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Properties of Mekong Delta Clay Stabilisation by Cement and Fly Ash for Whole Block Mixing Method

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ABSTRACT

The waste products of electricity by thermal power plants have released a large amount of fly ash into the environment which could create pollution. This paper presents the experimental results and parametric study to determine the unconfined compressive strength (UCS) of Mekong clay stabilisation by cement and fly ash (MCCF). In Case 1, Mekong clay (CL) was mixed with cement (C) at a rate of (10-30%) by dry weight; while in Case 2, CL clay was mixed with cement (C) (10-30%) and fly ash (F) (10-30%). Approximately 336 stabilised soil samples were made by wet mixing method with a water/binder ratio from 0.6 to 0.8. Bayesian Model Averaging (BMA) method was used to analyse the influence of parameters on the UCS, and the Principle Component Analysis (PCA) method was applied to analyse the results and determine the linear regression equation. The results show that with the low cement content (10%), the effect of fly ash is remarkable and UCS strength increased up to 30%. However, at the higher cement content (20% and 30%), the effect of fly ash on the UCS is not significant. Both models show high correlation coefficient R^2; hence, the proposed regression equations are reliable and could be use to determine the strength of the stabilised soil material. The research findings could help the engineer in using cement and fly ash to treat soft clay in the Mekong Delta area and reduce fly ash waste in the environment.

Keywords: Mekong Delta Clay, Fly Ash, Whole Block Mixing Method, Unconfined Compressive Strength (UCS), Bayesian Model Averaging (BMA), Principle Component Analysis (PCA).

1 INTRODUCTION

Fly ash is a waste product from a thermal power plant with a large volume; hence, finding a solution to reuse fly ash in construction is significant. The Mekong Delta of Vietnam has several thermal power plants and waste from these plants includes a very large volume of fly ash; however, there are limited reuse solutions for that material.

Building embankment in this area is challenging due to a thick soft soil layer. As the result, treating this soft soil to reduce the embankment settlement is important. Using soil-cement column to reduce settlement has been widely applied and many research results have already been published (Filz & Navin, 2006; Frikha et al., 2017; Kitazume & Terashi, 2013; Puppala et al., 2008; Yoobanpot et al., 2020). In addition, parameters such as the strength (UCS), elastic modulus (E_{50}) and other physico-mechanical properties of soil stabilised by cement (SSC) and fly ash (SSCF) have been deeply studied (Binal et al., 2016; Deepak et al., 2021; Do, Pham, Pham, et al., 2021; Do, 2012; Elahi et al., 2021; Kitazume & Terashi, 2013; Mohammad, 2010; Neramitkornburi et al., 2015; Suksiripattanapong et al., 2022; Terzić et al., 2018; Yoobanpot et al., 2017). Furthermore, statistical methods such as Bayesian Model Averaging (BMA), Principle Component Analysis (PCA), and Artificial Neural Network (ANN) have been applied to analyse experimental data and establish regression equations to

determine the properties of SSC and SSCF materials using the deep mixing method (Do, Pham, Nguyen, et al., 2021; Do, Pham, Pham, et al., 2021; Ghanizadeh & Rahrovan, 2019; Kobaka, 2021; Pham et al., 2021; Sharma & Singh, 2018).

This paper proposes a solution using fly ash to mix with cement to reinforce the soft ground by the mass method for the subgrade. Using soil-cement columns (CDM columns) and soil-cement columns combined with fly ash (CFDM columns) with short lengths of columns arranged close together to form a block of stabilised soil under the embankment is a suitable solution. This solution has also been found in the studies of Filz and Navin (2006) and Kitazume and Terashi (2013). This method is a technically effective solution, reducing settlement for embankment, saving construction time and reducing fly ash waste in the environment.

This paper focuses on determining the strength characteristics of clay materials in the Mekong Delta of Vietnam stabilisation by cement and fly ash by the deep mixing method. Stabilised soil samples were made with different binder contents in the laboratory conditions and UCS tests were conducted at 7, 14, 21, 28, 56, 112, 224, and 360 days of curing. Bayesian Model Averaging (BMA) and Principle Component Analysis (PCA) methods were used to analyse the results and built regression equations between the UCS strength, cement content, and fly ash content.

2 MATERIALS

2.1 Clay soil

Clay soil was taken in the area of Cau Ngang district, Tra Vinh province, Mekong Delta - Vietnam with a defined location as shown in Figure 1. This clay layer is a product of alluvial sediment and accretion over the ages and sea level change of the Pleistocene sedimentary period over 1000 years (Ta et al., 2021).The physical and mechanical parameters of the soil samples are shown in Table 1. Figure 2 shows the grain size distribution of the testing soil and fly ash. According to Unified Soil Classification System (USCS) ASTM (2017a)), LL=38.28% and IP = 10.3 > 7.0 so the clay soil is CL.



Figure 1. *Location of soil samples for testing*

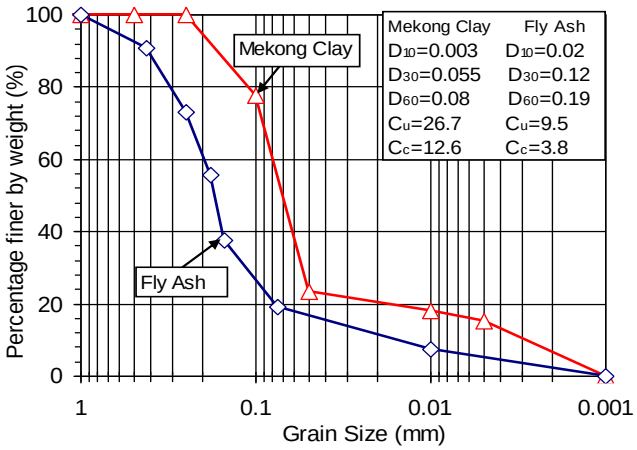


Figure 2. *Grain size distribution of clay and fly ash*

2.2 Cement

Cement used in the experiment is Portland cement PCB40 with the density of 3.083 g/cm^3, average fineness of 2.55%, cement strength after 3 days of approximately 24.7 MPa, and strength after 28 days of approximately 40.4 MPa.

2.3 Fly ash

Fly ash was taken from the Duyen Hai thermal power plant, Tra Vinh province with a fine grind of 2.25 %, density of 2.255 g/cm^3, and volumetric weight of 965 g/cm^3.

2.4 Chemical composition

The chemical composition of clay, cement, and fly ash is shown in Table 2.

Table 1. *Physical and mechanical properties of clay (according to ASTM (2017b))*

Properties	Unit	Value
Water content	%	38.26
Unit weight	g/cm³	1.92
Dry density	g/cm³	1.39
Specific gravity (G_s)		2.68
Void ratio (e_0)		1.75
Liquid Limit (LL)	%	38.28
Plastic limit (PL)	%	28.25
Plasticity Index (IP)	%	10.3
Viscosity (B)		0.94

Table 2. *The chemical composition of clay, cement, and fly ash*

Oxide	Clay (MC) (%)	Cement (C) (%)	Fly ash (F) (%)
Fe_2O_3	17.28	-	7.125
RuO_2	3.99	-	1.395
SiO_2	50.42	20.97	54.436
Al_2O_3	15.56	6.774	25.514
Na_2O	-	2.628	-
MgO	1.08 -	2.628 -	1.025
TiO_2	2.01-	-	1.32
CaO	1.188	58.52	2.569
K_2O	4.37	-	4.07

3 RESEARCH PROCEDURE

3.1 Research process

To understand the effect of fly ash on stabilised soil, the experimental program was conducted for two sample combinations:

- Case 1 includes Mekong clay (CL) mixed with cement (C) with the content of 10, 15, 20, 25, and 30% by dry weight;
- Case 2 includes Mekong clay (CL) mixed with cement (C) and fly ash (F) with the cement content of 10, 20, and 30% and the fly ash content of 10, 20, and 30% by dry weight, respectively.

Stabilised soil samples were mixed by the wet mixing method with the water/cement ratio (W) from 0.6 to 0.8. This is a reasonable ratio for cement and water to create mortar. The mixture is flexible for injection pump during the drilling of wet mixing cylinders to create a full block combination to treat soft soils under the embankment. Figure 3 shows the experimental planning diagram of two sample combinations.

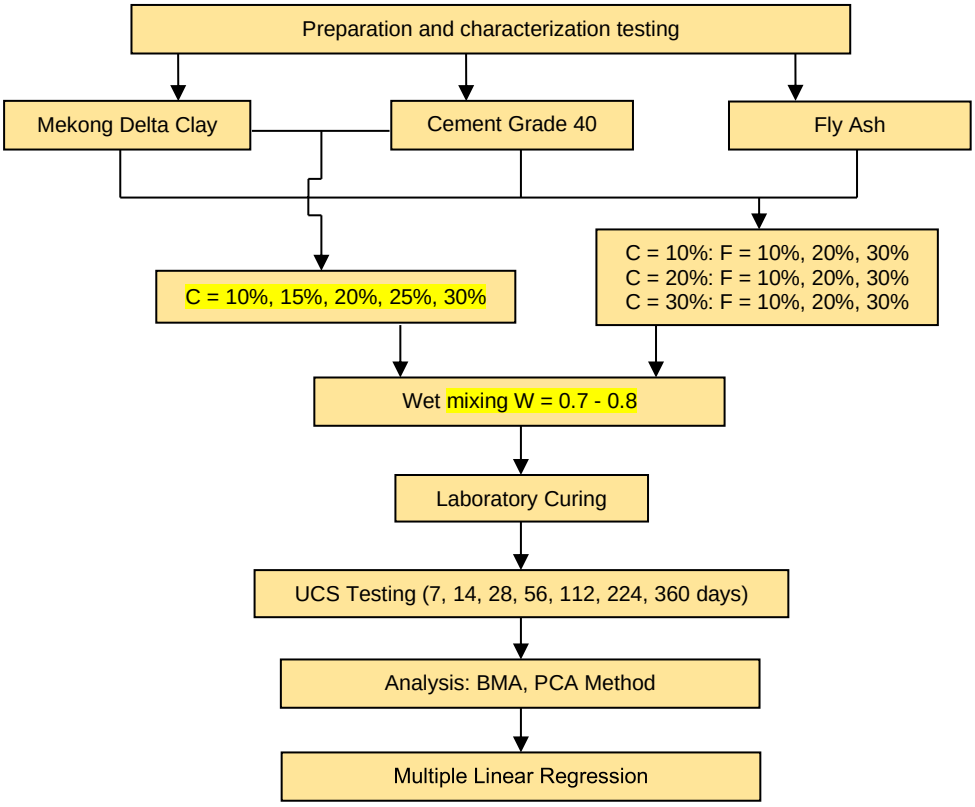


***Figure 3**. Flow chart of the study*

3.2 Experimental procedure

The cube moulds with a size of 70.7*70.7*70.7 mm were used. The samples were made and cured according to standard TCVN (2012). The inside surface of the mould is smooth, the flatness error does not exceed 0.05 % of the edge length, and the error of the edge length does not exceed 1/150.

Sample casting: Natural soil was mixed with cement with a suitable water/cement ratio in the mixer for a duration of 5 to 10 minutes. The mixture was put into the mould in 3 layers, then the steel rod with 10 mm diameter, 350 mm long, one end shaped like a bullet was used to compact. The compaction was conducted from the outside to the inside in a spiral. The first layer was penetrated to the bottom, the following layers were 10 mm to 15 mm into the previous layer. Then remove the excess mixture on the mould surface, smooth the surface, and cover the sample with the rubber cap (Figure 4a).

Curing samples: The moulded samples were removed from the mould after 24 hours of casting, and then all samples weight were measured. The samples then were soaked in a water bath for curing for 3 days. Finally, these samples were placed in a 90 % moisture room at a laboratory temperature of 27±2 ^{0}C (Figure 4b).

UCS tests: The UCS testes were immediately conducted on the samples after being removed from the curing room to avoid changes in humidity and temperature. Place the sample in the centre of the lower plate of the compressor. When the upper compression plate is in close contact with the specimen, adjust the spherical base so that the specimen surface is in uniform contact with the load plate. The load at 10-15 N/s or 1-2 mm/min was applied until the specimen fails. Three samples were tested and the averaged result was used for each case (Figure 4c).



a. Casting



b. Curing



c. Testing

Figure 4. *Stabilised soil samples: Making, Curing, and Testing*

Calculation of results: Unconfined compressive strength UCS (MPa) of the stabilised soil specimens were calculated by equation (1):

$$UCS = P/A \quad (1)$$

Where: P is the load (N); A is the area of the specimen (mm^2).

A group of samples consisting of 3 samples were tested, and the average results were recorded.

4 RESEARCH RESULTS

4.1 Experiment results

Results of UCS test of samples (UCS) for Case 1: Clay (CL) stabilisation by cement with the cement content C = 10-30% are shown in Table 3, and Case 2: Clay (CL) stabilisation by cement with C = 10-30% and fly ash F = 10-30% are summarised in Table 4.

Table 3. *UCS results in Case 1 without fly ash*

No	Binder content	UCS (MPa)							
		7 days	14 days	21 days	28 days	56 days	112 days	224 days	360 days
1	10% C	0.24	0.44	0.68	0.80	0.82	0.88	0.97	1.21
	W=0.8	0.26	0.48	0.69	0.79	0.83	0.89	0.98	1.23
		0.20	0.46	0.63	0.84	0.86	0.93	1.12	1.25
2	15% C	0.47	0.82	1.14	1.30	1.39	1.52	1.68	1.73
	W=0.76	0.47	0.89	1.13	1.31	1.38	1.58	1.66	1.76
		0.51	0.78	1.18	1.33	1.39	1.53	1.68	1.74
3	20% C	0.67	1.13	1.57	1.85	1.95	2.04	2.18	2.23
	W=0.74	0.65	1.16	1.56	1.82	1.99	2.08	2.12	2.21
		0.68	1.12	1.48	1.79	1.96	2.11	2.14	2.28
4	25%C	0.83	1.39	1.85	2.33	2.36	2.58	2.63	2.78
	W=0.72	0.88	1.37	1.84	2.38	2.42	2.56	2.68	2.71
		0.8	1.46	1.96	2.31	2.43	2.59	2.81	2.83
5	30% C	1.08	1.83	2.31	2.87	2.91	2.99	3.12	3.31
	W=0.70	1.12	1.77	2.33	2.82	2.96	3.02	3.25	3.42
		1.09	1.87	2.41	2.79	2.89	3.15	3.28	3.48

Table 4. *UCS results in Case 2 with fly ash*

No	Binder content		UCS (MPa)							
	Cement	Fly ash	7 days	14 days	21 days	28 days	56 days	112 days	224 days	360 days
1	10% C	10%F	0.58	0.72	0.92	1.05	1.15	1.25	1.33	1.42
		W=0.75	0.51	0.70	0.96	1.06	1.21	1.26	1.31	1.44
			0.59	0.78	0.94	1.07	1.18	1.28	1.36	1.45
		20%F	0.60	0.77	0.98	1.20	1.23	1.28	1.30	1.32
		W=0.78	0.63	0.79	1.03	1.18	1.22	1.30	1.32	1.33
			0.62	0.89	1.02	1.17	1.23	1.32	1.33	1.34
		30%F	0.60	0.88	1.06	1.21	1.23	1.25	1.29	1.31
		W=0.8	0.69	0.88	1.07	1.21	1.23	1.26	1.31	1.33

			0.66	0.88	1.05	1.23	1.26	1.29	1.33	1.35
2	20% C	10%F	0.94	1.33	1.62	1.92	2.12	2.32	2.56	2.86
		W=0.74	0.87	1.34	1.64	1.94	2.22	2.45	2.66	2.88
			0.93	1.35	1.71	1.93	2.32	2.46	2.68	2.89
		20%F	1.03	1.40	1.71	1.96	2.25	2.38	2.46	2.68
		W=0.77	1.02	1.41	1.72	2.00	2.26	2.41	2.48	2.65
			0.99	1.37	1.73	2.05	2.32	2.46	2.51	2.71
		30%F	1.13	1.45	1.77	2.09	2.32	2.44	2.48	2.68
		W=0.8	1.11	1.44	1.78	2.15	2.34	2.46	2.51	2.64
			1.10	1.46	1.79	2.12	2.36	2.48	2.54	2.61
3	30% C	10%F	1.28	2.00	2.63	3.17	3.35	3.55	3.78	3.99
		W=0.72	1.30	1.97	2.64	3.16	3.45	3.65	3.84	4.03
			1.32	1.99	2.64	3.05	3.44	3.68	3.85	4.12
		20%F	1.41	2.27	2.70	3.21	3.32	3.45	3.48	3.68
		W=0.76	1.44	2.04	2.73	3.24	3.41	3.48	3.54	3.69
			1.43	2.07	2.71	3.22	3.38	3.45	3.51	3.67
		30%F	1.57	2.15	2.90	3.33	3.42	3.48	3.52	3.66
		W=0.8	1.58	2.26	2.79	3.35	3.42	3.51	3.61	3.72
			1.56	2.26	2.72	3.36	3.40	3.48	3.59	3.67

The strength development in Case 1 and Case 2 over time (t = 7, 14, 21, 28, 56, 112, 224 and 360 days) are shown in Figures 5 and 6.

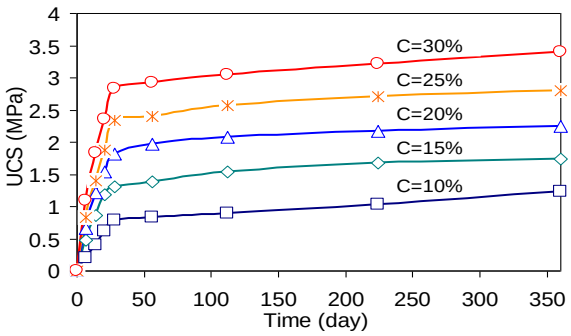


Figure 5. *Strength development in Case 1*

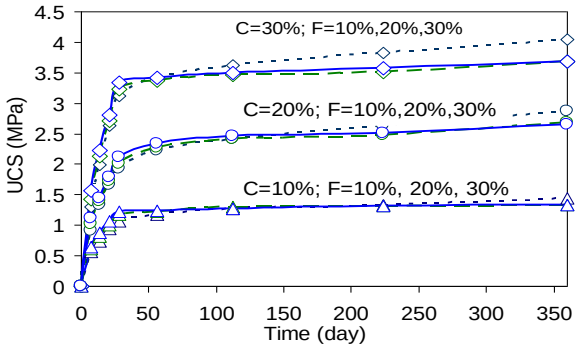


Figure 6. *Strength development in Case 2*

4.2 Statistical analysis and linear regression

Select variables: For Case 1, input variables are unconfined compressive strength UCS (MPa), cement content C (%), water/cement ratio (W), and curing time t (day).

For Case 2, input variables are unconfined compressive strength UCS (MPa), cement content C (%), fly ash content F (%), water/cement ratio (W), and curing time t (day).

4.2.1 BMA analysis

The correlation analysis between the variables for Case 1 and Case 2 is shown in Figures 7 and 8.

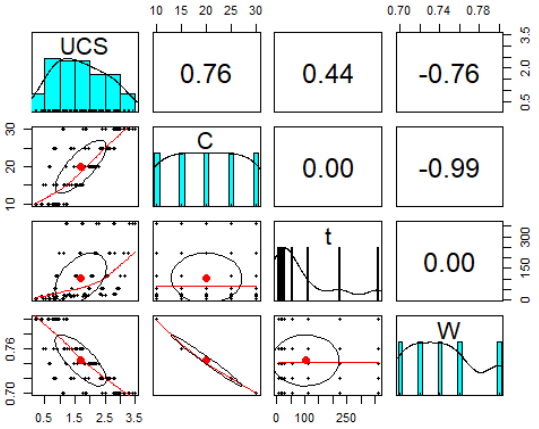


***Figure 7**. Correlation analysis of variables for Case 1*

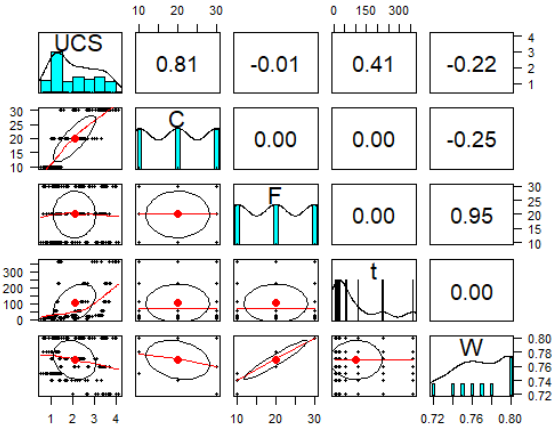


***Figure 8.** Correlation analysis of variables for Case 2*

For Case 1, the cement content, the curing time and the water/cement ratio are all correlated with the UCS value. In which, UCS has a large positive correlation with the cement content with the correlation coefficient R = 0.76; at the same time, UCS also has a negative correlation with the water/cement ratio with the correlation coefficient equal to the correlation coefficient between UCS and cement (R = -0.76). UCS has a moderate positive correlation with t with the correlation coefficient of R = 0.44.

For Case 2, Figure 8 demonstrates that the UCS has the largest positive correlation with the cement content with the correlation coefficient R = 0.81 and UCS has a moderate positive correlation with the curing time t with the correlation coefficient R = 0.41. In contrast, UCS had a rather small negative correlation with the water/cement ratio W (R = -0.22) and very little correlation with the fly ash content (R = -0.01). Figures 9 and 10 show the results of BMA analysis with the selected models for Case 1 and Case 2.

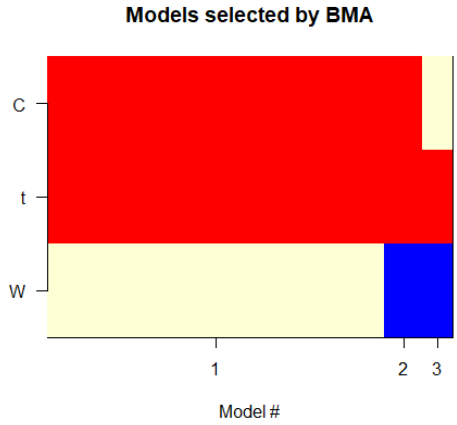


***Figure 9**. Model selected by BMA for Case 1*

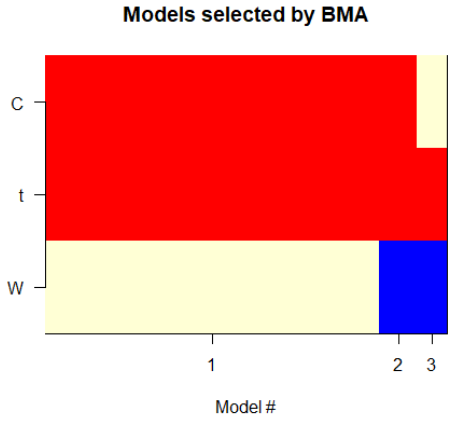


***Figure 10**. Model selected by BMA for Case 2*

The results of the multivariable regression from BMA analysis for the three best models in Case 1 and Case 2 are shown in Tables 5 and 6. Equations (2) and (5) have the largest posterior probability of 0.831 and 0.872, so these equations are the most suitable equation to determine the UCS of soil stabilisation by cement and fly ash.

***Table 5**. The regression equation for Case 1*

Model	Equation	R^2	PP	Equation number
I	UCS = -0.4502 + 0.0909C + 0.0032t	0.780	0.831	(2)
II	UCS = 2,936 + 0.0715C + 0.0032t – 4.031W	0.780	0.093	(3)
III	UCS = 15.1 + 0.0032t – 18.52W	0.770	0.076	(4)

***Table 6**. The regression equation for Case 2*

Model	Equation	R^2	PP	Equation number
I	UCS = -0.229 + 0.0975C + 0.0034t	0.831	0.872	(5)
II	UCS = 0.157 + 0.097C + 0.0034t – 0.491W	0.831	0.066	(6)
III	UCS = -0.209 + 0.0975C -0.001F+ 0.0034t	0.831	0.062	(7)

Note: PP: Posterior Probability

4.2.2 PCA analysis

XLSTAT software was used to analyse the results. Figure 11 is a circle representing PCA analysis. That figure shows that the UCS strength has a good correlation with the cement content C and curing time t. Figure 12 shows the relationship between the eigenvalues of the planes and the cumulative variable in Case 1.

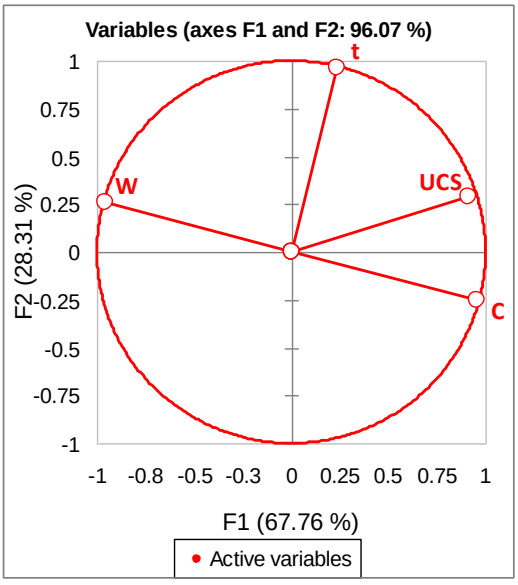


***Figure 11**. PCA analysis for 4 variables UCS, C, t, and W in Case 1*

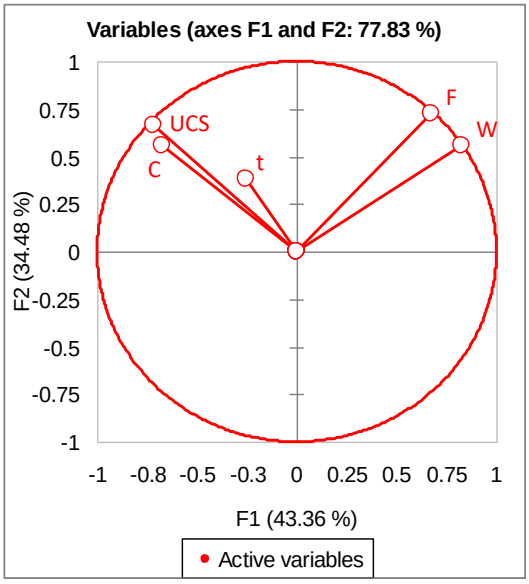


***Figure 12.** PCA analysis for 5 variables UCS, C, F, t, and W in Case 2*

For Case 2 using cement and fly ash, the PCA analysis is shown in Figure 12. That figure shows that UCS strength has a good correlation with the cement content C and the curing time t, and a low correlation with the fly ash content F. It means that the effect of fly ash on UCS is much smaller than that of the two independent variables (cement content and curing time).

Linear regression analyses were established for the variables in Case 1 and Case 2 for unconfined compressive strength, cement content, and fly ash content. Table 7 shows the selected regression equations for Cases 1 and 2. It could be seen that all P values in the 5 selected models are lower than 0.05, so the parameters of the independent variable are statistically significant and the proposed regression equations are significant and could be used in practice.

***Table 7.** Predictive models*

Predictive models	Model	Dependent parameter	Independent parameter	P values
Case 1	I	UCS	UCS=f(C,t,W)	< 0.05
	II	C	C=f(UCS,t,W,UCS.t,UCS.W,t.W)	< 0.05
Case 2	III	UCS	UCS=f(C,F,t)	< 0.05
	IV	C	C=f(UCS,F,t,W,UCS.F,UCS.W)	< 0.05
	V	F	F=f(UCS,C,W,UCS.C)	< 0.05

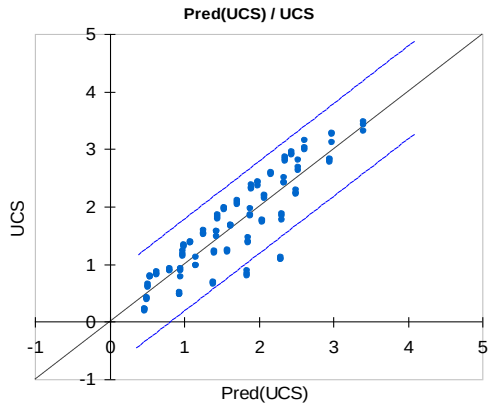
***Table 8.** Predictive models for UCS with performance indices*

Model	Equation	R^2	Sign

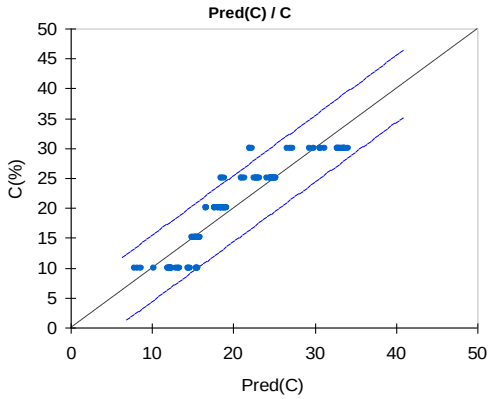
I	UCS = 0.088C - 0.003t -0.537W	0.956	(8)
II	C= 94.341UCS + 0.572t +20.628W-0.0038UCS.t-125.389UCS.W-0.66t.W	0.984	(9)
III	UCS = 0.093C - 0.006F +0.003t	0.969	(10)
IV	C= 101.73UCS - 0.333F -0.019t+19.761W+0.615UCS.F-140.281UCS.W	0.975	(11)
IV	F = -5.658UCS - 0.37C +37.52W+0.219UCS.C	0.884	(12)

Table 8 shows the established multivariable regression equations, in which the coefficients of determination R^2 of the selected models are from 0.884 to 0.984. Figure 13 shows the predicted UCS, C values in Case 1 and the UCS, C, F values in Case 2 and the measured values from the experiment.

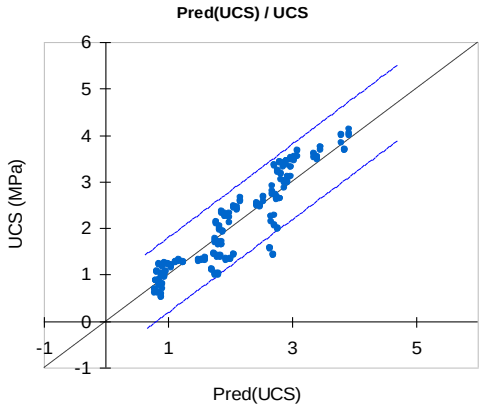
Because all regression equations have statistical significance, in case of without fly ash it can be estimated the compressive strength UCS (MPa) and cement content C (%) by the equations (8) and (9), respectively. In case of using fly ash, the compressive strength UCS (MPa), cement content C (%) and fly ash content F (%) can be estimated from the equations (10), (11) and (12), respectively.



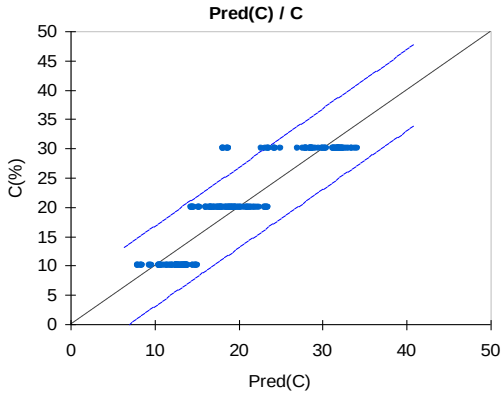
(a) Model I



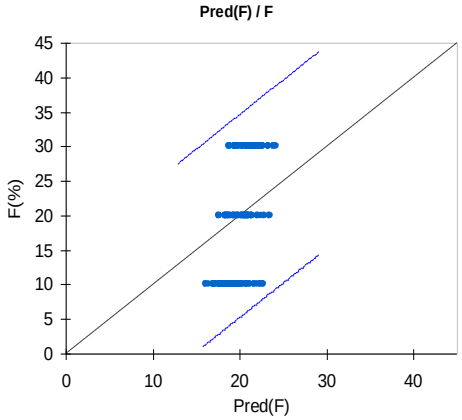
(b) Model II



(c) Model III



(d) Model IV



(e) Model V

***Figures 13**. Measured versus predicted variables based on different models*

5 CONCLUSIONS

(1) Using fly ash combined with cement to treat soft soil as CDM and CFDM columns are necessary. It could reduce the amount of fly ash waste from thermal power plants, and reduce environmental pollution.

(2) The stabilised soil samples were made and conducted the UCS tests for two cases of samples without fly ash and with fly ash at 7, 14, 21, 28, 56, 112, 224, and 360 curing days. The results show that with the low cement content (10 %), the effect of fly ash is remarkable and UCS strength increased up to 30%. However, at the higher cement content (20% and 30%), the effect of fly ash on the UCS is not significant.

(3) BMA Analysis was applied to evaluate the correlation of variables and build a regression equation between UCS and independent variables. In Case 1 without using fly ash, the best models were shown in equations (2), (3) and (4); and in Case 2 using fly ash, the best models were shown in equations (5), (6) and (7). When combined with posterior probability assessment, equation (2) and equation (5) are suitable models to estimate the UCS value according to the variables in two cases.

(4) XLSTAT software was used to analyse variables from two cases. The regression equations were established to estimate independent variables based on dependent variables from 120 experimental data in Case 1 and 216 data in Case 2. The results show that the coefficient of determination R^2 is high and P value is less than 0.05, which illustrates that all regression equations have good statistical significance.

(5) Regression equations for Case 1 without fly ash to were established to determine the strength UCS = f(C, t, W, t.W) and cement content C = f(UCS, t, W, UCS.t, UCS.W, t.W) with R^2 = 0.958 and R^2 = 0.984, respectively.

(6) Regression equations for Case 2 with fly ash were established to determine the strength UCS = f(C, F, t) with R^2 = 0.969; cement content C= f(UCS, F, t, W, UCS.F, UCS.W) with R^2 = 0.975; and fly ash content F = f(UCS, C, N, UCS.C) with R^2=0.884.

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