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Compressive strength of cement stabilized fly ash-soil mixtures

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Abstract

Rajghat fly ash from Delhi, India, and Baumineral fly ash near Bochum, Germany, were mixed with the locally available soils—silt and Yamuna sand with Rajghat fly ash and Rhine sand with Baumineral fly ash—in different proportions. Cement, varying from 3–9% was added to stabilize the fly ash-soil mixtures. Cylindrical samples were prepared at optimum moisture content and maximum dry density and were cured for different duration. Unconfined compression tests were conducted on these samples. Correlations for unconfined compressive strength and secant modulus as functions of curing time, fly ash content, and cement content have been established. The data were analyzed with other correlations recommended in literature and comparisons between the correlations have been made. Correlations for water content as functions of curing time and cement content have also been established.

Keywords: Compressive strength; Fly ash; Portland cement; Soil; Stabilization

About 80 million tonnes of fly ash is being produced in India annually, of which less than 5% is used in the manufacture of bricks, pozzolana cement, and other products. Attempts are being made to increase the scale of utilization of fly ash. The Department of Science and Technology of the government of India has launched a Mission Project to deal with the huge production of fly ash. Fly ash can be used in highway embankments and in engineered fills. The performance of fly ash can be improved by stabilizing it with cement. In the present study, an Indian fly ash collected from an electrostatic precipitator of the Rajghat thermal power station in New Delhi and a German fly ash from a chemical manufacturing industry, Baumineral (near Bochum, Germany) have been used. They were mixed with the locally available soils and ordinary portland cement in different proportions. Cylindrical samples were prepared, cured for different duration, and tested to determine the unconfined compressive strength.

1. Materials

The chemical composition of the Rajghat and Baumineral fly ashes are given in Table 1. The CaO content is low. Both are classified as class F fly ash. Lack of self-hardening is a characteristic of class F fly ashes. The Rajghat fly ash was mixed separately with Delhi silt and Yamuna sand, and the Baumineral fly ash was mixed with Rhine sand. Table 2 gives the particle size distribution and physical properties of all the materials. The fly ash:soil proportion used in the experiments were 25:75, 50:50, 75:25, and 100:0 by dry weight. An additional proportion of 0:100 was also used in the Rajghat fly ash-Delhi silt mixture. The cement contents used were 3 and 6%. In Baumineral fly ash-sand mixtures, cement content of 9% was also used. A few samples of Rajghat fly ash-soil mixtures were stabilized with 1 and 2% cement content. Commercially available ordinary portland cement was used.

2. Experimental method

Light weight (standard Proctor) compaction tests were carried out to determine the optimum moisture content and maximum dry density of all fly ash-soil mixtures. The results of the compaction tests are shown in Table 3. Cylindrical samples of the fly ash-soil mixtures were prepared at their respective optimum moisture content and maximum dry density. For Rajghat fly ash-soil mixtures, 38-mm diameter and 76-mm long samples were prepared by static compaction. For curing, the samples were closely wrapped in a polythene bag and placed above water in a desiccator kept in a room where the temperature was maintained around 21°C. The Baumineral fly ash-soil mixture samples were

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Table 1
Chemical composition of fly ashes

Chemical composition	Rajghat fly ash (%)	Baumineral fly ash (%)
Silica (SiO_2)	61.21	52.26
Alumina (Al_2O_3)	30.07	25.74
Iron oxide (Fe_2O_3)	4.17	7.66
Lime (CaO)	0.10	0.21
Magnesia (MgO)	0.40	1.72
Titania (TiO_2)	2.60	not available
Soda (Na_2O)	<0.01	5.00
Potash (K_2O)	0.02	4.13
Sulphates (SO_3)	<0.01	0.81

100-mm diameter and 120-mm long and were dynamically compacted. During curing, the samples were placed above water in closed tubs. The humidity and temperature were maintained by the water. Generally, the samples were cured for 7, 14, 28, and 56 days. After curing, unconfined compression test was conducted and the water content was also determined. A minimum of three tests were conducted for each combination of the variables.

3. Results, analysis, and discussion

3.1. Unconfined compressive strength

Fig. 1 shows the variation of unconfined compressive strength (q_c) with curing time for Rajghat fly ash (R), which is typical of the result obtained for the different fly ash-soil-cement combinations. Without cement, the class F fly ash shows very little self-hardening property. There is significant gain in strength even with a small addition of cement and the gain depends on the cement content and curing time. Paya and colleagues [1] expressed the variation of compressive strength of fly ash-cement mortars with curing time, *t*, as Eq. (1):

$$q_c = a + b\log_{10}t \qquad (1)$$

Table 2
Properties and particle type of materials

Properties	Rajghat fly ash	Baumineral fly ash	Delhi silt	Yamuna sand	Rhine sand
Specific gravity	2.19	2.36	2.64	2.66	2.65
Loss on ignition	1.4%	3.47%	–	–	–
Specific surface area (m^2/N)	41.0	34.4	–	–	–
Particle type					
Coarse sand size, 4.75–2 mm	–	–	–	–	1%
Medium sand size, 2–0.475 mm	–	–	–	–	16%
Fine sand size, 0.475–0.075 mm	20%	14%	14%	94%	82%
Silt size, 0.075–0.002 mm	77%	79%	73%	6%	1%
Clay size, <0.002 mm	3%	7%	13%	–	–

Table 3
Results of light compaction (standard Proctor) tests

Mix designation	Fly ash-soil mixture	Maximum dry density (kN/m^3)	Optimum moisture content (%)	Void ratio*
R	Rajghat fly ash	10.52	36.5	1.04
RM1	75% R + 25% M	12.21	26.6	0.84
RM2	50% R + 50% M	13.54	22.6	0.73
RM3	25% R + 75% M	15.40	18.0	0.60
M	Delhi silt	17.66	14.0	0.47
RY1	75% R + 25% Y	11.92	28.6	0.88
RY2	50% R + 50% Y	13.64	22.6	0.73
RY3	25% R + 75% Y	15.11	17.5	0.64
Y	Yamuna sand	–	–	–
B	Baumineral fly ash	14.18	18.4	0.63
BSI	75% B + 25% S	16.09	13.0	0.48
BS2	50% B + 50% S	17.95	10.0	0.37
BS3	25% B + 75% S	18.98	8.2	0.33
S	Rhine sand	–	–	–

* Void ratio at maximum dry density and optimum moisture content.

a and *b* are constants having units of stress. For self-hardening fly ashes, Moller and Nilson [2] have given a similar expression for q_c. Eq. (1) was used to analyze the compressive strength of a few fly ash-soil-cement combinations. The equation gave good coefficient of determination (R^2). For example, for Rajghat fly ash mixed with 6% cement, the analysis gave $a = -405.4$ kN/m^2, $b = 985.8$ kN/m^2, and $R^2 = 0.96$. Still, Eq. (1) may not be totally appropriate for the following reasons. First, for 1 day curing, $q_c = a$. However, *a* obtained by regression analysis may not be equal to the actual compressive strength after one day curing. *a* is also negative in some cases as in the present example, which indicates a negative compressive strength that is not true. Second, the validity of the correlation is not established only by R^2 being close to ± 1. The other statistics, namely the standard error, *F*-statistic, and *t*-value of the coefficients, should also be satisfactory. For the present example, the standard error was 102.1 kN/m^2, which is significant at low curing time compared to the compressive strength at that time. Further, the *t*-value for coefficient *a*

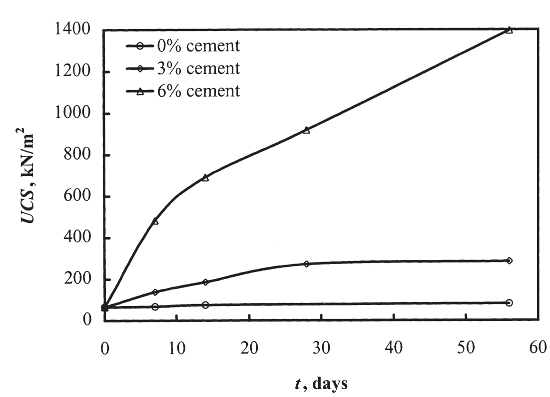

Fig. 1. Variation of unconfined compressive strength (UCS) of Rajghat fly ash with time.

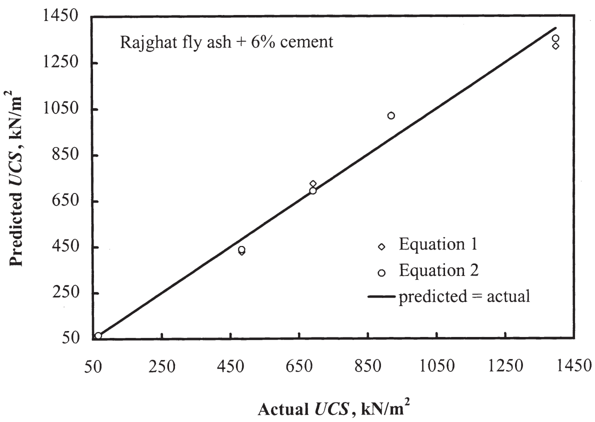

Fig. 2. Comparison between the predicted and actual unconfined compressive strengths.

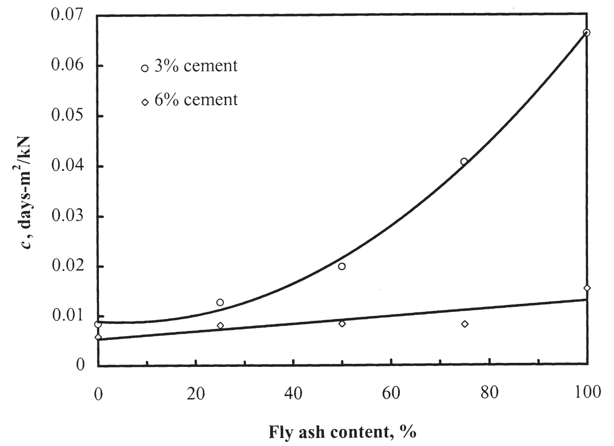

Fig. 4. Variation of c with fly ash content for Rajghat fly ash-silt mixtures.

failed the test. Third, the fly ash-soil samples possess an initial compressive strength ($t = 0$) that cannot be defined by Eq. (1). Fourth, according to Eq. 1, q_c increases indefinitely with time, which may not be true.

If the gain in strength with time is assumed to be hyperbolic, the unconfined compressive strength is expressed as Eq. (2):

$$q_c = q_{co} + \frac{t}{mt + c} \tag{2}$$

q_{co} is the measured initial unconfined compressive strength and m and c are constants obtained from the regression analysis of data in [t, $t/(q_c - q_\infty)$] coordinate system. Generally, it was found that Eq. (2) satisfied all the statistical requirements and gave better results than Eq. (1). For the Rajghat fly ash and 6% cement combination, $m = 0.000506$ m^2/kN, $c = 0.01523$ day m^2/kN, and $R^2 = 0.95$. Fig. 2 shows the comparison of the actual q_c values of the Rajghat fly ash and 6% cement combination with those estimated by Eqs. (1) and (2). Eq. (2) makes a slightly better estimate for q_c than Eq. (1). Eq. (2) gives the maximum value of q_c as in Eq. (3):

$$q_{c\max} = q_{co} + \frac{1}{m} \tag{3}$$

$q_{c\max}$ of the Rajghat fly ash and 6% cement combination is, therefore, expected to be 2042 kN/m^2, about 650 kN/m^2 more than its measured strength after 56 days of curing, which will be reached after a very long time. Whereas according to Eq. (1), this strength will be reached after 300 days of curing and will continue to increase thereafter. It can be further inferred from Eqs. (2) and (3) that the smaller the values of m and c, the larger is the gain in strength with time. The opposite is true for the coefficients a and b in Eq. (1). Eq. (2) is valid for all $t \geqslant 0$. But Eq. (1) gives negative value of q_c for the present example until $t = 3$ days.

The constants m and c that govern the strength gain depend upon the fly ash and cement contents in any fly ash-soil mixture. Figs. 3 and 4 show, respectively, the variation

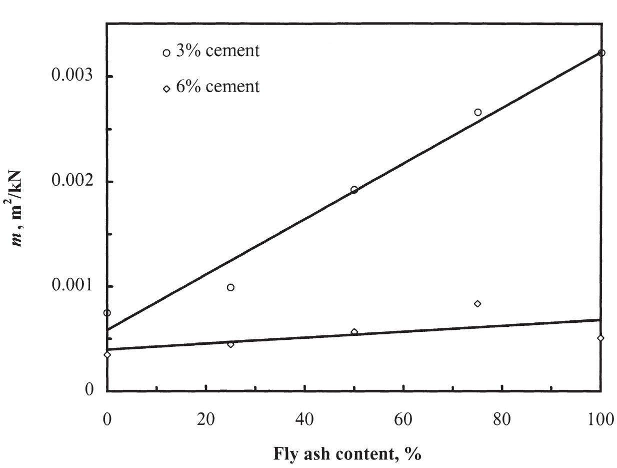

Fig. 3. Variation of m with fly ash content for Rajghat fly ash-silt mixtures.

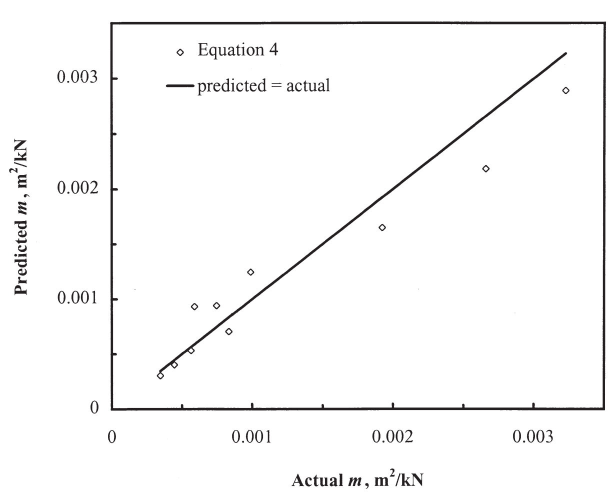

Fig. 5. Comparison of the predicted and actual values of m for Rajghat fly ash-silt mixtures.

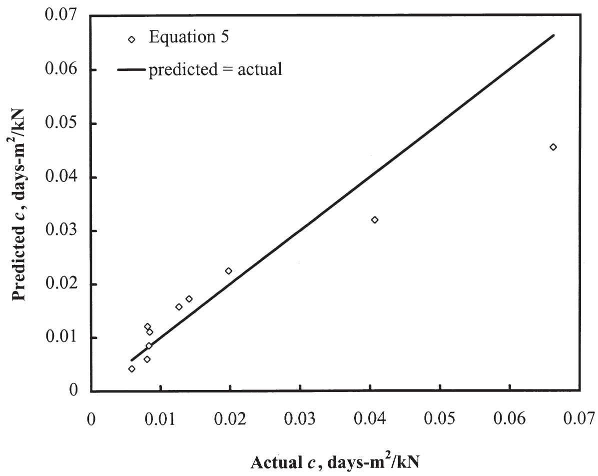

Fig. 6. Comparison of predicted and actual values of c for Rajghat fly ash-silt mixtures.

of m and c for the Rajghat fly ash-silt mixtures. As it could be expected, both m and c decrease with increase in the cement content. It is instructive to see that they increase with increase in fly ash content. In general, a similar trend was observed for the other fly ash-soil mixtures also.

The expressions for m and c for the Rajghat fly ash-silt mixtures, from exponential curve multiple regression analysis, are given by Eqs. (4) and (5):

$$m = 0.00292 \times 1.0113^{FA} \times 0.686^{C} \qquad R^2 = 0.91 \tag{4}$$

$$c = 0.0292 \times 1.014^{FA} \times 0.724^{C} \qquad R^2 = 0.87 \tag{5}$$

and from straight line multiple regression analysis, these are given by Eqs. (6) and (7):

$$m = 0.00251 + 0.000015FA - 0.00045C \qquad R^2 = 0.8 \tag{6}$$

$$c = 0.0342 + 0.00032FA - 0.0069C \qquad R^2 = 0.69 \tag{7}$$

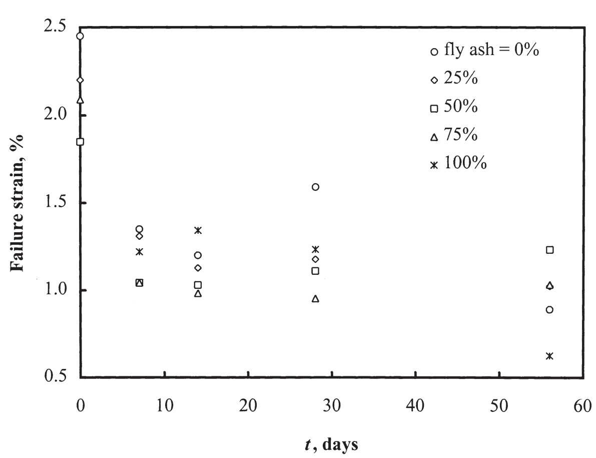

Fig. 7. Failure strain of Rajghat fly ash-silt samples stabilized with 6% cement.

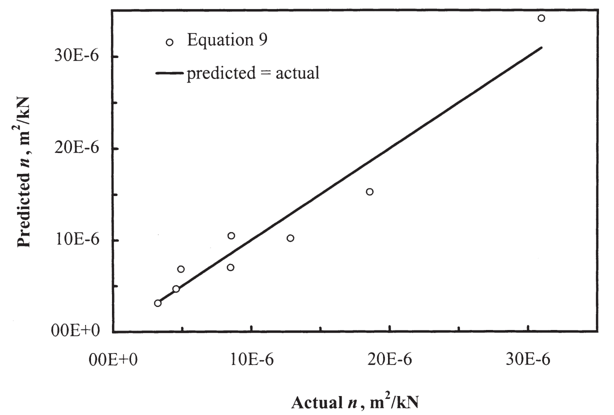

Fig. 8. Comparison of predicted and actual values of n for Rajghat fly ash-silt mixtures.

FA and C are, respectively, the fly ash and cement contents in percent. Eqs. (4) through (7) satisfied the other statistical tests. These equations are in agreement with the previous discussions about the effect of cement and fly ash contents on m and c. Further, the values of the coefficients of C in relation to those of FA indicate that the strength gain is more sensitive to cement content than fly ash content. The R^2 values indicate that Eqs. (4) and (5) are preferable to Eqs. (6) and (7). Figs. 5 and 6 show the comparison of the actual values of m and c for the Rajghat fly ash-silt mixtures with those estimated by Eqs. (4) and (5).

3.2. Failure strain

Fig. 7 shows the compressive strain at failure of the Rajghat fly ash-silt samples treated with 6% cement. The failure strain itself is small, varying from 1 to 2.5% and the failure is brittle failure. The failure strain generally tends to decrease with curing time.

3.3. Secant modulus

The secant modulus (E_s) is defined as the ratio of one-half of the compressive strength to the axial strain corre-

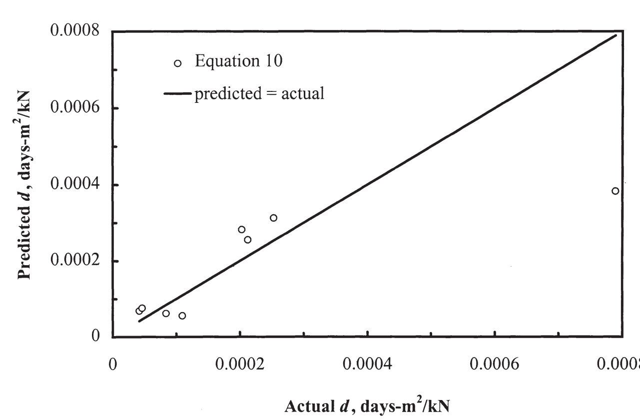

Fig. 9. Comparison of predicted and actual values of d for Rajghat fly ash-silt mixtures.

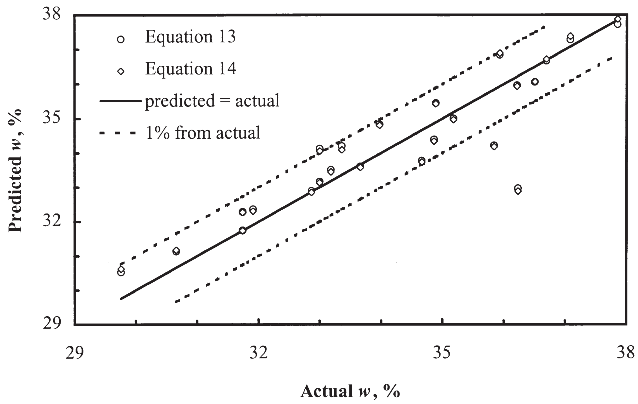

Fig. 10. Comparison of predicted and actual water contents for Rajghat fly ash samples.

sponding to this stress. If the gain in E_s with time is assumed to be hyperbolic it can be expressed as Eq. (8):

$$E_s = E_{so} + \frac{t}{nt + d} \quad (8)$$

E_{so} is the initial secant modulus; n and d are constants obtained from the regression analysis of data in $[t, t/(E_s - E_{so})]$ coordinate system. Analysis for constants n and d have been carried out in the same manner as for m and c explained before. The correlations for n and d for the Rajghat fly ash-silt mixtures from exponential curve multiple regression analysis are given by Eqs. (9) and (10):

$$n = 1.487 \times 10^{-5} \times 1.016^{FA} \times 0.771^{C} \qquad R^2 = 0.93 \quad (9)$$

$$d = 0.00116 \times 1.0041^{FA} \times 0.603^{C} \qquad R^2 = 0.74 \quad (10)$$

and from straight line multiple regression analysis are given by Eqs. (11) and (12):

$$n = 1.781 \times 10^{-5} + 1.921 \times 10^{-7} FA - 3.132 \times 10^{-6} C \qquad R^2 = 0.89 \quad (11)$$

$$d = 0.000484 + 3.491 \times 10^{-6} FA - 9.069 \times 10^{-5} C \qquad R^2 = 0.66 \quad (12)$$

The fly ash and cement contents have similar influence on n and d, and thereby on E_s, as they have on m, c, and q_c. As the R^2 values indicate, Eqs. (9) and (10) are preferable to Eqs. (11) and (12). Figs. 8 and 9 show the comparison of the actual values of n and d for the Rajghat fly ash-silt mixtures with those estimated by Eqs. (9) and (10).

3.4. Change in water content

For a particular combination of fly ash-soil mixture the initial moisture content (w_o) was same irrespective of the cement content. The water contents (w) of the samples were determined after the unconfined compression test. From this data the correlations between w, curing period, and cement content for the Rajghat fly ash were obtained as shown in Eqs. (13) and (14):

$$w = 37.52 - 0.0834t - 0.563C \qquad R^2 = 0.92 \quad (13)$$

$$w = 37.64 \times 0.9975^{t} \times 0.9836^{C} \qquad R^2 = 0.92 \quad (14)$$

t is in days and w and C are in percent. Eqs. (13) and (14) satisfied all statistical tests and gave equally good results. Significantly, both equations give the initial moisture content corresponding to $t = 0$ and $C = 0$ as very close to the actual value of 37.85%. They indicate that w decreases as both time and cement content increase. The influence of cement content is more pronounced than time, because the hydration of cement is dependent more on cement content than on time. Fig. 10 shows the comparison of the actual values of w for the Rajghat fly ash samples with those predicted by Eqs. (13) and (14). The predicted w mostly differ within $\pm 1\%$ from the actual values.

4. Conclusions

Empirical correlations have been established from the experimental study on cement stabilized fly ash-soil mixtures. The following are the conclusions from the study.

1. The gain in unconfined compressive strength and secant modulus of fly ash-soil mixtures with time can be assumed to be hyperbolic.
2. The gain in strength and modulus is dependent on the fly ash and cement contents. The gain in strength and modulus increase as cement content increases, but decrease as fly ash content increases. The cement content has a significantly higher influence than the fly ash content.
3. The water content of a fly ash-soil mixture depends on the curing time and cement content. The water content decreases as curing time and cement content increase. The influence of cement content is more pronounced than that of the curing time.

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