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RESEARCH ARTICLE

Correlation of CBR Values and Mackintosh Probe on Clay Soil with Variations of Bentonite, Kaolin and Sand

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Abstract

Coastal areas are typically characterized by non-uniform soil properties, often featuring soft, water-saturated soils with high plasticity, which frequently results in low soil bearing capacity. This study aims to investigate the relationship between California Bearing Ratio (CBR) values and Mackintosh Probe (MP) test results by utilizing a mixture of clay soil comprising bentonite and kaolin with sand in various compositions. These mixtures were prepared as laboratory test samples to simulate the soil conditions in these areas. The primary objective of this research is to develop a faster and more efficient alternative method for estimating soil bearing capacity in coastal regions. A total of 81 samples were prepared with variations in moisture content, compaction levels, and the composition of sand and clay mixtures. Testing was conducted using both CBR and MP methods. The analysis revealed a significant positive correlation between MP and CBR values, represented by the linear regression model: CBR = 0.7498 * MP, with a coefficient of determination (R^2) of 0.9542. This indicates that approximately 95.42% of the variation in CBR values can be predicted from the MP test results. The model's accuracy was further validated through training and testing using 5 randomly selected data points from the sample set. The findings suggest that the Mackintosh Probe can serve as a preliminary tool for estimating soil bearing capacity in coastal areas, particularly in field conditions where laboratory equipment is limited. However, for broader applicability, further validation of this model is necessary to accommodate more complex soil conditions in the field.

Keywords: Coastal area, Clay, Sand, CBR, Mackintosh Probe

1. Introduction

Soil is a construction material that plays a crucial role as a foundation to support buildings or structures above it. To effectively support loads, soil must possess good properties, ensuring adequate support capacity. One example is highly plastic clay, which has very fine grains (Anggraini & Saleh, 2021). Soil improvement is typically performed on specific soil types, such as those with high moisture levels, organic clays (Kusnadi, 2017), or other soil types considered bad or unsuitable. This is particularly relevant in coastal areas, which have varying soil bearing capacities.

Sandy soil is characterized by coarse grains measuring around 2 mm and easily absorbing water (Nugroho et al., 2024) (Rahmaniah et al., 2021). This type of sandy soil has unstable bearing capacity (Samsul Bahri & Elsandy, 2016). A process that can be used to assess the bearing capacity of coastal soil involves mixing variations of bentonite, kaolin, and sand. Bentonite mineral powder is a type of clay composed primarily of Monmorillonite, accounting for approximately 75% of its composition, with the addition of other minor Minerals. The structure of bentonite is an octahedral layer of aluminum silicate containing reactive -OH groups on its surface. This type of clay exhibits strong colloidal characteristics, and it has the ability to expand when exposed to water. In superabsorbent composites, interactions typically occur between bentonite mineral powder, the reactive portion of the monomer, and natural polymers (Astrini et al., 2010). Kaolin is a group of white to pale yellowish clay minerals, composed primarily of the mineral kaolinite. These minerals form through the weathering of feldspar rich rocks in humid climates.

Soil investigations aim to gather necessary soil information and data for both the planning and implementation stages. Laboratory and field tests can be conducted to determine the soil's bearing capacity . The correlation between these test results will encompass the soil's technical properties, including its physical and mechanical properties. Laboratory tests include Direct Shear, Unconfined Compression Strength (UCS), Triaxial, CBR, and others. Field tests, on the other hand, include DCP, SPT, CPT, Mackintosh Probe, and others (Natal et al., 2019)

This test is conducted by correlating the CBR test with a Mackintosh Probe. The Mackintosh Probe (MP) is a light weight and portable Penetration tool, allowing for quick and practical manual work, and is more economical than CBR testing. The weakness of the Mackintosh Probe test is that the data generated is only the number of blows, which provides little information about the properties of the soil being tested (Tanjung et al., 2013). Studies on the direct correlation between CBR (California Bearing Ratio) values and the Mackintosh Probe are still very limited, and not widely available in the available literature. This indicates a significant research gap that requires further exploration. By developing a relationship between these two parameters, research could significantly contribute to the efficiency of soil bearing capacity testing, particularly in the field.

2. Literature review

2.1 Previous Research

Research by Khoirun (Nisa' et al., 2022) showed that bentonite, despite its highly expansive nature due to its high-water adsorption capacity, can increase the cohesion and plasticity of the soil. However, this increase in plasticity can negatively impact stability if not combined with other materials. Along with stabilization efforts, a number of studies have also evaluated soil strength parameters using laboratory and field testing. Several studies have been conducted to evaluate the relationship between Mackintosh Probe (MP) test results, in the form of the number of blows per certain depth, with soil strength parameters such as the CBR (California Bearing Ratio) value (Indrayani et al., 2018; Katte et al., 2019; Kuttah, 2019), especially in clay soils stabilized with additives. Research by (Natal et al., 2019) showed a positive correlation between the number of Mackintosh probe strokes and the Qc value of the sounding test on various types of soil, including clay, with a coefficient of determination reaching 0.649. In addition, a study by (Fatnanta et al., 2013) revealed that the Mackintosh probe results can be correlated with the shear strength of soft soils significantly, although its effectiveness tends to decrease in very soft or water-saturated soils.

Soil erosion risk assessments generally require time-consuming laboratory tests, necessitating rapid alternatives such as the Mackintosh Probe test. In a study by Sulaiman et al., the Mackintosh Probe test and ROM analysis were conducted at three points along the Langat River, with three layers up to 1.5 m deep. They found an inverse correlation between the M-value and the ROM scale number with a coefficient of determination of 0.5885, indicating that the M-value can serve as an estimator of soil texture related to erosion potential (Sabri et al., 2022). n peat, CBR can be predicted with CBR = −2.1232 + 3.1162HCP, while in sand-clay the model becomes CBR = −13.4404 + 23.3252HCP + 7.1014γt (Nugroho et al., 2019; Nugroho & Yusa, 2012; Yusa & Nugroho, 2008).

Sabtan et al. (Sabtan & Shehata, 1994) conducted research by correlating the MP Value based on the Mackintosh Probe (MP) test with the Qc Sondir (Cone Penetration Test) Value. The results obtained provide a good or strong correlation value, where the equation obtained is Qc = 25.316MP + 30.806 with a limit of 0 MP <400 blow/ft with an R2 value = 0.6286 with an R value = 0.62861/2 = 0.7928, and there is also a correlation coefficient value from the Mackintosh Probe consistency value with the Cone Penetration Test, namely Qc = 0.1925MP + 1.794 with an R2 value = 0.8987 which indicates that there is a strong correlation between the two variables.

Table 1. Classification of Bentonite Clay

Test Parameters	Test Results
Liquid Limits (%)	210
Plastic Limit (%)	35,5
Plasticity Index (%)	173,5
Optimum Moisture Content (%)	29,5
Maximum Dry Density (g/cm^3)	1,22
UCS (kN/m^3)	240
Cohesion (kN/m3)	120,68
CBR (%)	1,5

Source : (Kumar et al., 2021)

2.2 Bentonite

If the liquid limit is greater than 50%, this indicates that bentonite clay can be classified as highly plastic and highly compressible (Kumar et al., 2021).

2.3 Kaolin

Kaolin is a type of clay composed primarily of the mineral kaolinite with the chemical formula $Al_2Si_2O_5(OH)_4$. Chemically, the oxide composition of kaolin minerals is purer than that of fly ash or slag (Nurhayati et al., 2013).

Table 2. Kaolin Classification

Parameter	Value / Range
Liquid Limit (LL)	30% – 70%
Plasticity Index (PI)	5% – 30%
Specific Gravity (G?)	2.63
Optimum Moisture Content (OMC)	16% – 18%

Source : (Raghunandan, 2020)

2.4 California Bearing Ratio (CBR)

The strength of the subgrade is greatly influenced by its water content. The higher the water content, the lower the CBR value. After road construction, water will absorb into the subgrade, resulting in a decrease in strength and CBR value until the water content reaches a stable level (Bernavida & Wulandari, 2021).

Table 3. Classification of Soil CBR Values

CBR (%)	General Level	Utility
0 – 3	Very Poor	Sub-grade
3 – 7	Poor to Fair	Sub-grade
7 – 20	Fair	Sub-base
20 – 50	Good	Base or Sub-base
>50	Excellent	Base

Source : (Bakri et al., 2022)

2.5 Mackintosh Probe (MP)

The Mackintosh probe is an important tool in geotechnics that provides vital information about ground conditions, which is very useful for various construction and civil engineering applications (Yapeter et al., 2013). The Mackintosh probe value is calculated by recording the number of blows required to penetrate the soil layer to a depth of 30 cm. This number provides a direct indication of the soil's density and hardness.

Table 4. Relationship between Soil Bearing Capacity and MP

Number of Blows/0.3 m of penetration		Consistency
Mackintosh Probe	SPT N	
<15	<2	Very soft
15-33	2-4	Soft
33-72	4-8	Medium
72-147	8-16	Stiff
147-322	16-30	Very Stiff
>322	>30	Hard

source:(Tarmizi et al., 2016)

3. Methods

This research is described in a flow chart (Fig. 1) that includes the main steps, starting from literature study and sample characteristics, material design and preparation, CBR and Mackintosh Probe testing, to the analysis used.

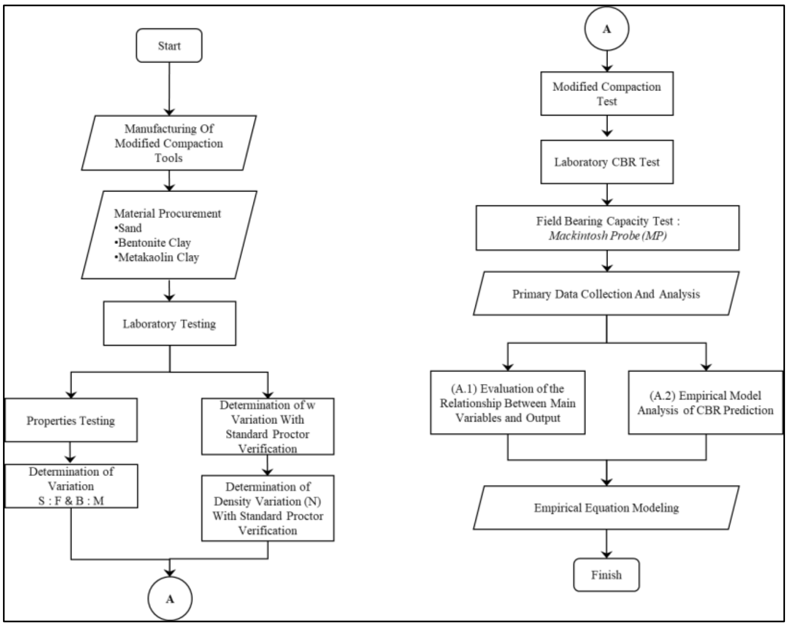

Fig. 1. Research Flowchart

3.1 Research Variable Limitations

The variable limitations used in this study are as follows:

- S = The percentage variation of Sand > 50%, this is based on an approach to estimating conditions in coastal areas.
- B = The variation in the percentage of bentonite used is ≥ 50%, based on the properties of bentonite which has high shrinkage and is very suitable for representing soft soil conditions. The role of kaolin which can neutralize the properties of bentonite is verified in the Atterberg limit test.
- N = The number of strokes in this study was locked from γdry max, which is the maximum stroke limit.
- w = The variation in water content taken is increased from the OMC value, to estimate soft soil conditions in coastal areas.

3.2 Determining the Number of Samples

Each sample used is expected to have soft soil properties so that it can represent the soil in coastal areas.

3.2.1 Determination of Variations for Sand and Clay

To determine the variation of S, the approach used is based on the Atterberg limit test. After the test is carried out, the soil conditions can be seen to obtain CH results, if the S variations used are S65, S70, and S80, while the B variations used are B70, B60, and B50. With the main target of the soil to be achieved is SC-CH based on USCS, it shows that the test results can still be said to be soil that has high plasticity.

3.2.2 Water Content and Number of Beats

Water content variations were conducted through Standard Proctor testing, which aims to obtain optimum water content (OMC) and maximum dry unit weight. In determining the water content variations used, considering the desired soil conditions, namely soft soil conditions, the water content variations used must be greater than the obtained OMC value. Considering the conditions previously stated, the water content variations used were 15%, 20%, and 25% (Fig. 2).

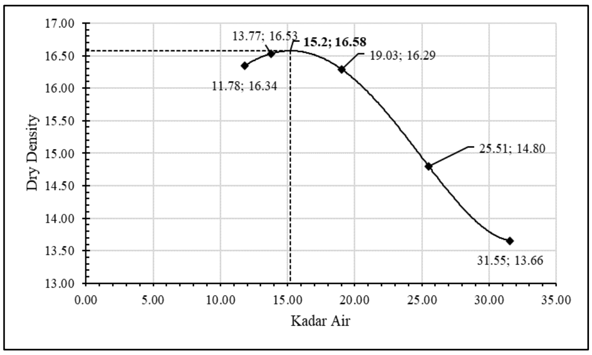

Fig. 2. Optimum Water Content and Maximum Dry Volume Weight Curve

Fig. 3. Modification Tools

To determine density variation with the modified tool (Fig. 3), the first step was to conduct a Standard Proctor compaction test to be used as a comparison with the modified tool. The results showed that to achieve γdry-max according to the standard Proctor, 40 blows were required with the modified tool (Fig. 4). For the determination of density variation carried out in this study, no more than 40 blows were allowed to be used to maintain soft soil conditions. The number of blows was set at N = 40, N = 32, N = 16.

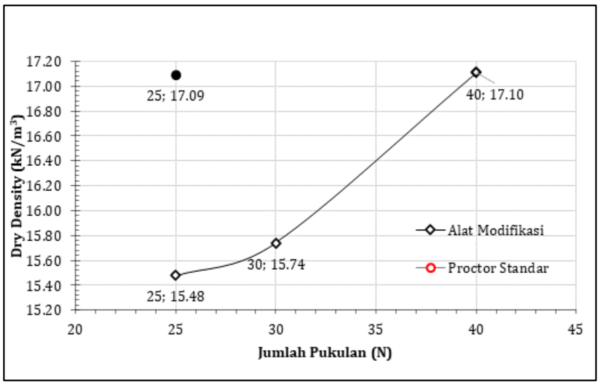

Fig. 4. Comparison Curve of Standard Proctor and Modified Compaction

3.2.3 Determining the Number of Samples

Based on the results of the determination, it can be determined that the number of samples to be used in this study is 81 samples.

Sand (S) = S-65, S-70, S-80
Bentonite (B) = B-70, B-60, B-50
Blows (N) = N-16, N-32, N-40
Water content (w) = 15%, 20%, 25%

3.3 Data Analysis Techniques

The data obtained from the test results on each combination of sample variations will be analyzed using the following steps:

a. Correlation analysis of soil parameters (water content, dry volume weight, impact) against CBR and MP to measure the strength and direction of the relationship.
b. Simple linear regression analysis to form a prediction model for CBR values based on MP values.
c. Evaluation of the performance of the equation model is carried out through residual analysis, as well as measuring the R^2 value.
d. Model validation using training and testing techniques with 5 randomly selected data.
e. Comparison of model results with actual CBR values to assess the level of accuracy and applicability of the equation model.

4. Results And Discussion

The analyze parameters were taken from two tests, namely CBR and MP. The Correlation conducted in this study also looked at the mixture variations: water content, and number of blows. In the MP test, data was taken at a depth of 5 cm. Therefore, the name MP 5 cm is the result of the number of blows of the MP tool of 5 cm of penetration. From a total of 81 data samples, the process of identification and elimination of outlier data was carried out (Raji et al., 2021). There were 3 data points that were removed from the analysis because the CBR and MP values showed a very large deviation from the general trend, thus disrupting the formation of a simple linear regression equation. After the outlier elimination process, 78 of datas obtained is ready for analysis. Of these, 5 data points were randomly selected to be used as testing data and 73 data points were used to form the regression equation.

4.1 Correlation Between CBR and MP

To understand the effect of actual water content on the bearing capacity of CBR and MP soil, a linear regression analysis was performed based on three levels of compaction energy represented by the number of blows N16, N32, and N40 (Fig.5 - Fig.7). The correlation confirmed that water content has a consistent negative effect on CBR and MP values at all compaction levels (Fakher et al., 2006) (Hossain & Ali, 1990). However, this effect is more pronounced on MP values, as seen from the generally higher coefficient of determination R^2 values. This indicates that MP is quite sensitive to changes in water content, thus potentially being used as a rapid prediction tool for soil bearing capacity conditions in the field.

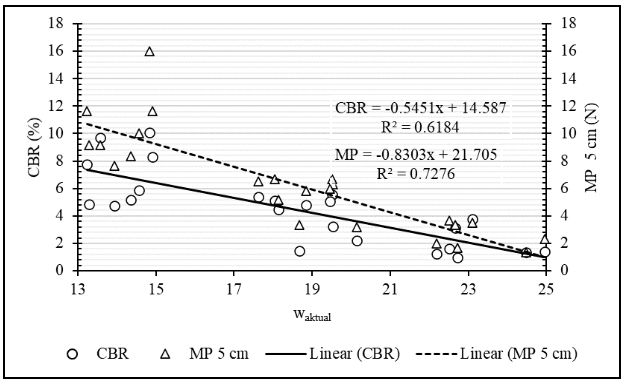

Fig. 5. Temporal correlation of CBR and MP values at N16

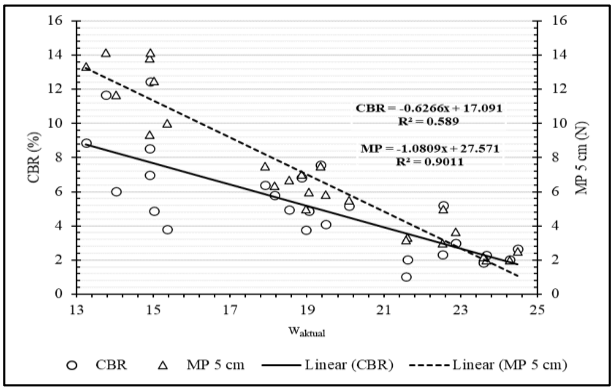

Fig. 6. Temporal correlation of CBR and MP values at N32

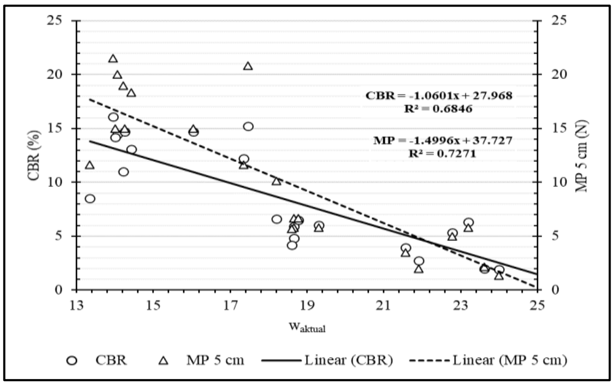

Fig. 7. Temporal correlation of CBR and MP values at N40

Based on the correlation between γdry and CBR and MP values analyze with three variations of water content, 15% w15, 20% (w20), and 25% (w25) on Figure 8, Fig. 9, and Fig.10, the results obtained show a positive trend between γdry and CBR and MP, especially at higher water content. This condition is in accordance with the principle that soil with high density generally shows tighter interparticle bonds, thus being able to provide greater bearing capacity.

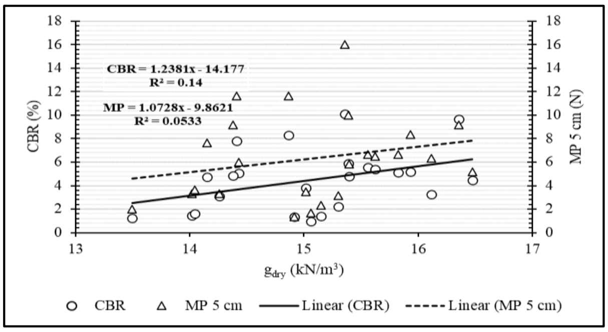

Fig. 8. Correlation of gdry to CBR and MP Values at w15

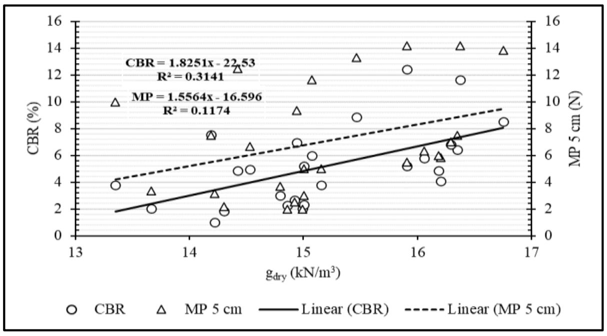

Fig. 9. Correlation of γdry to CBR and MP Values on w20

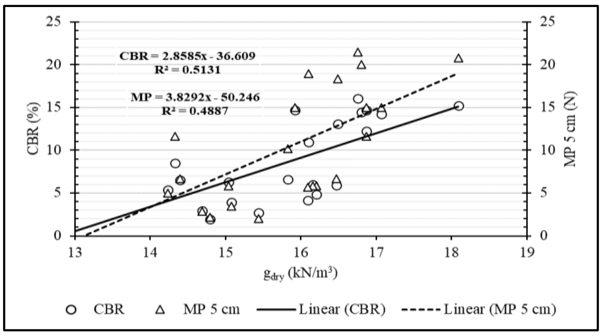

Fig. 10. Correlation of γdry to CBR and MP Values at w25

4.2 CBR Prediction Analysis Based on MP Variables

The analysis was carried out with the aims of building a mathematical model that connects CBR and MP test results (Fig. 11). Based on Fig.11, a linier empirical equation with R^2=> 0,95 is obtained that is strongly able to predict CBR based on MP values.

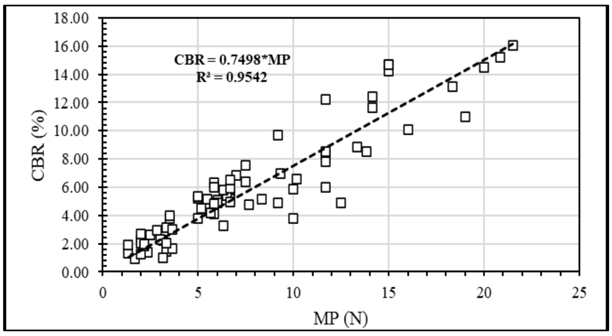

Fig. 11. CBR = MP graph

4.2.1 Empirical Models and Statistical Evaluation

Based on the test results, 78 remaining data were used in the training (73 datas) process to build a CBR value prediction model based on MP parameters through a simple linear regression approach .

From the modeling results, the equation CBR = 0.7498*MP was obtained with R² of 0.9542, which shows that 95.42% of the variation in the CBR value can be explained by the model built (Rousseeuw & Hubert, 2018).

4.2.2 Residual Analysis Verification

Based on the Verification conducted (Chang, 2000) (Topp & Gómez, 2004), the equation model can be said to be quite good. Verification was carried out using the interpretation of Q-Q Plot Residuals (Fig.12), Histogram Residuals (Fig. 13), and Residuals vs Fitted (Fig. 14).

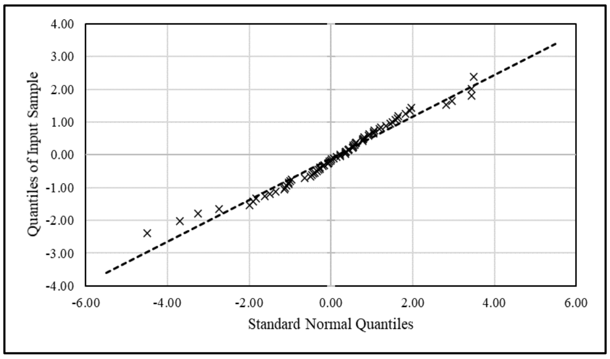

Fig. 12. QQ Plot Of Residuals

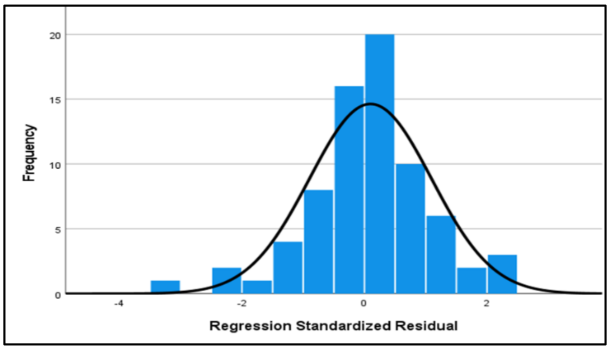

Fig. 13. Histogram Residual

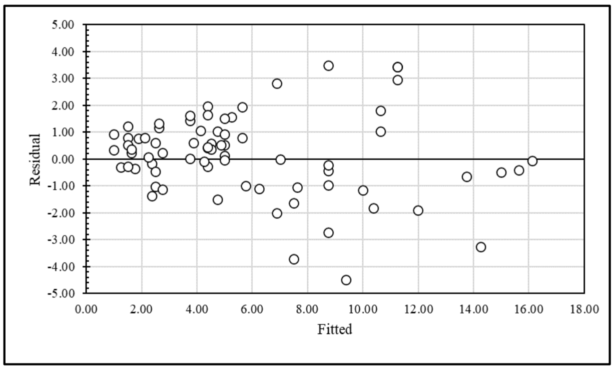

Fig. 14. Residual vs Fitted

4.2.3 Data Verification Through Training and Testing

To evaluate the performance and accuracy of the obtained equation, this study used five randomly selected data sets for testing (5 datas, Table 5), and the resulting equations were used for training. The verification results showed that the equation model performed very well in predicting CBR values based on the MP value parameter (Fig. 15).

Table 5. Training and Testing Verification Results

Sample	Sample Code	CBR Aktual	MP 5 cm	CBR Prediction
38	S80:B60:N16:W25	1.10	2	1.25
412	S65:B60:N16:W20	6.74	6	4.37
326	S70:B70:N32:W15	6.72	11	7.87
111	S80:B60:N40:W15	13.96	18	13.25
488	S65:B60:N40:W25	6.94	6	4.75

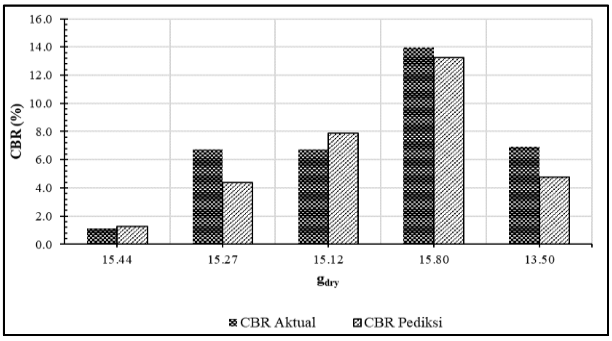

Fig. 15. Comparison of Actual CBR Values and Predicted CBR

4.2.4 Geotechnical Interpretation and Implementation Limitations

Geotechnically, the positive relationship between MP and CBR means that the increase in soil resistance to MP values is in line with the increase in CBR values (Bakri et al., 2022). This indicates that the MP parameter can be used as an initial indicator in estimating CBR values, especially in the process of evaluating the quality of stabilized or improved soils. Although this model has been validated and demonstrated good predictive performance, there are several important limitations that need to be considered before implementing this model widely:

a. Models are developed based on data from specific soils stabilized using specific materials or methods. Application to other soil types or stabilization methods requires additional testing.
b. The model is only valid within the range of MP and CBR values from the research data. Use outside this range may result in inaccurate estimates.
c. Testing was conducted under laboratory conditions. The effectiveness of the model in the field may be affected by other variables such as natural moisture, field density, and variations in soil texture (Fatnanta et al., 2024).

5. Conclusion

Based on the research conducted, it can be concluded that CBR testing can be correlated with Mackintosh Probe testing. Simulation of a mixture with a sand content of more than 50% and a minimum of 50% bentonite in the fine fraction successfully represents the characteristics of soft soil. The relationship between dry unit weight (γdry) and water content is proven to be non-linear. This is in line with the basic principles of the Optimum Water Content (OMC) and Maximum Dry Unit Weight (MDD) concepts, where the maximum density value will not be achieved if the water content is below or above the optimum point, so that an increase or decrease in water content does not always result in an increase in soil density. The results of the correlation analysis show that there is a fairly strong linear relationship between the California Bearing Ratio (CBR) value and the number of Mackintosh Probe (MP) strokes. The coefficient of determination (R^2) value obtained from several variations indicates that MP can be used as an estimation parameter to predict CBR values. This indicates that the Mackintosh Probe can be used as a practical and efficient rapid field test method in assessing soil bearing capacity.

The results of the linear regression analysis obtained the equation CBR = 0.75 * MP with an R^2 of 0.9542. The empirical equation model that utilizes the Mackintosh Probe (MP) variabel can be recommended as an alternative method for estimating CBR values without having to conduct direct testing in the field. However, its application still needs to consider certain geotechnical limitations, and further development is needed to improve the model's ability to predict soil types with more diverse characteristics.

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