Estimating the swelling potential of non-carbon–based binder (NCBB)-treated clayey soil for sustainable green subgrade using AI (GP, ANN and EPR) techniques

Kennedy C. Onyelowe[1,*], Ahmed M. Ebid[2], Michael E. Onyia[3] and Ezenwa C. Amanamba[4]

[1]*Department of Civil and Mechanical Engineering, Kampala International University, Bushenyi, Kampala, Uganda;* [2]*Department of Structural Engineering, Faculty of Engineering and Technology, Future University, New Cairo, Egypt;* [3]*Department of Civil Engineering, University of Nigeria, Nsukka, Nigeria;* [4]*Department of Civil Engineering, Gregory University, Uturu, Abia State, Nigeria*

Abstract

A zero carbon footprint stabilization approach has been adopted in this research to improve the swelling potential (SP) of clayey soils for a greener construction approach. Construction activities like earthworks during the cement stabilization of unstable soils utilized as reconstituted subgrade materials is responsible for the emission of unhealthy amount of carbon oxides into the atmosphere contributing to ozone layer depletion and eventual global warming. This has been substituted by using eco-friendly cementing materials, quicklime activated rice husk ash (QARHA), formulated in this research work. The SP of clayey soil treated with QARHA has been predicted using the learning abilities of genetic programming (GP), artificial neural network (ANN) and the evolutionary polynomial regression (EPR). This was aimed at reducing the over dependence on repeated laboratory visits and experiments prior to infrastructure (pavement) designs, construction and future monitoring of the performance of the facility. Multiple data were collected from multiple experiments based on the tested emergent material (QARHA) treatment proportions used in this work. The data were subjected to statistical analysis and predictive model exercises. At the end, the predicted models were validated on the basis of performance and accuracy. The performance indices showed that EPR and GP with R^2 of 0.997 outclassed ANN with R^2 of 0.994, but EPR outclassed the two, GP and ANN with a minimal error of 6.1%. The performances of GP, ANN and EPR were compared with a previously conducted model, which utilized the learning techniques of the adaptive neuro-fuzzy interface system (ANFIS) and it was observed that EPR and GP performed better than ANFIS but ANN performed at par with it. Generally, the predictive models can predict the SP of subgrade soil treated with QARHA, a non-carbon–based binder with accuracy above 90%, which is a very good outcome.

Keywords: carbon footprint–based materials; global warming; non-carbon–based binder (NCBB); artificial intelligence; sustainable subgrade; clayey soil; swelling potential

*Corresponding author: kennedychibuzor@kiu.ac.ug, konyelowe@gmail.com and konyelowe@mouau.edu.ng

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1 INTRODUCTION

Soil is the most fundamental element in civil engineering construction; it plays the ultimate role of support for all structures. For this reason, the adequacy of the soil is of great concern, without compromising the adverse impact of using carbon footprint–based binders like cement [1]. In the broad spectrum of soils classified in accordance with the American Association of State Highway and Transportation Officials, granular materials having 35% or less passing through the 0.075 mm mesh have been preferred for construction, particularly for pavements; however, in practice, in the field, it is common to meet problematic soils on the side of the divide—having more than 35% passing through the 0.075 mm sieve mesh. These problematic soils are typically silt and clay, the poorest being clayey soil. Over the years, studies have proposed ways of improving the geotechnical properties of these soils by employing compressive mechanisms and introduction of various additives [2–6].

Considering the cross-section of a typical pavement—rigid or flexible, and the idea of soil being the foundation material herein called the subgrade, a more difficult problem then arises when the subgrade is a clayey soil. Soil materials with significantly high clayey content are considered expansive—having the tendency to yield to volume fluctuations when the moisture content varies [7–9], especially with the reduction of surface evaporation due to the area being covered by a pavement [6, 10, 11].

Expansive soils also present as having clay minerals like montmorillonite and vermiculite [12] and smectite clay materials [13]. The totality of the internal and external areas of the mineral particles of expansive soil determines its swell ability, such that by mere enlargement of capillary films of clay minerals when water absorption occurs through the external areas, a small amount of swelling can occur [14]. Figure 1 shows that water ingress into expansive soil causes the water present in the voids to increase, thereby forcing the clay plates to move further away from each other; then, as the water evaporates, the clay plates move closer to each other.

Kariuki and Van Der Meer [14] stated that a soil is considered expansive if the liquid limit and plasticity index (PI) exceeds 50% and 30%, respectively. Other than adopting Atterberg limit tests as the indices for swelling potential (SP) of expansive soils, Kariuki and Van Der Meer [14] reported that cation exchange capacity test, saturated moisture content test and coefficient of linear extensibility can equally be adopted.

These expansive clay materials as subgrade are commonly the causes of several forms of pavement deterioration and, if unchecked, ultimately leads to a complete failure of the pavement or other structures [15–18].

To improve the strength and other engineering properties of these expansive subgrade soils, carbon emission–based cement has been extensively used as traditional binder materials [19–21]; however, for the sake of increased costs and various environmental concerns like carbon emissions that have been raised [22–27], use of industrial and agricultural waste materials have long been explored as total or partial replacement for cement and lime [26, 28] forestall the dangers of using these carbon-based binders.

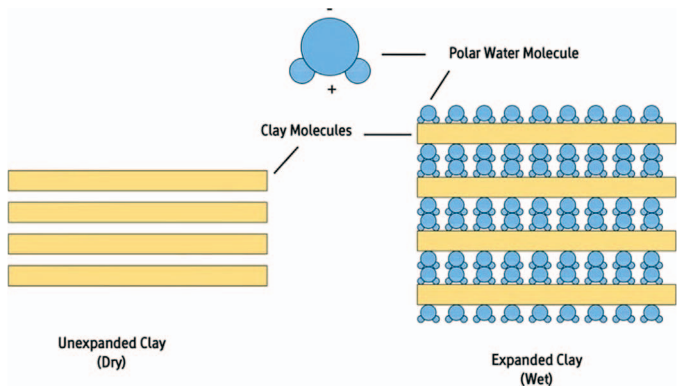

Figure 1. *Effect of water on the structure of expansive soil [13].*

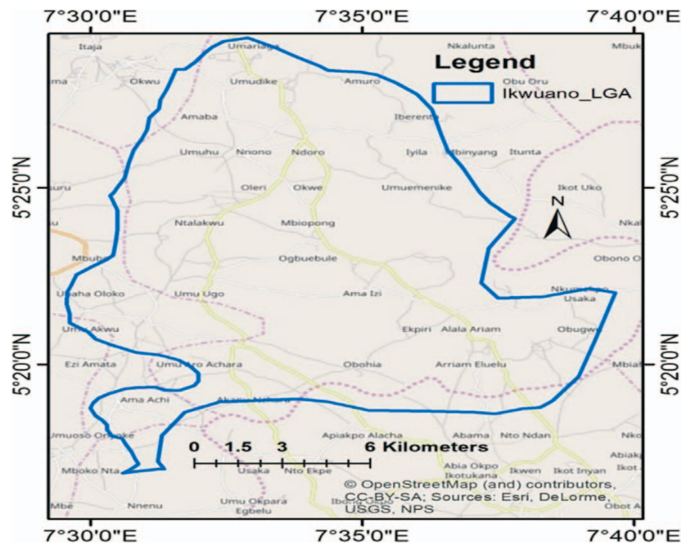

Figure 2. *Soil sample location map.*

Figure 3. *Reference soil preparation by sieving through a 2 mm aperture sieve.*

Using rice husk ash (RHA) and calcium carbide residue, which are non-carbon–based binder (NCBB) as stabilizing agents, at a 65:35 mix ratio, Liu *et al.* (2019) [29] studied the behavior of expansive soil. It was observed that with increase in the quantity of the binder mixture, fineness of soil, swelling pressure, SP and crack quantity reduced remarkably, while cohesion, angle of

Figure 4. *Rice husk as NCBB source.*

Table 1. *The used database.*

Q %	PI %	Measured SP %	ANFIS SP %
	Training set		
0.5	42	19.7	19.24
8.5	10	0.6	0.80
6	13	1.1	1.10
4.5	22	4.1	4.10
10.5	9	0.5	0.65
2	35	12.7	12.63
9.5	10	0.6	0.96
1.5	37.5	15	14.82
3	30	8.7	8.69
1	40	17.5	17.07
8	10	0.6	0.80
9	10	0.6	0.80
12	8	0.3	0.49
11.5	8	0.3	0.33
6.5	12	0.9	1.05
5.5	16	1.9	1.90
3.5	28	7.3	7.29
	Validation set		
10	10	0.6	0.96
2.5	31.5	9.8	9.76
7	10	0.6	0.46
7.5	10	0.6	0.63
11	9	0.5	0.65
4	24	5	7.29
0	45	23.35	22.86
5	19	2.9	2.90

internal friction and unconfined compressive strength improved greatly. The study further reported that these positive outcomes were achieved following the mechanism of replacement efficiency, ion exchange and coagulation reaction.

The behavior of expansive soil modified with RHA and sugarcane bagasse ash, activated by liquid alkaline (sodium metasilicate and sodium hydroxide) as NCBB was studied by Kishor *et al.* (2021) [30]. By monitoring the expansion ratio and free swell ratio at 7 days interval, for a maximum period of 21 days, it was found that increase in the stabilizing agents caused a decrease in the swell potential of the soil, as well as an increase in the strength as obtained from the unified compressive strength and California bearing ratio tests.

A by-product of the paper industry—calcium lignosulphonate—was adopted by Sharmila *et al.* (2021) [31]. In gradual proportions, under curing periods of 0–28 days, the expansive soil showed a decrease in swell pressure and swell potential and an average increase in strength properties at optimum lignosulphonate of 1.5%. The findings of this study were corroborated by Chavali and Reshmarani [32].

Demonstrating the effect of using lime and quarry dust independently and as a mixture of both as NCBB, on the swell index of expansive soil, Anand *et al.* (2020) [33] found that at optimum compositions of 9% and 24% for lime and quarry dust, respectively, the differential free swell reduced by 75% and 100%, respectively. On combining the two stabilizing agents, the effect was such that the PI decreased by 31% and 66%, respectively. Similarly, there was significant improvement in the strength properties as revealed by the unconfined compressive strength test, for all curing durations.

The literature on the effect of several emergent waste materials on swell potential of expansive soil is inexhaustible. However, little or no attempt has been made to model these effects, such that without repeated laboratory experiments and with limited parameters, forecasts can be made about the swell potentials of a given clayey subgrade soil. Hence, this paper seeks to adopt genetic programming (GP), artificial neural network (ANN) and evolutionary polynomial regression (EPR), to develop models to predict the swell potential of clayey subgrade soil treated with RHA activated by quicklime, using $SP = f(PI, Q)$ as the governing equation.

2 MATERIALS AND METHODS

2.1 Materials preparation

The clayey soil used for this research work was collected from Ndoro Oboro, Abia State borrow pit, the map location of which is presented in Figure 2. The soil was prepared as presented in Figure 3 in accordance with British Standard International BS1377 [34] basic requirements and stored for the laboratory work at room temperature. The rice husk collected from rice farms and local factories is presented in Figure 4. Also, the treated soil, which was mixed with quicklime activated rice husk ash (QARHA), was prepared in line with British Standard International BS 1924 [35].

The quicklime (CaO) used for the activation of RHA had the following properties 'whitish water-soluble caustic material with a melting point of 2613°C, boiling point of 2850°C, density of 3.34g/cm^3 and pH of 12.4, cubic halite structure, crystalline solid at room temperature, obtained from the burning of limestone, dissociates into the ions of calcium and oxygen, has abundant supply of calcium for calcination and pozzolanic reaction with clayey soil dipole minerals, forms hydrated lime in aqueous solution, and has indeterminate pH due to transition speed'. From the pozzolanic requirement of ASTM C618 [36] and BS 8615–1 (2019), CaO possesses cementing properties. According to Onyelowe *et al.*

Table 2. *Statistical analysis of collected database.*

	Training set			Validation set		
	Q %	PI %	SP %	Q %	PI %	SP %
Max.	0.50	8.00	0.30	0.00	0.46	0.46
Min	12.00	42.00	19.70	11.00	45.00	23.35
Avg	6.06	20.03	5.44	5.88	19.81	5.42
SD	3.66	12.18	6.56	15.55	11.44	7.35
Var	0.60	0.61	1.21	2.65	0.58	1.36

[6], 'the RHA was derived from the direct combustion of rice husk collected from rice mills in Abakaliki, Nigeria. The ash according to studies satisfies the requirements of a pozzolanic material in accordance with British Standard International BS 8615-1 (2019) and American Standard for Testing and Materials ASTM C618 [36] due to the presence of Al_2O_3, SiO_2 and Fe_2O_3 in its chemical oxides' composition. The release of silica and alumina from the activated rice husk ash triggers pozzolanic reaction in the clayey soil adsorbed complex interface through hydration and calcination'.

2.2 Experimental methods

Preliminary tests were conducted in accordance with BS 1377 [34] on the reference soil to determine the natural moisture content (NMC), the PI and SP with the Atterberg limit test method, the maximum dry density (MDD) and optimum moisture content (OMC) with the compaction test and the soil particle gradation with the particle size analysis (PSA) method. Also, the scanning electron microscopy and x-ray fluorescence tests were carried out on the soil, RHA and QARHA for the purposes of classification and characterization [37] and were done in accordance with the requirements of ASTM E1621-13 [38]. The QARHA was further utilized in varying percentages to treat the clayey soil in accordance with the soil stabilization requirements of BS 1924 [35] and multiple observations were taken for PI and SP. The multiple data from the laboratory exercises were collected and tabulated and applied in the intelligent learning prediction of SP.

2.3 Collected database and statistical analysis

In gathering the multiple experimental data points, 25 soil samples were tested to determine the following proprieties:

- QARHA dosage (Q) %;
- PI % and
- SP %.

The measured records were divided into training set (17 records) and validation set (8 records). Table 1 includes the complete dataset, while Tables 2 and 3 summarize their statistical characteristics and the Pearson correlation matrix, respectively. Finally, Figure 5 shows the histograms for both inputs and outputs.

Table 3. *Pearson correlation matrix.*

	Q	*PI*	*SP*
Q	1		
PI	−0.93674	1	
SP	−0.86454	0.970561	1

2.4 Research program

Three different artificial intelligence (AI) techniques were used to predict both PI and SP of the tested soil samples. These techniques are GP, ANN and polynomial linear regression optimized using genetic algorithm, which is known as EPR. All the three developed models were used to predict the values PI and SP using the measured QARHAdosage (Q). Each model of the three developed models was based on different approach (evolutionary approach for GP, mimicking biological neurons for ANN and optimized mathematical regression technique for EPR). However, for all developed models, prediction accuracy was evaluated in terms of sum of squared errors (SSEs). The following section discusses the results of each model. The accuracies of developed models were evaluated by comparing the (SSE) between predicted and measured values of PI and SP. Besides that, the predicted values of SP were compared with earlier predictions using adaptive neuro-fuzzy interface system (ANFIS) technique. The results of all developed models are summarized in Table 5.

3 RESULTS AND DISCUSSIONS

3.1 Preliminary characterization

The preliminary tests, the results of which are presented in Table 4 and Figure 5, show that the reference soil had 45% of the particles smaller than 0.075 μm, with highly plastic consistency and high degree of expansion with SP of 23% [37]. The soil was classified as an A-7-6 soil according to AASHTO classification [39]. The soil also exhibited low density with MDD of 1.25 g/cm³ obtained at OMC of 16%. It can also be observed from Figure 6 that the soil was poorly graded and unsuitable to be used as a subgrade material except treated to improve these properties. Table 5 and Figure 7 show the results of the chemical

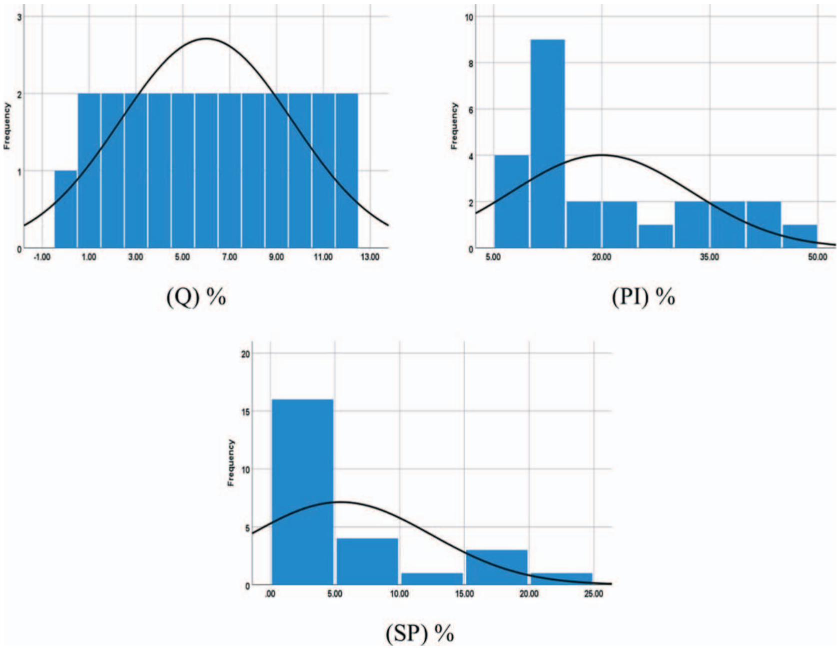

Figure 5. *Distribution histograms for inputs and outputs.*

Table 4. *Particle size distribution of test materials.*

Soil property	% Passing no. 200 sieve	NMC	LL	PL	PI	SP	AASHTO	MDD	OMC	DoE
Value	45	14	66	21	45	23	A-7-6	1.25	16	High

oxide composition of the materials and the surface morphology, respectively. It can be observed that the RHA and its composite, the QARHA as emerging supplementary binder exhibited high levels of pozzolanity with the three main compounds responsible for cementing showing a compound composition of more than 70% satisfying the conditions stipulated by ASTM C618 [36] on pozzolanic materials or supplementary cementing materials. Further on, shown in Figure 6 are the surface behavior of the material, which showed that RHA and CaO have gel-like formation but not as pronounced as those developed by their formulated composite, the QARHA, which shows an improved specie of supplementary binder through alkali activation. The tabulated values of SP and PI presented in Table 1 showed substantial improvement in the studied parameters, which shows that the gel formation as shown in the surface morphology of the binder materials added to the improved geotechnics of the clayey soil.

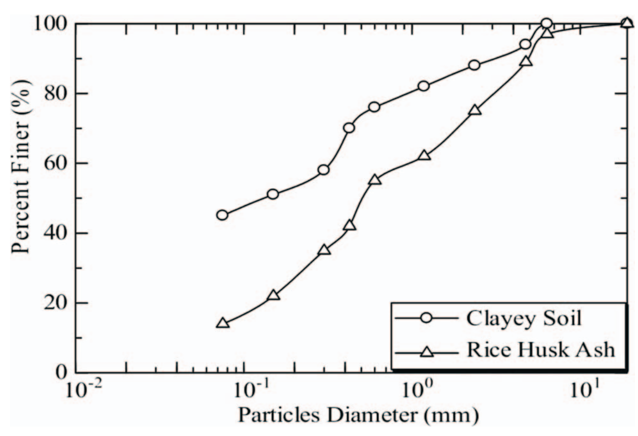

Figure 6. *Particle size distribution curve of the clayey soil and RHA.*

3.2 Prediction of PI and SP values

3.2.1 *Model 1—using GP technique*

The developed GP model started with the one level of complexity and settled at three levels of complexity. The population size, survivor size and number of generations were 100 000, 30 000 and 100, respectively. Equations (1) and (2) present the output formulas for PI and SP, respectively, while Figures 8a and 9a show their fitness. The average errors % of are 9.8% and 6.8%, while the R^2 values are 0.974 and 0.997 for PI and SP, respectively. The

Table 5. *Chemical composition of the additive materials.*

Materials	Composition (content by weight, %)												
	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2	LOI	P_2O_5	SO_3	*IR	Free CaO
Clay soil	12.45	18.09	2.30	10.66	4.89	12.10	34.33	0.07		5.11			
RHA	52.1	22.70	4.58	3.07	4.65	2.76	0.71	3.17	0.88				5.38
QARHA	53.5	24.8	17.3	2.95	0.5	0.03		0.02					

**IR is insoluble residue; LOI is loss on ignition.*

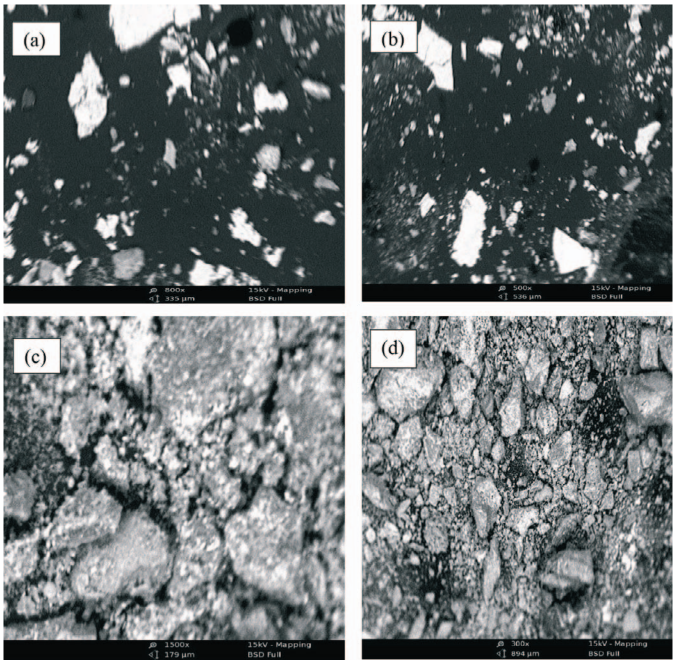

Figure 7. *Microstructural configuration of (a) clayey soil, (b) RHA, (c) quicklime and (d) QARHA.*

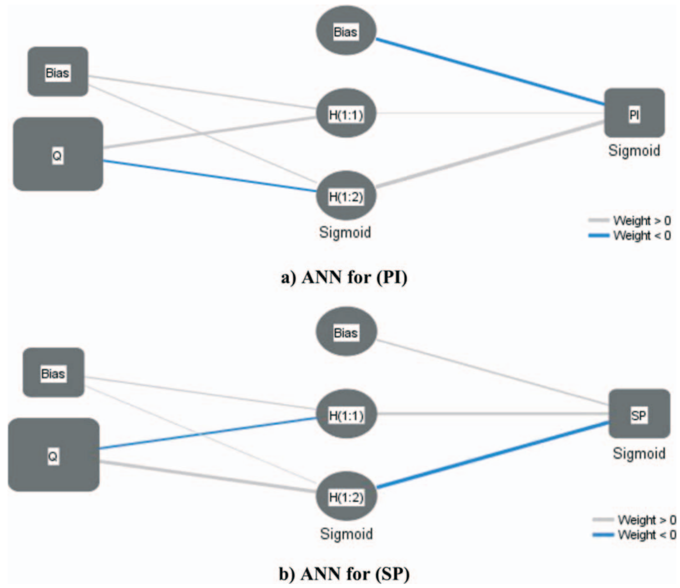

Figure 8. *Layout for the developed ANN's and their connection weights.*

intelligent verification agrees with the findings of [40–42]:

$$PI = 6.9^{(22-Q)/11} \quad (1)$$

$$SP = \frac{23}{(1.23 + Q/25)^{1.14\,Q}} \quad (2)$$

3.2.2 *Model 2—using ANN technique*

Two back propagation ANN's with one hidden layer and (sigmoid) activation function was used to predict the values of PI and SP. The used networks layout and their connation weights are illustrated in Figure 8 and Table 6. The average errors % of these networks are 5.1% and 9.6%, and the R^2 values are 0.992 and 0.994. The relation between calculated and predicted values is shown in Figures 9b and 10b, and the results agree with the results of previous works that utilized ANN prediction [40, 43].

3.2.3 *Model 3—using EPR technique*

Finally, the developed EPR model was limited to cubic level, for one input. The outputs were illustrated in Equations (3) and (4), and their fitness is shown in Figures 8c and 9c. The average errors% and R^2 values were 7.0%–0.986 for PI and 6.1%–0.997 for SP. These show that the closed form equations can be used to forecast future design and construction of SP and plasticity on the subgrade of treated clayey soils to an accuracy of over 95%. The summary of the performance of the models is presented in Table 7.

$$PI = 47 - 7.34\,Q + 0.35\,Q^2 \quad (3)$$

$$SP = 23.6 - 7.0\,Q + 0.68\,Q^2 - 0.022\,Q^3 \quad (4)$$

4 CONCLUSIONS

This research presents three models using three (AI) techniques (GP, ANN and EPR) to predict the values of both PI and SP using the measured NCBB, QARHA dosage (Q). The results of comparing the accuracies of the developed models with earlier

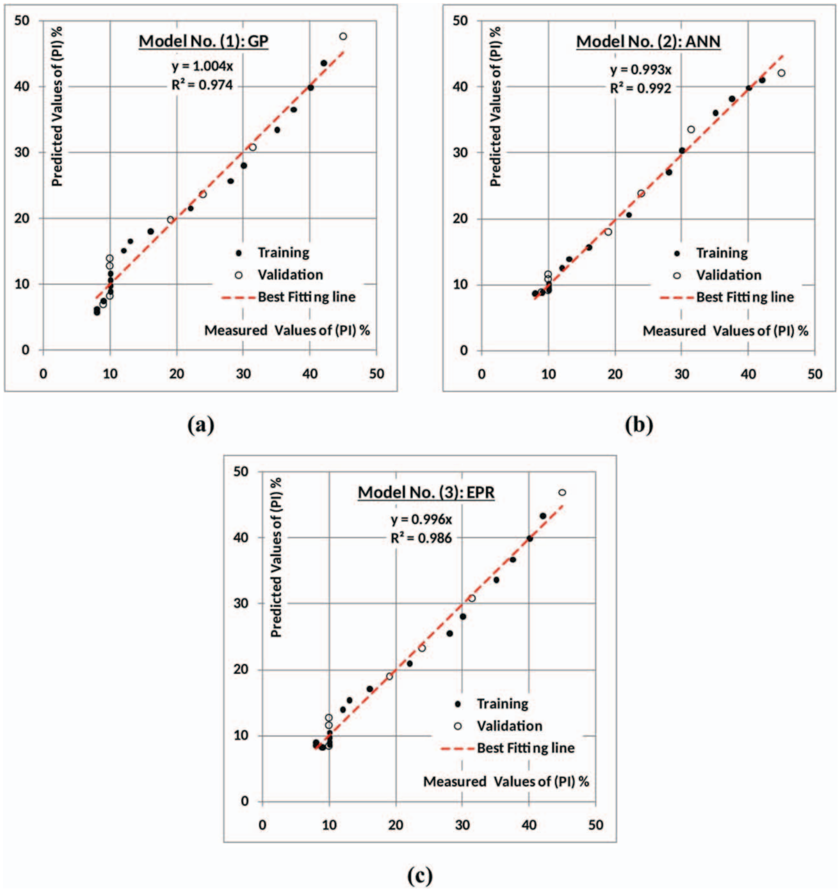

Figure 9. *Relation between predicted and measured PI values using the developed models.*

Table 6. *Connection weights for the developed ANN's.*

ANN for PI		Hidden layer 1		Output layer	**ANN for SP**		Hidden layer 1		Output layer
		H(1:1)	H(1:2)	PI			H(1:1)	H(1:2)	SP
Input	(Bias)	1.557	0.904		Input	(Bias)	2.517	0.582	
layer	Q	3.506	−3.476		layer	Q	−4.065	6.574	
Hidden	(Bias)			−5.466	Hidden	(Bias)			2.550
layer 1	H(1:1)			0.728	layer 1	H(1:1)			6.222
	H(1:2)			10.270		H(1:2)			−9.239

Table 7. *Accuracies of developed models.*

Technique	For PI			For SP		
	Developed model	Error %	R^2	Developed model	Error %	R^2
GP	Equation (1)	9.8	0.974	Equation (2)	6.8	0.997
ANN	Figure 2a	5.1	0.992	Figure 2b	9.6	0.994
EPR	Equation (3)	7.0	0.986	Equation (4)	6.1	0.997
ANFIS				After …	9.4	0.994

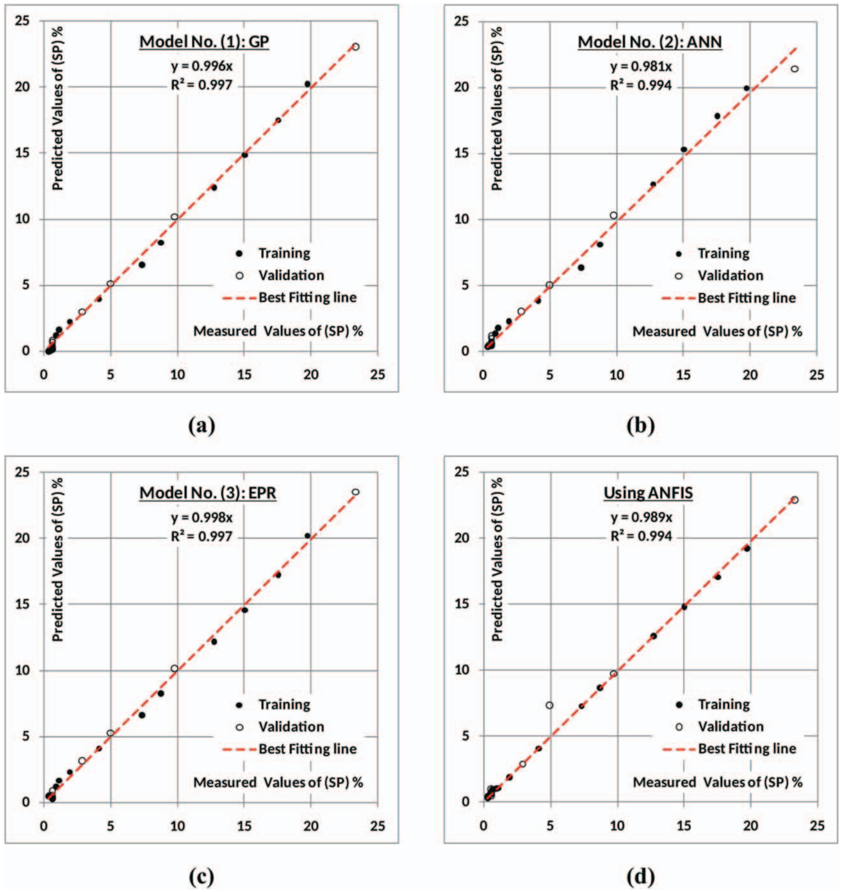

Figure 10. *Relation between predicted and measured SP values using the developed models.*

prediction technique (ANFIS) could be concluded in the following points:

- Overall stabilization protocol shows impressive improvement of the PI and SP of the NCBB treated clayey soil, and this shows the potential of strengthening weak soils utilizing carbon emission–free binder materials formulated from waste and activator materials blends that saves the environment from the devastating effect of the use of carbon footprint binders like cement during earthwork operations.
- The prediction accuracies of all developed models are close (90.4–94.9%), which gives an advantage to GP and EPR models because their outputs are simple equations and could be applied either manually or implemented in software unlike the complicated output of the ANN and ANFIS, which cannot be applied manually.
- All developed models indicated that both PI and SP nonlinearly decrease with increasing Q. Also, SP values nonlinearly increase with increasing PI.
- Like any other regression techniques, the developed models are valid within the considered range of parameter values; beyond this range, the prediction accuracy should be verified.

SUPPLEMENTARY DATA

Supplementary material is available at *International Journal of Low-Carbon Technologies* online.

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