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Estimation of Unconfined Compressive Strength (UCS) for Soft Soil Stabilised with Cement Using Multiple Linear Regression Analysis

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Abstract

This paper presents the development of a precise linear regression model for predicting the unconfined compressive strength (UCS) of soft soil stabilised using cement, in terms of the main effective factors, such as cement content and curing period. The empirical UCS model was developed using a secondary dataset collected from previous studies, which included published data sources such as journals, technical papers, proceedings, and theses. Meanwhile, the multiple linear regression analysis was used to develop a UCS model. The results indicate a strong and significant relationship between cement content and curing period in predicting the UCS value. A reasonably good regression coefficient of $R^2 = 0.93$ has been obtained for the UCS model. The UCS model demonstrated significant accuracy with the fitted regression model, yielding a determination coefficient value of $R^2 = 0.97$ and a low mean square error (MSE) value of 0.068. The developed UCS model presents a good way to estimate the unconfined compressive strength for soft soil stabilised using cement, and it will be practical for a preliminary design of a project where there are cost and time limitations.

1. Introduction

Soft soils are predominantly composed of fine-grained portion particles such as clay and silt, have a moisture content of up to 85%, are close to the liquid limit, and have a shear strength of less than 25kPa [1], [2]. These fine-grained particles have a high surface area, which contributes to the soil's high water-holding capacity and plasticity [3], [4]. Most previous researchers classified soft soil as a challenging soil due to its specific characteristics that affect engineering properties, such as low strength, low bearing capacity, low permeability, weak bearing capacity, and high compressibility. All these characteristics pose significant challenges in construction projects and can result in ground movement, differential settlement, and potential structural damage [5]-[7]. Soft soils exhibit low shear strength, which limits their ability to resist deformation and support loads, and this can lead to bearing capacity failures and stability issues [8].

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It is essential to stabilise unstable soils for civil engineering applications to achieve the required soil engineering properties for construction. Therefore, soil stabilisation is the process of enhancing the engineering properties, characteristics, and performance of a soil, especially for construction purposes [9]. Soil stabilisation is used to increase soil strength and durability, enhance the CBR value, and reduce settlement due to applied loads [10], [11]. The UCS test results provide valuable information about the relative composition of the soil and are widely used in various geotechnical projects such as foundations, retaining walls, slopes and embankments. This helps to assess soil strength and determine viable construction techniques [12].

The use of cement provides a practical and effective means of achieving stability and enhancing the overall performance of the treated soft soil, especially increasing the compressive strength of the soil. The advantage of using cement is that it minimises frost expansion, increases thermal conductivity, enhances strength, freeze-thaw resistance, and reduces cracking or swelling, especially in road construction [13]. It is generally accepted that unconfined compressive strength (UCS) increases with increasing cement content and decreases with increasing mix water content under otherwise similar conditions [14].

Traditional empirical methods for predicting UCS for stabilised soft soil have limitations, as they often rely on a limited set of laboratory tests and fail to capture the complex relationships between soil properties and stabilising agents. To address these limitations, several techniques have emerged as promising tools for developing prediction models for stabilised soils [15]-[17]. Precise prediction for the UCS of soft soil stabilised with cement is of utmost importance for the design and construction of various geotechnical structures.

The primary objective of this study is to develop a reliable and accurate prediction UCS model to estimate the unconfined compressive strength value for soft soil stabilised with cement using the multiple linear regression method. The study comprehensively examines the influence of various factors that contribute to the UCS model, including cement content and curing period. The results from this study will contribute to the practice of geotechnical engineering by providing an accurate prediction to estimate the UCS for soft soil stabilised with cement. The developed UCS model enables efficient planning, cost efficiency and sustainability of geotechnical projects.

2. Methodology

This study comprises a collection of 51 major datasets, which include laboratory UCS test results of soft soil stabilised with cement under various curing period and cement content conditions, as shown in Table 1. A substantial amount of data was gathered from published sources, including books, journals, technical papers, proceedings, and theses, related to the topic of soft soil stabilised with cement. Before statistical analyses were performed, all data were planned and reorganised to ensure accuracy. The descriptive statistics were used to explain the properties of the dataset in an easily understandable format, as well as to provide quantitative evaluation criteria. A thorough overview of descriptive data, including mean, standard deviation, maximum, minimum, mode, skewness, and kurtosis.

The multiple linear regression (MLR) model is a statistical analysis used to model the relationship between a dependent variable and multiple independent variables. This MLR technique was employed in this study, along with the statistical validity condition, to develop a UCS model for estimating the compressive strength of soft soil stabilised with cement. According to Kumar et al. [26] and Khalid et al. [27], the MLR model technique is a linear regression model method in an approach to achieve the best linear correlation in predicting a dependent variable based on one or more independent variables [26], [27]. The prediction of the UCS model was thoroughly evaluated using various performance metrics, including mean squared error (MSE), coefficient of determination (R^2), and standard estimated error (SE). Therefore, the developed UCS model achieved a higher coefficient of regression (R^2) and a lower value of standard estimated error (SE). Meanwhile, a 95% confidence level (0.05) was chosen for hypothesis testing, and confidence intervals are commonly used to indicate the level of statistical significance. This confidence level yielded a significant P-value of 0.05, which implies a 5% risk of rejecting the null hypothesis when it is true. In other words, it represents the probability of making an error, which is the error of concluding that there is an effect or difference when in fact there is none [28].

The most promising independent parameters, such as Curing Period (CP) and Cement Content (C), were chosen and evaluated using the Pearson correlation analysis. This hypothesis relies on the Pearson correlation and the significance of the P-value between the variables. The closer the Pearson correlation coefficient value is to 1, the stronger the correlation between variables; a correlation of 0 indicates no relationship between the variables. Meanwhile, the P-value < 0.05 means the correlation is significant [29].

The efficacy and reliability of the UCS model were thoroughly validated using a new independent dataset of 29 items collected from secondary data, which were not used in the model's development. The new datasets were compiled from published data in journals, technical papers, proceedings, and theses. The relationship between the predicted developed models and the measured data was examined for model validation, and the plot shows the scatter points closely aligning between the predicted and measured values [30]. The performance and reliability of the developed UCS model were evaluated using three key metrics: coefficient of determination (R^2), mean square error (MSE), and T-test [28].

Table 1 *A dataset collected for UCS model development [18]-[25]*

No	Data Collected		
	CP (days)	*C* (%)	UCS (kPa)
1	1	1.0	177.26
2	1	3.0	552.54
3	1	5.0	742.38
4	3	1.0	214.79
5	3	3.0	649.67
6	3	5.0	892.49
7	7	1.0	39.65
8	7	1.0	247.90
9	7	2.0	71.95
10	7	3.0	396.19
11	7	3.0	731.35
12	7	3.0	797.00
13	7	5.0	860.04
14	7	5.0	967.55
15	7	5.0	1388.00
16	7	7.0	2067.00
17	7	8.0	1830.00
18	7	10.0	2800.00
19	7	12.0	3940.00
20	14	1.0	45.23
21	14	1.0	272.19
22	14	2.0	93.10
23	14	3.0	654.10
24	14	3.0	768.00
25	14	3.0	840.43
26	14	3.0	912.36
27	14	5.0	1082.34
28	14	5.0	1159.15
29	14	5.0	1592.60
30	14	5.0	1595.00
31	14	7.0	2100.00
32	14	7.5	2143.73
33	14	7.5	2345.75
34	14	8.0	2220.00
35	14	10.0	3252.87
36	14	10.0	3340.00
37	21	3.0	910.00
38	21	5.0	1676.00
39	21	7.0	2304.00
40	28	1.0	52.74
41	28	2.0	91.95
42	28	3.0	999.30
43	28	3.0	1070.00
44	28	3.0	1220.93
45	28	5.0	1808.00

No	Data Collected		
	CP (days)	*C* (%)	UCS (kPa)
46	28	5.0	2160.41
47	28	7.0	2400.00
48	28	7.5	3325.44
49	28	8.0	2380.00
50	28	10.0	4243.34
51	28	10.0	3750.00

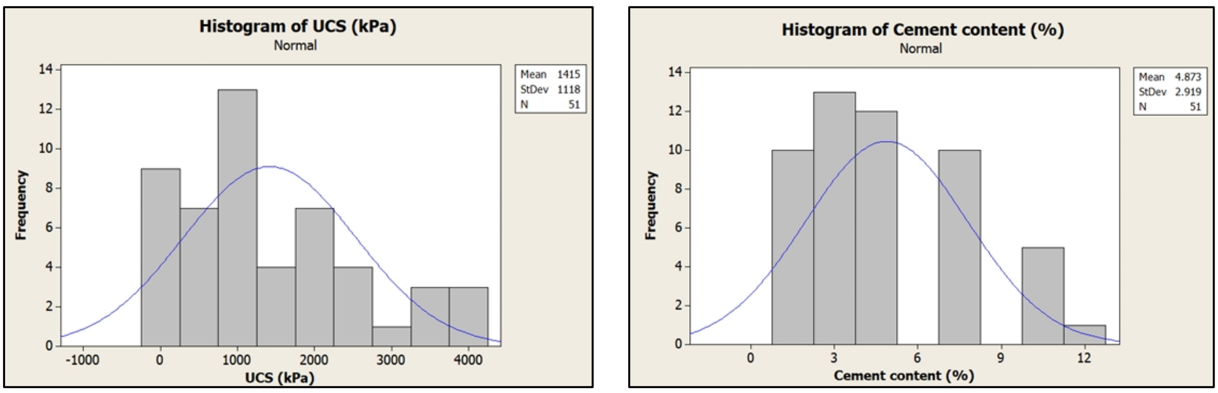
3. Results and Discussion

The formulation developed in this study for the UCS model is discussed in detail in this paper, in accordance with the statistical validity to predict the unconfined compressive strength (kPa) of soft soil stabilised using cement. Table 2 presents the triangulation correlation pattern results for the UCS prediction of soft soil stabilised with cement. It shows that there is a significant and strong correlation between independent parameters, such as Curing Period (CP) and Cement Content (C), that influence the Unconfined Compressive Strength (UCS). It can be seen that the Pearson correlation result is near 1 for the curing period and cement content, which are 0.350 and 0.946, respectively. The correlation result shows a strong and significant positive correlation between the curing period and cement content, with a P-value of ≤ 0.05. However, it was found that a very high correlation existed between the cement content and curing period in determining the UCS. This indicates that the cement content has a significant impact on the UCS value for soft soil stabilised with cement.

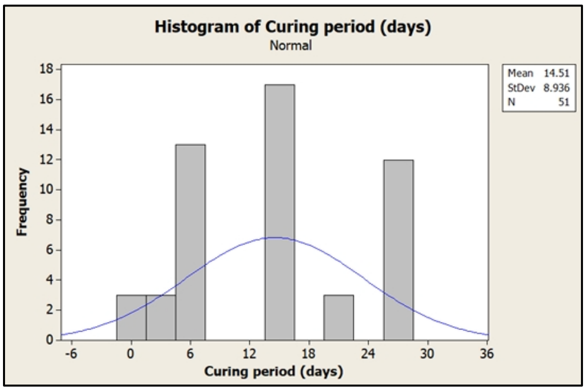
Table 2 *Correlation results between variables to predict the UCS*

	CP (days)	*C* (%)
C (%)	0.161 0.258	-
UCS (kPa)	0.350 0.012	0.946 0.000
Cell Content: Top: Pearson Correlation Bottom: P-Value		

Prior to developing the UCS model for soft soil stabilised with cement, the details of descriptive statistics results for the 51 datasets obtained were described in an easily understandable form, as shown in Table 3. It shows the data gathered for the curing period, cement content and UCS value were normally distributed as shown in the histogram result in Fig. 1. Although the data is normally distributed, there is a skewness in the data distribution as shown in the boxplot result in Fig. 2 for curing period, cement content and UCS value. However, it can be seen that the range of skewness and kurtosis was between -2 and 2, as shown in Table 3. George & Mallery [31] stated that any score for skewness and kurtosis in the range of -2 to 2 is accepted as meeting the normal distribution requirement [31].

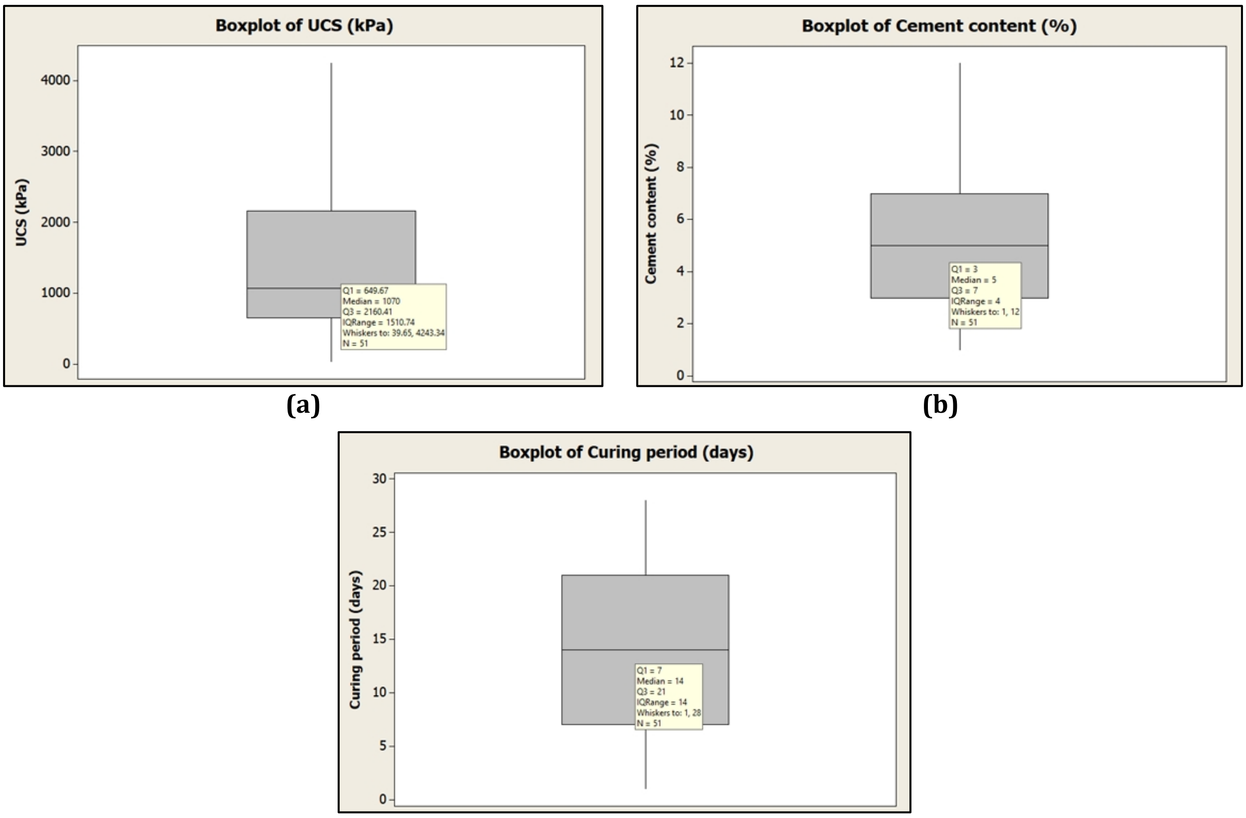


(a) **(b)**



(c)

Fig. 1 *Histogram result for (a) UCS value; (b) Cement content; and (C) Curing period*



(a) **(b)**

(c)

Fig. 2 *Boxplot result for (a) UCS value; (b) Cement content; and (C) Curing period*

Table 3 *Descriptive dataset results for developing a UCS model*

Variable	No. of Data	Mean	Std. Dev.	Min.	Max.	Skewness	Kurtosis
CP (days)	51	14.51	8.94	1.00	28.00	0.37	-1.08
C (%)	51	4.87	2.92	1.00	12.00	0.55	-0.55
UCS (kPa)	51	1415	1118	40	4243	0.80	-0.12

Considering the good relationships between cement content and curing period as independent variables to predict the UCS (kPa) as a dependent variable, a UCS model was finally developed, yielding a reasonably good regression (R^2 = 0.93), as shown in Eq. (1).

$$UCS\ (kPa) = -658 + 25.4CP + 350C \tag{1}$$

Table 4 presents the normality residual results for the developed UCS model for soft soil stabilisation with cement. The results from the Anderson-Darling test, Ryen-Joiner test, and Kolmogorov-Smirnov test indicate that the residual scores for all parameters and the UCS dataset were in normal distribution, simulated at the highest level of significance with P-value > 0.05 and no deviation data between the model sample and the residual sample in a systematic way.

Table 4 *The normality residual results for the UCS model*

Test	P-Value	SE	R^2 (%)
Anderson-Darling	0.463	-	-
Ryen-Joiner	> 0.10	-	-
Kolmogorov-Smirnov	> 0.15	-	-

Meanwhile, Table 5 shows the regression analysis results for the UCS model, and the results indicate a significant level of P-Value < 0.05 for all variables, with a coefficient of determination, R^2 is 93.5% and a lower SE value for each variable. It makes a strong relationship in such conditions, with a larger R-Squared value and a lower SE value, which supports the good prediction suggested for the UCS model.

Table 6 presents the results of the variance analysis, indicating that the available data are represented by the regression model created to predict the UCS value. Furthermore, the UCS model can be used with the main parameters, such as the cement content and the curing period. The unconfined compressive strength of soft soil stabilised by cement can be reliably predicted by the developed UCS model, as demonstrated by the result of a significance level of P-value < 0.05. It demonstrated that the curing period and cement content play an important role in the UCS value for soft soil stabilised with cement.

Table 5 *The regression analysis results for the UCS model*

Test	Coeff.	P-Value	SE	R^2 (%)
Constant	-658.0	0.00	0.121	
CP	25.4	0.00	0.046	93.5
C	350.0	0.00	0.051	

Table 6 *The analysis of variance results for the UCS model*

Test	P-Value	R^2 (%)
Regression	0.00	-

The descriptive results for the independent dataset used for validation of the UCS model testing are shown in Table 7. It shows that the independent dataset for validation testing was normally distributed, but skewed due to the range of skewness and kurtosis, which fell within the range of -2 to 2. For the validation test, the prediction UCS model was compared with the measured UCS data, and the results are shown in Table 8. In this validation model exercise, the developed UCS model has a high coefficient of determination (R^2 = 0.97) and a lower mean square error (MSE) value of 0.068. The higher coefficient of determination value and lower MSE value will provide higher accuracy for the developed UCS model. Meanwhile, the T-test result, which shows the significance of the P-value, is 0.896, which is greater than 0.05. This indicates that there is no significant difference in the mean between the UCS-predicted model and the UCS-measured model, given a P-value of 0.05 or greater.

Table 7 Descriptive statistic results for the independent dataset for model validation

Variable	No. of Data	Mean	Median	Std. Dev.	Min	Max	Skewness	Kurtosis
CP (days)	29	20.10	14.00	15.85	6.00	60.00	1.36	1.67
C (%)	29	6.17	6.00	3.07	0.00	11.00	-0.30	-0.95
UCS (kPa)	29	2003	2390	1083	227	3483	-0.26	-1.51

Table 8 *Validation results for the developed UCS model based on UCS-predicted versus UCS-measured*

Model	T-Test (P-Value)	MSE	R^2
UCS	0.896	0.068	0.97

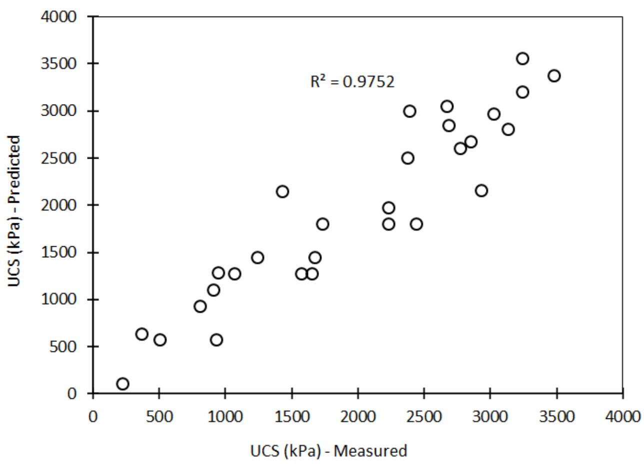


Fig. 3 *Comparison of fitted graph for UCS-predicted vs UCS-measured*

The precision of the model was verified by comparing the graph of data distribution between the UCS-predicted and UCS-measured values from the best-fit trend lines, as shown in Fig. 3. It is evident that the fitted plot is closely scattered between the data of UCS-predicted and UCS-measured values, with a high coefficient of determination of R^2 = 0.97. It shows the strong relations between the predicted values and the measured values. Therefore, the UCS model is a reliable method for estimating the compressive strength of soft soil stabilised using cement.

4. Conclusions

The developed UCS model is quite accurate and may be useful in predicting the compressive strength for soft soil stabilised with cement in the absence of laboratory data. It shows that the curing period and cement content are the effective factors for the UCS result. However, the cement content had the most significant effect on the UCS result compared to the curing period. The prediction of the developed UCS model exhibits a linear correlation between curing period and cement content, showing a convincing regression coefficient with R^2 = 0.93. Meanwhile, the measured and predicted values of the UCS model were found to be in satisfactory agreement with R^2 = 0.97 and MSE = 0.068. It is recommended that the proposed UCS model for soft soil stabilised with cement be practical for a preliminary design of a project with financial and time limitations.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Mazidah Mukri and Norazlan Khalid;* ***data collection:*** *Nur Hazwani Rosli and Zakiah Razak;* ***Analysis and interpretation of results:*** *Norazlan Khalid, Ismacahyadi Bagus Mohamed Jais, Nur Hazwani Rosli;* ***Draft manuscript preparation:*** *Mazidah Mukri and Norazlan Khalid. All authors reviewed the results and approved the final version of the manuscript.*

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Int. Journal of Integrated Engineering Vol. 18 No. 5 (2026) p. 21-29

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