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S. J. Abbey,[1] S. Ngambi,[2] and E. Ganjian[2]

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[1] School of Energy, Construction and Environment, Coventry University, Coventry, CV1 5FB, United Kingdom (Corresponding author), e-mail: samjonax@yahoo.com

[2] School of Energy, Construction and Environment, Coventry University, Coventry, CV1 5FB, United Kingdom

ABSTRACT

This paper presents the possible inclusion of pulverized fuel ash (PFA) and ground granulated blast slag (GGBS) in cement deep soil mixing for enhancement of unconfined compressive strength (UCS) of weak soil materials for construction purposes. The main focus of this paper was to investigate the UCS of cement-, cement/PFA- and cement/PFA/GGBS-improved soils, and development of mathematical and graphical models for prediction of UCS for use in design and construction. Samples of cement, blends of cement and PFA, and cement/PFA/GGBS were prepared using 5 %, 10 %, 15 %, and 20 % by weight of dry soil and tested for UCS after 7, 14, 28, and 56 days. A multiple regression analysis was conducted using the SPSS computer program. The results showed that soil materials with lower plasticity show higher strength development compared to those of higher plasticity for cement improvement. The study has also revealed that the inclusion of PFA and GGBS can cause a reduction in the amount of cement in deep soil mixing, which can result to reduced cost and emission of carbon dioxide (CO_2) during construction. The developed mathematical and graphical models could give reliable predictions of UCS for weak soil materials with initial UCS less than or equal to 25 kPa and for water to binder ratio of unity based on the observed agreement between experimental and predicted data. The developed multiple regression models have also been validated using different mixtures of 6 %, 8 %, 12 %, and 16 % of binders.

Keywords

weak soil, deep soil mixing, unconfined compressive strength, strength model, cement-improved soils, cement/pulverized fuel ash/ground granulated blast slag–improved soil, regression model

Introduction

Soil improvement becomes very necessary when the present state of a soil, in terms of its engineering properties, fails to meet the proposed use of the site. Deep soil mixing techniques have been designed to address the problems associated with performance of weak engineering soils due to poor resistance of these soils to shear deformation, low bearing capacity, and excessive vertical compression (Shakri et al. 2014). Undoubtedly, cement-soil mixing technique has been widely employed in the construction field for strength enhancement and improved compressibility, (Abbey et al. 2015; Farouk and Shahien 2013; Gaafer et al. 2015; Chen et al. 2016). Unconfined compressive strength (UCS) is one of the most important parameters in the design of cut-off walls for prevention of seepage in water-retaining walls. The UCS of portland cement (PC) stabilized soils are usually high, making PC the most commonly used binder in soil improvement, (Holm 2003; Terashi 2003; Consoli et al. 2015; Oana 2016). Chen et al. (2016) examined the variation in the UCS of marine clay improved with cement during a wet deep mixing work at the Marina Bay Financial Centre in Singapore. In their study, the UCS of the improved clay was found to vary from about 700 kPa to about 5 MPa. The 28-day UCS of samples improved with cement and prepared using wet mixing method is always higher than those prepared by dry method (Pakbaz and Farzi 2015). According to Chen et al. (2016), strength distribution in deep mixing–improved soils is affected by in situ soil properties and the chemical reactions between soil and cementitious constituent. UCS increases with increase in cement content, especially for nonplastic soils (Asturias and Lorenzo 2015). Weak soils respond differently in terms of their UCS when mixed with cement, GGBS, and PFA, depending on the plasticity of the unimproved soils (Celik and Nalbantoglu 2013; Abbey et al. 2016). Lately, problems particularly associated with cost and the environment have emerged because the production of every ton of PC releases approximately one ton of carbon dioxide (CO_2) (Ganjian et al. 2015). CO_2 is a key contributor to greenhouse gas emissions that are contributing highly to global climate change. The production of cement accounts for approximately 8 % of global CO_2 emissions according to Ganjian et al. (2008). Therefore, the possibility of reducing the amount of cement and inclusion of pozzolans such as PFA and GGBS would provide greener deep soil mixing operations. For these reasons, investigation into possible inclusion of waste (byproduct) materials and reduction in cement content during deep soil mixing was investigated. According to Gyanen et al. (2013), better soil gradation, increase in strength, and reduction in plasticity properties are the most likely achievable results in the use of additives like GGBS and PFA in soil improvement. Akinmusuru (1991) observed an increase in strength with increasing GGBS content up to 10 %. According to Gupta and Seehra (1989), partial replacement of GGBS with fly ash causes an increase in UCS in comparison to natural soil. Increase in the percentage of GGBS can lead to considerable reduction in pavement thickness (Ashish et al. 2014) during improvement of subgrade materials. Obuzor et al. (2012) found that the application of industrial byproduct material (GGBS) activated by lime can enhance the bearing capacity of clay soils and give durable road structural layers, especially in areas prone to flooding.

However, these studies have not stated clearly the applicability of these byproducts in deep soil mixing and their effect on soil type in terms of plasticity, and consideration of model development for prediction of UCS of soils improved with cement and waste material inclusion such as PFA and GGBS. Therefore, this study focuses on investigating UCS of cement-, cement/PFA-, and cement/PFA/GGBS deep mixing–improved soils and development of a numerical and graphical model for prediction of UCS.

Methodology

LABORATORY STUDIES

The UCS of a deep mixing–improved soil is an indication of the degree of reaction in the soil-binder-water mixture based on the rate of hardening of the improved mixture. Therefore, the type of binder used during deep mixing could be of great significance in determining the extent of improvement. In the ongoing study, five soil samples with varying plasticity and UCS less than 25 kPa were studied. The Atterberg limit test was conducted based on procedures outlined in the British Standard BS 1377-2:1990, *Methods of Test for Soils for Civil Engineering Purposes* (1990). The different soil types were improved using cement, a blend of cement and PFA, and cement/PFA/GGBS. Table 2 shows chemical compositions of the different binders used. Cement contents of 5 %, 10 %, 15 %, and 20 % by weight of dry soil were used for the cement-improved soils. The cement/PFA-improved soils consisted of a 50 % reduction in cement content used in the case of soil-cement and inclusion of an equal amount of PFA. The cement content was further reduced to 33.33 % and replaced with equal amounts of PFA and GGBS to produce cement/PFA/GGBS-improved soils. In all, the total percentage of binder was kept constant, summing up to 5 %, 10 %, 15 %, and 20 %. The wet deep soil mixing was conducted on the investigated soils with initial properties presented in Table 1, and during mixing, the percentage of water added to each mix was equal to the percentage of binder being mixed, making the ratio of percentage of water to that of binder equal to unity (i.e., w:b = 1). The soil samples after proper mixing were placed into 40-mm diameter by 76-mm height cylindrical tubes in stages, and in each stage, the cylinder

TABLE 1 Summary of the initial properties of the investigated soils.

Soil Properties	Symbol	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5
Moisture content (%)	w	86	45	36	61	54
Liquid limit (%)	ω_l	68.0	41.66	45.16	87	63.12
Plastic limit (%)	ω_p	30.83	36.67	30.1	42.3	53.20
Plasticity index	I_p	37	5	15	45	10
Unit weight (kN/m^3)	Υ	25	23	22	24	21
Specific gravity	G	2.55	2.35	2.24	2.45	2.14
Unified classification	USCS	CH	ML	MI	MH	MH
Strength (kPa)	UCS	12.8	14.4	18.5	16.3	14.8

TABLE 2 Summary of chemical compositions of the different binders.

	Oxides (%)											
Binder	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	hP_2O_5	SO_3	LOI
Cement	19.63	0.26	4.71	3.25	0.09	1.17	64.09	0.27	0.73	0.20	2.94	3.22
PFA	52.15	0.87	19.61	7.10	0.07	2.00	4.40	1.06	1.93	0.45	0.54	9.48
GGBS	33.28	0.57	13.12	0.32	0.316	7.74	37.16	0.33	0.474	0.009	2.21	4.42

was tapped several times against a hard surface in order to ensure the removal of any air bubble trapped within the samples. To ensure that equal degree of compaction at saturation was achieved for all mixed samples, a dead weight of 10 kg was placed on the mixed samples in the cylindrical tubes before extraction. Since UCS is directly related to density, it is affected by degree of compaction and water content in the mixture Little and Nair (2009). The improved samples were then sealed, wrapped with a thick plastic, and cured under water for 7, 14, 28, and 56 days. The samples were subjected to a UCS test at the end of each curing period.

Multiple Regression Analysis

Multiple regression analysis was conducted as a means of developing mathematical expressions that could predict the performance of deep mixing–improved soils in terms of their UCS using the analysis of variance (ANOVA) approach.

The numerical models have been developed based on results of UCS tests conducted on five different soil samples improved using cement, cement/PFA and cement/PFA/GGBS. The predicted models followed the general equation of multiple regression analysis as shown in Eq 1.

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3}, i = 1,2,3 \ldots ..n \qquad (1)$$

Where Y_i is the dependent variable (UCS). The subscript on Y represents the particular time of interest at which the UCS is measured. β_i is a numerical constant depending on the relationship between UCS and the independent variables (binder content and curing time). $X_{i\ 1,2,3}$ are independent variables at different observational units and β_o is a constant. In this analysis, it was assumed that random errors are normally and independently distributed with zero mean and common variance, and there are no random errors in the independent variables.

$$\text{Random error assumptions} : \in_i \sim NID\,(0,\sigma^2)$$

The null hypothesis of the F-test in ANOVA for multiple regression analysis is that the model has no explanatory power. This is same as saying that all the coefficients on the independent variables are zero, meaning none of the independent variables helped in predicting the dependent variable. Also, the null hypothesis for T-statistics assumes zero coefficients for a given independent variable. The significance of these tests was tested to ascertain the reliability of the proposed models.

Results and Discussion

Effect of Cement and PFA/GGBS inclusion on UCS

The effect of cement with and without PFA and GGBS on the UCS characteristics of the weak soils was investigated. Three series of UCS tests were conducted to assess the strength development of these soils with varying plasticity and initial UCS. The first series was designed to investigate the effect of the addition of cement alone on the UCS of the varying plasticity soils on samples cured for 7, 14, 28, and 56 days. The second and third series were conducted to study the effect of cement/PFA and cement/PFA/GGBS addition on the UCS of the investigated soils.

The results showed that irrespective of the initial strength and varying plasticity of the investigated materials, UCS improved upon addition of cement, cement/PFA, and cement/PFA/GGBS as expected, making the improved materials suitable for use as subgrade materials. The results shown in **Fig. 1a–1c** revealed that, as cement content increases from 5 % to 20 %, soils with lower plasticity indexes exhibit higher strength enhancement compared to soils with slightly higher plasticity. Similarly, for soils of higher plasticity improved with the combination of cement/PFA and cement/PFA/GGBS with cement content less than or equal to 5 %, the UCS in this case increases more than that of soils with lower plasticity indexes at the end of each curing period, as shown in **Figs. 1a–1c** and **2**. It could be seen that as the percentage of cement in the mix increases, the UCS of soils with low plasticity increases. This may indicate the suitability of cement for deep mixing improvement of soils with low plasticity. The strength enhancement on addition of GGBS and PFA might be due to calcium ion exchange and pozzolanic reaction in PFA (Ailin Nur et al. 2011). The strength increase may have also been due to gradual formation of cementitious compounds between PFA and GGBS and the presence of calcium hydroxide in soil (Yadu and Tripathi 2013). The combination of cement/PFA/GGBS and cement/PFA with a reduced amount of cement resulted in higher UCS compared to the natural soil. This might be due to the higher cementing power of GGBS compared to that of PFA. MacPhee et al. (1998) found that the hydraulic reactions of GGBS have a "pore-blocking" effect. This may have also resulted in the observed greater ultimate

FIG. 1

UCS of cement-, cement/PFA-, and cement/PFA/GGBS deep mixing–improved soils at (a) 7-day, (b) 14-day, and (c) 28-day curing periods.

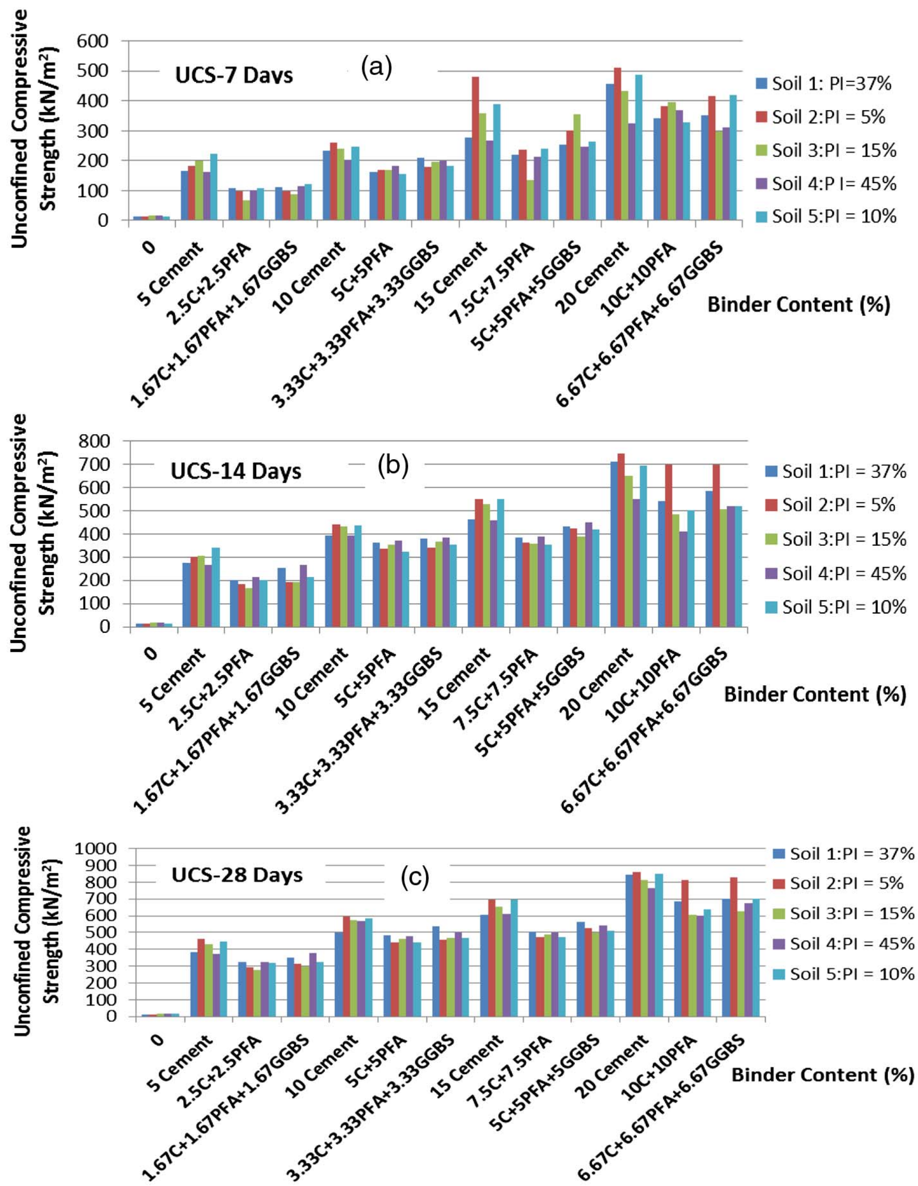
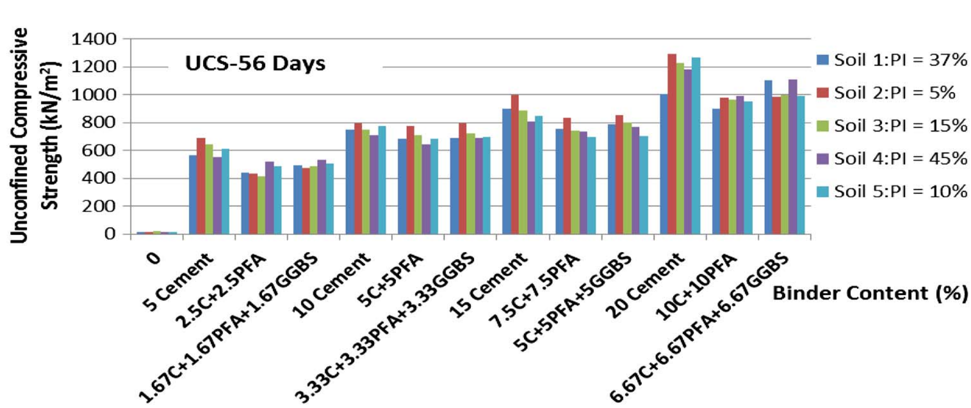


FIG. 2

UCS of cement-, cement/PFA-, and cement/PFA/GGBS deep mixing–improved soils at 56 days.



UCS. Sridevi and Sreerama (2014) have stated that soil-GGBS mixtures could be used in highway embankments. This implies that deep mixing soil-PFA/GGBS mixtures with a reduced amount of cement can provide fill materials of comparable strength to most over-consolidated soils based on the results obtained from this study. According to Ashish et al. (2014), increase in percentage of GGBS can lead to considerable increase in strength and thus reduction in pavement thickness during improvement of subgrade materials. The increase in strength over time may also be due to the possibility of suction development in pore fluid because of partial saturation of the improved samples after curing (Hemant and Mahendra 2015), but in this study, samples were soaked for about 90 minutes before testing, reducing the effect of suction development. Hence, it is believed that the increase in strength over time is due to pozzolanic reaction of byproducts used, and the longer age is expected to increase further.

Regression Model Development

Tables 3 and **4** show model summaries of the analysis output of three multiple regression analyses conducted based on experimental results of UCS of the improved soils. The tables also show the model's explanations of variabilities of the response data around the mean. Three different regression models have been developed for prediction of UCS of cement-, cement/PFA-, and cement/PFA/GGBS-improved soils with initial UCS less than 25 kPa, as shown in Eqs 2–4.

TABLE 3 Model summary for T-test, F-test, and P-values from ANOVA.

Model	T-test			F-test	P-value
	Constant	Binder Content	Time		(<0.05)
1. Cement	−1.229	17.88	23.04	499.98	0.000
P-value	0.223	0.000	0.000		
2. Cement/PFA	−3.268	16.55	23.454	482.78	0.000
P-value	0.002	0.000	0.000		
3. Cement/PFA/GGBS	−2.901	17.95	24.411	538.77	0.000
P-value	0.005	0.000	0.000		

TABLE 4 Constants and model numerical coefficients from ANOVA.

Improved Soil Type	Constants	Model Numerical Coefficients			
	β_o	β_1	β_2	R^2	Adjusted R^2
Cement	−25.27	25.37	10.49	0.924	0.922
Cement/PFA	−59.24	20.7	9.42	0.922	0.92
Cement/PFA/GGBS	−52.02	22.21	9.69	0.964	0.929

Putting $X_1 = B_c =$ Binder content (%) and $X_2 = C_t =$ Curing time (days) and substituting the numerical coefficients and constants from **Table 4**, the mathematical models could then be expressed to follow the general form of a multiple regression model. Eqs 2–4, show the proposed regression models for prediction of UCS for the following deep mixing improved soil systems:

- Soil-Cement:

$$UCS = -25.25 + 25.37B_C + 10.49C_t [Adjusted\ R^2 = 0.922] \quad (2)$$

- Soil-Cement/PFA:

$$UCS = -59.24 + 20.7B_C + 9.42C_t [Adjusted\ R^2 = 0.92] \quad (3)$$

- Soil-Cement/PFA/GGBS:

$$UCS = -52.02 + 22.21B_C + 9.69C_t [Adjusted\ R^2 = 0.929] \quad (4)$$

In order to test the significance of the null hypothesis of the F-test in ANOVA for multiple regression analysis, the P-values (representation of the significance of the null hypothesis) were compared to some alpha level (0.05) (Rawlings et al. 1998). The results showed P-values less than 0.05 as shown in **Table 1**, and, therefore, very strong evidence to reject the null hypothesis and accept the developed models. Also, the null hypothesis for T-statistics assumes zero coefficients for a given independent variable. From **Table 1**, the P-values of the two independent variables were found less than 0.05, which also shows strong evidence to reject this hypothesis. **Table 2** shows that the model coefficients are significantly different from zero, which is very strong evidence to accept that the developed model, as shown in Eqs 2–4, has explanatory power. The coefficients of multiple determination values of 0.922, 0.920, and 0.929 show that the above models explain 92.2 %, 92.0 %, and 92.9 % of the variability of the response data around the mean for cement-, cement/PFA-, and cement/PFA/GGBS-improved soils. In other words, the adjusted R^2 values represent the percentages of the total variability in the UCS that is explained by binder contents (%) and curing time (days). This implies that the developed models could be reliably used in predicting UCS of deep mixing–improved soils with initial strengths less than 25 kPa at a water to binder ratio equal to one. The predicted models have been used to develop a graphical model that could be employed in estimating appropriate binder contents for any known value of UCS between 100 kPa to 2,600 kPa, as shown in **Fig. 3**.

The comparison between experimental and predicted results using Eqs 2–4, as shown in **Fig. 4a–4c**, shows reasonable agreement between experimental and predicted results based on R^2 values.

The agreement between experimental and predicted values shows that any prediction made using the proposed

FIG. 3

Graphical model for prediction of UCS of cement-, cement/PFA-, and cement/PFA/GGBS deep mixing–improved soils.

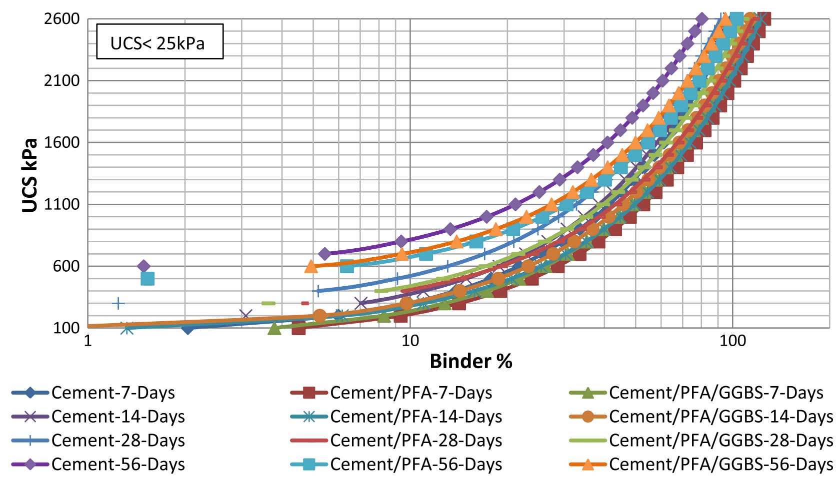
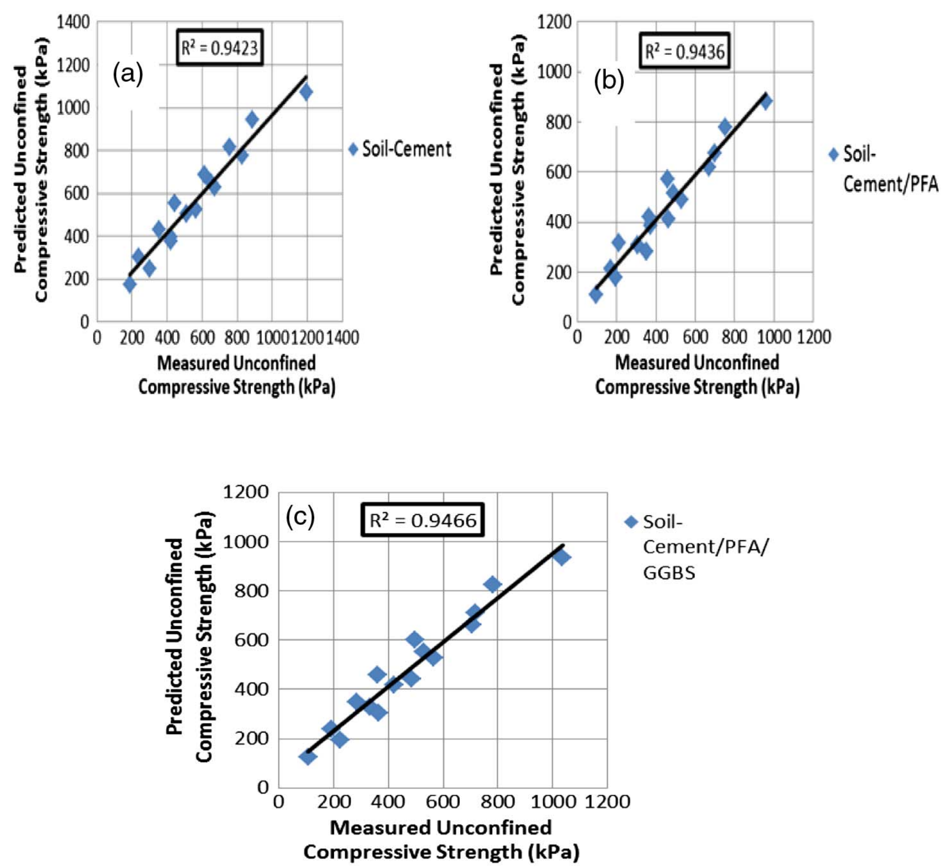


FIG. 4

Comparing experimental and predicted values of UCS of (a) cement-, (b) cement/PFA-, and (c) cement/PFA/GGBS deep mixing–improved soils.

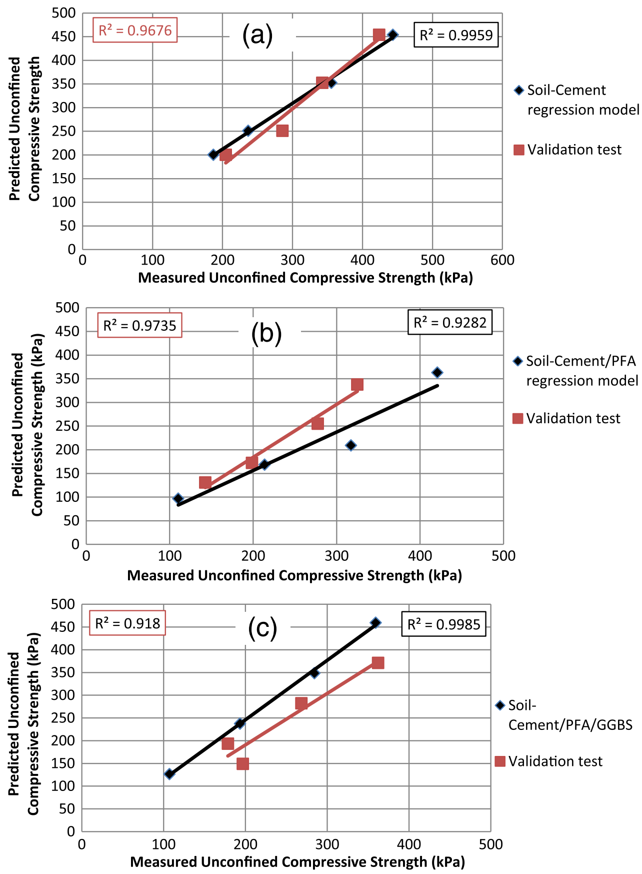


mathematical and graphical models could provide a satisfactory estimate of UCS (kPa) and binder contents (%), respectively. In order to justify this and strongly rely on any prediction made using these models, a validation test was conducted.

Validation of regression models

The proposed regression models were validated by preparing twelve different mixes, comprising of cement, cement/PFA, and cement/PFA/GGBS. The samples were prepared using 6 %, 8 %, 12 %, and 16 % binder/byproduct percentages. The cement-, cement/

FIG. 5 Validation of regression models for prediction of UCS of Deep Mixing-improved soils.



PFA-, and cement/PFA/GGBS-improved materials followed the same mix procedure as stated earlier, except that, in this case, different percentages of binders (6 %, 8 %, 12 %, and 16 %) were used for the purpose of validation. The improved samples were cured under the same curing condition for 7 days and subjected to UCS test under the same test condition. The UCS test results were then compared with predicted results as shown in **Fig.** 5a–5c.

The graphs of experimental UCS against predicted UCS have been plotted as a way of validating the desired regression models and ascertaining their usability in prediction of UCS in design and construction industries. The validation test results show good agreement with predicted values with spreads of 6 %, 8.2 %, and 9.9 % due to material variabilities within the system of improved material. This implies that the proposed regression model for soil-cement can predict the results within ±6 %, whereas the cement/PFA and cement/PFA/GGBS can predict the results within ±8.2 % and ±9.9 %, respectively.

Conclusion

Based on the analysis and results of this study, it can be concluded that weak soils of varying plasticity and initial UCS less than 25 kPa can effectively be improved with the addition of cement and cement/PFA/GGBS and are suitable for use as subgrade materials. Soils with lower plasticity show higher strength development upon addition of cement than soils with higher plasticity. Deep soil mixing with cement/PFA/GGBS mixtures might be suitable for use in highway embankments with the potential of providing fill materials of comparable strength to most overconsolidated soils. The results of this study have also revealed that PFA and GGBS could be used in deep soil mixing with a reduced amount of cement and thus reduce cost, CO_2 emission, and environmental impact of cement deep soil mixing. The developed mathematical and graphical models could reliably predict UCS for soils with initial UCS less than or equal to 25 kPa and for a water to binder ratio of unity.

References

Abbey, S. J., Ng'ambi, S., and Coakley, E., 2016, "Effect of Cement and By-Product Material Inclusion on Plasticity of Deep Mixing Improved Soils," *Int. J. Civ. Eng. Technol.*, Vol. 7, No. 5, pp. 265–274.

Abbey, S. J., Ng'ambi, S., and Ngekpe, B. E., 2015, "Understanding the Performance of Deep Mixing Improved Soils—A Review," *Int. J. Civ. Eng. Technol.*, Vol. 6, No. 3, pp. 97–117.

Ailin Nur, J. O., Hafez, M. A., and Norbaya, S., 2011, "Study of Bearing Capacity of Lime-Cement Columns with Pulverised Fuel Ash for Soil Stabilization Using Laboratory Model," *J. Geotech. Eng.*, Vol. 16, pp. 1595–1605.

Akinmusuru, J. O., 1991, "Potential Beneficial Uses of Steel Slag Wastes for Civil Engineering Purposes," *Resour. Conserv. Recycl.*, Vol. 5, No. 1, pp. 73–80.

Ashish, K. P., Pandey, V., Krishna, M., and Singh, J. P., 2014, "Soil Stabilisation using Ground Granulated Blast Furnace Slag," *Int. J. Eng. Res. Appl.*, Vol. 4, No. 5, pp. 164–171.

Asturias, R. P. and Lorenzo, G. A., 2015, "Unconfined Compression Behavior of Cement Treated Non-Plastic Soil Reinforced with Small Diameter Steel Bars," *Int. J. Eng. Technol.*, Vol. 15, No. 4, pp. 29–34.

BS 1377–1, 1990, *Methods of Test for Soils for Civil Engineering Purposes*, British Standard Institution, London, England, www.bsigroup.com

Celik, E. and Nalbantoglu, Z., 2013, "Effects of Ground Granulated Blast-furnace Slag (GGBS) on the Swelling Properties of Lime-Stabilized Sulphate-Bearing Soils," *Eng. Geol.*, Vol. 163, pp. 20–25.

Chen, E. J., Liu, Y., and Lee, F. H., 2016, "A Statistical Model for the Unconfined Compressive Strength of Deep Mixed Columns," *Geotechnique*, Vol. 66, No. 5, pp. 351–365.

Consoli, N. C., Winter, D., Rilho, A. S, Festugato, L., and Teixeira, B. S., 2015, "A Testing Procedure for Predicting Strength in Artificially Cemented Soft Soils," *Eng. Geol.*, Vol. 195, pp. 327–334.

Farouk, A. and Shahien, M. M., 2013, "Ground Improvement Using Soil-Cement Columns: Experimental Investigation," *J. Alexandria Eng.*, Vol. 52, No. 4, pp. 733–740.

Gaafer, M., Bassioni, H., and Mostafa, T., 2015, "Soil Improvement Techniques," *Int. J. Sci. Eng. Res.*, Vol. 6, No. 12, pp. 217–222.

Ganjian, E., Jalull, G., and Sadeghi-Pouya, H., 2015, "Using Waste Materials and By-Products to Produce Concrete Paving Blocks," *Constr. Build. Mater.*, Vol. 77, pp. 270–275.

Ganjian, E., Sadeghi-Pouya, H., Claisse, P., Waddell, M., Hemmings, S., and Johansson, S., 2008, "Plasterboard and Gypsum Waste in a Novel Cementitious Binder for Road Construction," *Concrete*, Vol. 42, No. 6, pp. 20–22.

Gupta, S. and Seehra, S. S., 1989, "Studies on Lime-Granulated Blast Furnace Slag as an Alternative Binder to Cement," *Highw. Res. Bull.*, Vol. 38, 1989, pp. 81–97.

Gyanen, T., Savitha, A. L. and Krishna, G., 2013, "Laboratory study on soil stabilization using Fly ash mixtures," *International Journal of Engineering Science and Innovative Technology (IJESIT)*, Vol. 2, No. 1, pp. 477–482.

Hemant, S. C. and Mahendra, K. V., 2015, "Strength Characterisation of Fibre Reinforced Cement-Fly Ash Mixes," *Int. J. Geosynth. Ground Eng.*, Vol. 1, No. 30, pp. 1–8.

Holm, G., 2003, "State of Practice in Dry Deep Mixing Methods," presented at the *Third International Conference on Grouting and Ground Treatment*, New Orleans, LA, ASCE, Reston, VA, pp. 145–163.

Little, D. N. and Nair, S., 2009, "Recommended Practice for Stabilisation of Subgrade Soils and Base Materials," Texas Transportation Institute, National Cooperative Highway Research Program, Doc. No 144, pp. 1–67.

MacPhee, D. E., Atkins, M., and Glassar, P. P., 1998, "Phase Development and Pore Solution Chemistry in Ageing Blast Furnace Slag–Portland Cement Blends," *12th Scientific Basis for Nuclear Waste Management*, Vol. 127 of MRS Proceedings, Cambridge University Press, Cambridge, England.

Oana, C., 2016, "Soil Improvement by Mixing Techniques and Performances," *Energy Procedia*, Vol. 85, pp. 85–92.

Obuzor, G. N., Kinuthia, J. M., and Robinson, R. B., 2012, "Soil Stabilisation with Lime-Activated-GGBS—A Mitigation to Flooding Effects on Road Structural Layers/Embankments Constructed on Floodplains," *Eng. Geol.*, Vol. 151, pp. 112–119.

Pakbaz, M. S. and Farzi, M., 2015, "Comparison of the Effect of Mixing Methods (Dry vs. Wet) on Mechanical and Hydraulic Properties of Treated Soil with Cement or Lime," *Appl. Clay Sci.*, Vols. 105–106, pp. 156–159.

Rawlings, J. O., Pantula, S. G., and Dickey, D. A., 1998, *Applied Regression Analysis: A Research Tool*, Springer Verlag, New York.

Shakri, M. S., Hafez, M. A., Adnan, M. A., and Nazaruddin, A. T., 2014, "Effect of Use of PFA on Strength of Stone Column and Sand Column," *J. Geotech. Eng.*, Vol. 19, pp. 3745–3755.

Sridevi, G. and Sreerama, R. A., 2014, "Efficacy of GGBS Stabilised Soil Cushions with and without Lime in Pavements," *Int. J. Emerging Technol. Comput. Appl. Sci.*, Vol. 9, No. 2, pp. 141–147.

Terashi, M., 2003, "The State of Practice in Deep Mixing Methods," presented at the *Third International Conference on Grouting and Ground Treatment*, New Orleans, LA, ASCE, Reston, VA, pp. 25–49.

Yadu, L. K. and Tripathi, R. K., 2013, "Stabilization of Soft Soil with Granulated Blast Furnace Slag and Fly Ash," *Int. J. Res. Eng. Technol.*, Vol. 2, No. 2, pp. 115–119.