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TECHNICAL ARTICLE—PEER-REVIEWED

Failure Assessment of Strength and Bearing Capacity on Marine Stabilized Subgrade Soil

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Abstract Abundance of natural waste such as seashells and emission of carbon dioxide when stabilizing soil using cement/lime becomes a great concern in protecting the environment and economic impacts in infrastructure engineering projects especially road pavement construction. The low strength and bearing capacity of subgrade pavement layer due to traffic loadings can cause road damage effects. This study assesses the failure strength and bearing capacity effects of single and combined additives on the stabilization of marine subgrade soil. The effectiveness of cockle shell powder (CSP) as a natural waste product and lime powder (LP) as an industry by-product in treated marine soil with the addition of different percentages of stabilizers to predict the strength and bearing capacity of marine stabilized soil was assessed. The effects of CSP and LP contents on the strength stabilized soil samples were examined through the unconfined compressive strength (UCS) test and soaked California bearing ratio (CBR) test. The study demonstrated the feasibility of using a simple ANN to predict the UCS by using additives. A relationship between UCS and bearing capacity ratio is established. Based on the CBR and UCS, the addition of CSP alone in stabilized soil gave low values. However, the combination of both additives CSP and LP resulted in considerably higher UCS and CBR values. The ANN prediction shows good performance and regression values. However, the relationship between UCS and CBR gives a fair coefficient of determination of $R^2 = 0.706$.

Keywords Cockle shell powder (CSP) · Lime powder (LP) · California bearing ratio (CBR) · Unconfined compressive strength (UCS) · Soil stabilization

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Introduction

Infrastructure projects have become tremendous demand in local and global industries which require large areas of land to construct structures in traffic and transportation, buildings, and foundations to provide better life. Due to rapid development in Malaysia, many construction projects must be constructed on soft ground, which can lead to several issues related to instability, settlement and lateral soil movement. The land located in coastal areas of Johor, Malacca, Klang, Penang and Alor Star of Peninsular Malaysia [1] is covered by residual-type and marine soil which can be generalised as having poor to average geotechnical properties due to the low strength and high compressibility of site conditions.

In road infrastructure construction, marine soil is important as a subgrade material for both flexible and rigid road pavements. Subgrade materials refer to the ground or soil underneath a road pavement which have low strength and capacity to support the weight of the road pavement and traffic loads. Failures of subgrade materials due to traffic loading for example plastic or permanent deformation lead to rutting of the pavement [2]. Russell et al. [3] presented an engineering method for the determination of cause and effect that lead to failure assessment. The method comprises four types of failure causes which are wear and tear, unknowns, actions (by person(s) and entity(s)), and acts of the natural world. Thus, it is necessitated to facilitate the failure assessment by some sort of soil stabilization to enhance the capacity of onsite material properties and meet the required standard to support the load [4] and quality of road subgrade and pavement layers, and reduce the total thickness of pavement as well as administrative costs [5]. There are three techniques for soil stabilization or soil improvement consisting of mechanical, chemical, and polymer techniques that should be considered to enrich and change the soil behaviour, eventually improve the soil strength, control the deformation, increase the lateral stability, form seepage cut-off, and restrain any negative impact on the environment.

There are many potential materials in subgrade treatment using the chemical soil stabilisation method or additives such as cement, lime [1], gypsum, sodium bentonite, calcium chloride, nano-chemical additives, fly ash, pond ash, bagasse ash and granulated blast-furnace slag [6, 7], coal waste, secondary steel slag [5, 8] and rubber tyre waste [9], waste tyre chips, and powders [10] in geotechnical applications of product manufacturing, industrial wastes, or natural wastes.

Many researchers have conducted studies on geotechnical properties of soil stabilization using lime additives via experimental works [1, 11, 12], computer-based prediction models [13], and both approaches [14–16]. Lime is widely used due to its cost-effectiveness and easy construction procedures, and the implementation of this method uses simple technology [17]. Mixing clay soil with lime will affect the soil properties immediately as cation exchange will start to occur amongst the metallic compounds related to the surface of clay particles and the Ca ions of lime. The addition of lime will decrease the diffuse double layer thickness, which can increase the charge concentration and the pore fluid viscosity [17]. The reason is that the particles inside the clay start to attract one another, making them closer, and thus flocculation occurs. Moreover, the soil pH value can increase to 10.5 when a suitable amount of water and lime is added to the soil. This addition can break down clay particles, releasing silica and alumina that will form calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) when reacting with the Ca from lime. CSH and CAH are cementitious products that are comparable with the products in portland cement. Subsequently, this will give a strong and flexible structural layer. Furthermore, many researchers have found that lime has the potential to modify soil plasticity. The plastic limit of soil can be modified with the presence of lime, and soil plasticity affects the thickness of the diffuse hydrous double layer surrounding clay particles [17]. Gadouri et al. [18] stabilized clay soil using lime showed reduction in plasticity index (PI) and increased the unconfined compressive strength (UCS). Saberian et al. [15] have shown the effect of lime concrete in increasing UCS by increasing the curing time and decreasing the degrees of saturation due to pozzolanic reactions and reduction of water. In addition, the UCS of lime-treated soil was found to be approximately four times the initial value [11].

However, these methods can be expensive and ineffective. Also, these additives are chemical-based, not economic, and non-environmentally friendly due to carbon dioxide emissions from cement and lime [11, 19]. In alternative, sustainable materials have become the interest as a means to diminish and replace the environmental and economic impacts on soil stabilization due to the use of lime. As a viable option, a natural waste-based product such as cockle shells or eggshells is recommended as the material is abundant in coastal areas and is also cheap.

Cockle shells are classified as *Anadara granosa*, which are mostly found along the western coast of Peninsular Malaysia. *A. granosa* contains calcium carbonate ($CaCO_3$) that can be commonly found in the form of limestone, chalk, and marble [20]. Nujid et al. [21] stated that $CaCO_3$ in cockle shells is similar to cement and lime additives. Therefore, cockle shell powder can be an effective additive in improving soil strength parameters.

Cockle shell powder is another additive with almost similar characteristics as lime. Cockle shell powder contains 90% calcium (Ca), which is a major constituent of lime; thus, cockle shell powder is a better and economical stabilizing admixture [22]. Moreover, the utilization of waste materials (e.g. seashell powder) will reduce the effects of soil stabilization on the environment and society because waste materials are more environmentally friendly. This utilization will indirectly contribute to sustainable development in geotechnical engineering, in which the core practise is to be environmentally friendly and resource-efficient. Nevertheless, the use of cockle shell powder as an additive has not yet been fully implemented in soil stabilization techniques due to the lack of studies and research regarding its effectiveness in improving soil stability. Table 1 shows the chemical composition of cockle shell powder [23, 24].

The use of sustainable non-biodegradable waste materials as additives to stabilize expansive subgrade materials has become an emerging trend in sustainable stabilization

Table 1 Chemical composition of seashell and cockle shell powder [23, 24]

	Percentage (%)		
Oxide	Ground seashell	Cockle shell ash	Cockle shell ash
SiO_2	1.60	–	0.07
Al_2O_3	0.92	–	0.03
CaO	51.56	98.99	99.00
MgO	1.43	–	–
Na_2O	0.08	–	0.49
K_2O	0.06	–	0.06
H_2O	0.31	–	–
P_2O_5	–	–	0.03
SO_3	–	–	0.14
Fe_2O_3	–	–	0.05
Mg	–	0.51	–
Si	–	0.078	–
Na	–	–	–
LOI	41.48	–	0.20
Others	–	< 0.1	0.28

via the use of locally available industrial waste to improve the engineering properties of soil [4]. Waste and secondary materials such as silica fume, volcanic ash, rice husk, bitumen, kiln dust, natural fibre and ground granulated blast-furnace slag (GGBS) can be used as a partial substitute in conventional subgrade stabilization in improving geotechnical properties of the soil such as UCS and California bearing ratio (CBR) which are amongst the important parameters in stabilized subgrade pavement.

The UCS is the maximum load per unit average cross-sectional area at which the cylindrical specimen of soil falls in compression. The shear strength of composite soil can be obtained experimentally by conducting a triaxial test or shear box test. In the study, the UCS is performed. The UCS of weak and expansive subgrade treated soils can potentially be increased using material additives in stabilization. Saldanha et al., [19] combined lime additives with eggshells rich in calcium carbonate for soil stabilization and found that the strength and stiffness of the stabilized soil improved. Mozumder and Laskar [25] predicted the UCS of stabilized clayey using ground granulated blast furnace slag (GGBS), fly ash (FA), and a blend of GGBS and FA (GGBS + FA) and compared it to a multi-variable regression (MVR) analysis. It was found that the GGBS-base is an effective method for treating clayey soil and yields a much higher strength than FA-based geopolymer stabilized samples under identical mix proportions. Gu et al., [8] added secondary steel slag (SSS) with lime and proved the performance improvement in subgrade treatment. Ardah et al., [26] evaluated the resilient modulus and permanent deformation of very weak subgrade soils with high moisture content using cementitious materials (fly ash and hydrated lime) for treatment. Pooni et al., [27] revealed that the calcium-based stabilizers are effective in treating expansive soils by increasing strength across the moisture ranges tested. Ardah et al., [26] found that the correlation between the UCS and resilient modulus for cementitious treated soils can be misleading based on laboratory results. The UCS values increased with a higher stabilizing binder content of 8% by soil weight of milled eggshells and cement mixture a ratio of 1:1 stabilized lateritic soil [28].

The CBR number is obtained as the ratio of the necessary unit load to affect a certain depth of penetration of the penetration piston. This CBR value is widely used in the design of base course, subbase, and subgrade in pavement construction. Ruiz et. al, [29] utilized seashell wastes in sandy subgrade stabilization and found an increase in the CBR of sandy soil from 51% to more than 100%. Oluwatuyi et al., [28] stabilized lateritic soil with milled eggshells, cement, and a mixture of both in a ratio of 1:1 (at varying percentages of 0, 2, 4, 6, and 8% by weight of the soil) for potential use as a highway construction material. The test results showed that both unsoaked and soaked CBR values increased with higher stabilizing binder content at 8% by weight of the soil. Stabilized subgrade materials increased with an increase in cement content thus increased the soaked CBR and UCS [30].

Another issue when obtaining the results of laboratory works and field data for several studies and observations is the need for a long period of time and careful supervision. Besides that, the testing is costly and requires a long period for every study [13, 16, 31]. For these reasons, a prediction model by statistical and mathematical analyses and artificial neural networks (ANN) can be used as an alternative to predict the effective optimum additive content of the additives without conducting any laboratory testing (resource-intensive trial-and-error procedure) by which laboratory trials may not be representative of the overall site [32]. The ANN is also useful in predicting the geotechnical properties of stabilized soil such as UCS and CBR. A study by [33] found that an ANN-based model successfully established the correlation between the index properties and shear strength parameters of normally consolidated plastic clays. Tizpa et al. [34] developed a prediction model and compared the results obtained from the model with the experimental data. From the comparison, the ANN model achieved highly accurate prediction and by increasing the database, the existing model could be upgraded. Ghorbani and Hasanzadehshooiili, [35] predicted the UCS and CBR of micro silica-lime stabilized sulphate silty sand using ANN and evolutionary polynomial regression (EPR) models in deep soil mixing in selection the optimized percentage of stabilizers. Nujid et.

al, [21] correlated CBR and plasticity index of stabilized cockle shell powder as additives in marine soil which indicates good agreement between the parameters.

In another way, [16] developed a regression relationship between the index properties of soil with CBR and found weak correlators of CBR hence they are practically not cost-effective for pavement design. Muthu Lakshmi et al., [14] correlated unsoaked CBR and UCS for clayey sand and poorly graded sand using simple linear regression analysis (SLRA) that showed the increase in UCS and CBR strength were attained on the dry side of the optimum moisture content curve. Saputra and Putra [36] obtained a high correlation between CBR and UCS scores for laterite soils in Palangka Raya, Indonesia.

This study aims to assess the strength and bearing capacity of stabilizing marine soil using a natural waste-based product which is cockle shell powder and a combination of cockle shell powder with lime powder as additives to stabilize marine soil. A network is developed to predict the shear strength of the stabilized soil and a relationship between UCS and bearing capacity of the stabilized soil is proposed.

Materials and Methods

In this section, the materials and methods are presented in two sections to achieve the purpose of the study. The first section describes the experimental works performed to evaluate the effectiveness of different percentages of additives used in stabilized soil where samples were collected and prepared to conduct UCS and CBR testing.

Meanwhile, in the next section, ANN is used to predict the geotechnical properties of stabilized soils. The accurate prediction of the plasticity index, shear strength, and bearing capacity of the soil is useful to overcome any circumstance raising from laboratory testing which can be benefited on site. A relationship between UCS and bearing capacity of the stabilized soil is proposed on failure assessment.

Experimental Works

Sample Collection and Preparation

Marine soft soil used in the present study was collected from a construction site in Seberang Jaya, Pulau Pinang (Site A) by an open excavation to a depth of 7 m below ground level and compared to the soil of Kuala Kedah, Kedah (Site B) [24]. The soil samples were taken from the two different sampling point locations of marine soil in Pulau Pinang and Kedah of Peninsular Malaysia as shown in Fig. 1. From the visual observation during the soil sample collection, the marine soft soil was greyish in colour with some fragments of shell. Samples were packed, labelled, and transported to the laboratory for studies.

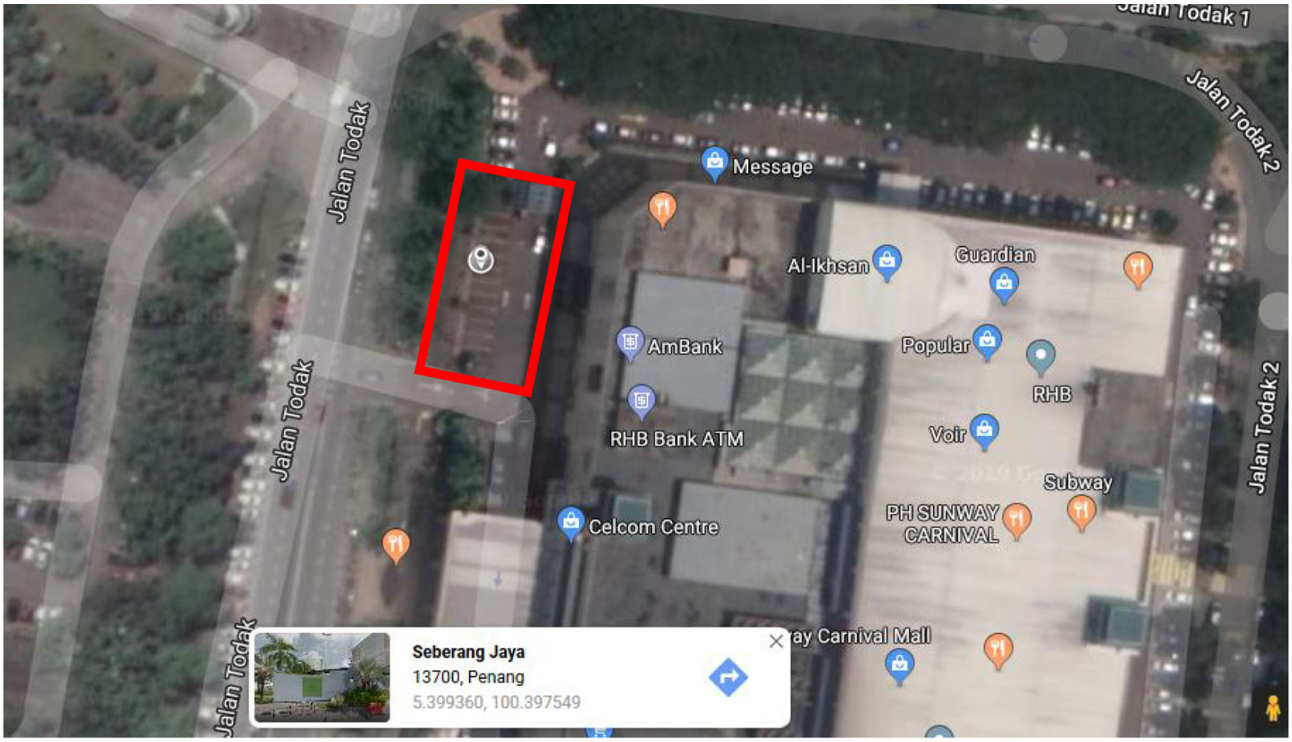
According to [24], the soil from Site B is classified as silt of high plasticity (MH) with a high liquid limit and low plastic limit. The liquid and plastic limits of soil are estimated to be 68 and 32 respectively. The soil contains 41.05% sand, 50.37% silt, and 8.44% clay. The maximum dry density of the soil is 1.64 Mg/m^3 and its optimum moisture content is 16.34%.

Cockle shells used in the study were collected from Pulau Aman, an island off the coast of Seberang Perai, Pulau Pinang. The shells were crushed into small pieces and then ground using a grinder to obtain cockle shell powder as the recommended average particle size of the powder was 20.80, 29.87, and 13.56 µm [37]. However, the formed product depends on the grinding process [38]. The powder was retained on a 75-µm sieve (no. 200) in accordance with ASTM D1140-17 [39] for laboratory testing and was used as a filler between soil particles as well as stabilizer. According to [40, 41], the chemical composition of cockle shell powder consists of 98-99% CaO, 0.49% Na_2O, and the remainders are SiO_2, Al_2O_3 and SO_3.

In order to evaluate the effects of cockle shell powder and lime powder in soil stabilization on strength parameters of the specimens, twelve groups of specimens from each site location, including one group of natural specimens as control, one group of specimens stabilized with cockle shell powder, and one group of specimens stabilized with a mixture of cockle shell powder and lime were used in two tests i.e. unconfined compression test (UCT) and CBR.

To evaluate the shear strength parameters of the mixtures, a series of UCTs were carried out on soft soil-controlled specimens, soil mixtures with cockle shell powder and soil treated with a combination of cockle shell powder and lime. The laboratory tests were carried out with different contents of cockle shell powder (0%, 2.5%, 5%, 7.5% and 10% of soil dry weight) from a previous study performed by [24] and from a present study, 16% of cockle shell powder of soil dry weight were added to soil specimens.

In the present study, the percentage of additives used was based on the previous study conducted by [42] in which the optimum percentage of cockle shell powder is 16% for UCT specimens and 20% for CBR specimens. The hydrated lime ($Ca(OH)_2$) used in this study was obtained locally from a nearby hardware store and using lime in soil stabilization has proven successful and is considered effective to improve the strength [43] and considered as a secondary additive in the combination of soil mixture.



(a) Location of Soil Sample Collection (Site A)

(b) Location of Soil Sample Collection (Site B) [36]

Fig. 1 **a** Location of soil sample collection (Site A). **b** Location of soil sample collection (Site B) [36]

In addition, 16% lime was used in the soil mixture together with 16% cockle shell powder of soil dry weight to evaluate the effectiveness of stabilized soil for UCS. For the CBR, 20% cockle shell powder of soil dry weight was used to evaluate the effectiveness of stabilized soil. The 16% and 20% lime of dry weight were, respectively, combined with 16% and 20% cockle shell powder in specimens for UCS and CBR tests due to initial testing results showing that the addition of cockle shell powder only does not increase strength of stabilized soil. Table 2 shows the admixtures used in the stabilization process of marine soil for Site A and Site B with different stabilizer types and percentages of stabilizers used in the soil mixtures.

For the UCT, the remoulding of the soil specimen was prepared using the conventional method in accordance with BS 1377: Part 7: 1990 [44]. The laboratory tests were carried out with different contents of cockle shell powder (0%, 2.5%, 5%, 7.5% and 10% of soil dry weight) from a previous study performed by [24] and from a present study, 16% cockle shell powder of soil dry weight was added to soil specimens [42]. The soil was mixed with cockle shell powder for the first batch and a combination of 16% cockle shell powder with 16% lime was used for the second batch of testing and placed inside the mould in three layers, whereby each layer consists of 27 blows to obtain uniform compaction. According to [43], further addition of 6% and 9% lime increases the strength more significantly. Thus, 16% is enough to show effectiveness in stabilized soil. Then, the soil specimen was removed from the mould using a soil extruder and tested directly to avoid any loss of moisture content in the specimen.

In the sample preparation and testing for bearing capacity assessment, the sample was prepared in accordance with BS 1377: Part 7: 1990 [44] similar to the UCT sample. The laboratory tests were carried out with different contents of cockle shell powder (0%, 2.5%, 5%, 7.5% and 10% of soil dry weight) from a previous study performed by [24] and from a present study, 20% cockle shell powder of soil dry weight was added to soil specimens [42]. 6 kg of the samples were mixed with cockle shell powder for the first batch and a combination of 20% cockle shell powder with 20% lime was used for the second batch which was then divided into three portions whereby each portion was compacted with 62 blows using a rammer. After the compaction of all portions, the sample was trimmed and removed from the mould. In this study, the bearing capacity of the soil was considered in the soaked effect. The CBR value for the soaked condition was determined, in which the prepared mould and sample were soaked in water for four days (normal soaking period). After that the soil specimen was tested using the CBR test machine. Two or three more samples were prepared and tested to obtain an average CBR value of the marine soil.

Sample Testing and Analysis

To assess the strength and bearing capacity of the composite soil, the UCT and CBR tests were performed. All tests were conducted in accordance with BS 1377: Part 7:1990. The UCT and CBR tests were used to assess the effectiveness of cockle shell powder and lime powder in stabilizing marine soil and to evaluate the strength and bearing capacity of the marine soil. The percentage of additives used in the testing for the present study was based on the optimum percentage of additives from a previous study conducted by [42] on the influence of seashell powder on black cotton soil during stabilization.

A triaxial machine was used to test the prepared specimens under the deformation rate of 1.5 mm/min. For this

Table 2 Admixtures in Stabilized Soil

	Site A	Site B
Location	Pulau Pinang, Malaysia	Kedah, Malaysia
Soil type	Marine	Marine
Stabilizer mixture (Unconfined compressive strength)	Cockle shell powder (CSP) and Lime powder (LP)	Cockle shell powder (CSP)
	16% CSP	0% CSP
	16% LP	2.5% CSP
	16% CSP + 16% LP	5.0% CSP
		7.5% CSP
		10.0% CSP
Stabilizer mixture (California bearing ratio)	Cockle shell powder (CSP) and Lime powder (LP)	Cockle shell powder (CSP)
	20% CSP	0% CSP
	20% LP	2.5% CSP
	20% CSP + 20% LP	5.0% CSP
		7.5% CSP
		10.0% CSP

study, the readings were taken at 0.25 mm intervals of vertical displacement. Two or three more samples were prepared and tested to obtain an average value of the UCS of the marine soil. For the second batch of testing, the marine soil was mixed with the combination of cockle shell powder and lime powder, and the process was repeated. The CBR machine was used to test the prepared specimens of the marine soil mixed with cockle shell powder and a combination of cockle shell powder and lime powder.

For this testing, the steps were identical with the UCT, but the CBR test mainly focussed on determining the effectiveness of cockle shell powder on the soil bearing capacity of the marine soil. The testing will measure the shearing resistance of soil under controlled moisture and density conditions. From the testing, the bearing capacity of marine soil can be evaluated, and it can be determined whether cockle shell powder is good enough to be a subbase or subgrade in pavement construction.

ANN Prediction

The ANN is used to predict the geotechnical properties of stabilized soil. The accurate prediction of plasticity index, shear strength, and bearing capacity of the soil is useful to overcome any circumstance raising from laboratory testing for site benefit purposes. In this study, for the ANN's aim, the databases consist of results collected from several experimental studies of different types of soil stabilized using different percentages of stabilizers published in the literature. The prediction only focussed on the shear strength of the stabilized soil from the input and output parameters of the ANN. Both published tables are presented in the next section.

Data Collection

In this study, the database consists of 82 data sets obtained from several previous experiments on different additives to stabilize various soil types. This database consists of the percentage values of stabilizer soil, which will be the input parameter, and the output parameter is shear strength of the composite soil as shown in Table 3 at various minimum, maximum, and average values of input and output parameters.

Development of ANN Model

The models were used to develop a back-propagation network using the Levenberg-Marquardt algorithm to train the network. Levenberg-Marquardt, also known as the damped least-squares method, is designed to work specifically with loss functions, which take the form of a sum of squared errors. One input value which is the percentage of the stabilizing agents of the composite soil was assigned to predict the UCS of the soil. The optimum number of neurons in the hidden layer is 10. Thus, the network consists of three layers with one input, two hidden layers with ten neurons, and one output.

In this study, the 83 input datasets consist of two column vectors. The first vector is the percentage of the stabilizing agents of the experimented soil in percentage respectively. The output, which is the targeted outcome (i.e. the shear strength of the composite soil), was set as a one-column vector with similar matrix dimensions as the input datasets. For this study, about 70% (59 samples) of the data were allocated for the training set, 15% (12 samples) for validation, and the remaining 15% (12 samples) for testing. The validation dataset was used to measure the network generalization capability. The training performance of ANN was monitored by mean square error (MSE) and epoch number. The MSE value can be expressed by the following Eq. 1:

$$\mathrm{MSE} = \frac{1}{n}\left(\sum_{i=1}^{n}(y_{\mathrm{i}} - y_{\mathrm{T}})^2\right) \quad \text{(Eq 1)}$$

where i is number of datasets, y_{i} is the predicted shear strength of the composite soil value at the ith data by the ANN model, and y_{T} is the targeted shear strength of the composite soil value at the ith data.

Table 4 shows the neural network characteristics and parameters used in the study for training and assessing the ANN model performance. The lower the value of MSE between the target and the output data, the better the network prediction. If the value obtained is in an acceptable range, it will ensure the network prediction for the hidden test data and if the network reaches the satisfactory value of MSE, the amount of test data is unimportant [45].

Results and Discussion

Site A shows that the untreated soil is classified as high plasticity clay (CH) with a high liquid limit and low plastic limit. The liquid and plastic limits of soil are estimated to be 68.7 and 36.67, respectively. The maximum dry density of soil is 1.563 Mg/m^3 and the optimum moisture content of soil is 20.24%.

The basic index properties of untreated soil from Site B, in summary, are given by [24]. The soil used from Site B is classified as silt of high plasticity (MH) with a high liquid limit and low plastic limit. The liquid and plastic limits of soil are estimated to be 68 and 32, respectively. The soil contains 41.05% sand, 50.37% silt and 8.44% clay. The

Table 3 Input and output parameters of ANN prediction

	Parameters	Unit	Minimum	Maximum	Average
Input	Percentage of stabilizer	(%)	0.5	40	20.25
Output	Unconfined compressive strength	kPa	50.0	2177.5	1113.75

Table 4 Neural network characteristics and parameters

Characteristics	Value/description
Total number of inputs	83
Number of training samples	59
Number of testing samples	12
Number of validation samples	12
Number of optimum neurons in hidden layers	10
Training algorithm	Levenberg-Marquardt
Performance	Mean squared error
Number of optimum epochs	9
Calculation	MEX

maximum dry density of soil is 1.64Mg/m^3 and the optimum moisture content of soil is 16.34%.

In this experimental study on evaluating the strength of stabilized marine soil for subgrade bearing capacity, the percentage of cockle shell powder used in the testing was based on a previous study by [42], whereby the test was conducted to determine the influence of seashell powder on black cotton soil during stabilization. From the study, the optimum percentage of the seashell powder was 16% for the UCT and 20% for the CBR test. For the second batch of testing, lime powder was added together with cockle shell powder using the same percentage to the soil sample. The effects of different percentages and different types of stabilizers are discussed in the following sections [46] as studied the performance of seashell powder on subgrade soil stabilization with the influence of admixtures content.

Unconfined Compressive Strength (UCS)

The typical stress-strain diagram curve derived from an UCT of the control sample and stabilized samples from Sites A and B are presented in Fig. 2 for different percentages of CSP and different types of stabilizers used for soil stabilization. The x-axis is the strain with respect to axial stress determined from the calculated applied maximum load.

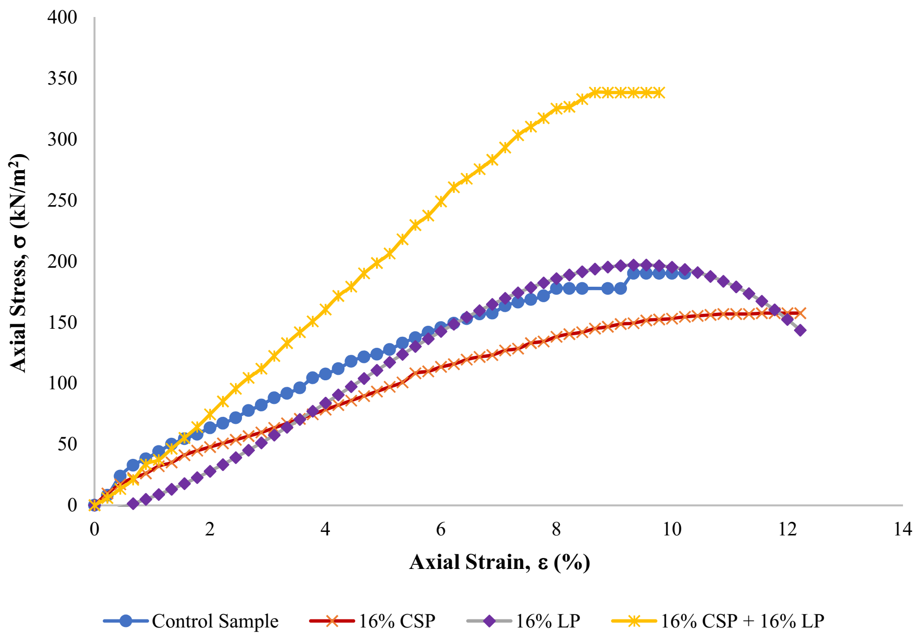
Site A from the present study has the peak value of the stress-strain diagram which is equal to a UCS value of 338.4071 kPa for an addition of 16% CSP and LP. The maximum UCS at Site B is 636.061 kPa for 10% CSP content in the soil mixture. The results from the present study also show that the UCS value with 16% CSP is 157.52 kPa which indicates that cockle shell powder has a lower value of axial stress than the control sample. However, after lime powder is added together to the soil, the value increased rapidly. In contrast to Site B, the control sample has the lowest UCS value, and the USC strength of stabilized soil increased with increasing CSP content. These results indicate that a mixed design with a CSP of more than 10% is unsuitable for stabilizing the soil because of the effects of inadequate fillers. The addition of less than 10% CSP also resulted in a reduction in the UCS of marine soil at early stages of the mixture. It is proven that the efficient percentage of replacement stabilizers is around 5% to 10% soil replacement with cockle shell powder [23].

These findings align with the results reported [47] in which the CSP acted as a filler material requiring a binding agent to bind with soil particles of sizes 0.125-0.25 mm to offer the highest decomposition rate [40] and cockle shells is a promising source of calcium oxide (CaO) with similar compounds found from the decomposition of calcium carbonate (CaCO3) sources such as limestone. The experimental evidences indicate the necessity of carbonation reaction using a binding agent that enhances the reaction between the CSP and LP with the clay minerals [48]. However, the high content of CaO in the cockle shell ash will cause a slow hydration process [41]. When the binding agent is introduced along with the CSP, such as the cement in the concrete, the strength will be improved significantly [49].

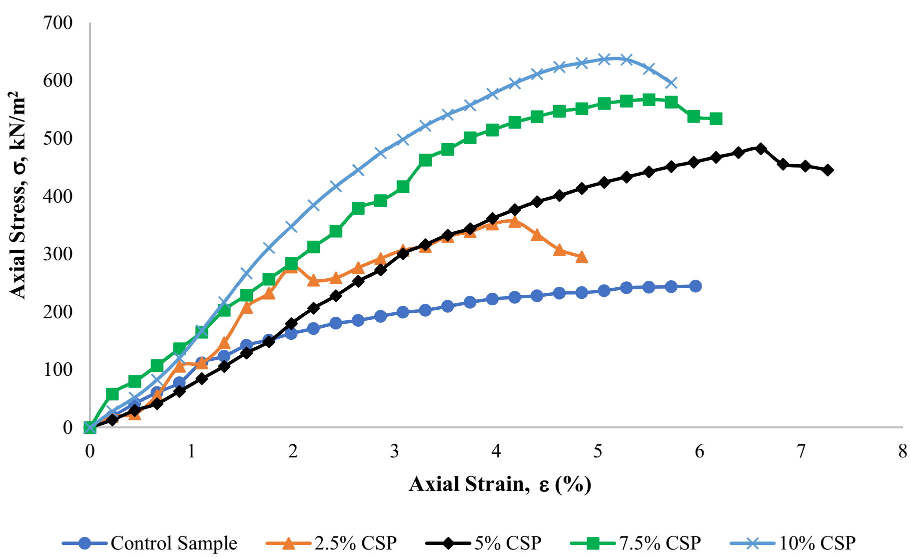
Table 5 presents the values of the UCS of present and past studies using different types and percentages of stabilizers in treated soil. The treated stabilization soil increases in strength with increasing percentage of stabilizers for Site B. However, the results obtained from Site A using only cockle shell powder as the stabilizer of the marine soil are lower than the results of the control sample even though the testing was conducted using the optimum percentage values of the cockle shell powder from the previous study [42].

Meanwhile, the study conducted by [42] proved that cockle shell powder could increase the value of UCS of the black cotton soil. However, in the current study, an opposite result was obtained as the UCS of the marine soil added with cockle shell powder is lower than the control sample. The value of the UCS of the control sample was 96.5 kPa which is higher than the stabilized soil's value of

Fig. 2 **a** Stress-strain curve of treated marine soil with the addition of 16% cockle shell powder and lime powder (Site A). **b** Stress-strain curve of treated marine soil with the addition of 2.5%, 5%, 7.5% and 10% cockle shell powder (Site B)



(a) Stress-Strain Curve of Treated Marine Soil with the Addition of 16% Cockle Shell Powder and Lime Powder (Site A)



(b) Stress-Strain Curve of Treated Marine Soil with the Addition of 2.5%, 5%, 7.5%, and 10% Cockle Shell Powder (Site B)

78.5 kPa. This means that the reaction to form a cementitious compound within the soil did not occur properly.

Similar results have been found in assessing the compressive strength of concrete whereby CSP was used as a replacement material for cement in concrete mix design [23]. As the percentage of filler material increased as a cement replacement in concrete mix design, a decrease in the compressive strength of concrete occurred as more water is required and the high content of CaO in the cockle shell ash will cause the slow hydration process [41]. By adding the CSP together with LP to improve the UCS of marine soil with the presence of lime, CaO and calcium carbonate, the CaCO3 in the calcite cockle shell gained a higher strength with the combination [23]. It also reduced the water demand and workability of mixing soil with stabilizers by incorporating CSP, especially in mortar or cement [37].

Table 5 Unconfined compressive strength (UCS)

Site A (present study)			Site B [24]		
Stabilizer types	Percentage (%)	Unconfined compressive strength (kPa)	Stabilizer types	Percentage (%)	Unconfined compressive strength (kPa)
Control sample	0	96.5	Control sample	0	246.92
CSP	16	78.5	CSP	2.5	356.241
LP	16	71.78	CSP	5.0	481.99
CSP+LP	16 each	188	CSP	7.5	566.917
			CSP	10.0	636.785

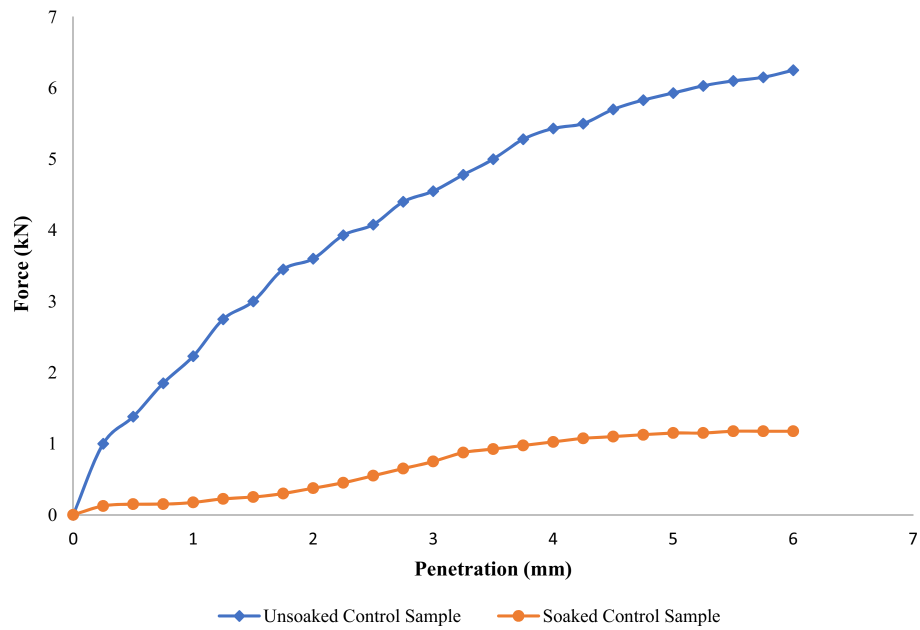


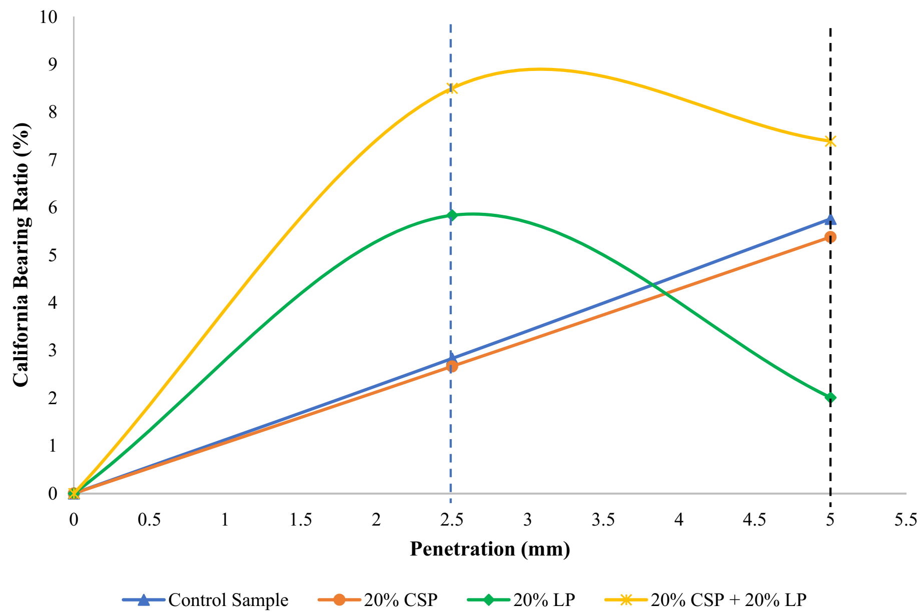
Fig. 3 Force versus penetration graph of unsoaked and soaked control samples

Table 6 California bearing ratio (CBR)

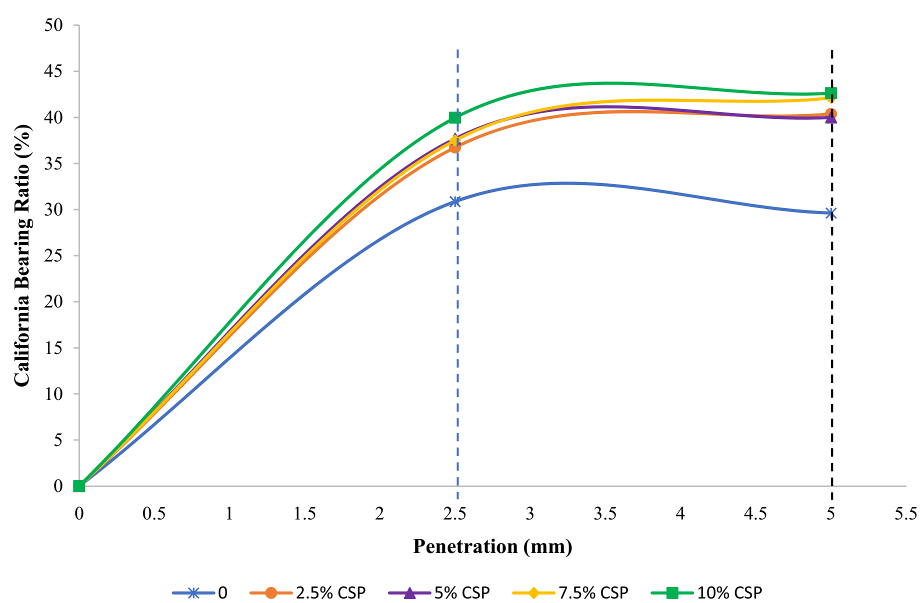
Site A (present study)			Site B [24]		
Stabilizer types	Percentage (%)	California bearing ratio (%)	Stabilizer types	Percentage (%)	California bearing ratio (%)
Control sample	0	5.76	Control sample	0	30.87
CSP	20	2.82	CSP	2.5	40.38
LP	20	4.57	CSP	5.0	40
CSP+LP	20 each	7.39	CSP	7.5	42.13
			CSP	10.0	40.88

Thus, from the results obtained, lime powder has again been proven as one of the most effective stabilizing agents for treating soil and improving the strength of marine soil [43, 48, 50] as cementitious reactions took place in producing CSA and CAH in the hydration process between lime and water whereby the value of the UCS of the marine soil increased to twice the value of the control sample which was also reported by [11]. Besides that, the UCS increased to four times the initial value which is related to the decrease of pores and lime content in the pozzolanic reactions and reduction of water. From the study, several conclusions can be made, such as marine soil has fine particles (clay and silt) due to the reaction between lime and clay [11] and a lower strength than black cotton soil.

Fig. 4 **a** Comparison of different admixtures on CBR of stabilized soil (soaked sample). **b** Comparison of CSP percentages on CBR of stabilized soil (unsoaked sample)



(a) Comparison of Different Admixtures on CBR of Stabilized Soil (Soaked Sample)



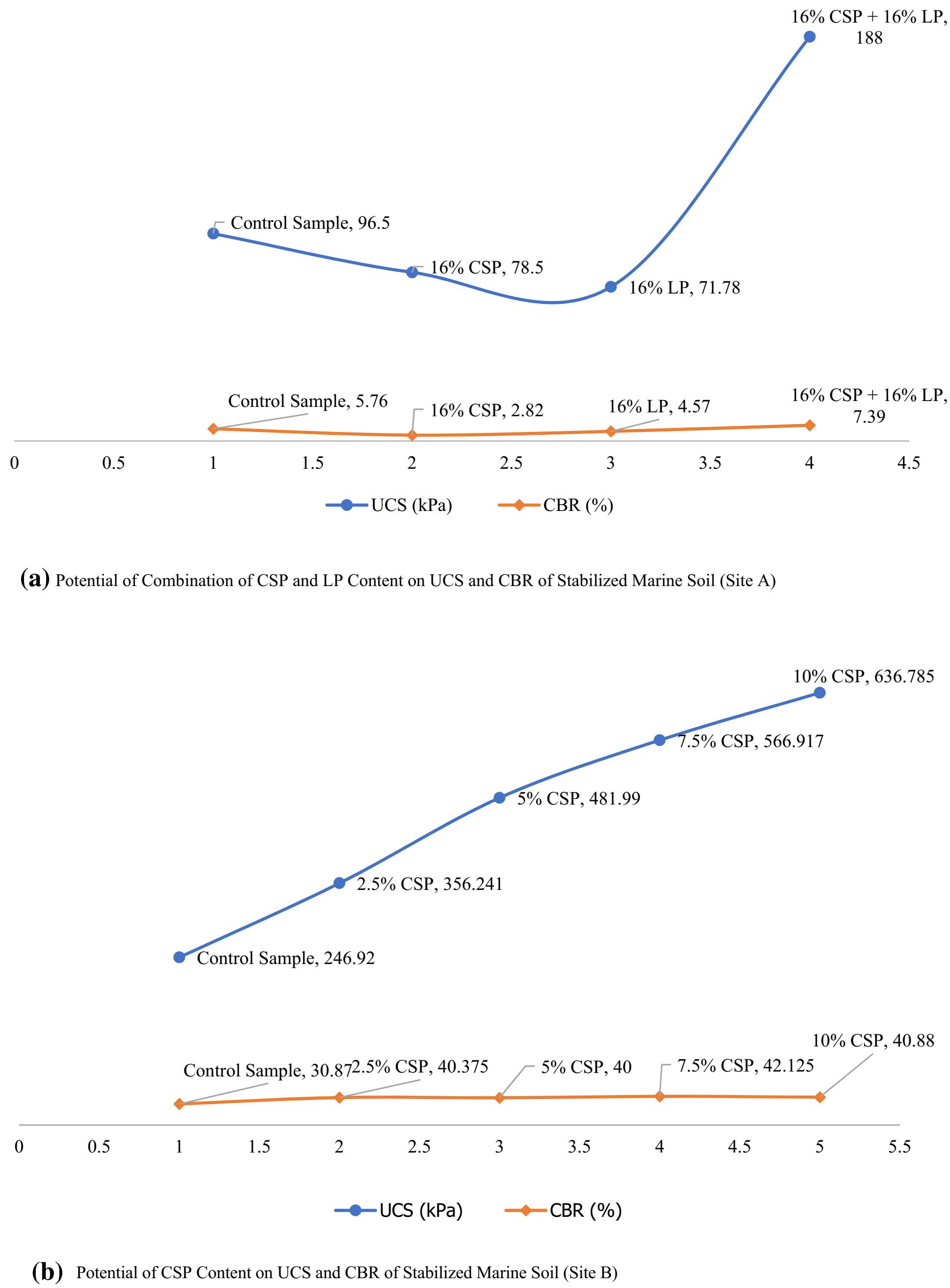
(b) Comparison of CSP Percentages on CBR of Stabilized Soil (Unsoaked Sample)

Moreover, the organic content acts as a cementing agent in the marine soil making it possibly moister and drier [1] than black cotton soil.

California Bearing Ratio (CBR)

The CBR tests were carried out on different types and percentages of stabilizers from the present and past study by [24] for both soaked (Site A) and unsoaked condition (Site B) samples. The soaked condition is used to assess the soil strength of subgrade in wet conditions critically compared to unsoaked conditions where samples were soaked in water for four days before the testing start [51]. The results of force versus penetration for unsoaked and soaked conditions of control samples are presented in Fig. 3 which indicates that the force increases with the depth of penetration for both conditions. The unsoaked condition of the control sample reached the maximum forces at failure compared to the control sample in the soaked condition which contained more water content by which the wet

Fig. 5 **a** Potential of Combination of CSP and LP Content on UCS and CBR of stabilized marine soil (Site A). **b** Potential of CSP content on UCS and CBR of stabilized marine soil (Site B)



condition led to decrease in soil strength. As the moisture content of the soil increases, the CBR value decreases due to the reduction of the shear strength and density of the experimental fine-grained soils [52].

Table 6 shows the CBR values of soaked condition samples from Site A and unsoaked condition samples from Site B at the top penetration reading. The untreated soil or control sample has the lowest CBR value of 5.76% for the top penetration in the soaked condition meanwhile the unsoaked condition sample showed a 30.87% CBR value in the dry condition. In addition to that, the 20% CSP of samples from Site A gave a low value of CBR that nevertheless started to increase by adding a secondary additive of lime that improved the CBR value due to the lime acting as a cementation material stabilizer which can increase the compressive strength [51]. By using the primary and secondary additives from CSP and LP, respectively, in soil stabilization as a partial substitute in conventional subgrade stabilization, the workability and durability of expansive subgrade can be improved while simultaneously getting economic benefits and improvement in the engineering properties of soil [4].

The results obtained show that the CBR value of the soil added with 20% cockle shell powder is lower than the control sample. This finding also indicates that the result is in contrast with previous studies of Site B [24], by which cockle shell powder could improve the bearing capacity of the soil [42] in supporting the achievement of an optimum CBR value of 3% by the addition of eggshell powder in clay type soil [51]. Furthermore, the CBR value increases with an increase in RHA content of up to 10% but an increase in RHA from 10% to 15% does not improve the load-carrying capacity significantly [53].

Figure 4a shows the percentages of the actual load causing the penetrations of 2.5 mm and 5.0 mm with the standard loads into soil in both soaked and unsoaked conditions of samples from Site A and B, respectively. The CBR ratio is a ratio of the bearing load that penetrates marine soil to a specific depth compared to the load giving the same penetration into the soil. The present study shows that the CBR ratio increases linearly with penetrations of 2.5 mm and 5.0 mm in the control sample with an addition of 20% CSP content. The addition of 20% LP and a combination of CSP and LP as primary and secondary stabilizers resulted in the optimum CBR at 2.5 mm and decreasing CBR values at 5.0 mm penetration. The resulting improvement in soaked CBR value with the addition of CSP and LP can be attributed to the pozzolanic reaction between the clay and pozzolanic material forming additional cementitious material that bounds particles together and enhances the strength of the soil [17].

It is proven that a combination of cockle shell powder and lime powder gain a tremendous increase in the CBR values of the soil whereby the lime acted as a cementation material stabilizer that can increase the compressive strength [51] indicating that the addition of cockle shell powder followed by compaction increases the load-bearing capacity of the marine soil tremendously from 1% to 28% compared with the control sample.

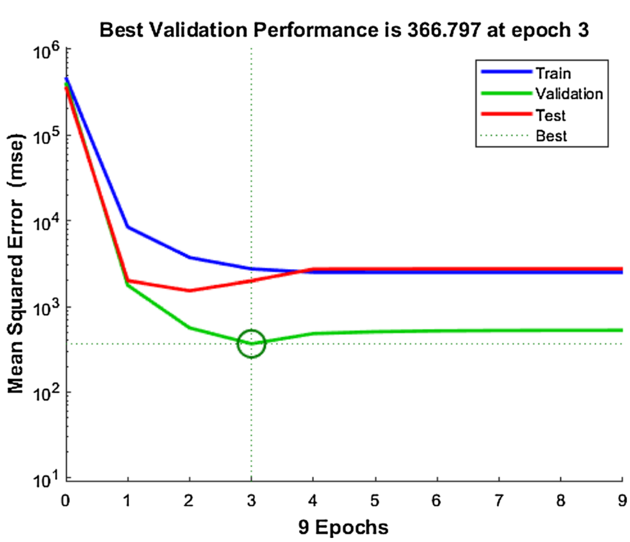


Fig. 6 Performance of ANN

Meanwhile, in Fig. 4b, there is a different trend showing the addition of CSP content giving an increment of CBR values at 2.5 mm top penetration and slowly getting constant when reaching the 5.0 mm penetration mark. The differences between the unsoaked and soaked conditions due to the tension forces under the soaked conditions which were having additional resistance to penetration under the unsoaked conditions are destroyed [53]. Figure 4a and b show that the CBR in soaked conditions of the present study is lower than the CBR in unsoaked conditions which agrees to the results found by [53, 54] due to the softening of the unstabilized sample during soaking.

Several factors might affect the results, which are similar to the UCT, whereby the mixture of soil and additives was not prepared properly and the volume of water used is too high, thus increasing the moisture content of the soil. Other than that, as the soil was soaked for four days, its moisture content was affected due to the curing effect [53, 54]. The reason for this is that the water infiltrated the soil reducing its strength thus became much weaker than the original unreinforced soil. Due to swelling, the testing on the top part of the sample was impossible as the penetration reached over 6 mm without any values.

Failure Assessment of Strength and Bearing Capacity on Marine Stabilized Subgrade Soil

This study aims to evaluate the potential of cockle shell powder as a binder between the additive and soil particles, which can initiate a reaction and eventually increase the UCS and CBR value of the marine soil. Fig. 5a presents the UCS and CBR at different types and percentages of CSP and LP in treated marine soil. The CBR value of the sample mixed with cockle shell powder is lower than the control sample. The cockle shell powder lowers the CBR value of the marine soil whereby the soil particles fail to resist the higher forces when penetrated, hence decreasing the bearing capacity of the soil. By adding more than 10% CSP content which is beyond the optimum UCS value, less significant effects can be seen by which the UCS produced an inward concave-shaped curve.

Meanwhile, the combination of CSP and LP in treated marine soil mixture shows an increase of 12.17% from the value of 5.76% to 7.39% that brought to a higher increment of UCS as well as CBR values. These findings are in line with the study conducted by [53] on the combination of different stabilizers in stabilized soil using cement, pond ash (PA), rice husk ash (RHA) mixed with clay soil which has sizes comparable to sizes of silt, as well as sand and fine particles, and has better gradation thus contributing to

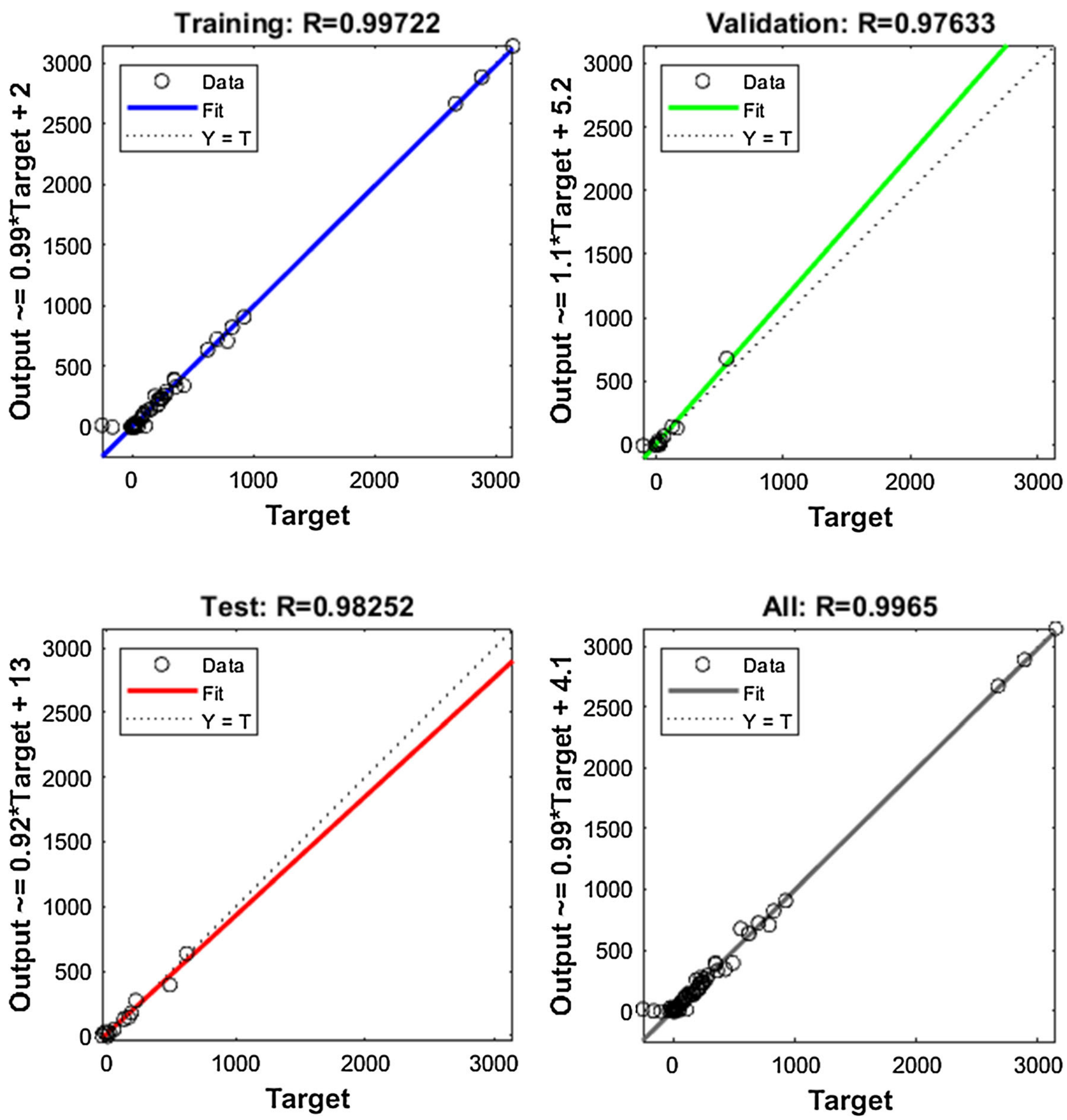


Fig. 7 Regression of ANN

greater frictional resistance. Due to this reason, the combination has greater potential to improve the strength of clay. Suthar and Aggarwal, [54] used different percentages of lime content in pond ash in both unsoaked and soaked conditions that showed increasing bearing ratio with increasing lime content. This may be due to the combination of both additives that successfully create good bonding with soil particles. This bonding will create a cementitious compound that contributes to pozzolanic reaction, which can significantly improve the long-term performance of the marine soil in strength and bearing capacity of the stabilized soil [53–55].

However, these current results contradict the expectations in Fig. 5b, when adding other stabilizers from by-product cement, lime, fly ash [43, 56] or waste materials such as eggshell [57] or CSP content to high percentage less than 10% [53], the results are similar to the past UCT results reported in those findings which indicated that the increase in stabilizers content will increase the strength and bearing capacity of marine soil.

Also in this study, fifty-nine data samples (70%) were used for training, twelve samples for validation (15%), and twelve samples for testing (15%) the network ability to generalize the data to estimate the strength of stabilized soil on subgrade bearing capacity using ANN. The characteristics of the used ANN are presented in Table 4.

The MSE between the predicted and measured values of input and output neurons was calculated in each epoch until

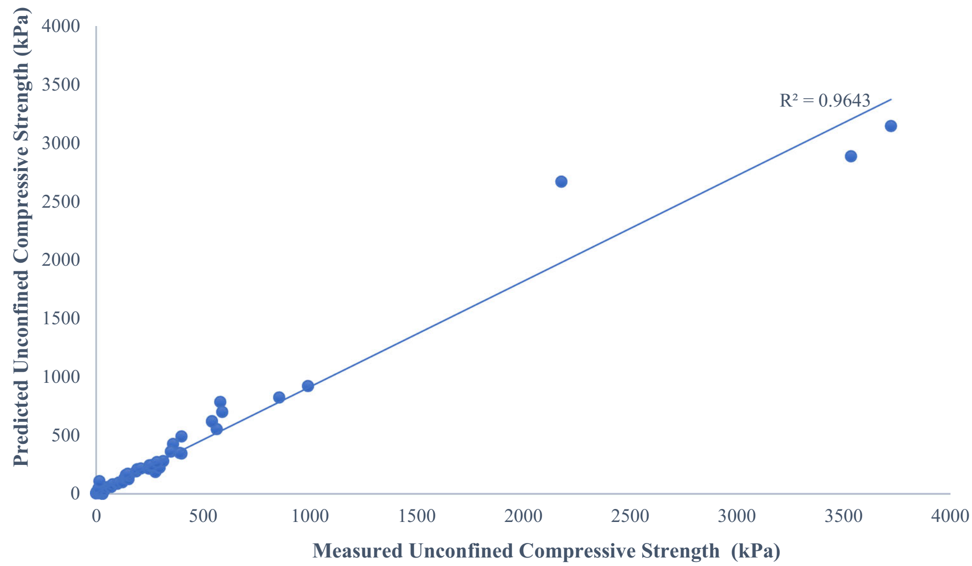


Fig. 8 Predicted and measured unconfined compressive strength

the minimum error value was met to find the optimum network, which is in the 9th epoch as shown in Fig. 6. The MSE is used to validate the performance of the models to predict the strength of stabilized soil. The best validation performance for the ANN model was 366.707 at epoch 3. The training and testing samples show similar trend however the validation samples drop far beyond the trend indicating a measured network generalization and halt training when generalization stops improving at epoch 3.

In terms of the R analysis, the results of the training dataset (Fig. 7) indicate that the R values of the ANN model vary from 0.976 to 0.997 indicating that all datasets from training, validation, and testing have a good fit with the user data which shows the capability for predicting the strength of stabilized soil in this study. This is also in line with [58] that predicted the UCS of geopolymer stabilized using ANN where training and testing datasets gave R values of 0.996 and 0.982, respectively, in contrast to [59] which predicted the strength of soil using the testing dataset of the ANN was one of the four models (PANFIS, GANFIS, SVR, ANN) which has a poor capability of prediction.

This indicates that the model can capture the input-output relationship by extracting the controlling features from the database presented to the network. Moreover, by using the correct inputs, the ANN will be able to model the strength parameters of stabilized marine soil with reasonable accuracy, and the model can also generalize the training data to simulate new data tests. Hence, this study agrees with the previous study that predicts the geotechnical properties of the soil from their index parameters [34, 45, 60].

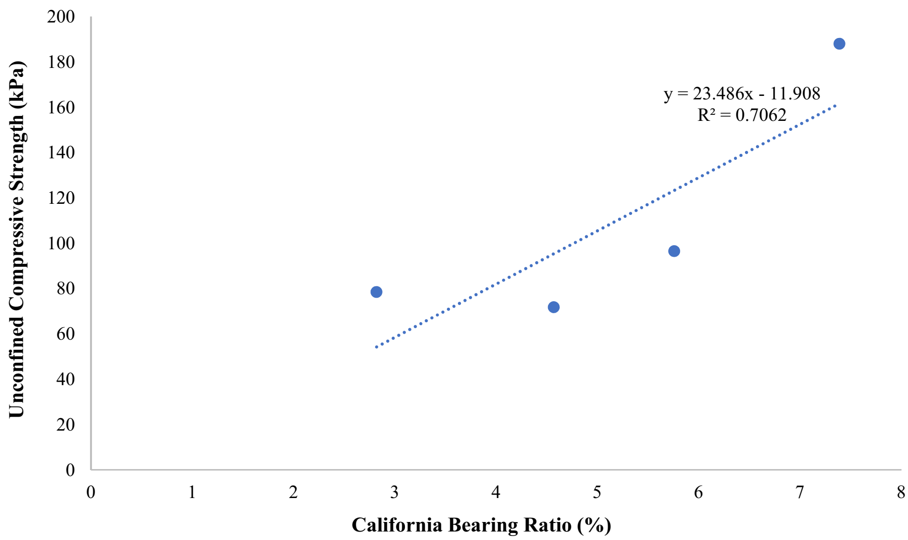
Figure 8 presents the regression plot for the predicted and measured UCS values in the testing phase. From the figure, it can be observed that the value of the coefficient of determination (R^2) is 0.96, which is near 1. This means that the regression line exactly fits the data used, and all of the variations between the predicted and measured values can be rationalized by the model because the model can be considered as 96% error-free, whereas when $R^2 = 0$, it shows that there is no linear correlation between the predicted and target values.

The evaluation on strength of stabilized marine soil for bearing capacity is estimated and results are presented in Figures 9a and 9b for soaked (Site A) and unsoaked (Site B) conditions, respectively. The relationship proposed shows the value of the coefficient of determination (R^2) for both conditions is less than one indicating a bad relationship in contrast to a study [36] done on soft soil. This is due to the different percentage content and type of stabilizers used for soaked and unsoaked conditions which gave inconsistent results. Past studies [23, 31, 52, 59] showed the prediction of the UCS and CBR using index geotechnical properties of soils such as liquid limit, plastic limit, maximum dry density and optimum moisture content using either the empirical mathematical method or machine learning method.

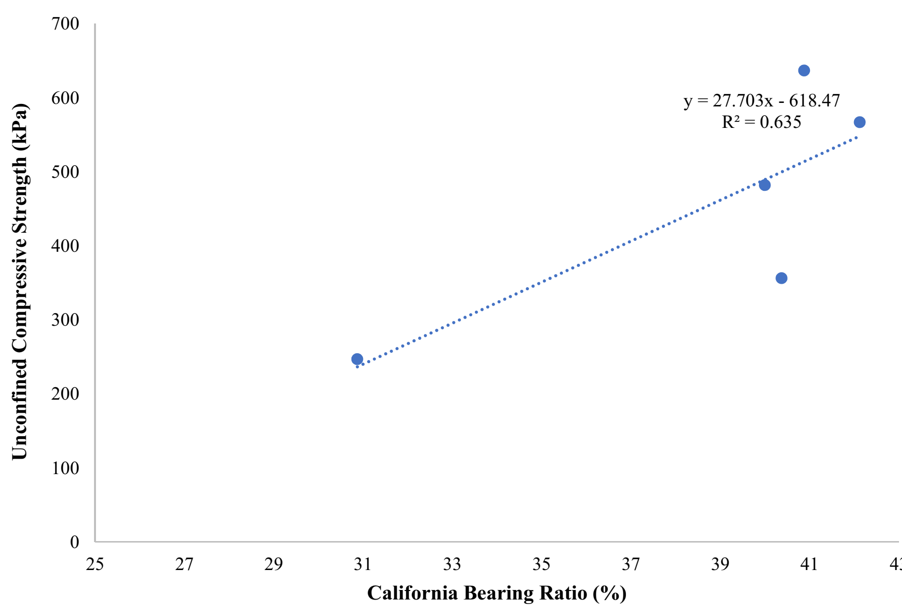
Conclusion

This study was performed to assess the failure strength and bearing capacity of marine stabilized subgrade soil. The study demonstrated the feasibility of using a simple ANN to predict the UCS using additives. A relationship between

Fig. 9 **a** Unconfined compressive strength and California bearing ratio (Site A). **b** Unconfined compressive strength and California bearing ratio (Site B)



(a) Unconfined Compressive Strength and California Bearing Ratio (Site A)



(b) Unconfined Compressive Strength and California Bearing Ratio (Site B)

UCS and bearing capacity ratio is established. Based on the obtained results, the following conclusions can be drawn:

- The 16% CSP content alone as a stabilizer does not increase the UCS thus by adding LP as a secondary additive, the results show that the compressive strength of the soil increased. Meanwhile, the CBR results show that the combination of 20% cockle shell powder and 20% lime powder in the treated soil gave higher values of CBR compared to the single content use of CSP stabilizer in the soil mixture.
- The regression (R) values of the ANN model vary from 0.976 to 0.997 indicating that all datasets from the training, validation, and testing have a good fit with the used data which shows a capability for predicting the strength of stabilized soil.
- The UCS and bearing capacity ratio fairly shows that the relationship between natural waste additives and treated soils can be misleading.

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