

EVOLUTIONARY POLYNOMIAL REGRESSION FOR PREDICTING THE UNCONFINED COMPRESSIVE STRENGTH OF LIME-STABILIZED

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Abstract

Peat has a lack of strength, making it unsuitable for foundations or road construction. The results of 104 unconfined compressive strength (UCS) on peat stabilized with various lime percentages are presented in this article. The strength performance of peat soils stabilized with lime in soaked and unsoaked conditions was also evaluated. Evolutionary Polynomial Regression (EPR) models are constructed to predict the UCS values using the data obtained from the tests. After evaluating the various functions, the EPR model with a hyperbolic tangent function is the best model for predicting the UCS. The proposed EPR models may benefit practitioners when determining the optimal amount of stabilizers to utilize in soft-ground improvement projects. In this section, we show and expand on applying the suggested models to the design of soft ground mixing. Additionally, by applying the created relationships to a new instance, the comprehensiveness of the established relationships is shown, as is the practicality of the suggested relationships for usage during the preliminary design stage. The findings of this study have important implications for estimating the quantity of lime required in ground peat improvement work.

Keywords: Evolutionary Polynomial Regression; Ground Improvement; Lime; Peat Stabilized; Prediction Models; Unconfined Compressive Strength

Introduction

Around the globe, extremely organic soil covers more than 30 million hectares of tropical agricultural area, and peat soil accounts for around 4.5 percent of the total area (Moayedi and Nazir, 2018). In Malaysia, approximately three million hectares are covered with peat soil. Among these areas, Selangor has nearly 200,000 hectares of peat area, of which 63% covers the Sabak Bernam district. The peat layers of Sabak Bernam vary in depth from less than a meter to 20 m, depending on the area. Typically, peat is easily recognizable by its dark brown or blackish-brown color. It has physical

properties with organic content and high moisture levels as well as low density (Mamat *et al.*, 2019). Peat is produced from a mixture of organic matter such as plant and animal waste that decomposes and soil with high humidity. In other words, it is derived from chemically altered and fossilized vegetation. Peat is composed entirely of water and decomposed plant fragments with virtually no real strength in its natural state.

Peat is often one of the most challenging soils due to its poor shear strength, low specific gravity, and high-water content. It is also very compressible.

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In comparison to inorganic soils, peat has unique geotechnical properties. Due to peat soil's high compressibility, settlements excessively when structures are built on top, resulting in geotechnical instability issues, even when a load is applied. Numerous studies have examined the shear strength parameters of different peats (Kazemian *et al.*, 2011; Moayedi *et al.*, 2013; Latifi *et al.*, 2016). A large and growing body of literature has investigated the engineering properties of peat and found shear strengths in the range of 3 to 17kPa. Due to the fact that the shear strength of a soil is controlled not only by the material itself but also by the applied stress and configuration, there is no way to prevent variations. Fibers are introduced into the mix of peat, changing many conceptualizations of how peat behaves concerning strength and durability. In a preliminary study conducted by Huat, (2006), peat strength indicates some confusion over whether peat should be regarded as a frictional substance, similar to sand, or a cohesive material akin to clay. A shallow vertical effective pressure for consolidation is produced by the low unit weight and submergence of surficial peats, which is caused by the fact that they are encountered as submerged surficial deposits. Consequently, the peat associated with it has a high porosity and hydraulic conductivity equivalent to fine sand or silty sand. When exposed to shear force, the material should behave as drained like sand.

A number of researchers have emphasized that soil stabilization is an efficient method of increasing shear strength (Jha and Sivapullaiah, 2015; Arifuzzaman *et al.*, 2017; Mamat *et al.*, 2017; Choobbasti *et al.*, 2019). In this regard, it may significantly increase the strength of peat. However, owing to peat's high water content, stabilizing it is very challenging. Additionally, since peat is formed of disintegrated plant fragments, it has a lower pH, which means it can interact chemically and biologically with the passage of time and environmental conditions (Hernandez and Al Tabbaa, 2009). These disadvantages make peat soil deposits unsuitable for use in most civil engineering projects. Moreover, development on this land can lead to failure as its instability bears the load, increasing excessive settlement (Raftari *et al.*, 2014). Although some research has been performed on peat stabilization, a lack of information is available on peat soils' behavioral performance, especially in Malaysia, which is stabilized with additives such as lime and cement. As a result, the selection of additive materials for ground improvement is inherently quite selective. Recent developments in soil stabilization studies have led to a renewed interest in exploring the effects of soil mechanical behaviour in several aspects.

Asgari *et al.* (2015) found that the presence of cement and lime in soft soils could significantly increase the soil's unconfined compressive strength (UCS). Although Saadat and Bayat, (2019) used ANFIS to predict UCS for lime stabilizers, the resulting accuracy was 84%, and it could be improved by diversifying the use of other prediction models. However, a lack of studies in evaluating the UCS characteristics of peat stabilized with lime, especially in the accuracy of predictions. It should be noted, the UCS test is a measure for the soil strength samples and is used as a soil strength stabilization index as well as can be used for a design in civil engineering projects.

Traditionally, chemical stabilizers that use conventional binders have gained the belief of many researchers in studies in this field compared to non-conventional (Abdel-Salam, 2018; Hossain *et al.*, 2019). Lime is one of the chemical stabilizers with conventional binders that have been effectively employed as a competent stabilizer for peat soil to overcome the problems associated with such problematic soils (Moayedi and Nazir, 2018). Furthermore, lime has a vital pozzolanic reaction element and characteristics (Jha and Sivapullaiah, 2020; Oluwatuyi *et al.*, 2020). Nonetheless, performing several tests to determine an appropriate stabilizing pattern requires considerable time consumption at an expensive cost. Thus, reliable predictive models would considerably aid in soil stabilization and engineering structure design. This paper uses evolutionary polynomial regression (EPR) as a cost-effective predictive method, and novel models for predicting the UCS of stabilized samples are provided. The UCS was performed using peat samples from Sabak Bernam, Malaysia, in soaked and unsoaked conditions with 25 blows to collect a database for EPR modeling. Lime is employed as a stabilizer agent in this study.

Materials and Methods

The soil utilized in this study is peat from Sabak Bernam, Malaysia. Peat samples were obtained from a depth of 4 to 5 m below the ground surface by dredging using a drilling machine in an area of oil palm agricultural land near the Politeknik Sultan Idris Shah. It is then dried in the air in laboratory conditions, after which the sample is loosened. Table 1 summarizes the physicochemical properties of the peat utilized in this study. The lime as additives were obtained from the locally available market. It contains over 50% quick lime and is classified as hydrated lime. The chemical composition of lime is shown in Table 2.

Table 1. Physicochemical properties of a peat sample

Parameters	Values
Water content (%)	214
Specific gravity	1.58
Bulk unit weight (kN/m^3)	11.6
Void ratio	8.75
Liquid limit (%)	62
Plastic limit (%)	54
Organic content (%)	66
Fibre content (%)	51
Degree of humification	H ₁ -H ₄
pH	5.4
Electric conductivity ($\mu\text{S/cm}$)	177
Optimum moisture content (%)	42.35
Maximum dry unit weight (kN/m^3)	10.2
Unconfined compressive strength (kN/m^2)	9

Table 2. Chemical composition of lime

Chemical names	Amount (%)
Potassium oxide (K_2O)	3.8
Sulfuric trioxide (SO_3)	0.8
Magnesium oxide (MgO)	2.62
Calcium oxide (CaO)	51.3
Ferric oxide (Fe_2O_3)	0.12
Silicon dioxide (SiO_2)	1.3
Aluminium oxide (Al_2O_3)	0.25
Loss on ignition (L.O.I)	38

In both soaked and unsoaked conditions, we performed strain-controlled UCS testing. The soil sample was compacted in a 1000 cm³ volume mould with five layers, and a rammer of 25 blows compacted each layer. After mixing samples, they were separated on the plastic shelf at 37°C for 7, 28, 60, and 90 curing days, respectively. Soaked samples were put on porous stones after being wrapped with a water-absorbing towel. It is were then placed in a dark plastic bag and securely sealed. Following that, it is arranged on a container containing water until the porous stone is moistened with water. Each of the stated UCS test findings utilized in EPR modeling is the average of UCS values obtained from multiple additive's percentages. Figure 1. shows the sample preparation process for the USC test.

Results and Discussions

In this section, the UCS performance with varying percentages of lime, the development of an EPR prediction model, and the investigation of the applicability of the proposed equation are presented.

**Figure 1. Samples preparation and testing program**

Unconfined compressive strength of lime-stabilized peat

The results of UCS analysis of unsoaked samples combined with varying lime percentages at varied curing durations are shown in Figure 2. The baseline peat had a UCS value of 9 kN/m^2 , as seen in Table 1. According to the figure, adding 1% lime to peat enhanced its compressive strength. After 28 days, the compressive strength increased by around 43%, while the maximum strength obtained after 90 days is a 76 percent increment. Subsequently, when added 2% of lime was, the findings revealed that the UCS value rose thrice after 28 days of curing and more than fivefold after 90 days. The UCS tests on untreated and treated peat with varying percentages of lime indicate that the peat treated has a significant effect on compressive strength. Peat and lime responded most strongly within 60 days of curing time, with the growth rate slowing down significantly afterward.

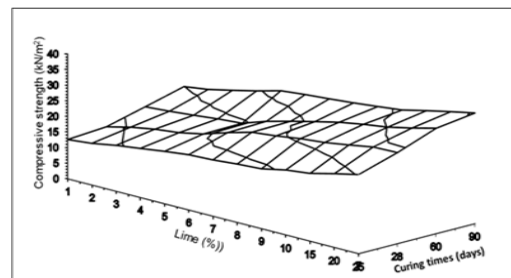
**Figure 2. UCS variation at different combination of lime treated unsoaked peat**

Figure 3. illustrates the UCS results for soaked samples containing varying percentages of lime and curing times. The results for 1 percent lime showed that soaking the samples decreased the compressive strength of stabilized

peat by about 58 percent after seven days of curing time compared to the unsoaked samples. After 28 days of treatment, the decrease was 52 percent. The UCS of 2 percent lime-treated peat was reduced to 50% after 28 days of curing compared to unsoaked samples. The strength reduction remained constant after 60 days of curing. After 28 days of curing, it seemed as if a 3% lime was added to the peat and then soaked, resulting in a 48 percent strength loss compared to the unsoaked samples. However, after 60 days of cure time, the decrease was 32%. Following soaking the samples, the compressive strength of the selected peat with lime seemed to have reduced, according to the UCS tests performed on them. The strength drop was mitigated by prolonging the curing period. On the other hand, the compressive strength rose when the peat soil was stabilized with lime, even for the wet samples.

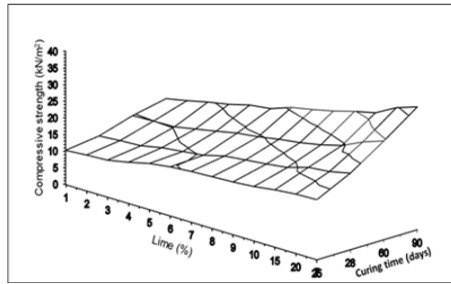


Figure 3. UCS variation at different combination of lime treated soaked peat

UCS prediction performance

In this study, EPR was used to predict USC values. EPR is a novel hybrid regression combination between numerical and conceptual regression. The fundamental concept of EPR is to utilise evolutionary programming to develop a system model under investigation and then use the least square estimate to obtain constants (Giustolisi and Savic, 2006). The general formulation of EPR may be written as Equation 1.

$$O_v = \sum_{j=1}^m F(I, f(I), c_j) + c_0 \quad (1)$$

which, O_v is the predicted output, in which c and c_j is constant parameters, F is a function from generating process, I signify the matrix of input, f denotes a function of user-defined, and m is the target's maximum count. Equation 1 is obtained using the same equation as in Ahangar-Asr *et al.* (2011).

As in previous studies, the EPR output may be constrained by various restrictions that can be

imposed throughout the evolutionary, including the functions employed, the number of terms used, the range of exponents utilised, and how many generations have been run (Rezania *et al.*, 2011). As the number of evolutions increases, it progressively collects new participant parameters resulting in equations defining the correlation between the system's various properties. The coefficient of determination is used to determine the accuracy of the output models. For example, let us assume that the model's fitness is unacceptable and that the other termination conditions are not fulfilled. In such a scenario, the existing model goes through another evolution, creating a new model (Ahangar-Asr *et al.*, 2011). As described before, the UCS prediction is made using three input parameters, respectively. In Equations 2 to 4 (polynomial, exponential and hyperbolic tangent), various UCS relationships are presented, along with their corresponding coefficients of determination.

$$[2.837 \times L^{0.5}] - [0.0513 \times L^2] + [0.00082 \times L] - 0.745; \quad R^2 = 90\% \quad (2)$$

$$[-12.232 \times e^{-0.25L}] - [0.674 \times L \times e^{0.25CC}] + [0.00064 \times CC^2] \times e^{(-0.25L+0.5CC)} + 12.452; \quad R^2 = 92\% \quad (3)$$

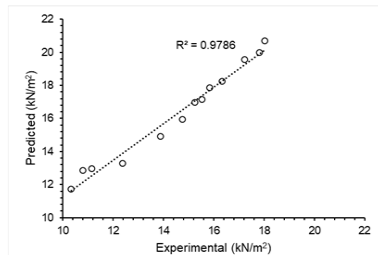
$$[-0.00325 \times L^{-0.5} \times CC \times \tanh(L)] + [0.00335 \times L^{-0.25} \times CC^2 \times \tanh^2(CD)] + [3.55 \times CC^{0.25} \times \tanh^{0.25}(CD)] + [6.58 \times 10^{-5} \times CC^{0.25} \times CD^{0.25}] - 4.25; \quad R^2 = 95\% \quad (4)$$

where L is the lime percentages, CD is the curing periods, CC is curing condition and the hyperbolic tangent of x is denoted by $\tanh(x)$.

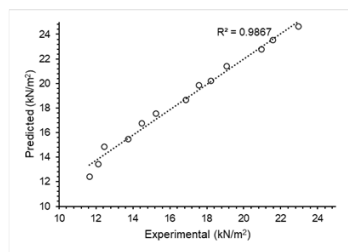
As can be seen in the above equations, the R^2 values for polynomial, exponential and hyperbolic tangents are 90%, 92% and 95%, respectively. This indicates that the hyperbolic tangent produces a relationship between the input and output parameters more precisely than the exponential tangent function provides. This is due to the fact that the applied function form is similar to the change in UCS as a function of the parameters being used in the computation. As a result, the third model is chosen to be studied further. From the data in Figure 4, the determination coefficient for UCS models that have been cured for seven days, 28 days, 60 days, and 90 days are acceptable values of 97.86 percent, 98.67 percent, 98.97 percent and 99.77 percent, respectively, indicating that suggested models are capable of predicting UCS values. On average, the accuracy of predictions using this EPR is 99 percent. Interestingly, the USC model for 90 days cured is predicted fairly accurately, approaching 100 percent.

Figure 5. illustrates the distribution error in the EPR model for UCS values prediction cured in 7 days, 28 days, 60 days and 90 days. The existence of good fitness between measured and predicted UCS values shows that the proposed correlations are efficient and useful for predicting lime stabilised peat UCS values. Furthermore, they may be of use to engineers during the preliminary design phase and when estimating the effect of lime on UCS in

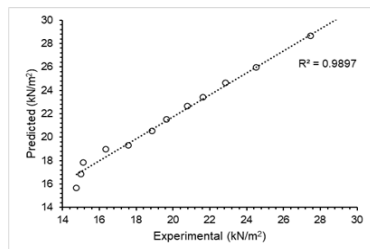
civil engineering projects. As shown in Figure. 4, there are several prediction errors for various amounts of lime in the UCS correlation, particularly for samples with more than 15 percent lime admixture. Although the overall relative error was small, i.e. below 20%, samples cured over 90 days were below 12% for all lime percentage mixtures. This is due to the lime percentage's significant impact and its influence on formed relationships.



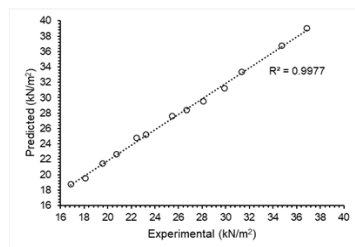
(a)



(b)

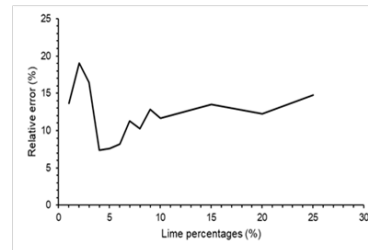


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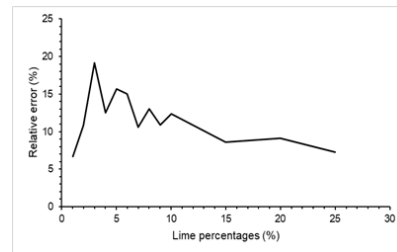


(d)

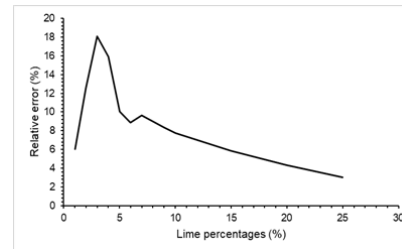
Figure 4. UCS data comparison between experimental and predicted for soaked peat (a) 7 days cured, (b) 28 day cured, (c) 60 days cured and (d) 90 days cured



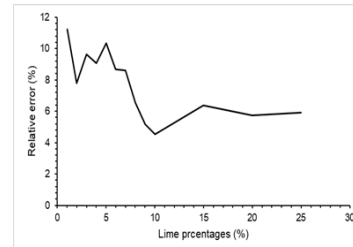
(a)



(b)



(c)



(d)

Figure 5. Relative errors in EPR prediction of USC for soaked peat (a) 7 days cured, (b) 28 day cured, (c) 60 days cured and (d) 90 days cured

Table 3. Relative error for the proposed equation to predict the UCS values

Lime (%)	Measured (Yusof <i>et al.</i> , 2015) (kN/m ²)	Predicted Eq. (4) (kN/m ²)	Relative Error (%)	Lime (%)
2	30	27.4	9	2
4	29	28.7	1	4
8	75	82.9	11	8

Application of proposed UCS equations

The use of EPR modeling as a powerful, quick, accurate, and economic soft computing methodology is assessed in this paper to predict the UCS of stabilized peat. As discussed previously, various accurate prediction models based on modeling techniques were developed. These newly developed approaches may be employed as efficient replacements for time-consuming and expensive experimental test programmes during the design phase where data are insufficient or information about the behaviour of a subgrade material is lacking.

Some interpretations are required to allow practitioners and engineers to evaluate quality in the field effectively. Applying experimental relationship equations for UCS is a popular strategy during the quality control phase of soft ground improvement projects. These equations are due to stabiliser content, material characteristics, shear-wave velocity, and other variables (Madhyannapu *et al.*, 2010). Thus, in this study, such equations for predicting UCS are developed, considering curing circumstances, curing periods, stabiliser amounts, and using the proposed correlations in the design of soft ground improvement projects is explored further.

In order to assess the applicability and simplicity of the proposed equations, a complete data set of peat stabilized with lime was used to predict the UCS values. In this regard, other data sets available for peat stabilization using lime found in the literature (Yusof *et al.*, 2015) are considered examples of applications for the proposed equations. Equation 4 was used to predict UCS cured for 28 days. As shown in Table 3, although this equation is not explicitly developed for the characteristics of this peat, it can still predict UCS quite well. The comparative analysis shows that when a low amount of lime is used, the proposed equation produces values within an acceptable range. Table 3. also includes prediction errors for various lime percentages. The key reason for such errors in high lime-content peats may be variances in the peat's characteristics. This straightforward example demonstrates the simplicity of the suggested linkages for peat stabilization. Obviously,

the predicted values can reach the target well, and this equation is suitable for determining the amount of lime needed to increase the strength of peat in civil engineering projects. Additionally, it states that it may be used to predict the UCS of other problematic peat in the first stabilization efforts.

Conclusions

To provide a cost-effective and speedy alternative to experimental testing for determining the UCS of stabilized peat, we developed evolutionary polynomial regression as a novel model using soft computing approaches. The data obtained experimentally were used to evaluate the performance of stable peat with lime for unsoaked and soaked conditions and developed an EPR model. The addition of lime improved the UCS of the peat in the present study. The UCS test result revealed that the characteristics of stabilized peat varied and were dependent on the quantity of lime used and the curing period. Soaked samples from the UCS tests demonstrated that soaking lowered the strength of the treated peat; however, extending the curing period mitigated the loss in strength.

Moreover, UCS measurements on the soaked sample revealed that increasing the quantity of lime lowered the compressive strength. In EPR modeling, novel correlations for the prediction of UCS have also been effectively shown. The percentages of lime, curing days, and curing conditions are employed as input data to establish UCS relationships in this application. The high precision and low relative error values of the given EPR relationships make them useful for peat stabilization. The application of the proposed UCS equations has been demonstrated using straightforward data samples from the literature, and a high degree of consistency has been obtained. Further work needs to be done to establish whether incorporating learning algorithms such as genetic algorithms can improve the accuracy of the results.

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