Prediction of the cementing potential of activated pond ash reinforced with glass powder for soft soil strengthening, by an artificial neural network model

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Abstract. The effect of Pond Ash (PA) activated with sodium chloride (NaCl) solution and reinforced with glass powder on the mechanical properties of soft clay soil, which comprise of the California bearing ratio (CBR) and the unconfined compressive strength (UCS) has been studied in this research work. The PA requires pozzolanic improvements to meet the ASTM C618 requirements for pozzolanas. In the present research paper, further emphasis has been on the machine learning prediction of CBR and UCS of the soft clay soil stabilized with a composite of PA. Generally, the studied soft clay soil properties, which were the microstructure, microspecter/micrograph, oxide composition, Atterberg limits, compaction behavior, free swell index (FSI), CBR and UCS significantly improved due to the enhanced cementitious ability of the activated and reinforced PA. The multiple data collected from this general stabilization result were used to predict the soil's CBR and UCS by the artificial neural network (ANN) technique. The results showed high performance of the model in terms of the sum of squares error (SSE) of 1.5% and 2.0% and the coefficient of determination (R^2) of 0.9979 and 0.9973 for the CBR and UCS models, respectively. The models also outclassed the performances of other models from the literature.

1 Introduction

Soil is one of the most widely used natural resources which is the uppermost layer of the earth and is formed by the continuous breakdown of rocks in the presence of temperature, water, pressure, frost, etc. Although all soils have the same mineral particles, organic matter, water and air, their properties might vary from one location to another because of the parent material i.e., the rock from which the soil has come, temperature, precipitation, and human influence [1]. The classification of soil can be viewed from the perspective of soil as a material and resource which can be in geology, agriculture, and engineering [1]. In the civil engineering field, cohesive soil has been the major challenge in the construction of foundation design, underground and earth retaining structures, pavement design, excavation, embankment and dams because of its poor bearing capacity, high compressibility, and low permeability [2]. Cohesive soil which is also known as black cotton soil is a soft soil that majorly contains iron, lime, magnesium, carbonate, phosphorus, and a few amounts of organic matter [3].

Due to the presence of a problematic mineral called montmorillonite found in it, it can be hazardous to construct structural buildings and other civil engineering structures on it, which calls for the need to boost the preferable properties of the soil such as the porosity, loading carrying capacity and hardness [4]. In order to improve its engineering characteristics to be suitable for construction several methods like drainage, surface compaction, vibration, grouting, consolidation, injection, soil reinforcement, thermal treatment, electro-osmosis, Geo-synthesis, chemical and mechanical stabilization are used. Some of these methods are costly and tedious to carry out but stabilization is low-cost construction and pollution controlling [2]. The fast development of industrialization caused the production of waste materials in large quantities which are hazardous to health and the environment [5]. A thermal power plant generates electric energy for industrial usage which alongside produce some waste by-product that contains 90% of fly ash and it affects the environment by polluting soil, water, and air [6].

Fly ash is made up of tiny particles that rise with the flue gas while that which does not rise it termed bottom ash. Pond ash is the term used to describe the leftover fly ash and bottom ash that are held in ash ponds. Pond ash consists of silica, alumina, and iron. It is known to be a weak pozzolan material because of the presence of silica in it [6]. Pond ash has been used in a variety of geotechnical applications including developing lands, highway embankments, road construction, and low-lying

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areas for the development of commercial and residential sites because it improves the soil strength and reduces the suck and shrink characteristics [7]. Glass powder is a by-product material from the process of glass treatment, it has been most often used as soil stabilizer because it can create impressive change in the properties. Glass powder has been used in landfilling, load construction, highway pavement, and drainage purpose. When used, it was discovered it is a good building material that reduces the load of landfilling. In drainage, it reduces the time of water accumulation behind the wall because of its high permeability. It has the physical property of high permeability, small strain stiffness, and high crushing resistance which made it a good pozzolan material [8].

This research work is keen to study the effect of pond ash activated with sodium chloride (NaCl) solution and reinforced with glass powder on the mechanical properties of soft clay soil which comprises the Unconfined Compressive Strength (UCS) and the California bearing ratio (CBR).

Lakshmisha and Manoj attempted to reduce the moisture movement capacity of the Black cotton soil by the addition of pond ash. Black cotton soil stabilized with pond ash increases the maximum dry density and reduces the specific gravity. When 30% pond ash (by weight of soil) was added to Back cotton soil, it improves the strength carrying capacity to a maximum extent and a long tern curing effect was recorded. Also, when the optimum pond ash was added, it improves the California bearing ratio (CBR) value by 128% [9]. Bharat and Nirpinder investigated the result of California bearing ratio (CBR) tests on Black cotton soil with varying percentages of pond ash. The soaked CBR value of virgin soil increased by 624% on the addition of 20% pond ash for 7 days, 14 days, and 28 days of curing the samples [2]. Kolay and Sii studied the stabilization potential of class F pond ash on tropical peat soil. According to the UCS test, the amount of pond ash (i.e., 5%, 10%, 20%) applied to the original peat sample improved the compressive strength of the peat that had been stabilized with it. With the addition of 20% pond ash to the original peat soil weight, the compressive strength of the peat-pond ash sample nearly doubled from the original peat soil. In comparison to the original tropical peat soil's compressive strength of 77.6 kPa, the UCS value for stabilized peat soil with the addition of 20% pond ash by weight after 28 days provided the greatest average compressive strength of 153.9 kPa [10].

Some of the other studies on soft soil were conducted by using glass powder. Syed and Sudipta examined the impact of using waste glass powder to stabilize the soil. Through the addition of glass powder, both the soaked and unsoaked CBR increased reaching maximum values of 22.5% and 10.4%, respectively. Once 8% of glass powder of dry-weight of soil was added, the UCS increased to 133.5 kN/m^2, while decreased to 119.7 kN/m^2 when 10% of Glass powder was added [11].

Additionally, several scholars look into soil stabilization by applying machine learning for predictive modeling. Eyo and Samuel investigated the use of machine learning techniques called gradient boosting (GB) to model the unconfined compressive strength (UCS) of soils stabilized by cementitious addition. By an overall accuracy of 0.920, weighted scores for precision and recall rate of 0.938 and 0.920, respectively, and an overall lift of 5 in a multinomial Classification, GB Algorithms demonstrate a very high capacity to distinguish between positive and negative UCS categories (firm, very stiff, hard) [12].

Most of the studies in the literature affirm the use of pond ash with glass powder in soft soil strengthening as an environmentally responsible project as this totally replaced cement, which has been established as having high carbon emission. It has been realized that using the idea of artificial intelligence (AI) as applied in this work could save money, time, and resources during the design stages of soil improvement, choice of curing duration, laborious trial batching of binder type, quantities, optimal combinations, extensive laboratory analysis and the determination of other influencing factors were performed.

2 Methodology

2.1 Treated Soil Database and Statistical Analysis

The soft soil's basic properties were tested according to BS 1377 [13] to characterize it and the treatment was carried out based on BS 1924-1 [14]. A database of 25 soil samples tested to determine the physical and mechanical properties of pond ash (PA)-treated soft soil reinforced with glass powder (GP) was tabulated and utilized in this research project. Generally, the soil was found to be an A-7(5) group of soil based on ASHTO classification with a plasticity index of 17.07%, which translates to a highly expansive consistency. It also possessed a free swell index of 110, optimum moisture content of 21.15% with an associated maximum dry density of 1.34g/cm^3. The SEM, XRF, and XRD were carried out on the soil and the GP-NACL-PA blend to study the microstructure and mineral composition of the test materials [15-20]. The following were the mixture materials and the treated soil parameters; Glass Powder content (GP) %, Sodium Chloride content (NACL) %, Pond Ash content (PA) %, Liquid limit (LL) %, Plastic limit (PL) %, Free Swell Index (FSI) %, Optimum Moisture Content (OMC) %, Maximum Dry Density (MDD) g/cm^3, California Bearing Ratio (CBR) %, and Unconfined Compressive Strength (UCS) MPa. The measured records were divided into a training set (20 records) and a validation set (5 records). In Tables 1 and 2, their statistical characteristics and the Pearson correlation matrix, are summarized [21-26]. Figure 1 presents the distribution histograms for both inputs and outputs.

Table 1. Statistical analysis of the collected database.

	Min.	**Max.**	**Mean**	**Range**	**Variance**	**S.D.**	**Skewness**	**Kurtosis**
GP	0.00	9.17	4.23	9.17	7.84	2.80	0.27	-1.17
NACL	0.00	13.09	6.17	13.09	17.34	4.16	0.14	-1.28
PA	0.00	22.47	10.15	22.47	49.42	7.03	0.13	-1.21
LL	33.27	57.19	45.72	23.92	36.11	6.01	-0.16	-0.40
PL	29.97	42.60	36.01	12.63	15.07	3.88	0.07	-1.18
FSI	47.89	125.85	82.68	77.96	471.52	21.71	0.07	-0.81
OMC	12.24	23.20	17.27	10.96	7.60	2.76	0.42	-0.34
MDD	1.24	2.00	1.56	0.76	0.03	0.19	0.34	-0.16
CBR	1.61	11.34	6.51	9.73	10.17	3.19	-0.27	-1.38
UCS	1.07	2.88	2.03	1.81	0.38	0.61	-0.17	-1.57

Table 2. Pearson correlation matrix.

	GP	NACL	PA	LL	PL	FSI	OMC	MDD	CBR	UCS
GP	1.00									
NACL	1.00	1.00								
PA	0.99	1.00	1.00							
LL	-0.67	-0.66	-0.64	1.00						
PL	0.70	0.69	0.70	-0.12	1.00					
FSI	-0.89	-0.90	-0.89	0.86	-0.41	1.00				
OMC	-0.78	-0.80	-0.79	0.85	-0.22	0.95	1.00			
MDD	0.72	0.72	0.74	-0.10	0.80	-0.46	-0.32	1.00		
CBR	0.96	0.97	0.97	-0.57	0.67	-0.84	-0.77	0.74	1.00	
UCS	0.97	0.97	0.97	-0.56	0.69	-0.82	-0.75	0.73	0.98	1.00

2.2 Research Program for the Intelligent Prediction

An Artificial Neural Network (ANN) [21-26], was used to predict the values of both CBR and UCS for the treated soil using the measured GP %, NACL %, PA %, LL %, PL %, FSI %, OMC %, and MDD g/cm^3. The prediction accuracy was evaluated in terms of the Sum of Squared Errors (SSE) [21-26].

3 Results and Discussion

3.1 Microstructure of the Test Materials

Figure 2 shows the surface configuration of the soil and the mixture of glass powder, sodium chloride, and pond ash. The GP-NaCl-PA blend structure shows a crystal structure of strong pozzolanic configuration according to Bauluz Lazaro [15]. The tetrahedral layer consists of a dominant structure of silica and quartzite minerals, which gives it the strengthened pozzolanic ability when utilized in soil stabilization. Fig. 3, which shows the micrograph of the mineral structure of the mixed blend of GP-NaCl-PA and the soft soil also confirms the binding ability of the GP-NaCl-PA blend with rich composition of quartz, calcite and other cementing strength-based minerals. This agrees with the surface configuration of the composite blend. Generally, the microstructural and mineralogical analyses conform with the results of UCS and CBR improvement of the treated soft soil, which shows a strength increase with the addition of the activated PA reinforced with GP.

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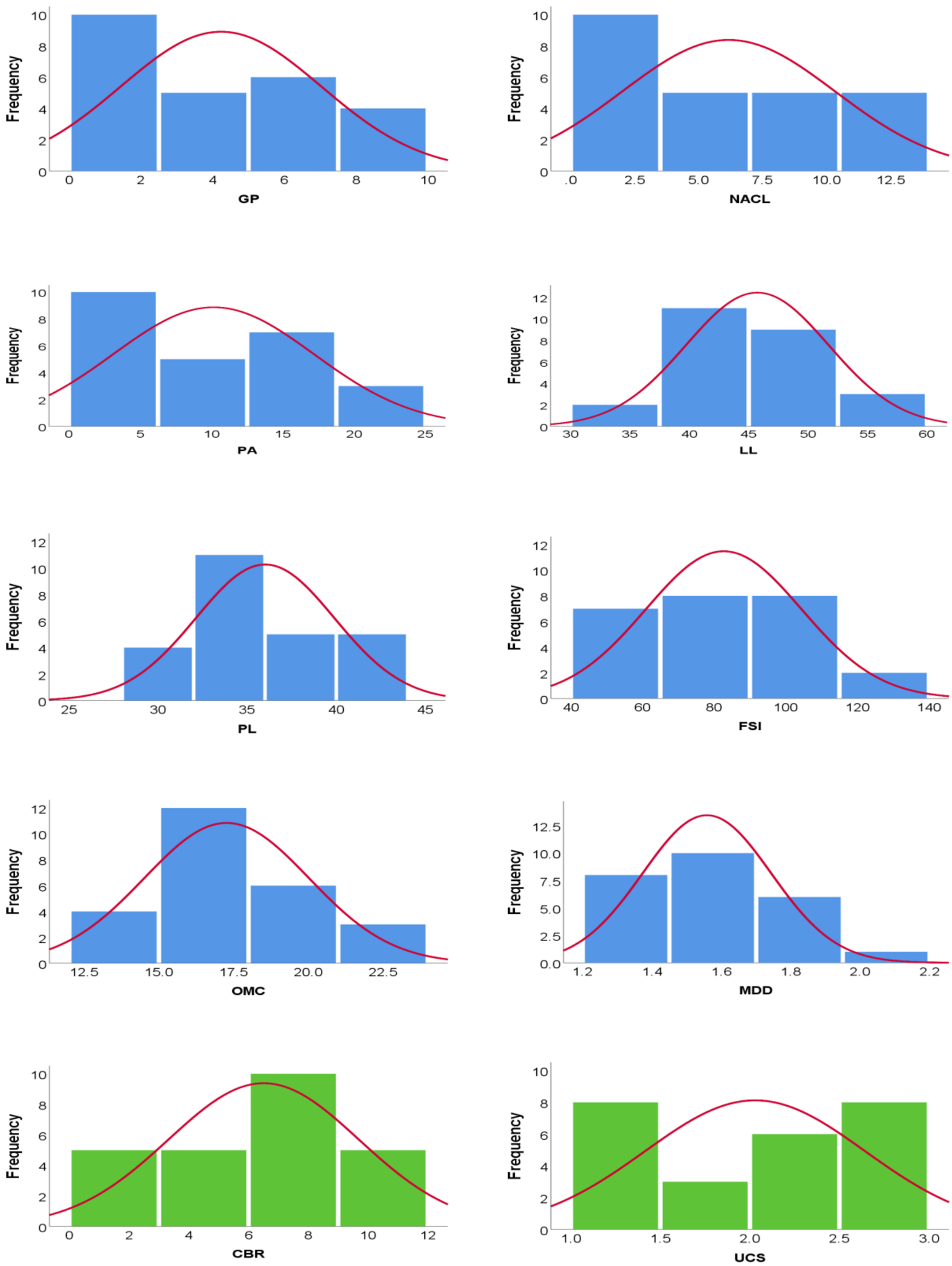

Fig. 1. Distribution histograms for inputs (in blue color) and outputs (in green color).

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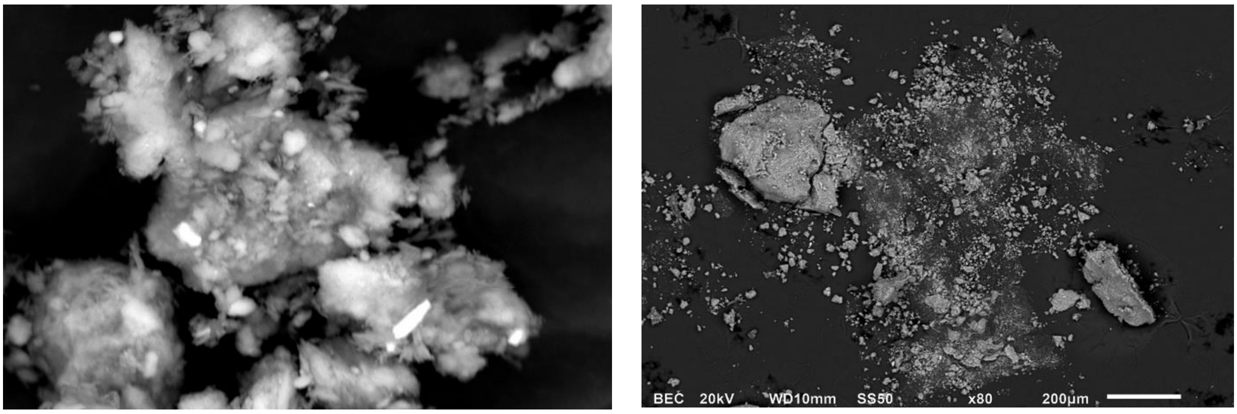
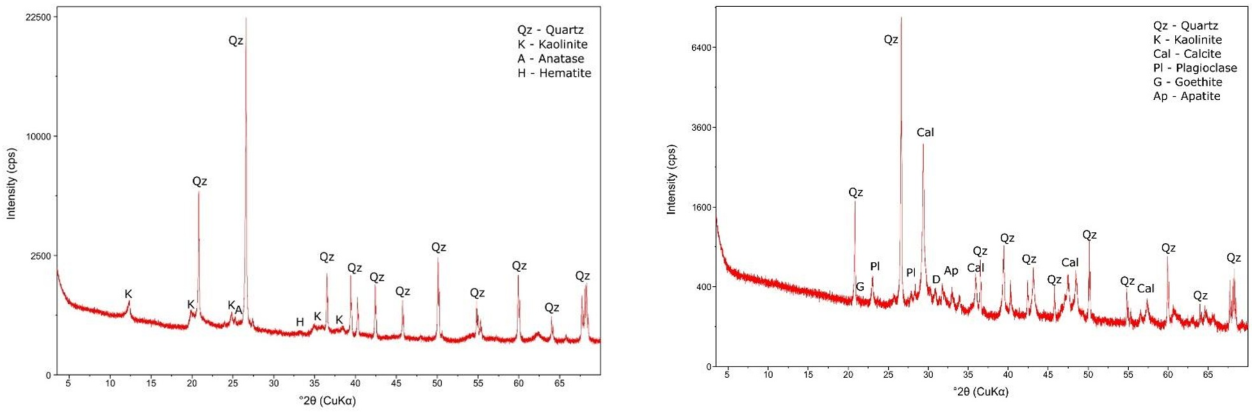


(a) (b)

Fig. 2. The microstructure of; (a) GP-NaCl-PA blend and (b) untreated soft soil.



(a) (b)

Fig. 3. The micrograph of; (a) untreated soft soil and (b) GP-NaCl-PA blend.

3.2 Prediction of the CBR and the UCS of the PA-GP-Treated Soft Soil

A backpropagation ANN with one hidden layer of the 10:3:2 model network and Hyper Tan activation function [21-26] was used to predict both the CBR and UCS values of the PA-GP-Treated Soft Soil. The used network layout and its connection weights are illustrated in Figure 4 and Table 3. The average errors of these models were 1.5% and 2.0% and the corresponding R^2 values were 0.998 and 0.997 for the CBR and UCS, respectively. It also showed a near-perfect fit between the predicted and measured values. The relation between calculated and predicted values is shown in Figure 5. The absolute summation of the link weights at each node in the input layer presents the relative importance of each considered parameter as shown in Figure 6. It can further be observed from the relative importance of the studied parameters of the stabilization exercise and following a model that GP, PA and NACL showed a strong influence on the predicted model, which agrees with their role in the stabilization protocol as a strong hybrid binder in their blended constitution and agreeable to composite ash behaviors [16-20]. Overall, the eco-friendly materials (GP and PA), which improved the studied strength characteristics of the soft soil have provided a potential for their utilization in the stabilization of soft soil to meet the sustainability requirements for environmentally responsible soft soil reengineering. Also, the models are based on this PA and GP soil stabilization potential and their carbon neutrality pathway to save the environment from cement utilization emissions.

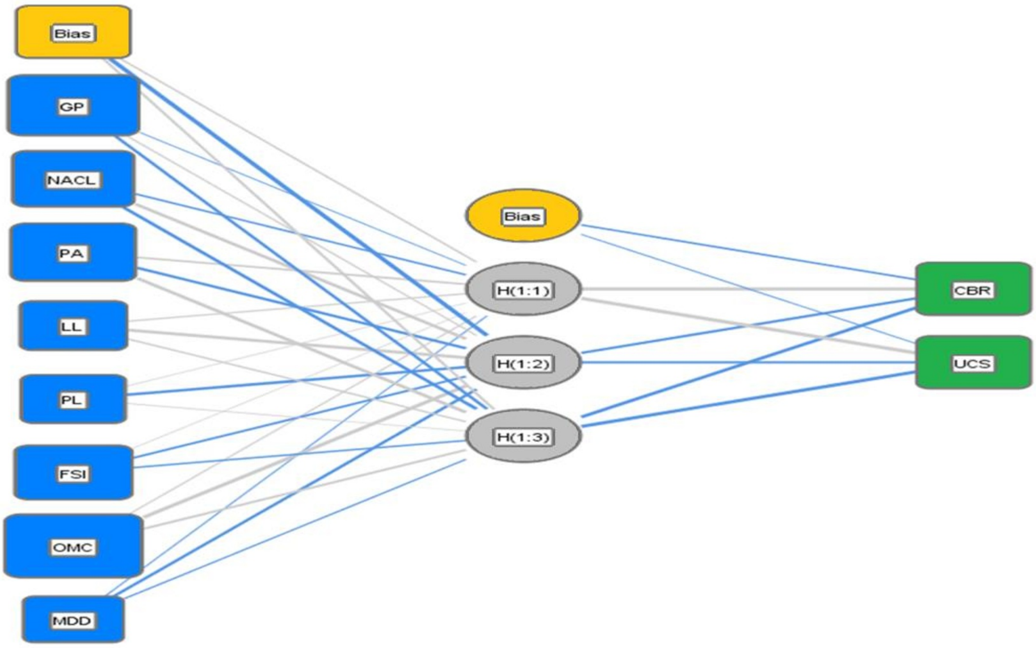


Fig. 4. Architecture layout of the developed ANN model and its connection weights.

Table 3. Connection weights for the developed ANN.

		Hidden Layer			
		H(1:1)	H(1:2)	H(1:3)	
Input Layer	(Bias)	0.31	-3.21	0.72	
	GP	-0.16	0.27	-0.93	
	NACL	-0.45	1.66	-1.48	
	PA	0.76	-1.28	2.00	
	LL	0.29	2.57	0.32	
	PL	0.03	-1.55	0.09	
	FSI	0.01	-0.81	-0.38	
	OMC	0.27	2.82	0.82	
	MDD	-0.18	-1.00	-0.27	
		Hidden Layer			
		H(1:1)	H(1:2)	H(1:3)	(Bias)
Output Layer	CBR	3.23	-1.19	-2.30	-0.67
	UCS	3.95	-0.86	-3.09	-0.19

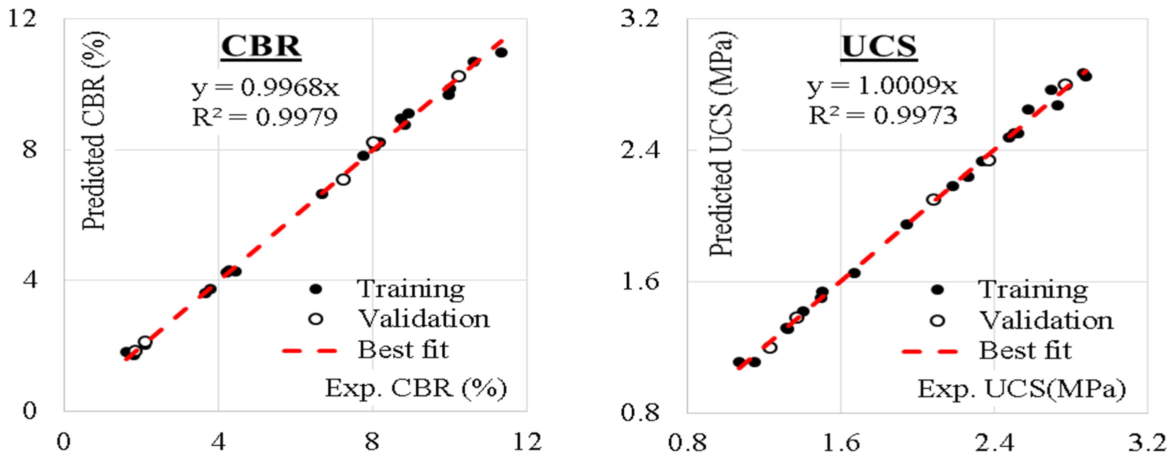


Fig. 5. Relation between predicted and calculated (CBR) values using the developed models.

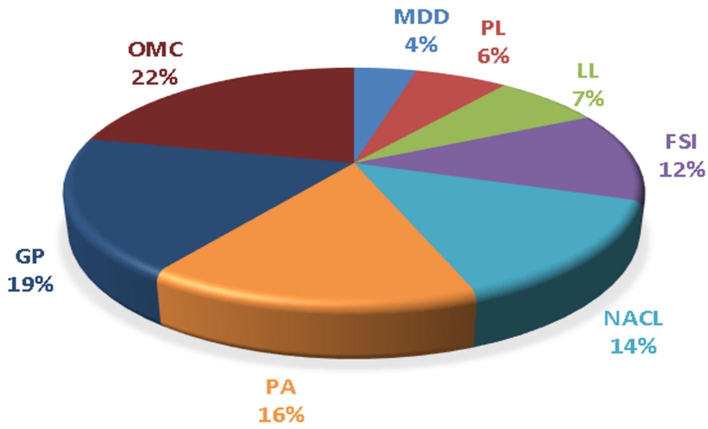


Fig. 6. Relative importance of each considered parameter.

4 Conclusions

This research presents the strength behavior of a GP-NACL-PA treated soil and an artificial neural network model to predict the values of both the California Bearing Ratio (CBR) and the Unconfined Compressive Strength (UCS) for the treated soil using the measured Glass Powder content (GP), Sodium chloride content (NACL), Pond Ash content (PA), Liquid Limit (LL), Plastic Limit (PL), Free Swell Index (FSI), Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) as the independent parameters. The results could be concluded as follows:

- The NACL-activated PA reinforced with GP showed a potential to be used as an alternative binder in soft soil stabilization as it substantially improved the strength properties in terms of the CBR and the UCS of the treated soil.
- The prediction accuracies of the ANN model were 98.0 and 98.5% with R^2 values of 0.998 and 0.997 for the CBR and the UCS, in that order.
- Absolute summation of weights in the ANN model, showed that OMC has about 25% of the total importance, both OMC and GP have about 45%, and four contents OMC, GP, PA and NACL have about 75% of the total importance while other parameters have the rest 25%. It indicates that the mixture contents have a major impact on both CBR and UCS.
- Generally, the utilization of the GP and the PA in the stabilization as a total replacement for cement has provided a pathway for carbon neutrality for a healthier construction environment and the elimination of the cement's carbon footprint.
- As in other regression techniques, the herein generated formulas are valid only within the considered range of parameter values, and beyond this range, the prediction accuracy should be verified.

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