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Influence of Porosity and Cement Index on the Strength of Cement-Stabilized Soil

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Abstract

The article is divided into four chapters: Introduction, Materials and Methods, Results, and Conclusions. It explores the potential for determining unconfined compressive strength (R_C) using porosity and the cementation index (n/C_i) as an alternative to the water-to-cement ratio (w/c) in surface stabilized soils. The study investigates three stabilized soil mixtures with cement contents of 3%, 5%, and 7%, each tested at moisture levels ranging from 6% to 11%. A comparison between the n/C_i and w/c indicators is presented, along with the calibration process for the n/C_i indicator. Furthermore, a detailed methodology for determining the n/C_i indicator is provided. The article also examines correlations between R_C and the secant modulus of elasticity (E_{50}). The findings contribute to the development of efficient methods for assessing the mechanical properties of surface-stabilized soils and demonstrate the practical application of the n/C_i indicator..

Key words: unconfined compressive strength test, stabilization, secant module, porosity/cement index ratio, water/cement ratio.

1. Introduction

Soil stabilization is one of the essential topics in geotechnics or road engineering. This method involves improving soil properties by mixing it with other materials [2, 8]. According to the world literature, stabilization can generally be divided into mechanical stabilization and chemical stabilization [9, 14]. The mechanical stabilization process involves modifying the soil to improve it by adding other soils to improve compatibility and other elements, such as reinforcement. Chemical stabilization involves changing the properties of the soil by adding chemically active materials [14]. Such materials can include cement and lime, which belong to the group of hydraulic binders, i.e., those that bind and solidify when mixed with water through hydration reactions and processes.

Currently, one of the more commonly used chemical stabilization methods is mixing soil with cement to produce a material called stabilized soil [6]. Mixing cement, soil, and water together and then compacting the resulting mixture to the desired density produces a material with increased compressive strength and stiffness and less ability to absorb water [8]. This method has been used since 1915, when cement stabilization was used during the construction of a road in Saracosta, Florida [1]. Since then, the method of stabilizing soil with cement has been widely used during the construction of linear structures such as highways. Stabilized soil is mostly used for the road base layer or surface soil improvement during road construction.

The final effect of soil stabilization with cement depends on the amount and type of binder used. In general, it should be considered that as the binder content in the cement-ground mixture increases, its

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unconfined compressive strength increases [20]. In addition to the binder content, the final effect of the improvement also significantly depends on the properties of the hydraulic binder used. Currently, there are 5 basic types of cement, which differ in the content of the main components. Portland cement has been most commonly used for soil stabilization due to its availability and cost-effectiveness [13]. However, this trend has changed in recent years due to the attempt to reduce CO2 emissions and protect depleting natural resources [16]. Therefore, additives such as recycled materials or other waste products have been used [3, 11, 12, 18]. The most commonly used additives to reduce the need for binder include granulated blast furnace slag and fly ash [7, 17].

In addition to the amount and type of binder, another critical factor affecting stabilized soil's strength is the water/cement ratio. It has been observed that for a given water content, there is a maximum limit to the cement content above which cement grains cannot hydrate and thus cannot properly participate in pozzolanic processes [10]. To achieve complete hydration of Portland cement, 4.2 moles of water must be provided for each mole of cement [19]. Therefore, it can be assumed that the minimum water-to-cement ratio (w/c) should be 0.42 [19]. This ratio is commonly used in the deep soil mixing process (DSM), while it is less widely used in surface soil stabilization. This is due to the limitation of its modification by changing the amount of water in the mixture. In the case of surface soil stabilization, the water content should allow the optimum moisture content to be achieved, ensuring proper compaction of the mixture. For this reason, some researchers have decided to modify the described index by replacing the amount of water (w) with porosity (n) [5]. Such a procedure appears to be used in the case of surface stabilization.

This study investigates the effect of porosity (n) and cement index (C_i) on the unconfined compressive strength (R_c) of stabilized soil and compares the n/C_i index with the w/c index. In addition, it analyses the effect of the strength of the stabilized soil on the modulus of elasticity at 50% of the ultimate stress.

2. Materials and Methods

This study presents the results of unconfined compressive tests conducted on three mixtures. Each mixture is a combination of soil, binder, and water. The base of each mixture is clSa soil, which is described in detail in subsection 2.1. The cement binder CEM V/A (S-V) 32.5 R-LH (Górażdże Cement S.A., Chorula, Poland) was used to produce the mixtures. A detailed description is given in subsection 2.2. In the purpose of modifying the n/C_i and w/c ratios, the binder and water contents were changed, with binder contents of 3%, 5% and 7%, respectively, and water contents ranging from 7% to 11%. The procedure for sample preparation and care was in accordance with PN-EN 14227-15. A detailed description of the procedures is given in subsection 2.3. The unconfined compression test, the measuring device used, and its calibration are described in detail in subsection 2.4. In subsection 2.5, the procedure for determining the analyzed indexes is described.

2.1. Soil

Physical and mechanical tests were conducted on the soil, which is the basic component of all analyzed mixtures. The physical properties of the soil were determined by aerometric analysis, using a complete set of sieves and a Casagrande apparatus. In addition, other necessary tests were carried out to precisely determine the physical properties of the soil. Cohesion and angle of internal friction were determined from triaxial compression tests. The main properties of the soil are summarized in table 1, and the grain size curve is shown in figure 1. The soil used in the article was classified as clayey sand (clSa). The classifications were conducted in accordance with the current standard PN-EN ISO 14688-2.

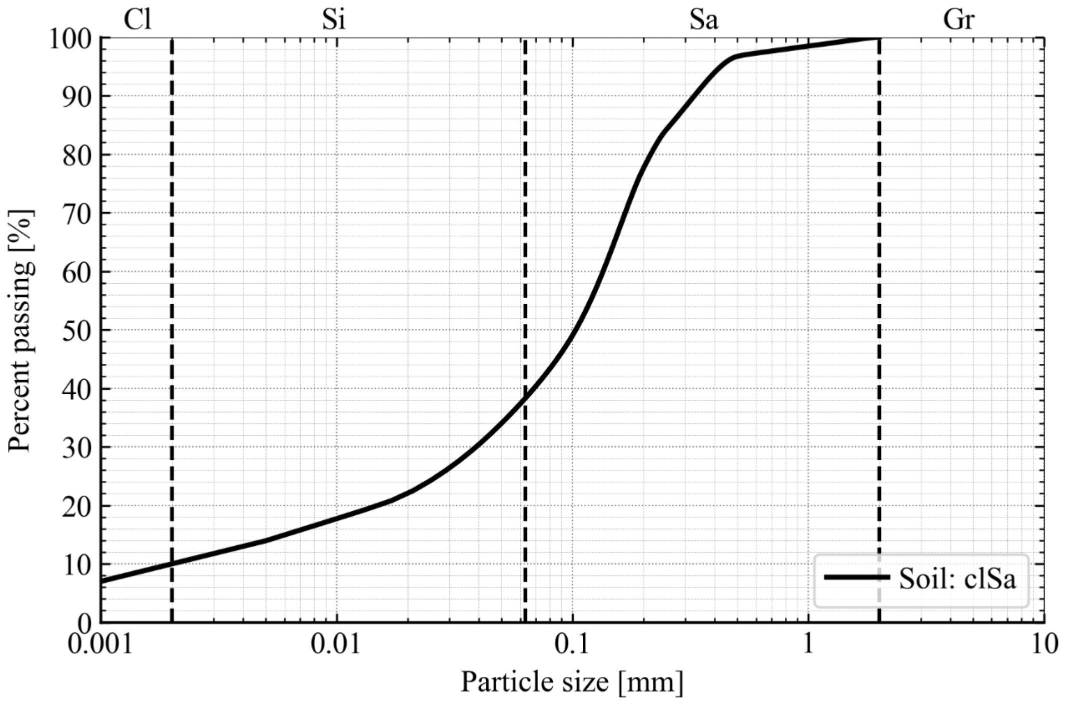

Figure 1. Grain size distribution curve of soil

Table 1. Properties of the soil

Physical properties of soil	notation	Value	Units
Coefficient of Curvature	C_C	5.33	[-]
Uniformity Coefficient	C_U	75	[-]
Plasticity index	PI	9.15	[-]
Liquidity index	LI	0.10	[-]
Liquid limit	LL	19,03	[%]
Plastic limit	PL	9,88	[%]
Specific gravity of soil	G_S	2.66	[g×cm^{-3}]
pH values	pH	8.95	[-]
Maximum Dry Density	MDD	1.98	[g×cm^{-3}]
Optimum Moisture Content	OMC	8.64	[%]
Cohesion	c’	7	[kPa]
Internal friction angle	φ’	34.5	[°]

2.2. Binder

The binder used is a composite cement containing Portland cement and a combination of blast furnace slag and pozzolana or fly ash. The material was stored under lab conditions and used before the expiration date declared by the manufacturer. The properties of the binder used are shown in table 2.

Table 2. Properties of binder.

Properties of binder	Value	Units
Required compressive strength after 2 days	≥ 10,0	[MPa]
Required compressive strength after 28 days	≥ 32,5	[MPa]
Specific gravity of cement - · G_{SC}	2.97	[g×cm^{-3}]

2.3. Sample preparation procedure and care process

All samples were prepared using three different mixes. The binder for each mixture was measured by weight to the dry weight of the soil, and the water was measured to the weight of the soil and cement. To ensure homogeneity, the mixtures were mixed to a uniform consistency. Each mixture was initially characterized by a moisture content of 7%. An amount of material was taken from the prepared mixtures to form a sample and determine the moisture content. After the sample was formed, the moisture content of the mixture was increased by adding water, after which it was mixed again. After this process, the material was again taken for moisture content determination, and another sample was formed. These operations were repeated seven times for each mixture, which made it possible to obtain stabilized soil samples with real moisture content in the range of 7% to 11%. The actual moisture content was determined in accordance with PN-EN 13286-1. For this purpose, each collected sample was placed in a weighed porcelain crucible and weighed again. The samples were then dried at 105°C for 24 hours. After drying, the crucible with the dried soil was weighed again. Based on the results, the actual moisture content of each sample was calculated. A RADWAG PS 6000/C/1 laboratory balance with a measurement accuracy of 0.01 grams was used in the study. All stabilized soil samples were prepared in cylindrical molds with a diameter and height equal to 8 cm. Before compaction, each mold was weighed. The prepared samples were compacted using a Proctor rammer, ensuring a constant specific energy of 0.59 J/cm³, according to PN-EN 13286-50. The samples were compacted in two layers, where each layer received 16 blows from a 2.5 kg rammer and 305 mm drop height. After compaction, each sample was weighed again. The density of the sample immediately after compaction was determined from the measured masses. After the samples were prepared, they were stored in a room with constant humidity and a temperature of 22°C ± 2°C for 28 days. The care process was in accordance with PN-EN 14227–15. After this period, an unconfined compressive test was conducted for all the samples.

2.4. Unconfined compression test

The unconfined compressive test was conducted using an Instron universal testing machine, model 5982. The machine was equipped with a displacement recorder and a load cell. During loading, the force was applied continuously with a constant stress increment of 0.05 N/mm^2/s. During the test, continuous recording of force and vertical displacement was carried out. Corrections were made in the recorded stress-strain relationships to ignore the effect of adjusting the test specimen. All calculations were performed using Bluehill 2.0 software. Basic information about the measuring device and the accuracy of the measurements is shown in table 3. The unconfined compressive strength (R_c) was determined based on equation 1. Then the secant modulus (E_{50}) was determined based on equation 2.

$$R_c = \frac{F}{A}\ [MPa] \tag{1}$$

Where R_c refers to the unconfined compressive strength [MPa], F is the ultimate applied force, and A is the specimen area.

$$E_{50} = \frac{\sigma_{0,5}}{\varepsilon_{0,5}}\ [MPa] \tag{2}$$

Where E_{50} refers to the secant modulus at 50% of the highest compressive stress, $\sigma_{0,5}$ is the stress at 50% of the peak compressive force and $\varepsilon_{0,5}$ is the strain at the stress of $\sigma_{0,5}$.

Table 3. Basic information about the measuring device

Details	Value	Units
Accuracy of force measurement	±0,5	[%]
Accuracy of displacement measurement	±0,01	[mm]
Accuracy of load speed	±0,1	[%]
Frequency of data registration	2,5	[kHz]

2.5. Methods of analysis

This article examines the possibility of using porosity and cement index to predict unconfined compressive strength. In order to calculate the n/C_i ratio, it is necessary to take into account the specific gravity of the soil (G_S), the specific gravity of the cement (G_{SC}), the moisture content of the sample (w), its volume (V), its mass (m) and the amount of cement (C) used. The calculated ratio was then compared with the traditional water/cement ratio. In order to calculate the n/C_i index, it is necessary to determine the bulk density (ρ_b) of the sample according to equation 3, the dry density (ρ_d) according to equation 4, the volume of the soil (V_S) according to equation 5, the volume of the cement (V_C) according to equation 6, and the volume of the voids (V_V) according to equation 7.

$$\rho_b = \frac{m}{V} \tag{3}$$

$$\rho_d = \frac{100 \cdot \rho_b}{100 + w} \tag{4}$$

$$V_S = \frac{(V \cdot \rho_d) - (V_C \cdot G_{SC})}{G_S} \tag{5}$$

$$V_C = V \cdot \frac{\rho_d \cdot C}{(100 + C) \cdot G_{SC}} \tag{6}$$

$$V_V = V - (V_S + V_C) \tag{7}$$

Then, using the determined values, porosity was determined according to equation 8, and the cement index was determined according to equation 9.

$$n = \frac{V_V}{V} \cdot 100\% \tag{8}$$

$$C_i = \frac{V_C}{V} \cdot 100\% \tag{9}$$

Where R_C refers to the unconfined compressive strength [MPa], β is the scaling coefficient, and α is the coefficient exponent.

3. Results

The research and the results obtained were conducted in accordance with the procedures described. The chapter is divided into three subsections. The first subsection discusses the applicability of the analyzed coefficients for determining the unconfined compressive strength of cement-stabilized soil. In the second subsection, the calibration of the selected coefficient was carried out. The third subsection presents the relationship between unconfined compressive strength and secant elastic modulus.

3.1. Comparison of n/C_i and w/c ratios

In the study, 21 cement-stabilized soil samples were analyzed. For each sample, unconfined compressive strength, n/C_i index and w/c index were determined. Variations of water content in the samples affected both water volume and porosity. Analysis of the results indicates that the optimum moisture content at which maximum unconfined compressive strength was obtained was close to the 10% value. As the moisture content increased or decreased, a decrease in the strength of the stabilized soil was observed. Table 4 shows the results of each sample.

Table 4. Tabular summary of research results

Sample no.	Cement	w	n/C_i	w/c	R_C	E_{50}
[-]	[%]	[%]	[-]	[-]	[MPa]	[MPa]
1	3	6.82	14.02	2.50	1.46	224.26
2	3	6.94	13.67	2.55	1.58	170.72
3	3	6.95	15.25	2.55	1.51	173.17
4	3	7.85	13.88	2.91	1.80	233.07
5	3	8.99	13.52	3.37	2.05	273.89
6	3	10.03	12.04	3.79	2.15	355.78
7	3	11.20	13.14	4.28	1.34	193.61
8	5	6.73	9.14	1.51	2.17	410.05
9	5	6.80	8.82	1.52	2.18	318.00
10	5	6.94	9.07	1.56	2.36	342.42
11	5	8.01	8.52	1.82	2.78	350.93
12	5	8.92	8.39	2.04	3.05	347.95
13	5	9.92	8.16	2.29	3.36	441.97
14	5	10.92	7.92	2.54	2.39	257.13
15	7	6.74	7.08	1.10	2.66	426.33
16	7	6.81	7.06	1.11	2.70	351.38
17	7	6.97	6.97	1.14	2.83	471.75
18	7	7.57	6.67	1.25	3.11	450.58
19	7	8.92	5.81	1.49	4.07	461.35
20	7	9.90	5.67	1.66	4.52	697.92
21	7	10.24	5.96	1.73	4.06	673.49

Analysis of the n/C_i and *w/c* indexes showed that a higher coefficient of determination of 0.84 was obtained for mixtures with variable moisture content when porosity and cement index were used in the correlation process. In comparison, the coefficient of determination for the w/c index was only 0.25. This phenomenon may be related to the specifics of the stabilized soil compaction process. The *w/c* ratio is usually used to determine the strength of materials such as stabilized soils used for deep soil improvement. The specific nature of such materials prevents them from being compacted similarly to surface stabilization. The main difference is the moisture content, which in the case of surface stabilization should be in the range of 90% to 105% of the optimum moisture content of the mixture, while in deep soil improvement, the optimum moisture content is not determined. The use of porosity and cement index to predict the unconfined compressive strength of surface stabilized soil seems a more appropriate approach than using the *w/c* ratio. Figure 2 presents the relationship between R_C and the *w/c* index, while figure 3 shows the relationship between R_C and the n/C_i index.

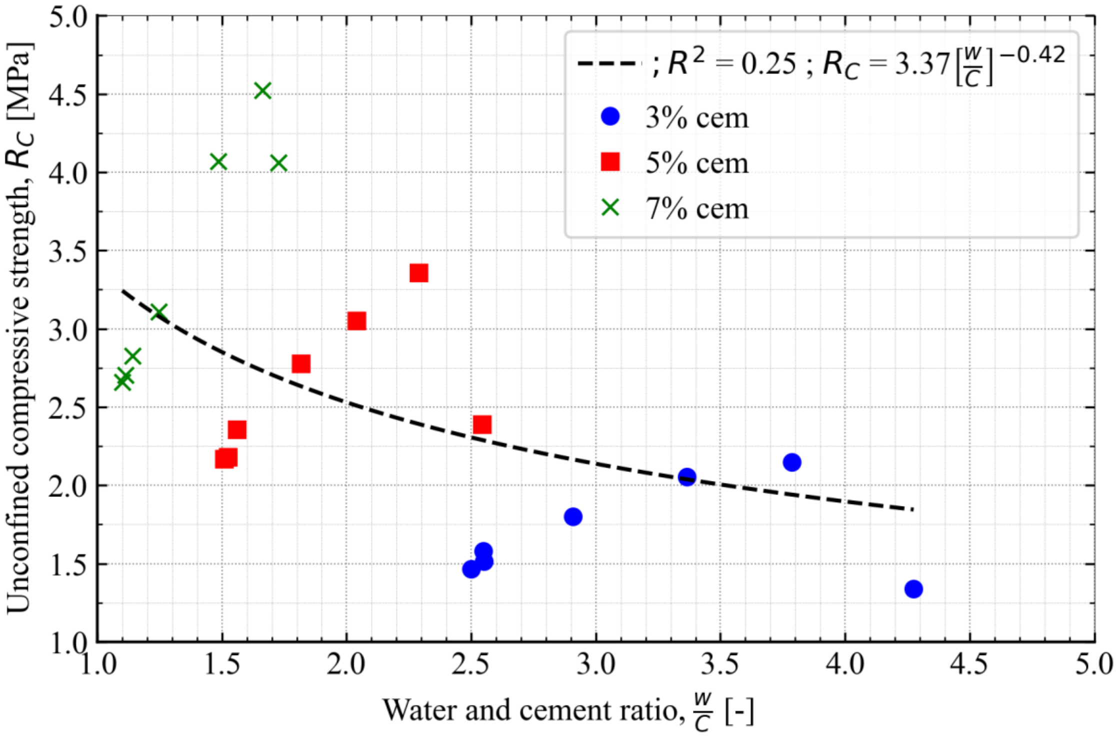

Figure 2. The relationship between R_C and the water/cement ratio.

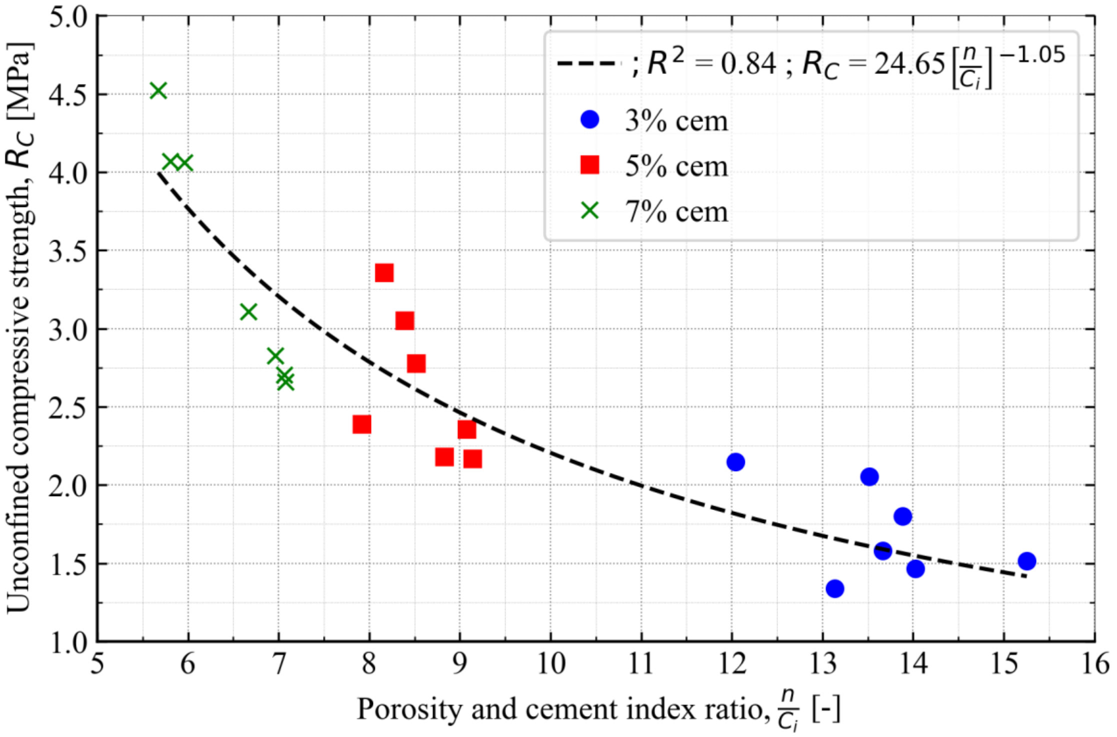

Figure 3. The relationship between R_C and the porosity/cement index ratio.

3.2. Calibration of the Selected Coefficient

In this subsection, a calibration of the relationship between R_C and the n/C_i index was carried out. For this purpose, the calibration parameter (*CP*), which is the exponent of the cement index, was used. Then, the empirical relationship was determined again, as described in equation 11.

$$R_C = \beta\left[\frac{n}{{C_i}^{CP}}\right]^{\alpha} \tag{11}$$

Where R_C refers to the unconfined compressive strength [MPa], β is the scaling coefficient, α is the coefficient exponent and CP is the calibration parameter.

As a result of the calibration, using a calibration parameter of 0.41, an increase in the coefficient of determination was achieved, reaching a value of 0.91 , as shown in Figure 4. The determined relationship demonstrated good accuracy, as confirmed by the statistical values: the root-mean-square deviation (RMSE) was 0.259 MPa, and the mean absolute percentage error (MAPE) was 8.88%. These results indicate a high level of model precision in predicting unconfined compressive strength, highlighting the effectiveness of the applied calibration parameter and analysis method.

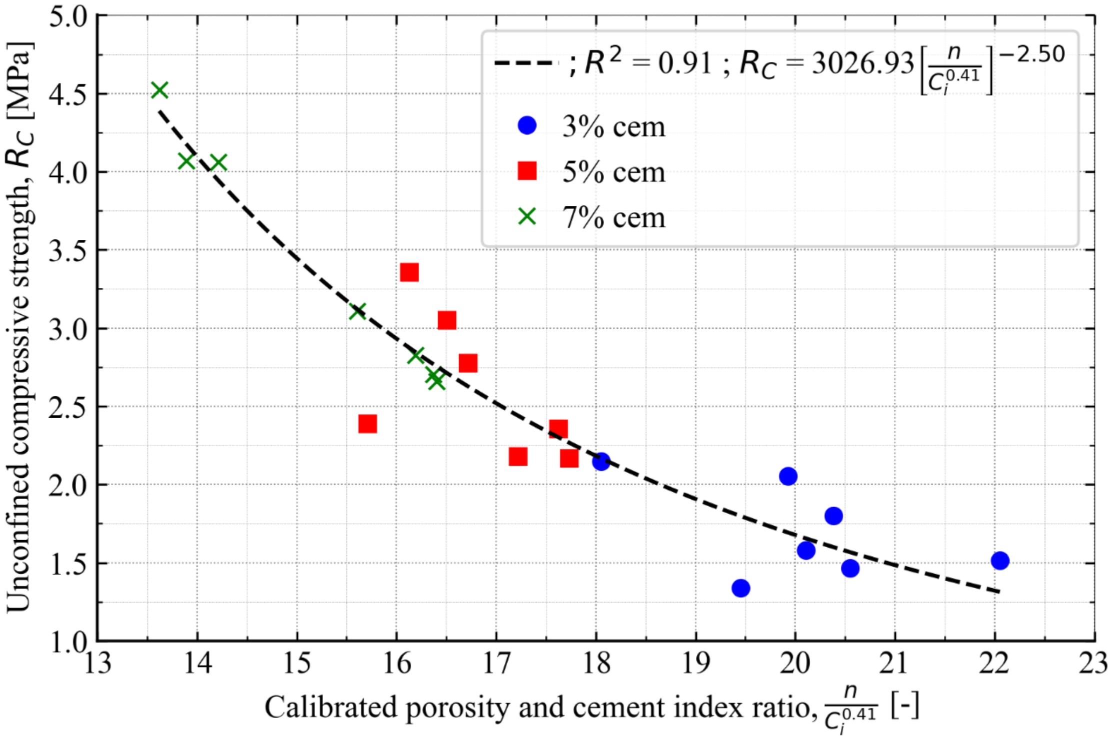

Figure 4. Calibrated relationship between R_C and ratio of porosity to cement index

3.3. Relationship between R_C and E_{50}

In addition to strength parameters, deformation parameters are also crucial for stabilized soils. In this study, the secant elastic modulus was determined at 50% of the failure stress. The moduli described by equation 2 were measured for all analyzed samples. This modulus is often correlated with the unconfined compressive strength of cement-stabilized soil, and a similar analysis was conducted in this study. The empirical relationship was characterized by a correlation with a coefficient of determination of 0.83. Furthermore, a statistical analysis was performed, which produced an RMSE of 57.89 MPa and a MAPE of 13.62%. These results confirm satisfactory model accuracy, indicating the potential practical applicability of the relationship in engineering practice. The results of this correlation are presented in figure 5. Table 4 summarizes the designated modules.

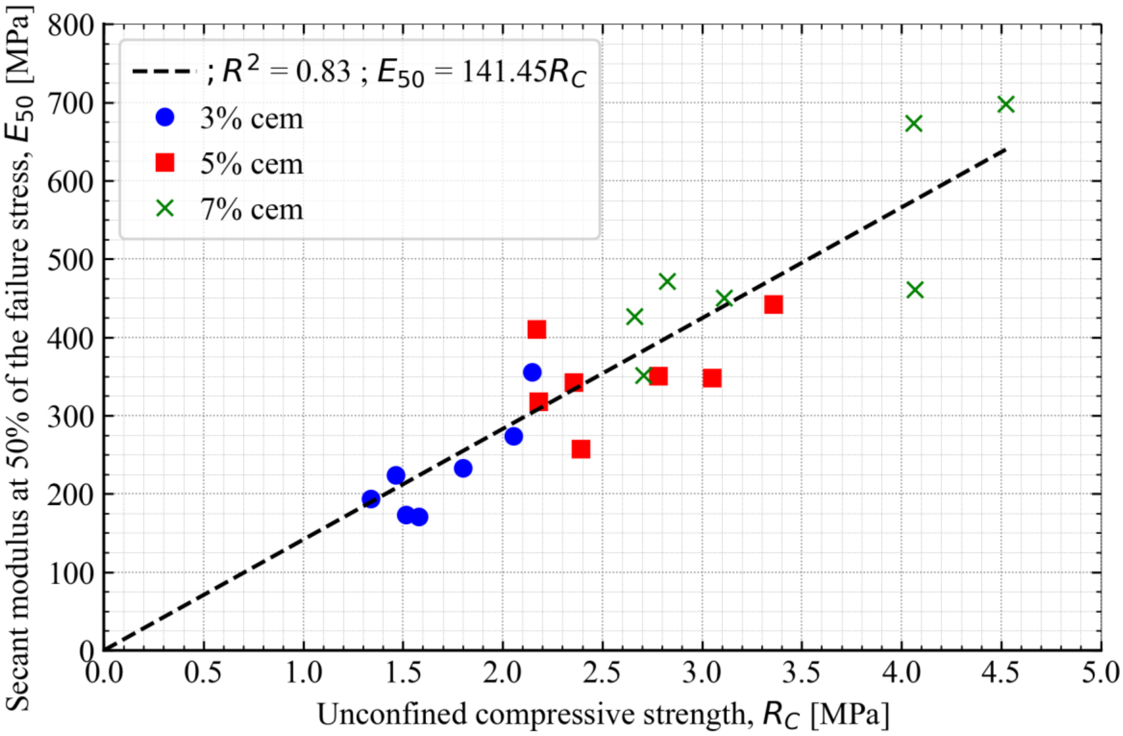

Figure 5. Relationship of R_C and E_{50} modulus

4. Conclusions

In this study, a detailed comparison was conducted between two indicators used in evaluating the properties of cement-stabilized soils: the traditional w/c ratio (water-to-cement ratio) and an indicator based on porosity and cement index. The analysis results clearly demonstrate that the n/C_i indicator exhibits greater effectiveness in predicting unconfined compressive strength compared to the classical *w/c* ratio. The alignment of these findings with the conclusions of other researchers reinforces their credibility [4, 5, 15]. However, in contrast to other authors, in the present study, a calibration of the n/C_i ratio obtained a higher calibration parameter of 0.41, while in the literature the often reported value of this parameter is 0.28. This discrepancy may be due to differences in the type of binder and soil used, which highlights their significant impact on the results of the experiments. In addition, analysis of the cement-stabilized soil mixtures showed that samples with a moisture content of about 10% achieved the highest compressive strength. This is about 1.5% higher than the optimum moisture content of soil (OMC), indicating an increase in the optimum moisture content of mixtures with cement content.

An analysis of the relationship between unconfined compressive strength and secant modulus of strain was also conducted. The results of this analysis showed a strong correlation between these parameters, which made it possible to develop an empirical equation. Statistical verification of the relationship confirmed its high accuracy and practical application, making it a valuable tool in the design and evaluation of cement-stabilized soils. Thus, the work provides important conclusions for engineering practice, highlighting the importance of selecting appropriate indicators to evaluate stabilized soil properties.

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