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Correlation models between CBR values and the results of index tests in granular subgrade soils in northern Colombia

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Abstract

In the present study, several models are worked to try to express the correlation between the results obtained in the laboratory CBR test and the index properties of the soils in the area surrounding the municipality of Sincelejo, located in the north of Colombia. For this purpose, altered samples of soils of a granular nature from 25 different sites were collected, in which laboratory CBR tests were carried out and maximum dry density, optimal moisture content, liquid limit, plastic limit and plasticity index were also determined. According to the results obtained, it was possible to establish that there is a good correlation between the values of maximum dry density and the optimal moisture content, with the CBR values of the soils of granular materials, which can be evidenced from of the high values obtained in the corresponding correlation coefficients R^2. On the other hand, it was possible to corroborate that the multiple linear regression models present better correlation values than the simple linear regression models.

Keywords: California Bearing Ratio, soil index tests, correlation equation, linear regression models, multiple linear regression

I. INTRODUCTION

The economic and social development of the populations has been related to the improvement of transportation systems and their road infrastructure. Communities grow in many ways, as it becomes easier to communicate with other populations or move from one place to another, and their development can also be negatively affected as there are deficiencies in these systems [1].

Based on the above, it becomes very important that the first stages that are carried out for the planning, design and construction of the road infrastructure, start from the knowledge of the specific characteristics of the project area, as well as the adequate characterization of the Foundation soils, in order to ensure that they are made according to the needs of the area. The design of the pavement is considered one of the most important aspects in the project of a road network and in its performance throughout its useful life [2]. Additionally, it can be said that one of the most relevant aspects for the good performance of a pavement structure is that it must have a reasonable modulus of rigidity and resistance to shear [3] and must be characterized according to its nature and properties.

In Latin American countries, the California Bearing Ratio (CBR) value is widely used to characterize the resistance properties of soils [4] and the bearing capacity of the subgrade soil is important to determine the thickness of pavements [5]. The CBR test is carried out to evaluate the resilient modulus and shear strength of the subgrade soils, however, this test is laborious and time-consuming. To overcome this limitation, it may be appropriate to correlate the CBR value of the soil with its index properties, such as grain size analysis, Atterberg limits, and compaction characteristics such as MDD (Maximum Dry Density) and %OMC (Optimum Moisture Content) [3].

On the other hand, regression analysis is a statistical technique to estimate the relationship between several variables or parameters that have a certain relationship with each other. The main approach of univariate regression consists of analyzing the relationship between a dependent variable and an independent variable, and can be represented through a formula (of a linear equation) with a dependent and independent variable. Instead, regression models with one dependent variable and several independent variables are called multilinear regression [6].

It should be noted that multiple linear regression models are often used as empirical models or approximation functions. That is, the true functional relationship between Y and X_1, X_2, … , X_p, is unknown, but in certain ranges of the regressor variables, the linear regression model is an adequate approximation to the true unknown function [7]. It should also be taken into account that these models or equations can be used to make a first estimate of a project in its conceptual phase, but they will never replace the real results of the tests [8].

The objective of this study is to determine the correlation between the altered CBR value of granular soils and the index properties of the soils in the area surrounding the municipality of Sincelejo, located in northern Colombia, ensuring that the models obtained, will allow characterizing the bearing capacity of subgrade soils in a quick, less laborious and economical way. For this purpose, particle size analysis, Atterberg limits were carried out, and their moisture content and compaction characteristics were determined, as well as laboratory CBR values. For the study, twenty-five soil samples located in different streets of the urban area of Sincelejo and of the surrounding roads were collected. Direct relationships were developed between the altered CBR values, in terms of MDD, OMC, PI, PL, LL, % Clay, % Sand, and % Gravel. For this purpose, the simple linear regression model was used, whose best correlations those were obtained between soaked CBR versus MDD and between CBR versus OMC, in which the highest valuesin the determination coefficients were obtained, in comparison with the other models. In addition, multiple linear regression analysis was used with models that related several index properties at the same time. This produced a large number of models to evaluate and they were selected to show in this document the correlations that best adjusted to the characteristics of the soils in the study area.

II. EXPERIMENTAL DESIGN, MATERIALS AND METHODS

II.I Study area description

Sincelejo is the capital of the department of Sucre, Colombia. It is located in the Northwest of the country in the Caribbean Region, specifically in the Montes de María subregion (Fig. 1). The city of Sincelejo is located exactly at 9º 18” north latitude, 75º 23” west latitude of the Greenwich meridian. It has a total area of 28,134 hectares, with a height of 213 meters above sea level. It limits the south with the municipality of Sampués and with the department of Córdoba; to the west with the municipalities of Los Palmitos and Tolú; to the north with Tolú and Tolú Viejo, and to the east with the municipalities of Corozal and Morroa. It is part of the Montes de María subregion. Sincelejo is located 987 kilometers from the capital of Colombia, Bogotá; 459 kilometers from Medellín; 140 kilometers from Montería; 220 from Barranquilla; 180 from Cartagena and 40 kilometers from the Port of Tolú [9].

The soil of the municipality of Sincelejo is typical of the mountain landscape. It is formed by surfaces of irregular and complex relief, with variable slopes and altitudes ranging from 50 to 260 meters. Sincelejo's climate is hot dry, with an average rainfall of 500 to 1200 millimeters per year. The plant formation according to Holdridge is the tropical dry forest. The annual average temperature is close to 27.15ºC; with a minimum annual average of 19.7ºC and a maximum of 35.3ºC. The municipality's hydrographic network is comprised of the micro-basins of the Grande de Corozal, Canoas, La Muerte, Mocha and San Antonio streams [9].

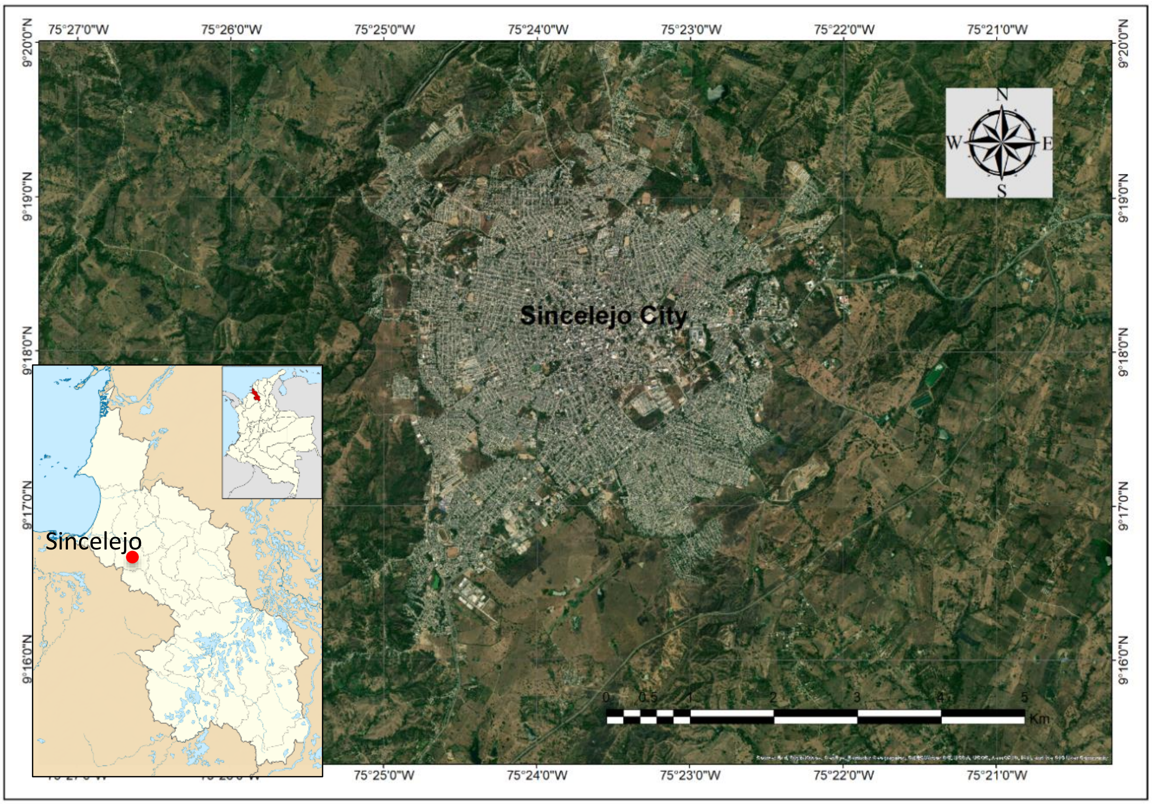

Fig. 1. Location of Sincelejo city (research area)

II.II Material and methods

For the investigation of the correlations of the physical properties of the granular subgrade soils with their bearing capacity properties (CBR), soil samples were taken at different sites located in the study area. A total of 25 representative samples were collected from different places in the city of Sincelejo, to later carry out their analysis in the laboratory. The field excavations were carried out to a depth of 1.50 meters and altered samples were obtained. The soil samples were packed in plastic bags and transported to the laboratory, following standard procedures to preserve their original moisture and density conditions. In the case of altered samples of granular materials, to carry out the CBR test, these were initially prepared, to later carry out the California Bearing Ratio (CBR) laboratory test [10], with which a related property was obtained with the bearing capacity of soils. On the other hand, in the case of the altered samples to obtain index values, a part of these were fractionated and oven-dried for 24 hours, and then carried out on these, the particle size analysis [11] and obtaining the limits of Atterberg [12], for which the Casagrande manual casserole was used to determine the Liquid Limit; while the Plastic Limit was obtained through the manual realization of rolls. With the particle size and limits values, the soils could be classified based on the Unified Soil Classification System (USCS) [13]. Additionally, from altered samples, the natural moisture of the samples was determined, as well as their respective maximum dry density and optimal moisture content. Subsequently, all the information obtained was organized in the Excel spreadsheet.

To estimate the correlation equations between the bearing capacity of soils and their different physical properties, the Multiple Linear Regression (MLR) was used, which allows predicting the values of a dependent variable, Y, given a set of p explanatory variables (X_1, X_2,…., Xp) [14]. Therefore, the MLR is a model that can be written as linear combinations because it involves more than one regressor variable. In general, the response of Y can be related to p regressor or predictor variables, as shown in Equation 1 [7].

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_p X_p + \varepsilon \qquad (1)$$

The previous model is called "multiple linear regression model" and contains p regressors. The parameters bj, j = 0,1, ..., p, are called the "regression coefficients". This model describes a hyperplane in the p-spatial dimensions of the regressor variables xj. The parameters bi represent the expected change in the response of Y, for each unit change in xi, when all the remaining regressor variables xi (i = / j) are held constant. For this reason, the parameters bj, j = 1,2 ,. . . , k, are often called partial regression coefficients.

Then, linear regression models were performed, which involved from one to three regressors, and statistical tests were performed to determine the adjustments that were generated with said regressors. During the investigation, the statistical software XLSTAT was used to use the MLR method in the geotechnical data series, with which they were able to obtain the correlation equations, as well as their the coefficient of determination (R^2) and finally, they were carried out to perform statistical tests that ensure that the application of the method is feasible on the data.

Table 1. Results of geotechnical tests

Sample	USCS Solis Classification	% Gravel	% Sand	% Clay	LL	PL	PI	MDD (Kg/m³)	% OMC	CBR (%)
1	SC	0.00	80.71	19.29	27.2	16.8	10.4	1879.73	14.35	14.5
2	SC	18.50	65.10	16.40	29.3	19.4	9.9	2008.18	9.83	18.0
3	SP-SC	17.39	70.78	11.83	33.4	22.9	10.5	1841.50	17.04	8.5
4	SC	31.71	36.38	31.92	25.7	16.5	9.1	2116.46	7.90	29.0
5	SC	37.41	41.52	21.07	26.3	15.0	11.3	2130.08	8.26	26.0
6	SC	19.99	56.76	23.25	24.6	15.6	9.0	2013.00	10.05	20.0
7	SC	13.82	68.32	17.86	32.9	18.5	14.4	1904.32	14.18	15.0
8	SC	1.25	84.10	14.65	34.9	24.1	10.8	1783.29	17.75	12.5
9	SM-SC	0.00	83.20	16.80	21.5	15.3	6.2	1861.27	14.49	15.5
10	SC	0.00	55.37	44.63	28.3	17.1	11.3	2052.00	7.17	26.9
11	SC	0.00	80.62	19.38	25.3	13.4	11.9	1959.47	12.85	17.0
12	SM-SC	2.63	65.00	32.38	17.5	12.7	4.8	1927.94	15.08	13.0
13	SC	8.67	58.93	32.40	19.6	9.9	9.7	1937.62	12.20	11.0
14	SC	0.00	84.30	15.70	25.0	17.4	7.6	1827.83	15.35	12.2
15	SC	0.00	50.70	49.30	30.2	16.4	13.8	1751.11	17.97	10.5
16	SM-SC	0.00	74.67	25.33	15.9	12.4	3.5	2040.00	5.27	25.0
17	SM-SC	0.00	70.67	29.33	14.8	10.2	4.6	2017.31	6.56	21.2
18	SM-SC	9.15	68.81	22.03	22.5	16.3	6.2	1981.58	11.69	17.0
19	SC	22.19	57.53	20.27	24.0	14.3	9.6	1969.14	11.52	16.0
20	SC	17.07	54.53	28.40	25.7	16.5	9.3	1864.64	13.50	14.0
21	SM-SC	0.00	72.27	27.73	20.8	15.3	5.4	1952.95	16.65	16.5
22	SC	4.88	74.59	20.53	30.7	15.4	15.3	1960.17	11.79	18.0
23	SC	7.88	51.29	40.82	21.5	13.5	8.1	1879.52	14.76	12.0
24	SC	18.42	65.25	16.33	21.5	13.9	7.6	2048.84	10.30	18.5
25	SC	12.32	68.36	19.32	25.1	15.5	9.6	1746.81	16.84	9.6

In Table 1. The results of the field and laboratory tests are shown and they were the regressor variables to apply the MRL method and to estimate correlation equations with the CBR values.

The details of the descriptive statistics were obtained through XLSTAT software: mean, standard deviation, variance, median and the range of the sample distribution, as presented in Table 2.

The statistical models used were chosen taking into account the regressors that best fit the model after carrying out a correlation test of the Pearson correlation coefficient between the CBR and soil index properties (Table 3). Besides some models that were implemented and yielded good results in previous similar studies in other regions of the world with similar characteristics [5]. For this, 8 models were selected (simple and multivariable), through which various index properties of the soils can be related, as shown in Table 4.

Table 2. Descriptive statistics of soils samples used

Statistics	% Gravel	% Sand	% Clay	LL	PL	PI	MDD	%OMC	CBR
No. Samples	25	25	25	25	25	25	25	25	25
Minimum	0.0	36.4	11.8	14.80	9.90	3.50	1746.81	5.27	8.5
Maximum	37.4	84.3	49.3	34.90	24.10	15.30	2130.08	17.97	29.0
Median	0.0	56.8	17.9	21.50	13.90	7.60	1864.64	10.05	12.5
Mean	7.9	68.3	21.1	25.10	15.50	9.60	1952.95	12.85	16.0
Variance	17.4	74.6	29.3	28.30	16.80	10.80	2013.00	15.08	18.5
Standard Deviation	9.7	65.6	24.7	24.97	15.77	9.20	1938.19	12.53	16.7

Table 3. Contingency table (correlation table)

Variables	CBR	% Gravel	% Sand	% Clay	LL	PL	PI	%MDD	OMC
CBR	**1**	0.318	-0.381	0.155	-0.209	-0.216	-0.134	0.881	-0.872
% Gravel	0.318	**1**	-0.686	-0.201	0.187	0.117	0.196	0.458	-0.299
% Sand	-0.381	-0.686	**1**	-0.575	0.022	0.187	-0.162	-0.424	0.335
% Clay	0.155	-0.201	-0.575	**1**	-0.240	-0.383	-0.002	0.056	-0.115
LL	-0.209	0.187	0.022	-0.240	**1**	0.850	0.825	-0.335	0.398
PL	-0.216	0.117	0.187	-0.383	0.850	**1**	0.404	-0.361	0.428
PI	-0.134	0.196	-0.162	-0.002	0.825	0.404	**1**	-0.197	0.232
MDD	0.881	0.458	-0.424	0.056	-0.335	-0.361	-0.197	**1**	-0.879
OMC	-0.872	-0.299	0.335	-0.115	0.398	0.428	0.232	-0.879	**1**

Table 4. Summary of selected models

Model	Description
Model 1	CBR vs MDD
Model 2	CBR vs OMC
Model 3	CBR vs % Gravel
Model 4	CBR vs % Sand
Model 5	CBR vs LL
Model 6	CBR vs MDD, OMC
Model 7	CBR vs MDD, %Gravel
Model 8	CBR vs MDD, %Sand

III. RESULTS

From the results of the index tests performed on the 25 samples of granular subgrade materials and after doing the statistical analysis in the XLSTAT program.

In Figures 2 and 3, it is possible to observe the two individual variables that best fit the data and the results of a simple linear regression, maximum dry density and optimal moisture content.

The regression analysis to correlate the CBR values with MDD is expressed by Equation 2 shown below, which is also represented in Fig. 2.

$$CBR = -73.3757 + 0.046472 * MDD \qquad (2)$$

For this correlation, $R^2 = 0.776$. Therefore, 77.6 % of the variation in CBR can be explained by the maximum dry density.

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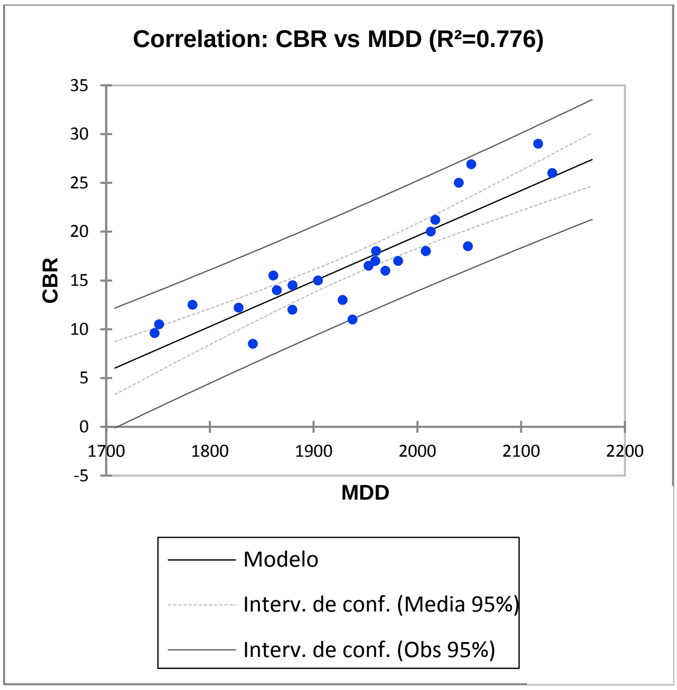

Fig. 2. Regression linear between CBR and Maximum Dry Density (MDD)

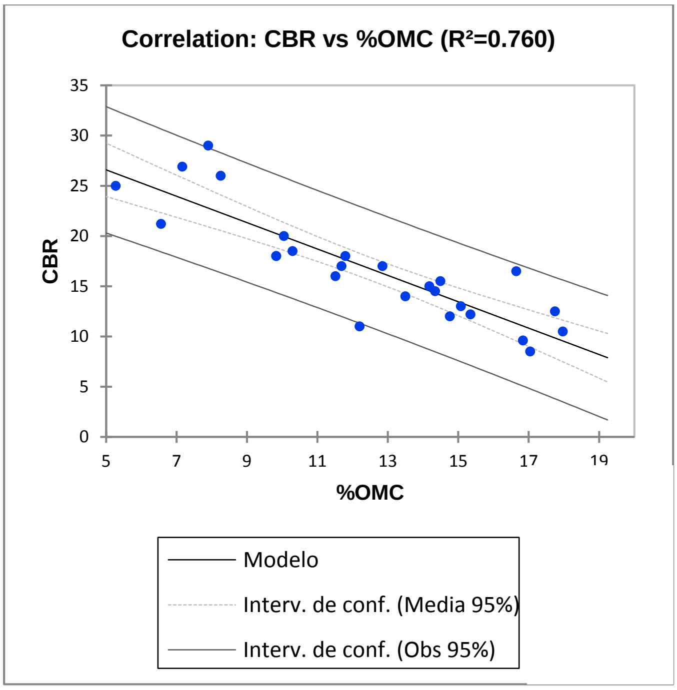

Fig. 3. Regression linear between CBR and Optimum Moisture Content (OMC)

On the other hand, the result of the regression analysis, when correlating the CBR values with OMC, is expressed by Equation 3 and is also represented, through Fig. 5.

$$CBR = 33.15928 - 1.31356 * OMC \qquad (3)$$

For this correlation, R^2 = 0.760. Therefore, 76 % of the variation in CBR can be explained by the optimal moisture content.

Fig. 4 shows the control chart for the experimental and predicted CBR values with the best fit equation (Model 6 with CBR vs MDD, OMC), where the correlation of the values can be seen. The straight line represents the points where CBR lab equals CBR pre. It is observed that a large number of points are quite close to the straight line. Only some points tend to deviate from the line.

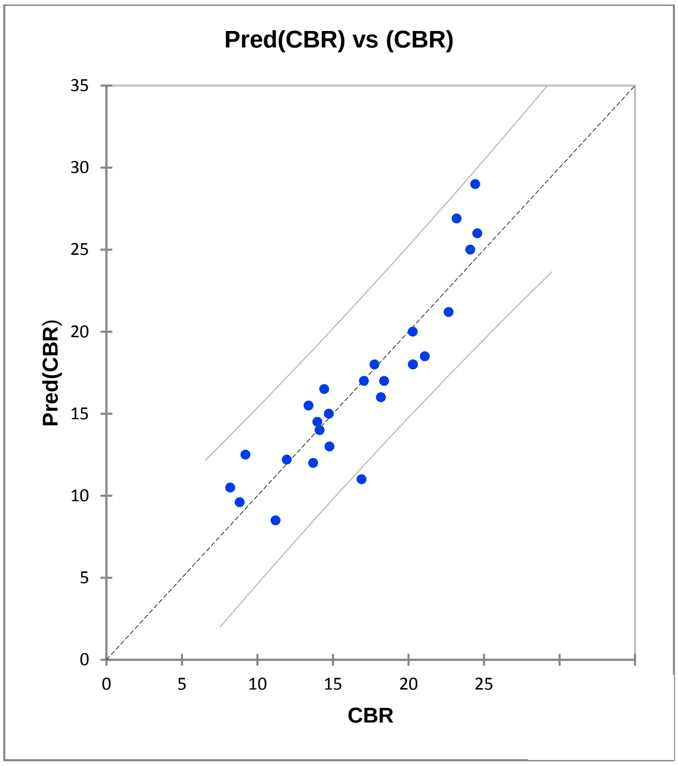

Fig. 4. Control graph showing plotted predicted CBR values vs experimental CBR values.

The equations obtained for each type of Simple and Multiple Linear Regression are summarized below (Table 5), as well as the coefficient of determination R^2.

In Fig. 5, the laboratory CBR values of the 25 samples of granular materials and the predicted CBR values with the best correlation equation are plotted. The graph shows the relationship of the two variables, and it can be seen that there is a mismatch between the two curves plotted in several of the surveys carried out. The graph shows a variation between the two CBR values. Generally, both charts follow the same pattern.

Table 5. Summary of selected models and equations

Model	Description	Regression equation	Type of regression	R^2
Model 1	CBR vs MDD	CBR = -73.37570 + 0.046472*MDD	SLR	0.776
Model 2	CBR vs OMC	CBR = 33.15928 - 1.31356*OMC	SLR	0.760
Model 3	CBR vs % Gravel	CBR = 15.11679 + 0.16228*% Gravel	SLR	0.101
Model 4	CBR vs % Sand	CBR = 27.33704 - 0.16223*% Sand	SLR	0.145
Model 5	CBR vs LL	CBR = 22.17634 - 0.21949*LL	SLR	0.044
Model 6	CBR vs MDD, OMC	CBR = -26.69262 + 0.0026570*MDD-0.64695*OMC	MLR	**0.801**
Model 7	CBR vs MDD, %Gravel	CBR = -77.89540 - 0.0054998*% Gravel + 0.0049080*MDD	MLR	0.785
Model 8	CBR vs MDD, %Sand	CBR = -72.69556 - 0.00040630*% Sand + 0.0046259*MDD	MLR	0.776

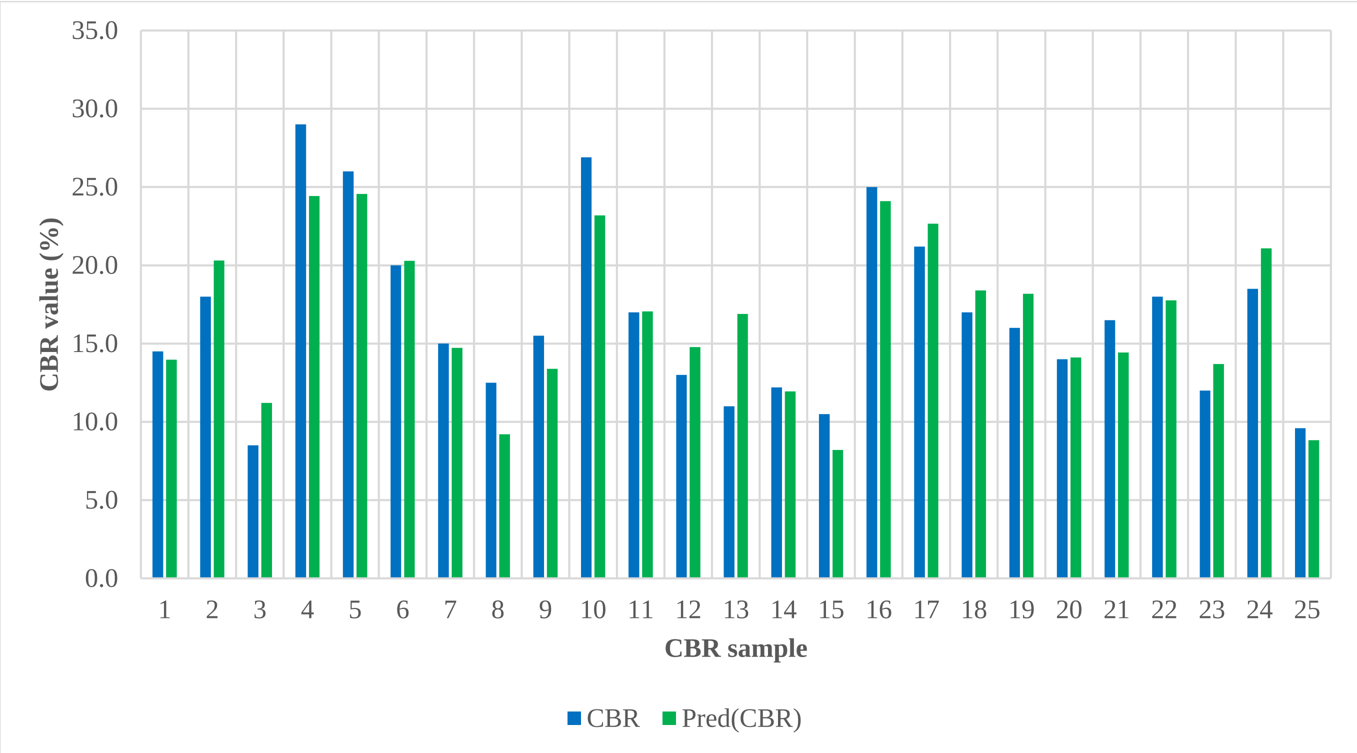

Fig. 5. Comparison graph between experimental and predicted CBR.

IV. CONCLUSIONS

Taking into account the results obtained in this work, it can be concluded:

There is a good correlation between the values of maximum dry density and the optimum moisture content, with the CBR values of the soils of granular materials. With these variables, the models and equations with the highest correlation coefficient R^2 were achieved.

The other index properties of the soils do not show a high relationship with the subgrade soils of the study area, therefore, simple models that involve these variables could not adequately predict the CBR values. It is possible that there is a relationship with these properties and it is expressed in a non-linear way, for which non-linear models should be applied, but it is beyond the scope of this study.

Multiple linear regression models present higher correlation values than simple linear regression models, thus providing more reliable equations or models when estimating these types of properties, which gives them an advantage over simpler models although they may be more laborious when working on them.

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