Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 55 No. 3 September 2024 ISSN 0046-5828

Analysis and Optimisation of Influencing Factors on the Performance of Cement Stabilised Marine Clay Using Response Surface Methodology

Rejin Raj P.[1], Vandana Sreedharan[2], and Abdul Nazar K. P.[3]
[1]*KTU Research Scholar, GCE Kannur, Kerala, India*
[2]*Professor, Department of Civil Engineering, GCE Kannur, Kerala, India*
[3]*Associate Professor, Department of Mechanical Engineering, GCE Kannur, Kerala, India*
E-mail: iamrejinraj@gmail.com

ABSTRACT: Cement stabilization is a go-to technique for improving the engineering characteristics of marine clays. As per the previous studies, numerous factors influence the effectiveness of cement stabilization. It is well established that the cement content, molding water, and curing periods are the major controlling factors. Due to the complex dynamics among such factors, there is a critical need to understand the interplay between these factors to achieve optimal performance in cement stabilization of marine clays. The paper adopts an analytical approach to quantify the impact of controlling factors using unconfined compressive strength (UCS) data. Design Expert 13 was employed for the experimental design and the response surface study. A central composite design (CCD) was adopted for the analysis, and the ranges of factors were fixed in accordance with the previous studies and the respective optimum moisture conditions. The ranges of cement content (CC), molding water content (MWC), and curing days (CD) were fixed as 5 to 15%,15 to 21%, and 0 to 14 days, respectively. The statistical analysis using ANOVA was used to arrive at a statistically significant quadratic model. A quadratic equation was generated depicting each factor's individual and interactive influence on the unconfined compressive strength of the cement-stabilized marine clay. The optimization results showed a maximum unconfined compressive strength value of 487.49 kPa for a cement content of 15%, curing days-14 days, and a molding water content of 19.67%. The study aids in understanding the extent of influence of binder content, molding, and curing conditions on the performance of cement-stabilized marine clay.

KEYWORDS: Response Surface Methodology, Cement Stabilization, Marine Clay, Marine Geotechnics, Soil Stabilization, and Clays.

1. INTRODUCTION

The growing need for construction on unsuitable land under challenging conditions the world over demands an imperative requirement for stabilization of all types of problematic soils (Chao, et al., 2006; Nelson et al., 2015). Marine clays are one such category that necessitates special attention. It is well understood that the inherent minerals and their water affinity determine the behaviour of fine-grained soils (Rao et al., 1990). The presence of chlorite and illite as the major minerals impart high sensitivity in marine clays due to the non-expanding lattice. The swelling and non-swelling clay minerals have a distinct influence on the behavior of the soil; investigations on Na-montmorillonite bentonite mixed with natural non-swelling Bangkok clay have substantiated the same (Por et al., 2015). Initial water content controls the physical and engineering behaviour of marine clays, and the presence of gibbsite and allophanes, organic matter, and cementing agents like iron oxides and carbonates cause irreversible changes to physical and strength characteristics on drying in marine clays (Sahib & Robinson, 2020). The susceptibility of engineering behavioural change according to its natural water content and the inherent soft nature of marine clay emphasizes the need for stabilization. There are numerous methods available for marine clay stabilization conventional methods like cement/lime stabilisations are well approved (see Table 1). The continued investigations on pozzolanic binder treatment of soft/ problematic soils have established the effectiveness of such binders. Using cement and fly ash on dredged sediments has produced improved strength and swelling behavior (Chompoorat et al., 2021; Chompoorat et al., 2021), thus enabling them to be used in road construction. The fly ash at different mixture ratios can act as a shrinkage-reducing agent for deep soil mixing purposes (Chompoorat et al., 2021; Chompoorat, 2022). Using lime yields a similar trend with dredged soils (Chompoorat et al., 2021). Despite the environmental concerns associated with cement stabilization, the cost-effectiveness and potency as a stabilizer make it one of the most widely used stabilization techniques compared to modern techniques. The soil type and the degree of stabilisation dictate the suitability of any binder. In the case of marine clay, the use of cement and lime is widespread, but the practice of using various waste materials as a binder is of recent interest (Attom and Al-Sharif, 1998; Zha et al., 2008; Basha et al., 2005; Baldovino et al., 2021). The Use of MICP (microbially induced calcite precipitation) is another promising technique in enhancing the strength characteristics of soft soils (Soyson et al., 2021; Punnoi et al., 2021), and reinforcement of techniques like soil bioengineering is also gaining the attention due to its sustainability an eco-friendly attribute (Phan et al., 2021; Phan et al., 2022).

Table 1 Relevant studies on cement stabilization of marine clays

Cement	Soil region / Type	Source
Ordinary Portland Cement (OPC)	Singapore Upper marine clay	(Xiao et al., 2014)
	Tokuyama marine clay	(Kang et al., 2017)
	Tokuyama Port clay	(Yamashita et al., 2020)
	Shanghai soft clay	(Khalid et al., 2018)
	Chennai	(Bushra and Robinson, 2012)
	Ennore coast	(Subramaniam and Banerjee, 2014)
	Lianyungang, China	(Liu et al., 2008)
	The Northern coast of Cyprus	(Ekinci et al., 2019)
	Kuttanad, India	(Bindu and Ramabhadran, 2011)

1.1 An Overview of Cement/Lime Stabilization of Marine Clay

Cement stabilisation has been in practice for centuries, and the use of cementitious materials for construction works dates to the ancient Egyptian Greek era. Cementitious materials historically were based on unsintered calcareous compounds combined with other siliceous materials. The initial development of soil-cement started in 1935, and the use of cementitious materials came to prominence in the 1960s (Makuza, 2013).

The introduction of cement into the soil-water system improves the mechanical behaviour of the soil at a macroscopic level. The physio-chemical changes at the microscopic level caused by the interaction between the cement and soil enable this change. The hydration reaction results in short-term strength gain. Calcium Silicate Hydrates (C-S-H) and Calcium Aluminate Silicate Hydrates (C-A-S-H) are two by-products of this reaction. A flocculated structure is formed due to the release of lime into the inter-particle voids; the secondary pozzolanic reaction between lime and clay minerals leads to the long-term strength of the soil-cement system (Bergado et al., 1996). The soil-cement characteristics are dependent on soil type, cement concentration, initial moisture, and compaction conditions (Moore et al., 1970).

If cured at a higher temperature, cement-stabilised soils are reported to attain a higher value for early-age and long-term strength (Zhang et al., 2014), indicating the influential role played by the curing conditions and duration in soft soil stabilization. The mechanism of cement stabilization is a complex phenomenon influenced by multiple parameters, affirming beyond doubt that the performance of cement-stabilised marine clays is significantly controlled by the interplay between various factors, and the relative importance of each of these factors needs to be understood extensively to arrive at an efficient and economic stabilisation. There is a dearth of systematic investigation in this direction, and therefore, a study with this objective is initiated.

2. MATERIALS AND METHODS

2.1 Materials

The soil was collected from the Cochin municipality near Marine Drive, Kerala, a southern state of India (10° 0' 0.1764" N, 76° 16' 24.258" E) at 22.36 m above MSL (Figure 1). The land uplifted by volcanic action was once covered by sea. The region has large deposits of marine clay extending up to a depth of 50 m. The soil samples were collected during piling operation at a depth of 10-20 m. The initial moisture condition was maintained while the soil samples were transported to the laboratory for testing. The geotechnical characteristics of the soil are presented in Table 2. The cement used for the study was slag cement, which was procured locally.

Table 2 Properties of the soil

Properties	
Colour	Blackish grey
Initial water content (%)	49.6
Liquid limit (%)	44.7
Plastic limit (%)	22.03
Shrinkage limit (%)	14.6
Soil Classification	CL
Specific gravity	2.72
Optimum Moisture Content (%)	18
Maximum dry density (g/cc)	1.6
Organic Content (%)	15.57
pH	5.85
Unconfined Compressive strength (kPa)	33.17
Gravel %	0.11
Sand %	34.28
Silt %	60.17
Clay %	5.44

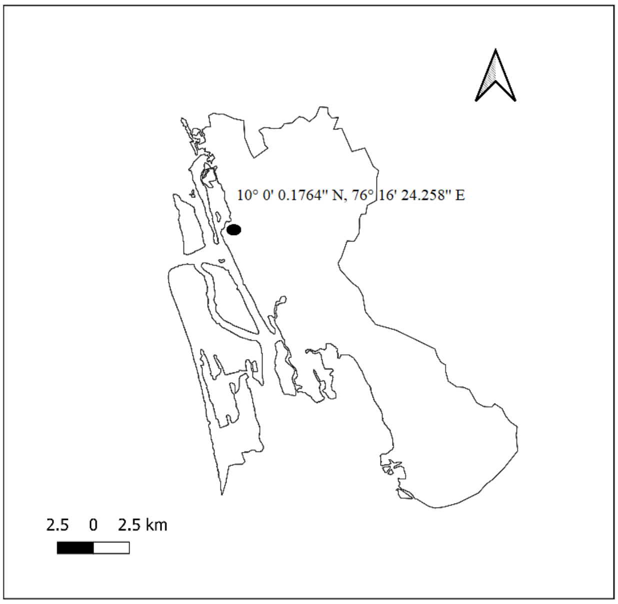

Figure 1 Site location

2.2 Sample Preparation and Experimental Procedure

The soil sample was oven-dried at 105°C. The experimental specimens were prepared with varying cement content from 5 to 15% by weight and varying moulding conditions. The specimens were cured for different periods of 7 and 14 days by maintaining the moisture content. The specimens sealed in polythene bags were stored in a desiccator during the curing period to ensure no moisture loss. The strength and deformation behaviour of the soil-cement mixtures were assessed by the unconfined compression test, carried out as per IS 2720 (Part 10):1991.

2.3 Design of Experiments

Design of experiments (DoE) is a tool to determine the relation between the input parameters and the response variable for any experimental system. It is an efficient and systematic approach that determines the allocation and method of experiments to suit the experimental objectives (Park, 2007). The design of experiments has been underappreciated by the geotechnical engineering community to date, whereas DoE can prove to be a potential tool that enhances the economic benefits of any stabilization process by reducing time and resources. The design of experiments significantly cut down the number of experimental runs to efficiently conduct the analysis in determining the interaction effect of the influencing factors. In the case of cement stabilization, the strength characteristics of the stabilised soil depend on multiple factors, which can be grouped as binder content curing and moulding conditions. To accurately establish an interplay between these factors, an investigator needs to conduct a large number of experiments. As the number of variables increases, it demands more number off experimental runs, which in turn may compromise the economy of the project. Therefore, a meticulous design of experiments (DoE) using standard methodologies is warranted to improve the overall experimental program.

The design of experiments has numerous techniques for arriving at optimal designs, including the one factor at a time method (OFAT), factorial designs, etc. One such strategy used in the design of experiments is the Response Surface Methodology (RSM). RSM is a collection of statistical and mathematical techniques beneficial for developing, refining, and optimizing the experimental inputs (Khuri & Mukhopadhyay, 2010). For optimization studies, RSM is effective. It includes statistical and numerical techniques for creating models and conducting optimisation studies (Adamu et al., 2021; Adamu et al., 2022; Iqbal et al., 2023). In addition, it helps establish the interaction between the affecting factors (Preece, 2007). The RSM basic steps are depicted in Figure 2 (Mahalik et al., 2010). Similarly, the use of RSM in soil stabilization studies is highly useful in optimizing the binder combinations and analysing the specific influential parameters on the degree of stabilization (Emmanuel et al., 2022; Olgun, 2013; Shahbazi et al., 2017).

In this study, RSM is effectively used to optimize the influential factors in the case of cement-stabilized marine clays by incorporating individual and interactive effects of influencing factors on the UCS of stabilized marine clay. The study will be beneficial for industries as most of them are relying on thumb rules to arrive at the optimum conditions, which is both time-consuming and expensive. A graphical abstract of the methodology is shown in Figure 3.

The response surface analysis was carried out using Design-Expert 13 (2021), released by Stat-Ease Inc, an open-source statistical software package.

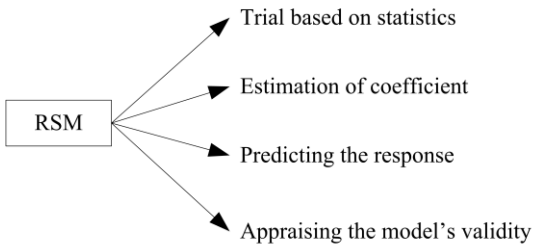

Figure 2 RSM basic steps

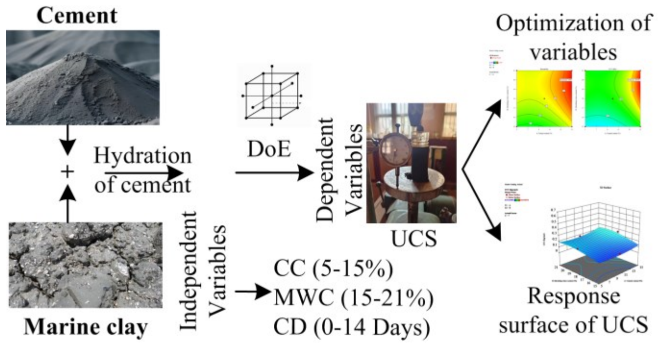

Figure 3 Outline of the study

2.4 Experimental Plan with RSM

The experiment was designed by employing a central composite design (CCD) as it has three groups of design points (Preece and Montgomery, 1978) minimum, maximum, and mean, i.e., the independent variable value will be its two extremities and their average. (Myers et al., 2009). This would be ideal for the response surface variable while complying with the assumptions of the analysis.

Two-level factorial or fractional factorial design points (2k), consisting of possible combinations of +1 and −1 levels of factor. $2k$ axial points (sometimes called star points) are fixed axially at a distance, say α, from the centre to generate quadratic terms. Centre points represent replicate terms; centre points provide a good and independent estimate of the experimental error.

2.5 Model Development

Even though several factors influence the cement stabilization of soil, cement content, curing days, and moulding water content is reported to be the most significant ones (Jan and Mir, 2018; Felt, 1955). Hence, these three factors were chosen as the input parameters for the proposed design of experiments. Twenty runs that included six central and axial points each and eight factorial points were obtained from the experimental design. The central point provides information on curvature in the build system, and axial points provide the details on pure quadratic terms (Myers and Montgomery, 2019). In a conventional study on stabilized marine clay where three influencing parameters are considered, a minimum of 27 experimental runs are necessary to incorporate all the combinations. However, in the case of CCD, experimental runs get reduced by 20 to arrive at the same level of inferences on the interplay of the influencing variables. The benefits are more pronounced when the interplay and interaction between a larger number of variables need to be studied on a stabilized clay system. Implementation of design and optimization is depicted in Figure 4.

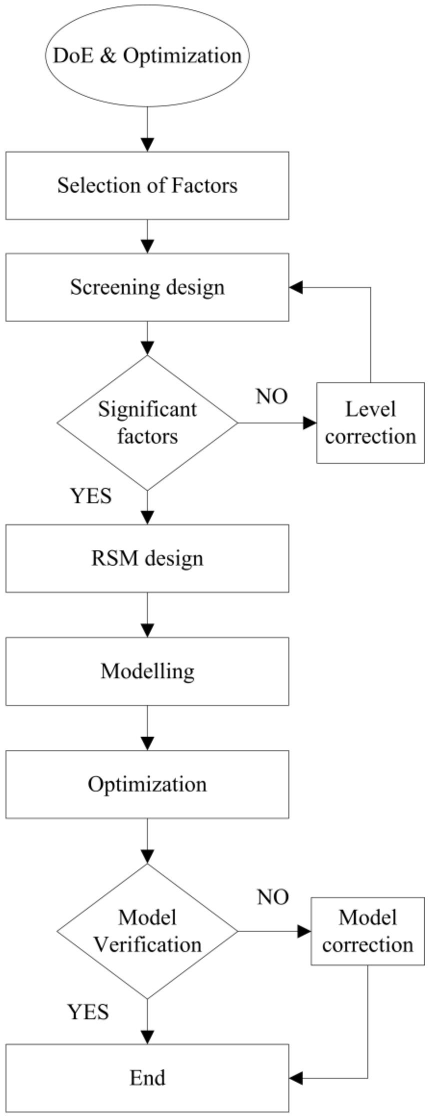

Figure 4 Flow chart for DoE & optimization implementation

The ranges for numerical (input) factors were chosen as cement content (5-15% by dry weight), moulding water content (15-21%), and curing days (0-14 days) based on preliminary studies. The UCS of the stabilized soil was taken as the response variable due to the similar parametric influence compared to those with other complex experimental setups. The ranges of independent variables are depicted in Table 3. For the data mentioned above the software package (Design Expert-13 by Stat-Ease Inc.) suggested a logarithmic transformation, which was carried out. With a standard confidence level of 95%, a quadratic model with the number of factors and levels equal to three was deployed to evaluate the response surface model. The backward elimination technique was carried out to create a formulation that would only consider statistically significant terms ($p \leq 0.05$) for effectively representing the relationship between the independent input variable and the response variable. The fitting of second-order polynomials is a strong suit of response surface methodology. Table 4 shows the results of the central composite design experiment and UCS values.

Table 3 Range of controlling factors used in the study

Factor		Units	Minimum	Maximum
A	Cement content	%	5	15
B	Moulding water content	%	15	21
C	Curing period	days	0	14

Table 4 Experimental design

Std.	Run	Factor 1, A: Cement content %	Factor 2, B:Moulding water content %	Factor 3 C: Curing days	Response: UCS (kPa)
4	1	5	15	0	54.67
7	2	15	18	7	191.56
15	3	10	18	7	110.50
20	4	5	15	14	169.03
16	5	10	18	14	305.21
19	6	15	15	14	242.48
18	7	10	18	7	110.50
8	8	10	18	7	110.50
9	9	15	21	14	487.49
3	10	15	15	0	53.95
2	11	5	21	14	242.36
17	12	10	15	7	83.07
5	13	5	21	0	98.94
14	14	10	21	7	130.96
10	15	10	18	7	110.50
11	16	10	18	7	110.50
1	17	10	18	0	84.67
12	18	5	18	7	149.29
6	19	15	21	0	95.96
13	20	10	18	7	110.50

2.6 Model Validation

The relation between independent input and response variables is established using multiple regression techniques. The regression equations are applied to generate the model to determine the relationship between the input and output variables. The model aids in understanding the relationship between the variables and the overall impact of such variables on the system. The experimental or the actual values will be validated with the generated model. The computation of R^2, Adjusted R^2, Predicted R^2, and good precision values are carried out, and their values depict the RSM model's validity. Table 5 shows the fit statistics. The R^2 value of 0.9737 shows a high correlation among factors in the design and also indicates the validation of the model generated.

Table 5 Fit statistics

Std. Deviation	0.1121	**R²**	0.9737
Mean	4.87	**Adjusted R²**	0.9583
Coefficient of variation %	2.3	**Predicted R²**	0.9075
		Adequate Precision	29.6198

2.7 Optimization

Optimization of independent variables through RSM consists of predictive model generation and coefficient determination using statistically designed experiments. Optimum quantities of independent variables (i.e., CC, MWC, CD) for the maximum unconfined compressive strength performance were done by the approach of desirability function (di) for the dependent variable (i.e., UCS). This method converts the dependent variable to an individual desirability function whose value ranges from 0 to 1. The value of 1 represents the most acceptable region, and the value of 0 represents rejection or target not achieved. Desirability function value 1 shows the statistical acceptance of the proposed optimum values for independent variables. Optimum values are selected based on the overall desirability (D). Equation 1 depicts the overall desirability represented as the geometrical mean of all individual desirability functions (Myers et al., 2009).

$$D = (d1.d2.d3...dn)^{(1/m)} \tag{1}$$

where, n is the number of response/dependent variables used in the optimisation study, in this study, the UCS is the only dependent variable, hence n = 1. So, magnitudes of overall desirability and individual desirability are equal.

For the optimization study, the software offers choices for the variables (Independent and dependent) like “in range,” “maximum,” “minimum,” and “target.” The optimization study for the independent variable was performed in range and dependent variables with “maximum” criteria.

Based on the range chosen already, an optimisation study was performed to predict the optimum amounts of CC, MWC, and CD to maximise the UCS performance. The optimisation results are shown in Table 6.

Table 6 Optimisation data

No.	Cement content (%)	Moulding water content (%)	Curing period (Days)	UCS (kPa)	Desirability
1	15.000	19.635	14.000	489.001	0.999
2	15.000	19.674	14.000	488.953	0.999
3	15.000	19.554	14.000	488.905	0.998
4	15.000	19.451	14.000	488.529	0.998
5	15.000	19.310	14.000	487.561	0.997
6	15.000	19.288	14.000	487.363	0.997
7	15.000	20.007	14.000	487.193	0.997
8	15.000	19.193	14.000	486.36	0.996
9	15.000	20.097	14.000	486.203	0.996
10	14.962	19.768	13.994	485.56	0.995
11	15.000	19.515	13.958	485.429	0.995
12	15.000	19.088	14.000	484.966	0.995
13	15.000	20.295	14.000	483.248	0.993
14	15.000	19.845	13.932	482.977	0.993
15	15.000	19.818	13.925	482.608	0.993
16	15.000	19.729	13.917	482.285	0.992
17	15.000	18.892	14.000	481.616	0.992
18	15.000	19.462	13.911	481.486	0.992
19	15.000	19.404	13.913	481.355	0.991
20	15.000	19.570	13.876	479.091	0.989

3. RESULTS AND ANALYSIS

3.1 Statistical Assessment of the Experimental Data

Using ANOVA, an effective statistical tool, the influence of the independent variables (CC, MWC, CD) on the response variable is studied. The individual effect and the interaction of independent variables on the response variable (UCS) were examined using ANOVA. A full-quadratic model assessed the significance of independent variables on the response variable with a confidence level of 95%. Insignificant variables and interactions ($p < 0.05$) are removed using a backward analysis of the model (AB, BC). ANOVA for the reduced quadratic model is shown in Table 7. Table 3 depicts the UCS values obtained via laboratory experiments using the experimental designs done by design expert software. The coded quadratic model Equation 2 was generated after the analysis. The regression analysis for the model is shown in Table 7. Equation 2 is a polynomial model and is critical in apprehending the relative impact of the factor by analysing the factor coefficients.

$$ln(ucs) = -5.15441 - 0.192415 * CC + 1.07186 * MWC - 0.000911 * CD + 0.003491 * CC * CD + 0.009507 * CC^2 - 0.027290 * MWC^2 + 0.003816 * CD^2 \quad (2)$$

Model F value is 63.38 (Table 7), which infers the significance of the model. The probability of the F-value this big due to noise is only 0.01%. By not considering the terms with p-value greater than 0.05, the noise reduction could improve the model.

The predicted value from the model vs. experimental results shown in Figure 5 shows a good statistical match, and Figure 6 shows the normal plot of residuals; the plot indicates whether the standard deviations between actual and predicted values follow a normal distribution. The residuals plotted against the predicted response show the constant variance assumption for the UCS values, as shown in Figure 7.

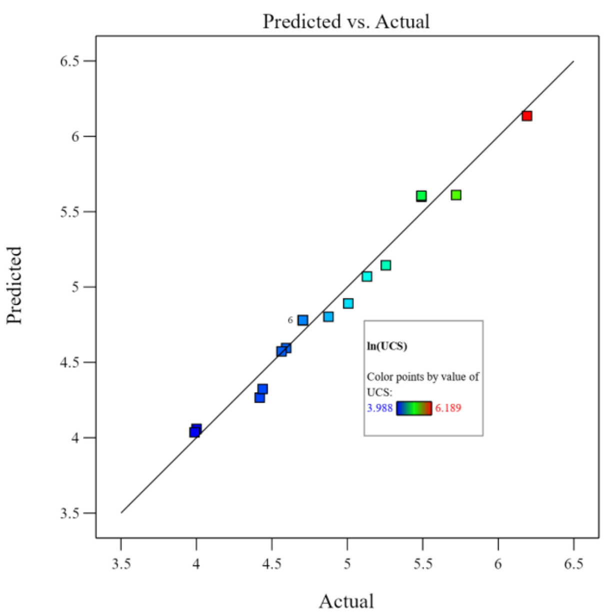

Figure 5 Predicted UCS vs Actual UCS

The fitness and significance of the RSM model are validated for R^2, Adj R^2, Pred R^2, and AP statistics, as shown in Table 5. The Predicted R^2 of 0.907 is in reasonable agreement with the Adjusted R^2 of 0.958 with a difference of less than 0.2. Adequate Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. The current ratio of 29.619 indicates an adequate signal, and the model can be used to navigate the design space as in the input factors interaction influences the response variable. The effect of the parameters on the relationship between the responses and the variable is visualized by the 3D surface in Figure 8.

Table 7 ANOVA RESULTS

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	5.57	7	0.7961	63.38	< 0.0001 (Significant)
A-Cement content	0.1601	1	0.1601	12.75	0.0039
B-Moulding water content	0.7198	1	0.7198	57.31	< 0.0001
C-Curing period	4.14	1	4.14	329.69	< 0.0001
AC	0.1522	1	0.1522	12.12	0.0045
A^2	0.1553	1	0.1553	12.37	0.0042
B^2	0.1659	1	0.1659	13.21	0.0034
C^2	0.0962	1	0.0962	7.66	0.0171
Residual	0.1507	12	0.0126		
Lack of Fit	0.1507	7	0.0215		
Pure Error	0	5	0		
Cor Total	5.72	19			

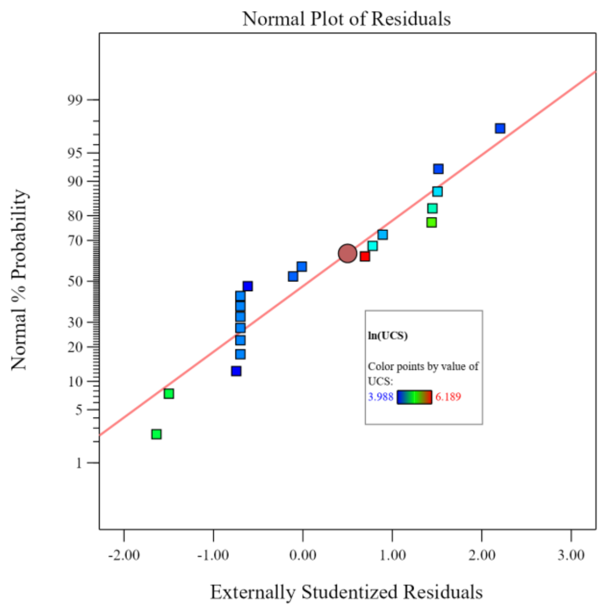

Figure 6 Normal plot of residuals

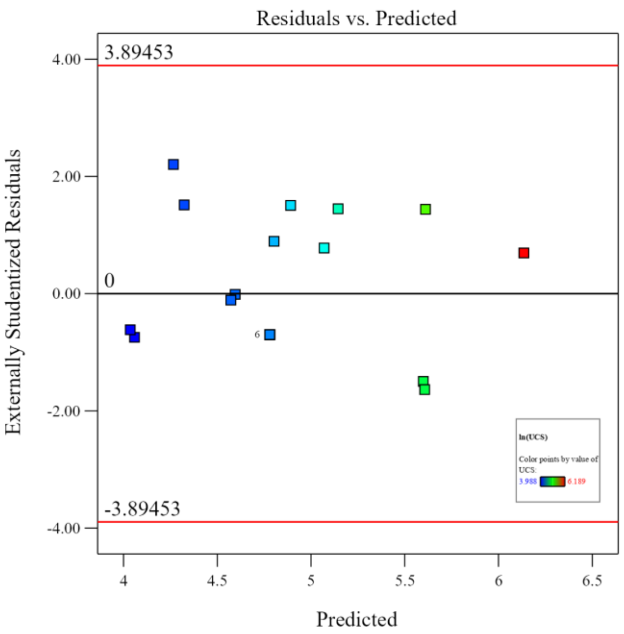

Figure 7 Residuals vs Predicted

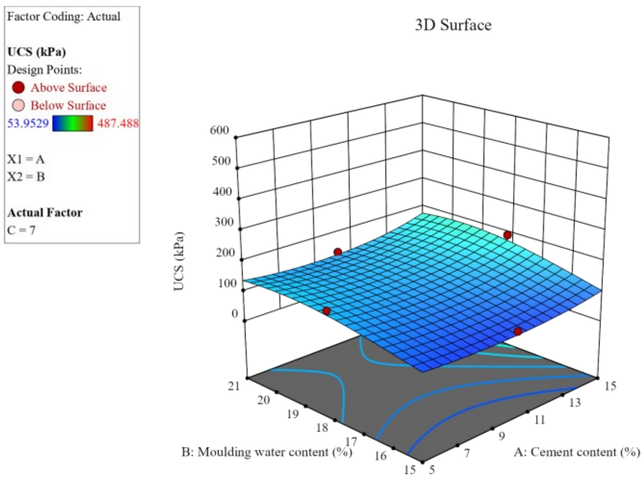

Figure 8 Response surface for UCS

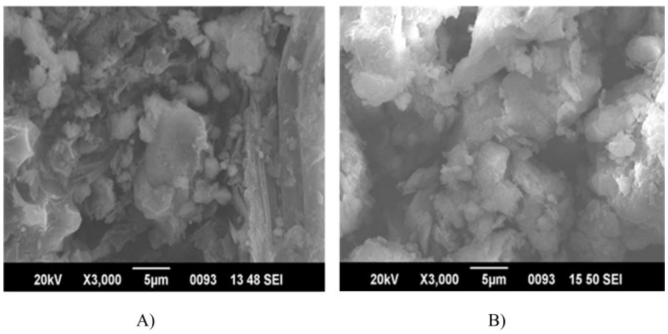

Figure 9 SEM marine clay (A) Untreated, (B) Treated

3.2 Effect of Cement Content, Curing Period, and Moulding Water Content on UCS

The unconfined compressive strength of cement treated marine clay increases with cement content irrespective of the moulding conditions. Hydration of cement resulting in the formation of Calcium Silicate Hydrates (C-S-H) and Calcium Aluminate Silicate Hydrates (C-AS-H) improves the strength characteristics of soil-cement system. Figure 9 shows the SEM images of untreated and treated marine clay, respectively, which brings out the binding and the change in the fabric. The cement treated marine clay indicates the formation of larger agglomerates of particles. These agglomerates appear denser and more compacted compared to the untreated clay. For a fixed cement content and molding condition, the UCS value of marine clay increases with the curing period. The curing period-strength data from Table 4 indicate a high strength increase rate with time as the hardening process of soil-cement is quick in the early stages of the hydration reaction. However, the long-term strength gain is by the pozzolanic action between SiO_2 and Al_2O_3 in the soil matrix and calcium hydroxide ($Ca(OH)_2$), which leads to further densification of the soil matric, as seen in Figure 9. The molding water enables the hydration reaction, which validates its influence on cement treatment of soil. The ANOVA results (Table 7) show a high influence of these parameters in the model generated, further establishing the influencing nature of Cement content, curing, and molding conditions.

3.3 Optimisation Results

The optimal quantities of dependent variables (CC, CD, MWC) in soil for maximizing the response variable (UCS value) were determined using the desirability function (d_i) approach. The value of d_i ranges from 0-1 converted from dependent variable x_i; when the variable values are within range, the d_i value is 1 and 0 when it is outside the expected range. The geometric mean, Equation 1, determines the total desirability.

For optimization, the ranges for dependent variables were selected the same as that of experimental conditions, as shown in Table 3, with a cement content of 5%, 10%, & 15%, molding water content of 15%, 18%, 21% and curing days from 0, 7, 14 days. Optimization runs are shown in Table 6. The dependent variables were kept 'in range', and the output variable was kept at 'maximum' as the software offered these options. From the software, the values for dependent variables corresponding to the maximum UCS value of 489.001 kPa were observed as cement content -15%, curing days-14 days, and molding water content 19.644%.

4. CONCLUSIONS

The study deploys RSM to establish the effect of influencing factors and their interplay on the strength characteristics of cement-stabilized marine clay. By analyzing the unconfined compressive strength (UCS) of cement stabilized marine clay, the influence of significant factors like cement content (CC), molding water content (MWC) and curing days (CD) was evaluated. A significant ($p \leq 0.05$) RSM quadratic model was developed with input variables CC (5 to 15%), MWC (15-21%), and CD (0-14 days). The quadratic model generated has been efficient in predicting the UCS value of cement-amended marine clay. Statistical significance of the input factors and their interaction was established using analysis of variance (ANOVA). ANOVA showed a higher significance value for the molding water content and curing period than for the cement content. The optimization study, maximizing the UCS value and keeping the input variables in range with RSM, yielded a maximum UCS value of 489.001 kPa with a cement content of 15%, a curing period of 14 days, and a molding water content of 19.644%. The laboratory experimental runs yielded the highest value for UCS as 487.488 kPa for a cement content of 15%, molding water content of 21%, and a curing period of 14 days which is comparable with the value obtained from the RSM model. The UCS values generated by the quadratic equation are very much comparable with the UCS values attained from experiments on marine clay systems within the same range of values for the influencing factors.

The optimization of binder in the stabilization of marine clays by conventional practice is time-consuming and uneconomical owing to the large number of experimental trials needed. This study has been instrumental in bringing out the use of the design of experiments as an effective tool to be utilized in suggesting the optimum conditions for cement stabilization of marine clay in terms of the amount of cement, molding water content, curing time, and compaction effort.

Therefore, the use of design of experiments in conjunction with RSM is proved to be appropriate in ensuring economic and efficient stabilization of marine clays, and this, in turn, can give better control in the stabilization process in the field. One major limitation on the application of RSM in soil stabilization can be cited as its inability to capture the dynamic nature of the soil cement system as soils exhibit extensive spatial temporal variations. Hence in future research, it is recommended to include more controlling variables such as clay content, organic content, and environmental and climatic factors while assessing the long-term strength gain of cement treated marine clays using this methodology.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge the APJ Abdul Kalam Technological University for the research opportunity provided as a part of the doctoral thesis.

6. REFERENCES

Adamu, Musa, Pattanawit Trabanpruek, Pitcha Jongvivatsakul, Suched Likitlersuang, and Mitsuyasu Iwanami. (2021). "Mechanical Performance and Optimization of High-Volume Fly Ash Concrete Containing Plastic Wastes and Graphene Nanoplatelets Using Response Surface Methodology." *Construction and Building Materials,* 308, 125085. https://doi.org/ 10.1016/j.conbuild mat.2021.125085.

Adamu, Musa, Pattanawit Trabanpruek, Varuj Limwibul, Pitcha Jongvivatsakul, Mitsuyasu Iwanami, and Suched Likitlersuang. (2022). "Compressive Behavior and Durability Performance of High-Volume Fly-Ash Concrete with Plastic Waste and Graphene Nanoplatelets by Using Response-Surface Methodology*." Journal of Materials in Civil Engineering*, 34, no. 9, 04022222. DOI: 10.1061/(ASCE)MT.1943-5533.0004377.

Arpajirakul, Soyson, Wiboonluk Pungrasmi, and Suched Likitlersuang. (2021). "Efficiency of Microbially-Induced Calcite Precipitation in Natural Clays for Ground Improvement." *Construction and Building Materials*, 282, 122722. https://doi.org/ 10.1016/j.conbuildmat.2021.122722.

Attom, M. F., and Al-Sharif, M. M. (1998). "Soil Stabilisation with Burned Olive Waste." *Applied Clay Science*, 13(3), 219-230 https://doi.org/10.1016/S0169-1317(98)00007-6.

Baldovino, J. J., Izzo, R. L., Rose, J. L., and Domingos, M. D. (2021). "Strength, Durability, and Microstructure of Geopolymers Based on Recycled-Glass Powder Waste and Dolomitic Lime for Soil Stabilisation." *Construction and Building Materials*, 271, 121874 https://doi.org/10.1016/j.conbuildmat.2020.121874.

Basha, E. A., Hashim, R., Mahmud, H. B., and Muntohar, A. S. (2005) "Stabilisation of Residual Soil with Rice Husk Ash and Cement." *Construction and Building Materials*, 19(6), 448-453 . https://doi.org/10.1016/j.conbuildmat.2004.08.001.

Bergado, D. T., Anderson, L. R., Miura, N., and Balasubramaniam, A. S. (1996). "Soft Ground Improvement in Lowland and Other Environments." *ASCE.*

Bindu, J., and Ramabhadran, A. (2011). "Study on Cement Stabilised Kuttanad Clay." In *Proc., Indian Geotechnical Conf,* 465-468.

Bushra, I., and Robinson, R. (2012). "Shear Strength Behavior of Cement Treated Marine Clay." *International Journal of Geotechnical Engineering*, *6*(4), 455-466. https://doi.org/10.33 28/IJGE.2012.06.04.455-465.

Chao, K. C., Overton, D. D., and Nelson, J. D. (2006). "Design and Installation of Deep Benchmarks in Expansive Soil." *Journal of Surveying Engineering, American Society of Civil Engineers*, 132(3), 124-131. https://doi.org/10.1061/(ASCE)0733-9453(2006) 132:3(124)

Chompoorat, T., Thepumong, T., Taesinlapachai, S. et al. (2021). "Repurposing of Stabilised Dredged Lakebed Sediment in Road Base Construction." *J. Soils Sediments,* 21, 2719–2730. https://doi.org/10.1007/s11368-021-02974-3.

Chompoorat, Thanakorn, Krisdha Thanawong, and Suched Likitlersuang. (2021). "Swell-Shrink Behaviour of Cement with Fly Ash-Stabilised Lakebed Sediment." *Bulletin of Engineering Geology and the Environment*. 80, 2617-2628. https://doi.org/10. 1007/s11368-021-02974-3.

Chompoorat, Thanakorn, Suched Likitlersuang, Suwijuck Sitthiawiruth, Veerayut Komolvilas, Pitthaya Jamsawang, and Pornkasem Jongpradist. (2021). "Mechanical Properties and Microstructures of Stabilised Dredged Expansive Soil from Coal Mine." *Geomechanics and Engineering,* 25, no. 2, 143-157. doi:10.12989/gae.2021.25.2.143.

Chompoorat, Thanakorn, Suched Likitlersuang, Thanakit Thepumong, Weeradetch Tanapalungkorn, Pitthaya Jamsawang, and Pornkasem Jongpradist. (2021) "Solidification of Sediments Deposited in Reservoirs with Cement and Fly Ash for Road Construction." *International Journal of Geosynthetics and Ground Engineering 7,* no. 4, 85. https://doi.org/10.1007/s40891-021-00328-0.

Chompoorat, Thanakorn, Thanakit Thepumong, Anupong Khamplod, and Suched Likitlersuang. (2022). "Improving Mechanical Properties and Shrinkage Cracking Characteristics of Soft Clay in Deep Soil Mixing." *Construction and Building Materials,* 316, 125858. https://doi.org/10.1016/j.conbuildmat. 2021.125858.

Ekinci, A., Ince, C., and Ferreira, P. M. V. (2019). "An Experimental Study on Compression and Shrinkage Behavior of Cement-Treated Marine Deposited Clays." *International Journal of Geosynthetics and Ground Engineering*, *5*(3), 1-17. https://doi.org/10.1007/ s40891-019-0172-z.

Felt, Earl, J. (1955). "Factors Influencing Physical Properties of Soil-Cement Mixtures." *Highway Research Board Bulletin,* 108.

Iqbal, Hafiz Waheed, Kantipok Hamcumpai, Peem Nuaklong, Pitcha Jongvivatsakul, Suched Likitlersuang, Chatpan Chintanapakdee, and Anil C. Wijeyewickrema. (2023). "Effect of Graphene Nanoplatelets on Engineering Properties of Fly Ash-Based Geopolymer Concrete Containing Crumb Rubber and its Optimization Using Response Surface Methodology." *Journal of Building Engineering*, 75, 107024. https://doi.org/10.1016/j. jobe.2023.107024.

Jan, Obaid Qadir, and Mir, B. A. (2018). "Strength Behaviour of Cement Stabilised Dredged Soil." *International Journal of Geosynthetics and Ground Engineering,* 4, 1-14 . https://doi.org/ 10.1007/s40891-018-0133-y.

Kang, G., Tsuchida, T., Tang, T. X., and Kalim, T. P. (2017). "Consistency Measurement of Cement-Treated Marine Clay Using Fall Cone Test and Casagrande Liquid Limit Test." *Soils and Foundations*, 57(5), 802-814. https://doi.org/10.1016/j.sandf.201 7.08.010.

Khalid, U., Liao, C. C., Ye, G. L., and Yadav, S. K. (2018). "Sustainable Improvement of Soft Marine Clay Using Low Cement Content: A Multi-Scale Experimental Investigation." *Construction and Building Materials*, 191, 469-480. https://doi.org/10.1016/j. conbuildmat.2018.10.034.

Liu, S. Y., Zhang, D. W., Liu, Z. B., and Deng, Y. F. (2008). "Assessment of Unconfined Compressive Strength of Cement Stabilised Marine Clay." *Marine Georesources and Geotechnology*, 26(1), 19-35. https://doi.org/10.1080/106411908 01937916.

Mahalik, K., Sahu, J. N., Patwardhan, A. V., and Meikap, B. C. (2010). "Statistical Modelling and Optimisation of Hydrolysis of Urea to Generate Ammonia for Flue Gas Conditioning." *Journal of Hazardous Materials*, 182(1-3), 603-610. https://doi.org/10.10 16/j.jhazmat.2010.06.075.

Makusa, G. P. (2013). "Soil Stabilisation Methods and Materials in Engineering Practice: State of the Art Review." urn:nbn:se: ltu:diva-24093

Moore, R. K., Kennedy, T. W., and Hudson, W. R. (1970). "Factors Affecting the Tensile Strength of Cement-Treated Materials." *Highway Research Record,* 315, 64-80 ISBN: 309-01814-5.

Myers, R. H., Montgomery, D. C., and Anderson-Cook, C. M. (2009). *Response Surface Methodology: Process and Product*

Optimisation Using Designed Experiments, 4th ed.; John Wiley Sons: Hoboken, NJ, USA, ISBN: 978-1-118-91601-8.

Nelson, J. D., Chao, K. C., Overton, D. D., and Nelson, E. J. (2015). "Foundation Engineering for Expansive Soils." *John Wiley & Sons, Inc.*, *New York, NY*. ISBN 0470581522.

Park, G. J. (2007). *Analytic Methods for Design Practice*. Springer Science & Business Media. ISBN:1846284724.

Phan, Trung Nghia, Anthony Kwan Leung, Viroon Kamchoom, and Suched Likitlersuang. (2023). "Reinforcement Losses in Soil Stabilisation due to Decomposing Roots of Chrysopogon Zizanioides and Chrysopogon Nemoralis." *Land Degradation & Development,* 34, no. 4, 1080-1096. DOI: 10.1002/ldr.4517.

Phan, Trung Nghia, Suched Likitlersuang, Viroon Kamchoom, and Anthony Kwan Leung. (2021). "Root Biomechanical Properties of Chrysopogon Zizanioides and Chrysopogon Nemoralis for Soil Reinforcement and Slope Stabilisation." *Land Degradation & Development,* 32, no. 16, 4624-4636. DOI: 10.1002/ldr.4063.

Por, S., Likitlersuang, S., & Nishimura, S. (2015). "Investigation of Shrinkage and Swelling Behaviour of Expansive/Non-Expansive Clay Mixtures." *Geotech. Eng. J. SEAGS-AGSSEA,* 46(1), 117-127.

Preece, D. A. (1978). "Design and Analysis of Experiments."

Preece, D. A.; Montgomery, D. C. (1978). "Design and Analysis of Experiments." *Int. Stat. Rev.,* 46, 120. ISBN:1119113474.

Punnoi, Benyapa, Soyson Arpajirakul, Wiboonluk Pungrasmi, Thanakorn Chompoorat, and Suched Likitlersuang. (2021). "Use of Microbially Induced Calcite Precipitation for Soil Improvement in Compacted Clays." *International Journal of Geosynthetics and Ground Engineering,* 7, no. 4, 86. https://doi.org/10.1007/s40891-021-00327-1.

Rao, Sudhakar M., Sridharan, A., & Chandrakaran, S. (1990). "Engineering Behavior of Uplifted Smectite-rich Cochin and Mangalore Marine Clays." *Marine Geotechnology,* 9(4), 243–259. https://doi.org/10.1080/10641199009388243.

Sahib, A. A., & Robinson, R. G. (2020). "Drying and Atterberg Limits of Cochin Marine Clay." *International Journal of Geotechnical Engineering,* 14(8), 986–993. https://doi.org/10.1080/19386362.2020.1711554.

Subramaniam, P., and Banerjee, S. (2014). "Factors Affecting Shear Modulus Degradation of Cement Treated Clay." *Soil Dynamics and Earthquake Engineering*, 65, 181-188. https://doi.org/10.1016/j.soildyn.2014.06.013.

Xiao, H., Lee, F. H., and Chin, K. G. (2014). "Yielding of Cement-Treated Marine Clay." *Soils and Foundations*, 54(3), 488-501. https://doi.org/10.1016/j.sandf.2014.04.021.

Yamashita, E., Cikmit, A. A., Tsuchida, T., and Hashimoto, R. (2020). "Strength Estimation of Cement-Treated Marine Clay with Wide Ranges of Sand and Initial Water Contents." *Soils and Foundations*, 60(5), 1065-1083. https://doi.org/10.1016/j.sandf.2020.05.002.

Zha, F., Liu, S., Du, Y., and Cui, K. (2008). "Behavior of Expansive Soils Stabilised with Fly Ash." *Natural Hazards*, 47(3), 509-523. https://doi.org/10.1007/s11069-008-9236-4.

Zhang, R. J., Lu, Y. T., Tan, T. S., Phoon, K. K., and Santoso, A. M. (2014). "Long-Term Effect of Curing Temperature on the Strength Behavior of Cement-Stabilised Clay." *Journal of Geotechnical and Geoenvironmental Engineering*, 140(8), 04014045. https://doi.org/10.1061/(asce)gt.1943-5606.0001144.

Zhou, N., Ouyang, S., Cheng, Q., and Ju, F. (2019). "Experimental Study on Mechanical Behavior of a New Backfilling Material: Cement-Treated Marine Clay." *Advances in Materials Science and Engineering*. https://doi.org/10.1155/2019/1261694.