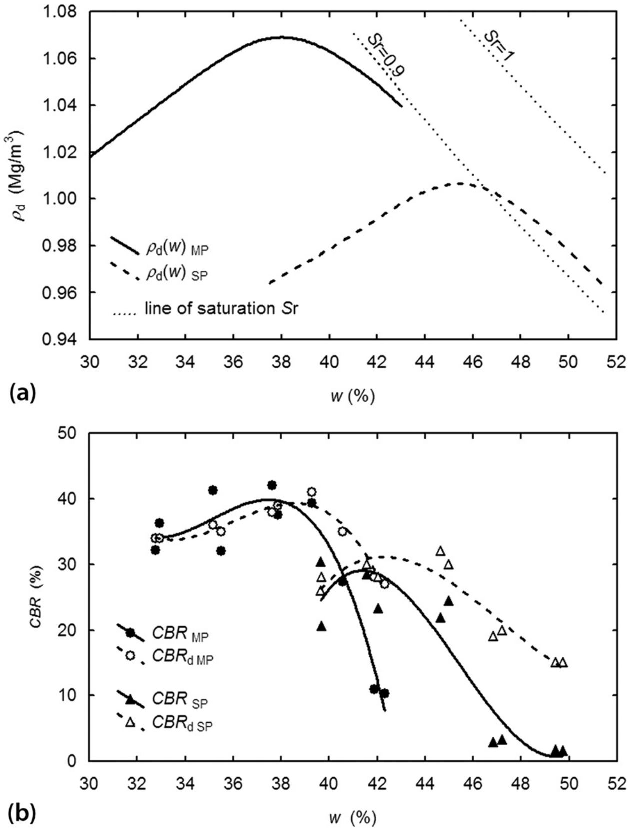
FIG. 2 Individual steps of preparing specimen for laboratory dynamic CBR test: (*a*) specimen after static CBR test and leveling surface, (*b*) mold with two bases for static (bottom) and dynamic (upper) tests, (*c*) specimen in mold with base for dynamic CBR before loading (on the left, base for static test, and on the right, mold extension to drive CBR piston), and (*d*) mold with extension ready for dynamic test.

CBR TESTS

The laboratory CBR tests were conducted to establish a relationship between bearing ratio and fly ash compaction. The tested specimens were compacted by two methods: SP and MP at moisture contents within the range of $w_{opt} \pm 5$ % for each compaction method. The fly ash was saturated 24 h prior to the test so that their moisture content could increase by approximately

FIG. 3 Dynamic CBR test by using a falling weight LFWD to produce a defined load pulse of the CBR piston.

FIG. 4 Comparison of (*a*) compaction curves for fly ash and (*b*) CBR test results versus moisture content at compaction: MP, modified Proctor method; SP, standard Proctor method; CBR, static test results; CBR_d, dynamic test results.



2.5 %. After that, it was deposited in sealed containers. All the specimens subjected to penetration were tested by both methods—static and dynamic—on the same specimens of fly ash to enable better comparison of the methods. Specimens were loaded with the ASTM 1883-07 [22] recommended load of 2.44 kPa (4.54 kg) during both penetrations, static and dynamic. The CBR tests were conducted on unsaturated specimens. Greater CBR value was accepted as a result calculated on the basis of pressing piston resistance, represented in a given depth: 2.5 or 5.0 mm. The static (classic) CBR research was done on fly ash specimens directly after compaction (**Fig. 1**). Because both tests were conducted using one specimen, the test procedure required turning the mold upside-down between penetrations.

TABLE 2 CBR(w) relationships for tested fly ash.

Equations	SEE (%)	$R^2(-)$
$CBR_{MP} = -299.34 + 0.78w^2 - 0.014w^3$	4.45	0.8860
$CBR_{d\ MP} = -130.66 + 0.37w^2 - 0.001w^3$	2.23	0.8025
$CBR_{SP} = 58.47–0.0005w^3$	5.90	0.7841
$CBR_{d\ SP} = -519.42 + 25.88w - 0.30w^2$	2.86	0.8468

Next, after accurately leveling the surface of the same specimen and replacing the mold base, CBR_d was carried out on the other side of the specimen. The CBR_d tests were conducted using the LFWD consisting of a falling mass (7.07 kN) vertically movable along the guide rod to produce a defined force pulse (3.6 MN/m^2) of the CBR piston. The electronic measurement system gauged the depth of the piston's penetration in the tested soil after a single impact. The individual steps of preparing specimen in laboratory are presented in **Figs. 2(*a*)–2(*d*)**, and CBR_d test is shown in **Fig. 3**.

TEST RESULT ANALYSIS

Figure 4 represents the results of standard and dynamic CBR testing, depending on moisture content at compaction, in relation to compaction curves of fly ash, obtained by means of two Proctor's methods. Static CBR results confirm earlier results obtained by the author. CBR of unsaturated specimens of fly ash reaches the highest values in the case of specimens compacted at the moisture content lower than optimum. The specimens compacted above optimum water content have still lower CBR values simultaneously with an increase of moisture content. These relationships can be observed in both methods of compaction—standard method and modified method. However, in specimens compacted with the use of the MP method, the curve CBR(w) definitely reaches maximum. The shape of the curves $CBR_d(w)$ is similar to that obtained according to the standard method, CBR(w). In the case of modified compaction, curves $CBR_d(w)$ and CBR(w) are characterized by a similar scope of moisture content; from $w_{opt\ MP} - 5$ % to optimum moisture content, $w_{opt\ MP}$ (difference in relation to CBR up to about 2 %). Once curve $CBR_d(w)$ exceeds $w_{opt\ MP,}$ it also exceeds standard curve, passing CBR by 16 % at $w_{opt\ MP} + 5$ %.

FIG. 5 Relationship between CBR value and dry density with an indication the points obtained at moisture contents at compaction $w = w_{opt} + (2.5\ \%–5\ \%)$: MP, modified Proctor method; SP, standard Proctor method; CBR, static test results; CBR_d, dynamic test results.

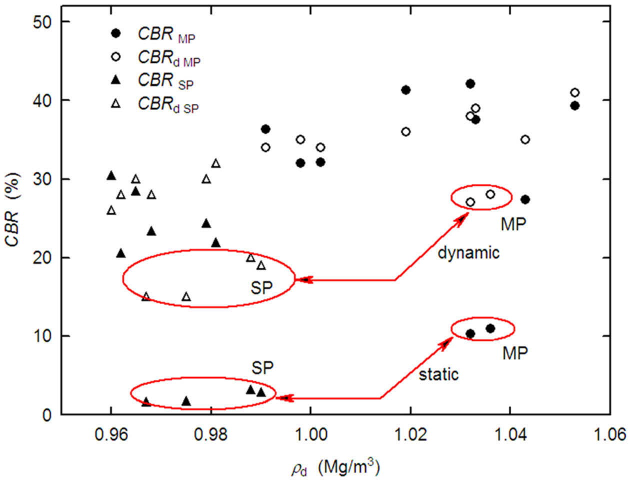
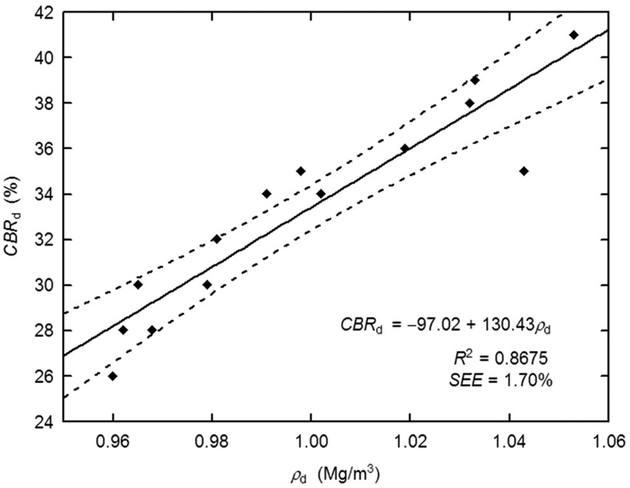


FIG. 6 CBR value versus dry density after excluding the points obtained at moisture contents at compaction $w = w_{\text{opt}} + (2.5\ \%–5\ \%)$, along with 95 % confidence interval.



In the case of standard compaction, at moisture level $w_{\text{opt SP}} - 5$ %, CBR$_d$ value approximately equals CBR value. After this, as the moisture content increases, the difference also increases and when the moisture level is equal to $w_{\text{opt SP}}$, the CBR difference is exceeded by 10 %. Polynomial equations for discussed CBR(w) relationships are presented in **Table 2**.

With further increase of moisture content, the difference may be as great as 13 %. Significant differences in the results of the studies conducted by means of static and dynamic methods at moisture level exceeding w_{opt} originate from the differences in the rate of loading and the lack of the possibility of pore pressure dissipation in the case of impact loading. Similar observations were made during studies on the influence of penetration rate on the resistance of saturated clayey soils in cone penetration tests, CPT [23].

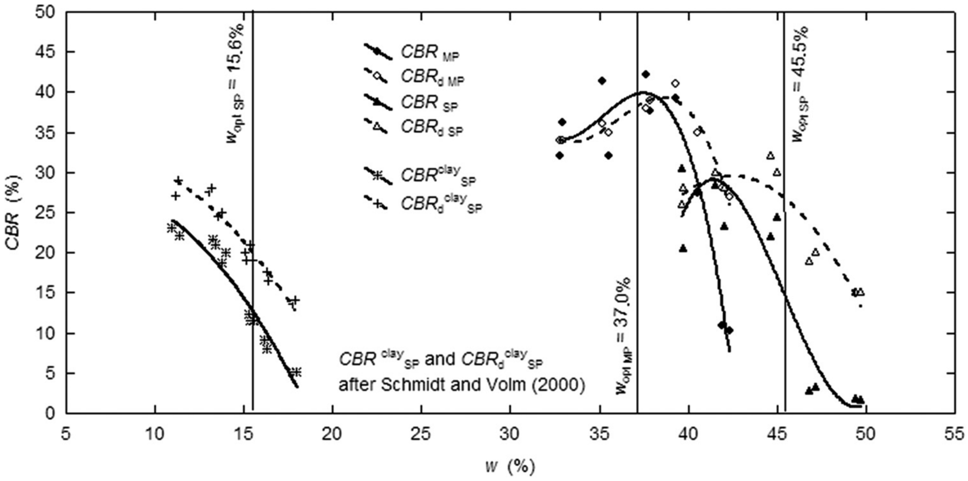
Figure 5 illustrates the dependence of static and dynamic CBR on dry density. It can be seen that there are points standing out, with the coordinates (ρ_d, CBR) obtained in the case of standard method at moisture content higher than optimum by at least 2.5 %, and in modified method greater by at least 5 %. This results from the dependence of mechanical parameters of fly ash on moisture content in the process of compaction. Once these points are excluded, statistically valid relationships—CBR(ρ_d)—appear, especially in the case of CBR$_d$ values, where for value CBR$_d$(ρ_d) coefficient of determination $R^2 = 0.8675$ and standard error of estimation (SEE) = 1.70 % were obtained (**Fig. 6**). SEE for inverse relationship–ρ_d(CBR$_d$), using for compaction control, is specified by value of SEE = 0.01 Mg/m^3.

CBR$_d$ dependence on CBR is also statistically valid, and so both methods, dynamic and static (classic), are significantly correlated to each other. The equation CBR$_d$ = 17.78 + 0.50CBR explains 84.1 % of variance in the value of statistic CBR for the whole data set (SEE = 3.11 %).

Figure 7 shows a comparison of the results obtained for fly ash and those obtained by Schmidt and Volm [19] for silty clay. Test results were presented in dependence on moisture content at compaction. CBR$_d$ dependence on CBR, determined for all the test results presented in **Fig. 7**, has improved from a statistical point of view. Equation CBR$_d$ = 14.69 + 0.59CBR explains 85.2 % of variance in the value of statistic CBR (SEE = 3.02 %). After taking into account the CBR values obtained in the case of standard method at moisture content greater than optimum maximum 2.5 %, and in modified method no greater than optimum water content, equation CBR$_d$ = 12.29 + 0.66CBR explains 90.3 % of variance in the value of statistic CBR (SEE = 2.44 %).

FIG. 7

Comparison of CBR test results for fly ash and obtained by Schmidt and Volm [19] for silty clay versus moisture content at compaction.



Conclusions

1. The dynamic CBR method as well as the static (classic) method can be used to assess compaction of fly ash and cohesive soils embedded in subgrade or layers of embankment. The results of studies of $\mathrm{CBR_d}$ and CBR are closely connected with the characteristics of compaction and highly correlated to each other.
2. The current quality control of compaction of fly ash as a fine-grained soil, conducted with $\mathrm{CBR_d}$ test methodologies and a loading system employing the light weight deflectometer, producing a defined force pulse on the cylindrical CBR piston, is recommended in the cases of embedded material at moisture contents insignificantly greater or less than optimum. $\mathrm{CBR_d}$ studies of soil compacted at moisture levels exceeding optimum water content may lead to overstating test results due to lack of pore pressure dissipation after impact ground loading.
3. The $\mathrm{CBR_d}$ test should be widely used due to its speed and ease of research as an alternative method to the classic method of quality control in compaction process or assessment of subgrade resistance to failure and load-carrying capacity. Research on other types of soils must also be investigated.
4. Dynamic CBR tests can be conducted in a laboratory in order to establish the values of $\mathrm{CBR_d}$ for soil compacted according to the requirements specified for a particular type of earthwork. Under field condition, once proceeding to compaction assessment, i.e., determining the $\mathrm{CBR_d}$ for a compacted layer is possible, the obtained result can be compared with required values pre-defined in laboratory.

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