

Evaluation of strength characteristics of cement-stabilized soil using the electrical resistivity measurement

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Abstract. In this study, the compressive strength of cement stabilized soil was predicted using the electrical resistivity measurement. The effects of the water to cement (w/c) ratio and recovered Carbon Black (rCB) contents were examined. A series of electrical resistivity and compressive strength tests were conducted on two types of stabilized soil after 28 days of curing. Multiple nonlinear regression (MNL) analysis was used to evaluate the relationship between the compressive strength and the electrical resistivity in terms of the rCB, C_u (uniformity coefficient), and w/c ratio. The results showed that the w/c ratio and C_u have a strong influence on the compressive strength and electrical resistivity of the cement stabilized soil compared to the rCB content. The use of a small amount of rCB led to a decrease in the void space in the specimen and was attributed to the increase strength and decrease electrical resistivity. A high w/c ratio also induced a low electrical resistivity and compressive strength, whereas 3% rCB in the cemented soil provided the optimum strength for all w/c ratios. Finally, a prediction equation for the compressive strength using the electrical resistivity measurement was suggested based on its reliability, time effectiveness, non-destructiveness, and cost-effectiveness.

Keywords: cement stabilization; compressive strength; electrical resistivity; recovered carbon black

1. Introduction

Soil-cement stabilization is an efficient and economical method that has been commonly used to improve the mechanical and physical properties of soil and also to reduce the cost of construction (Consoli *et al.* 2009, Chew *et al.* 2004). Previous studies have investigated various influencing factors including the relative density, w/c ratio, curing time, curing condition, cement type, cement concentration, and fine particles for the mechanical and physical properties of cemented soil (Wei and Ku 2019, Haeri *et al.* 2006, Consoli *et al.* 2011, Moon *et al.* 2020).

Recently, numerous researchers have attempted to add various additive materials such as fly ash (Chenari *et al.* 2018), pulverized fuel ash (Motamedi *et al.* 2015), carbonate (Huang and Airey 1998), lime (Jaubertie *et al.* 2010), nano-silica (Zhou *et al.* 2020), fiber (Guta and Kumar 2016), rice husk ash (Choobbasti *et al.* 2010), slag (Mahedi *et al.* 2018), polymer (Ateş 2013), and zeolite (Salamatpoor *et al.* 2018) to improve the engineering properties of the cemented soil. Using these byproducts is also an effective solution to minimize pollution, waste and, consequently, the cost of disposal. Recovered Carbon Black

(rCB) is a recycled material manufactured from waste tires, which can also be used as an additive to enhance the engineering properties of soils (Deghanpour *et al.* 2019, Tugume *et al.* 2018, Chhun *et al.* 2020). A study by Dehghanpour *et al.* (2018) showed that the addition of recycled nano carbon black in the concrete induced a reduction in electrical resistivity and an increase of the flexural and compressive strength. The use of carbon black to decrease the quantity of crushed rock aggregates used in lateritic soils for a pavement base layer was also investigated by Tugume *et al.* (2018). It was found that the mixture consisted of 50% lateritic soil, 40% crushed rock aggregates, and 10% carbon black providing the best result in the maximum dry density and CBR value. Moreover, Chhun *et al.* (2020) showed that the use of rCB content provided a positive effect on the compressive strength of the cemented sand and the authors also suggested the prediction equation of the compressive strength with a function of rCB, curing time, and w/c ratio.

Previous studies reported that soil-cement stabilization with additive materials could improve the engineering properties of soil. However, evaluation of the quality of the stabilized soils is needed. Henceforth, to evaluate the quality in earthworks, the unconfined or triaxial compression test for disturbed (reconstituted or compacted) and undisturbed (coring) samples of the stabilized soil has been commonly used. The strength characteristics from these laboratory tests are accurate and efficient but costly, time-consuming, and destructive (Liu *et al.* 2008, Zhang *et al.* 2021). Consequently, in the interest of using a non-

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destructive test, ultrasonic pulse velocity (Biswal *et al.* 2020), time-domain reflectometry (Yu and Drnevich, 2004), electrical resistivity (Chen *et al.* 2011), ground-penetrating radar (Hu *et al.* 1991), impact hammer (Okamoto *et al.* 1991), and needle penetration (Dipova 2019) all have been tried to investigate the engineering properties of stabilized soils in the last few years. Among these testing methods, the electrical resistivity test is a useful testing method that has several benefits over the other testing methods due to its simple, reliable, fast, low cost, non-invasive, and non-destructive characteristics. However, the electrical resistivity of stabilized soils strongly depends on various factors such as particle shape, porosity, degree of saturation, soil ion content, mineral composition, orientation, unit weight, and pore water salinity (Vincent *et al.* 2017, Lee and Shang 2011). As in the numerous studies that have examined the relationship between the electrical resistivity and the compressive strength of stabilized soils (Chen *et al.* 2011, Liu *et al.* 2008, Zhang *et al.* 2014, Seladji *et al.* 2010, Cardoso 2017, Wei *et al.* 2012, Mochida *et al.* 2017), the above-mentioned factors also have an influence on the compressive strength of stabilized soils.

A previous study by Zhang *et al.* (2014) used the electrical resistivity measurement to investigate the effect of the salt concentration and cement content on cement-stabilized clay. They reported that the salt concentration slightly influenced the compressive strength and electrical resistivity compared to the cement content, and accordingly, the electrical resistivity could be used to evaluate the compressive strength. Seledji *et al.* (2010) investigated the effect of compaction on the electrical properties of soils and found that compaction strongly affected the electrical tortuosity of soils. As the soils became dense, it might lead to less tortuous pathways for the electrical current flow in the soil specimen, resulting in a decrease of the electrical resistivity. They concluded that the electrical resistivity could be used to assess the compaction density. Cardoso (2017) measured the electrical resistivity to investigate the effect of the water-to-cement ratio on the hydraulic properties of cemented sand. Moreover, the use of the electrical resistivity measurement to predict the compressive strength of cement was conducted by Wei *et al.* (2012). Chen *et al.* (2011) also used the electrical resistivity measurement to evaluate the cement hydration properties of soil stabilization with cement. Similarly, Mochida *et al.* (2017) used electrical resistivity testing to evaluate the strength of cemented soil in an embedded pile. However, only a few studies have investigated the electrical resistivity of cement-stabilized soil with rCB and assessed the strength characteristics of the soil-cement stabilization using the regression technique.

Thus, the main objective of this study was to evaluate the compressive strength of cement-stabilized soil with rCB as an additive using the electrical resistivity measurement. The effects of the rCB concentration and the w/c ratio on the electrical and mechanical properties of the cement-stabilized soils were investigated. The electrical resistivity and compressive strength tests were conducted on reconstituted specimens at the end of 28 days of curing. The relationship between the compressive strength and electrical

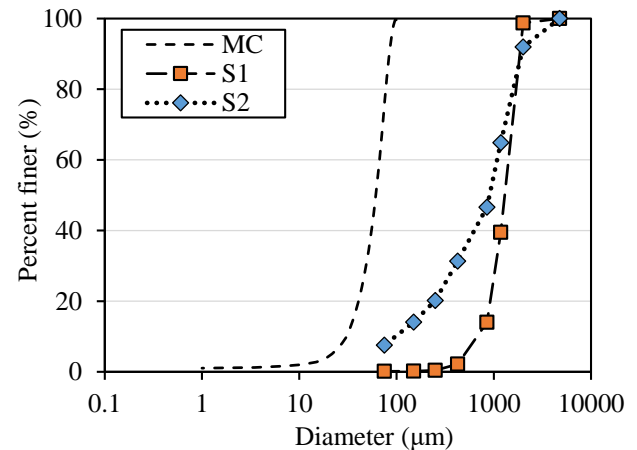


Fig. 1 Grain-size distribution of the sandy soil and MC

Table 1 Basic properties of the soil samples

Parameter	Value		Standard
	S1	S2	
Specific gravity	2.67	2.66	ASTM D854-14, (2017)
Sieve analysis	-	-	
D_{50}	1.05	0.91	
Gravel (%)	0.00	0.00	ASTM D421-85, (2007)
Sand (%)	99.87	92.54	
Fines (%)	0.13	7.55	
Soil classification	SP	SP-SC	ASTM D2487-11, (2011)
Unit weight	-	-	-
$\gamma_{d,max}$ (kN/m ³)	16.56	15.33	ASTM D4253-14, (2014)
$\gamma_{d,min}$ (kN/m ³)	13.57	13.09	ASTM D4254-14, (2014)

resistivity of the cement-stabilized soil was also discussed. Multiple nonlinear regression model was utilized to develop the prediction equation of the compressive strength of the cement-stabilized soil based on the experimental results.

2. Materials and methods

2.1 Materials used

In this study, two types of soil were used. The grain-size distribution and the basic properties of the testing soils are presented in Fig. 1 and Table 1. Here, S1 is a fine sand, and S2 is a weathered soil collected from Gangneung, South Korea. Based on the Unified Soil Classification System (USCS), the S1 and S2 were classified as poorly graded sand (SP) and poorly graded sand with silty clay (SP-SC), respectively. All experiments were conducted based on the standard of the American Society for Testing and Materials (ASTM). In this study, polycarboxylate (AP-50) was used as the superplasticizer to augment the dispersion of the MC and rCB particles. The properties of the superplasticizer are shown in Table 2. Microfine cement (MC) was used to stabilize the sandy soil. The grain-size distribution and the

Table 2 Properties of the superplasticizer

Parameters	Values
Appearance	Brown liquid
Solid Content (%)	50 ± 1
pH value	4 ± 2
Viscosity (cps)	1,000 Max.
Specific gravity	1.10 ± 0.04
Dosage % (20% base)	0.06 ~ 2.0

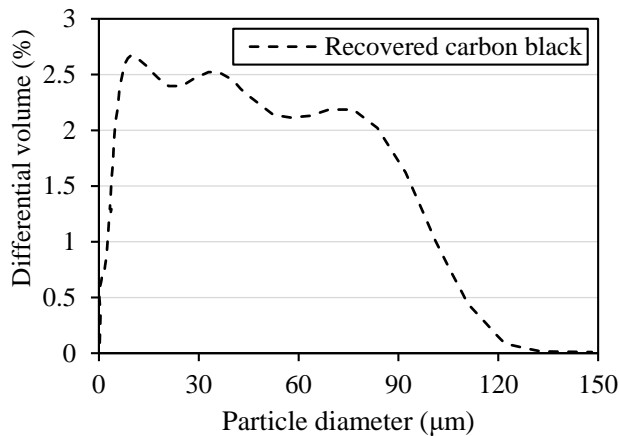


Fig. 2 Particle-size distribution of the rCB

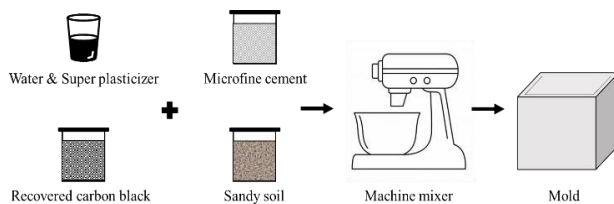


Fig. 3 Mixing procedure of the stabilized soil

chemical properties of the MC are also presented in Fig. 1 and Table 3, respectively. Recovered Carbon Black (rCB) with an average particle diameter of 25.27 µm was used. The grain size distribution is shown in Fig. 2.

2.2 Experimental methods

A full factorial test with 4×5 mixtures was conducted for both types of soil. For 40 various mixtures in total, three samples from each mixture were tested considering the three factors that effect the electrical and mechanical properties of the cement stabilized soil shown in Table 4. To reconstitute the stabilized soil, the predetermined ratio of dry soil sample (60% of relative density), MC, superplasticizer (1% of MC weight), rCB, and water were prepared as shown in Fig. 3. The water was first mixed with the superplasticizer for about 3 min, and then, the MC and rCB were poured into the mixture and stirred for 3 min. After that, the dry soil was poured and mixed for 3 min. The soil and cement mixture was poured into a mold and then compacted with a small mental tamp (300 g of weight) in three layers to reach homogeneity and a consistent initial

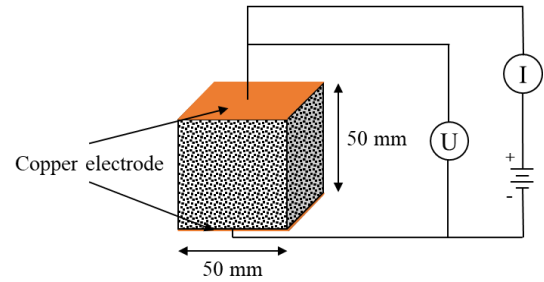


Fig. 4 Schematic diagram of the electrical resistivity test



Fig. 5 Electrical resistivity test set-up

Table 3 Chemical composition of the MC

Chemical composition (% by weight)	SiO ₂	Al ₂ O ₃ + Fe ₂ O ₃	CaO + MgO	Na ₂ O + K ₂ O	SO ₃
Microfine Cement	28.34	11.9	57.9	0.64	3.8

condition. All the cemented soil samples were then kept for hardening for about 24 hours. The stabilized specimen was demolded and cured in a constant temperature and humidity room with a temperature of 20±2 °C and a relative humidity higher than 95% until the end of the 28 curing days.

Figs. 4 and 5 present the schematic diagram and test set-up of the electrical resistivity test, according to ASTM G187-05, (2005). The testing apparatus of the electrical resistivity test consisted of a battery (12V, 18AH), copper electrodes, a specimen, and a digital multimeter (Fluke 18B+). To investigate the electrical resistivity of the stabilized specimen, two copper electrodes and filter papers saturated with saltwater were placed at the bottom and top of the stabilized soil sample, and a battery was also connected with the digital multimeter (Fig. 5). To ensure the full contact of the stabilized specimen and the copper electrode, a surcharge load of 1.57 kN/m² was applied on the top of the copper electrode, and then, the electrical voltage and electrical current were measured. Thus, the electrical resistivity of the stabilized specimen can be determined with following Eq. (1)

$$\rho = \frac{UA}{IL} \quad (1)$$



Fig. 6 Typical compression testing of a stabilized specimen

Table 4 Testing program

Independent variable	Case study	Level
w/c ratio	0.5, 0.75, 1, and 1.25	4
rCB content	0, 1, 3, 5, and 7	5
C_u	2.16 and 11.08	2

where ρ is the electrical resistivity ($\Omega \cdot m$); U is the electrical voltage applied to the specimen (V); A is the area of the specimen (m^2); I is the electrical current passing through the specimen (A), and L is the length of the specimen (m).

The stabilized soil specimens (50 mm cube) were reconstituted for the compressive strength test, according to ASTM C109/C109M 16a, (2016). As shown in Fig. 6, the stabilized specimen was compressed with a strain rate of 1 mm/min using a Universal Testing Machine (UTM) with a maximum capacity of 200 kN. The compressive strength in each mixture was calculated by the average of three samples.

2.3 Experimental methods

Multiple nonlinear regression (MNL) is a statistical technique for predicting the relationship between a dependent and one or more independent variables [43]. The general equation of the MNL model can be expressed by Eq. (2). As mentioned above, four design factors, the w/c ratio, rCB content, D_{50} , and electrical resistivity, were examined to develop the prediction equation of the compressive strength by the MNL method as shown in Eq. (3). The coefficient of determination (R^2), mean square error (MSE) and the root mean square error (RMSE) were used to evaluate the prediction equation. The value of R^2 generally ranges from 0 to 1, and the values close to 1 yield a higher accuracy of the prediction; inversely, lower values of the MSE and RMSE represent a higher accuracy of the prediction.

$$y = a + b_1x_i + b_2x_j + b_3x_i^2 + b_4x_j^2 + \dots + b_kx_ix_j \quad (2)$$

$$\sigma_p = f(rCB, w/c, C_u, \text{and } \rho) \quad (3)$$

Here, y is the dependent variable; a is the intercept; β is the coefficient of the regression; x is the independent

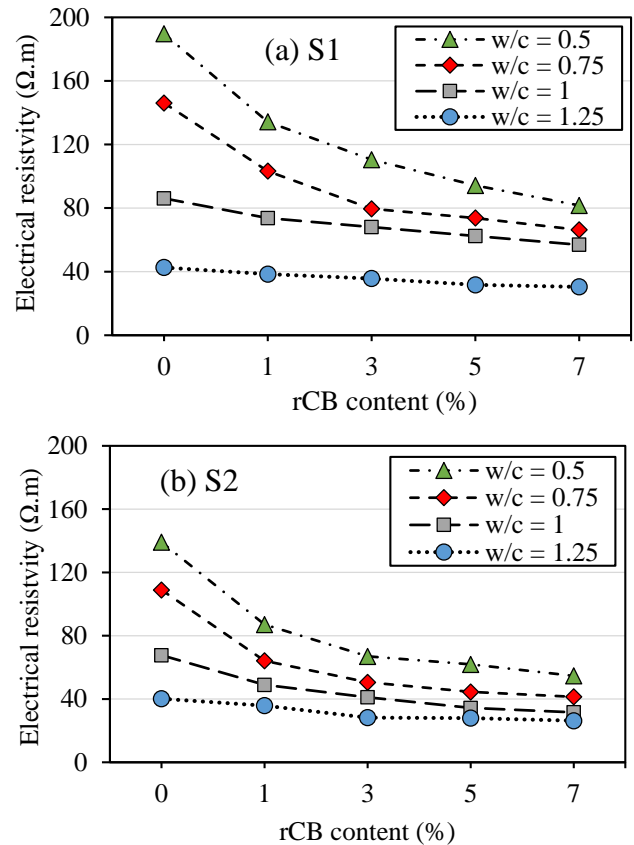


Fig. 7 Variation in the electrical resistivity with the rCB content: (a) Poorly graded sand (S1) and (b) Poorly graded sand with silty clay (S2)

variables; σ_p is the predicted strength of the stabilized soil; rCB is the recovered Carbon Black content; w/c is the water to cement ratio, C_u is the d uniformity coefficient, and ρ is the electrical resistivity.

3. Results and discussion

3.1 Electrical resistivity

Fig. 7 presents the average ρ result of the stabilized soils with different rCB concentrations, a curing time of 28 days, and four w/c ratios. From this, it was noted that the ρ of the cement-stabilized soil strongly depends on the amount of the rCB, the w/c ratio, and soil particle distribution. As the w/c ratio was decreased, the total amount of water and water in voids in the stabilized soil specimen also decreased. Therefore, the tortuosity of the electrical current path increased in the stabilized specimen which resulted in the increment of ρ . This increase also contributed to the hydration reactions being formed over time which also reduced the amount of water in the stabilized specimen. This result agrees well with the previous research by Mochida *et al.* (2017).

As the amount of rCB (0, 1, 3, 5, and 7% of the total MC weight) was increased, the pore space and the inter-particle spacing between the rCB particles decreased,

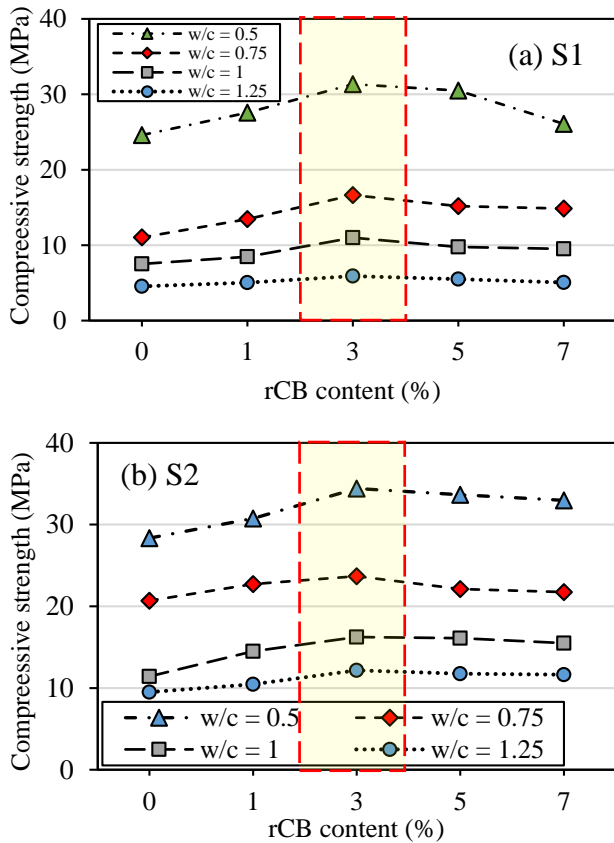


Fig. 8 Variation in compressive strength with the rCB content: (a) Poorly graded sand (S1) and (b) Poorly graded sand with silty clay (S2)

and more links to each other formed that were more conductive (Fig. 7). Thus, the rCB content enabled the current to pass through the specimen freely which caused a decrease in its ρ . This experimental result was consistent with the previous studies by Li *et al.* (2006), Al-Dahawi *et al.* (2016), and Lin *et al.* (2011). Irrespective of the w/c ratio and rCB content, it was noted that the ρ of the S2 sample was lower than S1. Due to the hydration process and further pozzolanic reaction of MC in the soil, with more fine particles in S2 which bonded to the between cement, sand, fine, and rCB particles matrix, it induced more linkages (the decrease of void ratio and conduct current in the cemented soil), thus reducing its ρ .

3.2 Compressive strength

For the same specimens with the electrical resistivity test, the compressive strength (σ) was evaluated. Fig. 8 shows the relationship between the σ for both sand and weathered soil in different rCB contents and w/c ratios. As can be seen in this figure, the σ of the S2 specimen was higher than that of S1. Similar to the mechanism in the electrical resistivity, the presence of fine particles that were bonded to the cemented soil matrix produced the increased strength in the cemented soil. As indicated in Fig. 8, the σ of the specimens containing different concentrations of rCB increases with the decrease in the w/c ratio. These results were caused by the decreasing amount of water in the

mixture, and the decreased water leads to high bonding stress between the soil particles (Azarsa and Gupta 2017, Wei and Ku 2020).

Unlike the electrical resistivity results, the σ of the cement-stabilized soil initially increased with the increasing rCB content and then decreased after the 3% rCB content for all w/c ratios. The increase of the σ (0 to 3% rCB) was due to the decrease in the void of the specimen by the rCB particles. It could also be contributed to the hydration reaction and adhesion between the soil particles and cement (Aderibigbe *et al.* 1985). For rCB contents higher than 3%, the σ , nevertheless, decreased. This decrease was due to the significant replacement of voids by rCB which yielded a more ductile behavior of the stabilized soil. This behavior was clearly shown in the stress-strain curve in a previous study by Chhun *et al.* (2020). Moreover, this result shows that the 3% rCB was an appropriate ratio to achieve the highest σ for both types of soils regardless of the w/c ratio.

As shown in Fig. 8, the σ of the stabilized soil containing rCB ranged from 4.55 to 34.42 MPa. At the optimum rCB concentration, the σ of the stabilized specimen S1 increased by about 1.87, 2.82, and 5.32 times for w/c ratios of 1, 0.75, and 0.5, respectively, compared to the case with a w/c ratio of 1.25 (Fig. 8(a)). Similarly, by comparing to the case with a w/c ratio of 1.25 for the S2 soil (Fig. 8(b)), the σ of the stabilized specimen increased, respectively, by about 1.28, 2.00, and 3.41 times for w/c ratios of 1, 0.75, and 0.5.

3.3 Prediction of the compressive strength

As shown in Fig. 9, a total of 40 data sets were used to develop the prediction equation of the compressive strength based on multiple nonlinear regression (MNLR) analysis. The w/c ratio, rCB content, C_u , and ρ were classified as independent variables while the σ was classified as the dependent variable. As a result of the MNLR analysis with a 95% confidence level, Eq. (4) was suggested to predict the compressive strength of the cement stabilized soil. Using this equation, the measured and predicted strengths were plotted as shown in Fig. 10. The R^2 , MSE, and RMSE values are about 0.937, 5.07, and 2.25, respectively, indicating a good correlation of the suggested model. Based on the result of the R^2 value, it means that 93.68% of the measured strength of the stabilized soil can be used for the prediction by using the explanatory variables.

$$\sigma_p = 0.001\rho^2 - 0.243\rho - 39.084w/c + 0.318C_u - 0.329rCB + 62.041 \quad (4)$$

Fig. 11 shows the percentage error between the measured and predicted strength as a function of the rCB content and w/c ratio. It can be observed that most of the data sets have an error lower than 20%. Only 8 points (20%) showed a slightly higher error than 20% which are due to the nonlinear increase of strength by the addition of the rCB concentration, the hydration reaction during the curing process, and the contribution of the w/c ratio. The variation in the cumulative frequency and the percentage error range are also presented in Fig. 12. This graph shows that most of the data have percentage errors ranging between 5 to 20%. It was also confirmed that 80% of the

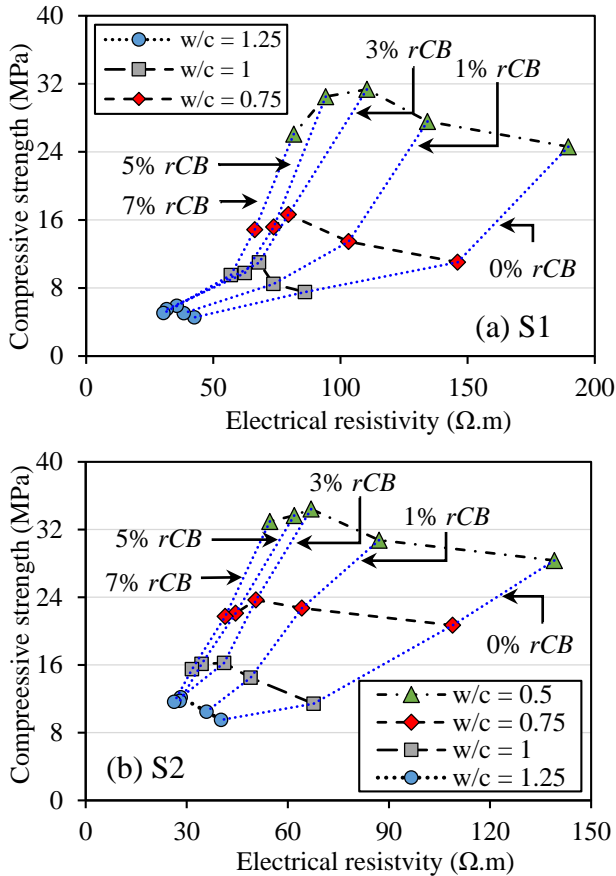


Fig. 9 Measured compressive strength with the electrical resistivity and *rCB* content

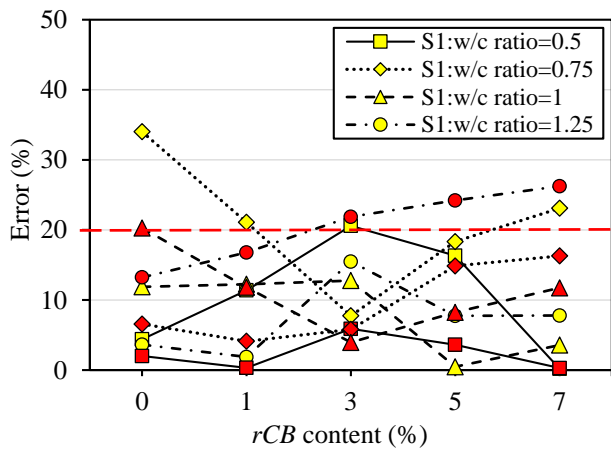


Fig. 10 Variation in the residual error by observation number

predicted strength had errors less than 20% compared to the measured strength. Thus, it can be concluded that the prediction equation from this analysis can be applied to estimate reliably the compressive strength of cemented soil with various *rCB* contents and *w/c* ratios.

Analysis of variance (ANOVA) was performed to investigate the interaction effect of all the independent variables and the dependent variable. The results of ANOVA are presented in Table 5. The *F*-value in the

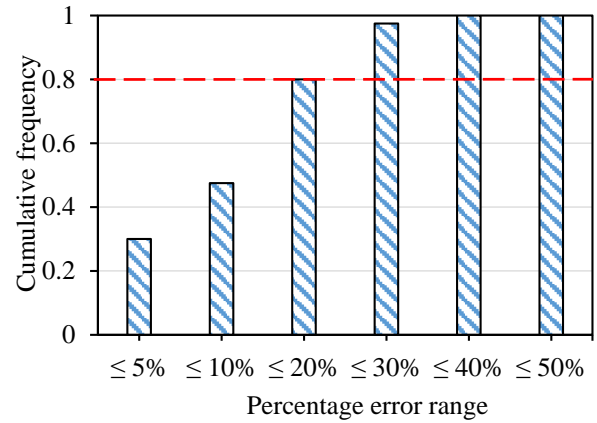


Fig. 11 Variation in the cumulative frequency by percentage error range

MNLR model is the ratio computed by dividing the mean square of regression by the mean square of residual. When using the *F*-test, the *P*-value for the null hypothesis can be rejected if the *P*-value is lower than a significant level ($\alpha=0.05$) corresponding to a 95% confidence level, whereas it cannot be rejected if the *P*-value is higher than α . Based on the analysis result, it can be noted that the *F*-value (100.86) is big enough to have a *P*-value (2.2E-19) smaller than the α which is only 2.2E-17% of the significant level of $\alpha (=0.05)$. By this result, the null hypothesis can be rejected which means that the prediction equation has a statistically significant relationship with the dependent variable and all the independent variables.

The interpretation of each coefficient (independent variable) in MNLR model was examined by the *P*-value for the null hypothesis of the *t*-statistic, and the results are summarized in Table 6. It is evident from Table 6 that the *P*-value of all the independent variables was found to be smaller than the significant level except for *rCB*; as a result, the null hypothesis can be rejected. The *P*-value of *rCB* is 0.2054 which implies that the probability that the noted *t*-statistic is 20.54% by chance. Thus, the null hypothesis cannot be rejected. In this analysis, it was found that the *w/c* ratio, C_u , and ρ had a significant role in this model, while the *rCB* content was not statistically significant. It is because the changing level of compressive strength by changing *rCB* is less than that by changing the *w/c* ratio and C_u , even though the effect of *rCB* on the compressive strength was clearly observed.

4. Conclusions

In this study, the use of the electrical resistivity measurement was examined to evaluate the strength characteristics of cement-stabilized soils. The effect of the *rCB* content and *w/c* ratio was then experimentally and statistically investigated for both sandy soils. The electrical resistivity and compressive strength tests were conducted for the stabilized soil after 28 days of curing. Irrespective of the *w/c* ratio and *rCB* content, it was observed that the S2 sample had higher strength and well-conducted electricity

Table 5 Result of ANOVA

-	Degree of freedom	Sum square	Mean square	F-value	P-value
Regression	4	1440.767	360.192	53.754	1.03E-08
Residual	15	100.511	6.701		
Total	19	1541.278			

Table 6 Result of the regression coefficients

-	Coefficients	Standard error	t-Statistic	P-value	95% confidence interval	
					Lower bound	Lower bound
Regression	62.041	7.631	8.130	1.76E-09	46.532	77.549
Intercept	-39.084	3.483	-11.222	5.62E-13	-46.161	-32.006
w/c	0.318	0.117	2.719	1.02E-02	0.080	0.556
rCB	-0.329	0.255	-1.291	2.05E-01	-0.846	0.189
ER	-0.243	0.077	-3.146	3.43E-03	-0.399	-0.086
ER ²	0.001	2.94E-04	2.724	1.01E-02	2.03E-04	0.001

compared to S1. This is due to the presence of a small amount of fine particles in the cement soil matrix generating a stronger bonded stress between the soil particles and well-conducted current. Similarly, the ρ value exponentially decreased by increasing the amount of rCB. However, the peak σ of the stabilized soil was achieved at an rCB content of 3% regardless of the w/c ratio. The ρ and σ decreased dramatically with the increasing w/c ratio due to the effect of the amount of water which induced a low bonding stress, and also, the tortuosity decreases for the electrical current path.

The suggested MNL model for predicting the compressive strength of the stabilized soil with the rCB content using the electrical resistivity measurement was highly correlated with the measured strength. Thus, the electrical resistivity measurement can be used for the quality control and monitoring of the cement-stabilized sandy soil with rCB because it is simple, non-destructive, and cost- and time-effective. However, the suggested MNL equation may be suitable only for sandy soil stabilization with a different rCB content and w/c ratio. Further studies, which use more parametric studies (curing time and different soil types) and take the field validation test into account, will need to be performed.

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