Prediction of unconfined compressive strength of cement stabilized pavement materials

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Abstract. This paper evaluated and justified suitable prediction equations for unconfined compressive strength (UCS) of cement stabilized pavement materials. Equations by multiple linear regression analysis were also proposed. Data including pavement recycling base and subbase layers were collected from the Bureau of Material, Analysis, and Inspection, Department of Highways, Thailand. Multiple linear regression was conducted using the SPSS software. Three equations obtained from multiple linear regression and past researches were compared. Two criteria were considered in the selection of equations in order to check the accuracy and precision of each equation. First criterion was based on the predicted UCS vs. actual UCS graph. The slope and interception values of each graph were evaluated. Second criterion used two indices: ranking distance (RD) and ranking index (RI). For a good correlation, both these indices shall approach zero. By considering the statistical analysis outputs from the two criteria, a relationship between UCS and California Bearing Ratio – water cement ratio [CBR/ (w/c)] proposed by Sunitsakul in 2012 was justified as a suitable equation to predict the UCS of cement stabilized pavement materials. The study also confirmed that the relationship proposed by Sawangsuriya in 2016 for fine-grained soil with plasticity index was not appropriate for the prediction of UCS because the majority of the samples were non-plastic.

1. Introduction
Cement stabilization involves blending cement with the marginal material to increase its mechanical properties through chemical reactions [1]. An unconfined compressive strength (UCS) test is often adopted in practice to evaluate the strength of cement stabilized materials used in highway construction. Due to the time and construction constraints, many researchers proposed a number of prediction equations for the UCS. With the availability of prediction equations, it is a challenge for engineers and practitioners to select suitable equation for their highway construction practices. To predict the UCS of cement stabilized pavement materials prior to the testing, existing prediction equations must be evaluated and justified.

The objective of this study was to evaluate and justify suitable equations for predicting the UCS of cement stabilized pavement materials. Selection of the prediction equations for the statistical analysis was performed based on the available data in the proposed equations and the applicability of proposed equation for pavement materials. Such prediction equations will help engineers and practitioners to estimate the UCS of cement stabilized pavement materials for highway construction practices. This study was limited to cement stabilized pavement materials only.
2. Literature review

Process of soil stabilization helps improving the durability and strength of in situ soils [2]. Cement stabilized soil or soil cement layers are semi-rigid and exhibit increased bearing capacity and durability. Soil cement provides strong and uniform support for pavement layers as well as firm and stable working platform for pavement construction. Use of Portland cement as a stabilizing agent helps increasing the inter-particle friction within the soil mass while reducing the moisture susceptibility of existing in situ material [3]. Previous studies have shown that soil stabilization is an economical approach in strengthening the earth for construction requirements and in diminishing the amount of soil exchange [5]. Soil cement can improve engineering properties like the Unconfined Compressive Strength (UCS) of stabilized material. Hardened soil cement mixtures also resist adverse environmental effects while reducing plasticity index, increasing shrinkage limit, meeting strength thresholds, and improving resilient moduli [1].

Factors including cement content, parent soil mineralogy and gradation, construction practices, and curing method can affect the performance of cement stabilized soils [6]. Many factors including the physical and chemical properties of the soil, the amount of cement, the porosity, and the moisture content at the time of compaction affect the behavior of soil cement [7, 8]. Over the years, engineers have attempted different methods to stabilize soils that are subjected to fluctuations in strength and stiffness properties as a function of fluctuation in moisture content. The engineering properties vary widely due to heterogeneity in soil composition, difference in micro- and macro-structure of soils, heterogeneity of geologic deposits, as well as difference in physical and chemical interactions between the soil and candidate stabilizers [1].

When cement stabilized material is used as a compacted layer over a soil with a low bearing capacity, the system tends to fail under tensile stresses at the base of the improved layer [9]. Thus, it seems to be more reasonable to use tensile strength as a direct measure of cement stabilized material’s strength. However, research has shown that the tensile strength of soil-cement typically ranges between 9% and 14% of the UCS [7, 10-12]. Because of those reasons, the UCS has been adopted as the most convenient test for the determination of the soil-cement strength and for the investigation of the effect of different variables on the soil-cement strength [13].

The UCS of soil is the load per unit area at which an unconfined cylindrical specimen of soil will fail in the simple compression test. The strength and stiffness of cement stabilized pavement materials are often evaluated through UCS tests. Preparation and curing of the samples used for UCS testing should be carried out in accordance with ASTM D 1632 in which it is recommended to moist cure for soil cement stabilized material samples. Testing of the cured samples should be performed following ASTM D 1633 in which it is needed to immerse the samples in water for two hours prior to testing [3]. It has been used systematically in most experimental programs to verify the effectiveness of the cement stabilization or to access the importance of influencing factors on the strength of cemented soils [9].

Table 1 shows the recommended tolerance limits for soaked compressive strength specified by ACI [14].

| Soil Type          | AASHTO Classification | Soaked Compressive Strength (psi) |
|--------------------|-----------------------|----------------------------------|
| Sand and gravelly  | A-1, A-2, A-3         | 300-600 400-1000                 |
| Silty              | A-4, A-5              | 250-500 300-900                   |
| Clayey             | A-6, A-7              | 200-400 250-600                   |

Table 2 shows the UCS criteria recommended by U.S. Army [4]. The lowest cement content in the mixture design that meets the requirements should be used as the design cement content.
Table 2. Unconfined compressive strength criteria [4]

| Stabilized Layers          | Minimum 7-Day Unconfined Compressive Strength (psi) |
|----------------------------|---------------------------------------------------|
|                            | Flexible Pavement | Rigid Pavement |
| Base Course                | 750               | 500            |
| Subbase, select material or subgrade | 250               | 200            |

2.1. Prediction of unconfined compressive strength of cement stabilized pavement materials

Several equations were proposed by previous research to predict the UCS of cement stabilized pavement materials. The Equation 1 proposed by Sunitsakul in 2012 [15] involving water to cement (w/c) ratio, soaked California Bearing Ratio (CBR), and UCS at seven days of curing period of soil-cement is illustrated in Figure 1.

\[
UCS = 0.427 \left( \frac{CBR}{w/c} \right)^{0.578}
\]

where

- UCS Unconfined compressive strength at 7 days curing time (MPa)
- CBR Soaked CBR at 95 % of maximum dry density based on modified Proctor compaction and is measured at 0.1 inch penetration (%)
- w/c Water to cement ratio

Some aspects of cement content for stabilizing pavement materials were studied by Sawangsuriya in 2016 [16] as shown in Figure 2 along with the prediction Equations 2 and 3 for the UCS at seven days curing time for mixtures having varied cement contents. The coefficient of the proposed equations reflects the properties of the materials (e.g. gradation, plasticity index etc.)

\[
UCS = CBR(\frac{f}{c})^{-0.6}
\]

\[
UCS = 12 CBR(\frac{f}{c})^{-0.6}
\]

where

- UCS Unconfined compressive strength at 7 days curing time (ksc)
- CBR Soaked CBR at 95 percent of maximum dry density based on modified Proctor compaction and is measured at 0.1 inch penetration (%) 
- f Fine content by weight (%) 
- c Cement content by weight (%)
The performance of lateritic soil cement mixtures was investigated by Jaritngam et al. [17] through an experimental study. The experimental results in terms of UCS were increased significantly with the increasing cement content as shown in Figure 3. A multiple regression Equation 4 based on cement content (c), curing time (D), and dry density ($\gamma_{dry}$) were proposed to predict the UCS of lateritic soil-cement. Good correlations between the experimental data and the proposed prediction equation was observed as follows.

$$UCS = -108.468 + 7.607c + 0.674D + 47.656\gamma_{dry}$$

3. Methodology

3.1. Statistical analysis on selected prediction equation

Data required for this study was obtained from the Bureau of Material, Analysis, and Inspection, Department of Highways (DOH), Thailand. Most of the mixtures had no plasticity while 10 out of total 55 mixes had plasticity. Ordinary Portland cement had been used for the cement stabilization process. Cement content of the mixes varied from 2% through 7% with respect to the dry weight of soil. Data obtained from the DOH were unconfined compressive strength (ksc), cement content (%), gravel content (%), fine content (%), California Bearing Ratio (%), maximum dry density (gm/ml), optimum moisture content (%), liquid limit (%) and plasticity index (%). UCS prediction equations for cement stabilized pavement materials were selected based on availability of data and their applicability to pavement materials. Selected equations were evaluated to determine suitable prediction equations. The best results were obtained from the prediction equation having the highest value of correlation coefficient (R). A logical assessment of the validity of the above correlation was evaluated using two different indices: ranking distance (RD) [18] and ranking index (RI) [19].
\[ RD = \left\{ 1 - \bar{y} \left( \frac{\text{Predicted value}}{\text{Measured value}} \right) \right\}^2 + \sigma_y^2 \left( \frac{\text{Predicted value}}{\text{Measured value}} \right)^{0.5} \]  

\[ RI = \bar{y} \left| \ln \left( \frac{\text{Predicted value}}{\text{Measured value}} \right) \right| + \sigma_y \left| \ln \left( \frac{\text{Predicted value}}{\text{Measured value}} \right) \right| \]

where 
- RD: Ranking distance 
- RI: Ranking index 
- \( \bar{y} \): Mean value 
- \( \sigma_y \): Standard deviation

For a good correlation, both these indices shall approach zero. The \( \bar{y}, \sigma_y, RD, \) and RI of predicted to actual values of UCS should be satisfactory and acceptable, suggesting the validity of the proposed equation for estimation of UCS.

Multiple Linear Regression Analysis (MLRA) was used to develop regression equations for the prediction of UCS of cement stabilized pavement materials using the SPSS (Statistical Package for the Social Sciences) software. Regression models were developed and coefficients for each independent variable were obtained from MLRA.

4. Results and discussion
The unconfined compressive strength (UCS) was the dependent variable. Cement content (C), fine content (f), California Bearing Ratio (CBR), and maximum dry density (MDD) were the independent variables. Optimum moisture content (OMC) was excluded from the analysis as it failed to show a significant linear relationship (\( R^2 = 2.045 \times 10^{-8} \)) and a correlation (Pearson linear correlation coefficient = 0) with UCS. Cement content showed the strongest linear relationship (\( R^2 = 0.72 \)) and the highest correlation with UCS (Pearson linear correlation coefficient = 0.85).

Three prediction equations could be obtained from MLRA. As they have significant independent variables and higher \( R^2 \) values, they were statistically analyzed and then compared with Equations 1, (2), (3), and (4). Three equations obtained from multiple linear regressions can be presented as follows.

\[ UCS = 8.518 + 3.834c - 0.323f + 0.069CBR \]  

\[ UCS = -58.332 + 3.791c - 0.379f + 33.169 \times MDD \]

\[ UCS = -52.005 + 3.787c - 0.319f + 28.882 \times MDD + 0.048 \times CBR \]

where 
- UCS: Unconfined compressive strength (ksc) 
- C: Cement content (%) 
- f: Fine content (%) 
- CBR: California bearing ratio (%) 
- MDD: Maximum dry density (gm/ml)
Table 3. Summary of multiple linear regression analysis

| Equation | Independent Variables | R   | R²   | Significance |
|----------|-----------------------|-----|------|--------------|
| Eq. 3    | c                     | 0.91| 0.82 | 0.00         |
|          | f                     |     |      |              |
|          | CBR                   |     |      |              |
| Eq. 4    | c                     | 0.91| 0.83 | 0.00         |
|          | f                     |     |      |              |
|          | MDD                   |     |      |              |
| Eq. 5    | c                     | 0.92| 0.84 | 0.00         |
|          | F                     |     |      |              |
|          | MDD                   |     |      |              |
|          | CBR                   |     |      |              |

Figures 4 and 5 show the variation of dependent variable UCS with independent variable CBR/ (w/c) for Equations 1, 2 and 3 respectively. For each graph, the dash line indicate variation of UCS/CBR values predicted by the equation and the solid line indicates variation of actual UCS/CBR values with f/c. A best fit curve was fitted for each data set to compare predicted values and actual values. A detailed summary of graphs is given in Table 4.

Figure 4. Variation of UCS with CBR/ (w/c)

Figure 5. Variation of UCS/CBR with f/c for Equations 2 and 3
Table 4. Detailed summary of graphs

| Equation | Independent Variable/Variables | Dependent Variable | Proposed Fitting Parameters | Best Fitting Parameters |
|----------|--------------------------------|-------------------|----------------------------|-------------------------|
|          |                                |                   | Coefficient | Exponent | Coefficient | Exponent |
| (1)      | CBR/(w/c)                      | UCS               | 4.35        | 0.58     | 4.72        | 0.49     |
| (2)      | f/c                            | UCS/CBR           | 1           | -0.6     | 0.63        | -0.2     |
| (3)      | f/c                            | UCS/CBR           | 12          | -0.6     | 0.63        | -0.2     |

A common and simple approach to evaluate models is to regress predicted vs. actual values (or vice versa) and compare slope value and interception value against the 1:1 line [20]. Table 5 shows the summary of predicted UCS vs. actual UCS for Equations 1, 2 and 3 and equations proposed by this study (7), (8), and (9).

Table 5. Detailed summary of predicted UCS vs. actual UCS

| Equation | Slope Value of Predicted UCS vs. Actual UCS Plot | Intercept Value of Predicted UCS vs. Actual UCS Plot |
|----------|--------------------------------------------------|-----------------------------------------------------|
| (1)      | 0.99                                             | 5.29                                                |
| (2)      | 1.45                                             | -5.53                                               |
| (3)      | 17.38                                            | -66.31                                              |
| (7)      | 0.83                                             | 4.11                                                |
| (8)      | 0.84                                             | 3.98                                                |
| (9)      | 0.82                                             | 4.39                                                |

Equation 3 shows the highest deviation from slope value = 1 and interception value = 0 in the predicted UCS vs. actual UCS graph. The nearest slope value to slope value =1 is given by equation (1). It has the 4th highest interception value of 5.29. Equation 8 proposed by this study gives the lowest difference in interception value = 0 and interception value = 3.98. Calculated RD and RI values for each equation are given in Table 6.

Table 6. Average RD and RI values

| Equation | Ranking Distance (RD) | Ranking Index (RI) |
|----------|-----------------------|--------------------|
| (1)      | 0.3                   | 0.59               |
| (2)      | 0.43                  | 0.89               |
| (3)      | 40.75                 | 232.57             |
| (7)      | 0.1                   | 0.19               |
| (8)      | 0.09                  | 0.18               |
| (9)      | 0.09                  | 0.18               |

For the average RD and average RI values, the lowest average RI (RI = 0.18) and lowest value for RD (RD = 0.09) were given by Equations 8 and 9. It showed that there is no significant improvement in the prediction equations when the number of independent variables is increased from three to four. Equation 3 gives the highest average RD (RD ~ 40.8) and highest average RI (RI ~ 232.6) values. This is because Equation 3 is recommended for the use of fine-grained materials with plasticity index. Majority of the samples had no plasticity except for ten mixtures which was negligible (Figure 5). Therefore, it can be justified that Equation 3 was not suitable for the prediction of UCS of non-plastic or a material with no plasticity index (PI).
5. Conclusion

Three UCS prediction Equations 1, 2 and 3 suggested by previous research were selected based on the availability of data and applicability to pavement materials. They were analyzed to come up with a suitable UCS prediction equation. To check the accuracy and precision of each prediction equation, predicted UCS vs. actual UCS graphs were plotted. The slope value and interception value of each graph were considered to test the significance of slope value and intercept value. Two indices (e.g. ranking distance (RD) and ranking index (RI)) were obtained. For a good correlation, both these indices shall approach zero. The RD and RI of predicted to actual values of UCS should be satisfactory and acceptable, suggesting the validity of the proposed equation for estimation of UCS. Depending on the results of the analysis, it can be concluded that the relationship between UCS and CBR/ (w/c) proposed by Sunitarakul in 2012 [15], Equation 1 was a very good prediction equation for the prediction of UCS of cement stabilized pavement materials. Results also showed that the Optimum Moisture Content (OMC) does not have a linear relationship ($R^2 = 2.045E-8$) and no correlation (Pearson Linear Correlation Coefficient = 0). Cement content has the strongest linear relationship ($R^2 = 0.72$) and the highest correlation with UCS (Pearson Linear Correlation Coefficient = 0.85). Study confirmed that Equation 3 proposed by Sawangsuriya in 2016 [16] was not suitable for the prediction of UCS as the majority of the samples were non-plastic.

For further studies, additional material properties such as porosity, initial shear modulus, and curing days suggested by Consoli in 2011 [8], and Jaritngam in 2012 [17] can be taken into account. More test materials can also be investigated to validate prediction equations. Further soil types can be investigated for any possible correlations.

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