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APPLICATION OF BIOMASS FLY ASH AS A POZZOLANIC MATERIAL FOR STABILIZATION OF LOW-SWELLING CLAY

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ABSTRACT: The present paper investigates the possibility of utilizing biomass fly ash to partially replace Type I Portland cement for stabilization of a low-swelling clay. It is found that the fly ash can be used as a pozzolanic material. The 10% replacement ratio is an effective ratio where the input of fly ash is sufficient for secondary reaction. The influential parameter controlling the strength development of blended cement is clay-water/cement ratio, w_c/C. The cement content of the blended cement is the summation of the input of cement, C_i and the equivalent cement, C_e. The C_e is determined based on the concept of an efficiency factor (k), which is adopted as a measure of the relative performance of supplementary cementing material compared with Type I Portland cement. The C_e is equivalent to kF where F is fly ash content and k is efficiency factor. From the analysis, the value of k is dependent upon the replacement ratio and curing time, and irrespective of binder content and water content. A phenomenological model for assessing the strength development is introduced and verified. It can possibly be applied as a simple and rational tool for predicting the strength development of other blended cement stabilized low swelling clays.

Keywords: Biomass fly ash, clay-water/cement ratio**,** equivalent cement, kaolinite, replacing efficiency factor

INTRODUCTION

Extensive urbanization and industrialization in coastal regions and lowland areas of many countries have necessitated to strengthen very soft ground to enhance its shear strength and reduce its compressibility so as to handle its stability and settlement problems. The strengthening processes by the deep mixing method (DMM) have been successfully done in different parts of the world. Of significance are the work done in Japan, Sweden, and recently in the United States. This method uses chemical additives to enhance mechanical properties of soft ground (Tatsuoka et al., 1996; and Uddin 1994). These additives could be lime and cement etc. Cement could be mixed in-situ by means of mixing platform, either in powder (Bredenberg, 1999) or slurry form (Terashi et al., 1979).

DMM has been applied popularly and successfully in Southeast Asia in which cement has been proved to be cheaper and more effective than quicklime (Broms, 1984). DMM technology was simultaneously developed in Sweden and Japan using the quicklime as the hardening agent. Later on, normal Portland cement slurry was used. The use of cement slurry in mixing instead of dry powder appeared to produce a uniform mixture of in-situ soft soil, which increases strength and enhances uniformity of improved soil. Due to the superiority in performance, the slurry method is widely used, especially in marine reclamation projects. The influential factors controlling field strength development of soil-cement pile were investigated by Horpibulsuk et al. (2004b).

DMM has introduced into practice a decade ago as one of suitable ground improvement schemes for soft Bangkok clay. It has been extensively applied in road embankments, foundations of light buildings, and slope stability, etc. The major material used in DMM is Portland cement due to cost effectiveness. Many researchers in concrete technology (Owens, 1979; Mitsui et al., 1994; Ollivier et al., 1996; Mindess, 1996; Igarashi et al., 1996; Ollivier and Massat, 1996; Jaturapitakkul 1999; Chindaprasirt et al., 2001; Yang and Su, 2002; Chindaprasirt et al., 2004 and Thumasujarit and Tangtermsirikul, 2004) attempted to use waste pozzolanic materials from industries such as fly ash and palm ash to reduce the input of cement.

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Note: Discussion on this paper is open until December 2009

Fly ash is the material extracted from flue gases of a furnace fried with coal of Electric Power Plant. The generation of fly ash is far in excess of its utilization. It can be used as a pozzolanic material for geotechnical and geoenvironmental infrastructures (Cokca, 1997). Pozzolanic material generally consists of silica, alumina, ferric oxide etc., and these compounds will form a cementitious material when combined with cement in the presence of water.

Fly ash, an industrial waste material, has been of great interest to geotechnical engineers for soil improvement. Kawasaki et al. (1981) used fly ash mixed with cement in the construction of a man-made island for the Hakucho Bridge in Hokkaido. Kitazume et al. (1999) studied cement stabilized fly ash as a potential fill material for backfilling water front retaining structures. Furthermore, the laboratory investigation demonstrated that fly ash can control the volume change of expensive clay (Kehew, 1995). Moreover, fly ash-lime admixture can reduce swelling, compressibility and increase strength of soil.

From above works, it is reasonable and useful to replace pozzolanic material (Fly ash) to Portland cement for ground improvement. In Thailand, an agricultural country, plenty of biomass fly ashes from flue gases of a furnace fried with natural material such as husk, wood, and sugarcane etc cause many problems such as disposal and pollution.

This biomass fly ash can be used as an alternative to conventional material. A feasibility study for utilizing biomass fly ash to partially replace Type I Portland cement in DMM is needed.

Besides cement and supplementary cementing material, the clay types control the strength development. Sridharan and Prakash (1999a and b) have indicated that all fine-grained soils can be classified as either non-expanding soil (Kaolinite) or expanding soil (Montmorillonite). The lower the swelling potential, the higher the strength and stiffness of stabilized clay.

This paper focuses only on the strength development of low swelling clay admixed with the cement and biomass fly ash. Non- to low swelling soil is found in some lowland areas such as Bangkok plain in Thailand (Horpibulsuk et al., 2007) and Ariake bay in Japan (El-Shafei, 2001).

A framework for the analysis and assessment of the strength development is the clay-water cement ratio hypothesis (Horpibulsuk and Miura, 2001 and Miura et al., 2001) and the concept of an efficiency factor (Papadakis, 1999 and 2000). A method of predicting strength development in cement-fly ash admixed low swelling clay using one point test is proposed in this paper.

MATERIAL CHARACTERISTICS IN CEMENT-FLY ASH ADMIXED SOFT CLAYS

Cement and clays are particulate materials, which exhibit physico-chemical interactions with the fluid with which they interact. Hence, they are considered as interacting particulate materials. In the case of cement based composites, aggregates are non-interacting materials with water, primarily due to their low specific surface and non-electrical nature of surfaces. In the case of soft clays, sand and silt are solid constituents, with the clay fraction being the interacting material having physico-chemical interactions with water. With the minimum clay fraction being available in the soil, the behavior of soft clay is governed mainly by the clay fraction. The role of sand and silt is to dilute the overall physico-chemical potential of the soil.

In the case of cement based composites, cement being the only interacting material, the hardened cement paste would provide continuity to its structure with the coarse constituents being in the embedded state. In the case of soft clay, the clay is already holding certain level of moisture. Due to physico–chemical interactions with water, the soft clay would have been already transformed into an engineering material with effective stress level corresponding to matrix suction of low but definite value (Nagaraj et al., 1994; Nagaraj and Miura, 2001). The soft clay would have a specific micro-fabric formed due to the interacting nature of the clay. For such a system if cementing agent is admixed**,** the strength gets enhanced with time due to transformation into a non-particulate state. Hence**,** it is a combination of two interacting materials with water as pore fluid. Horpibulsuk and Miura (2001); Miura et al. (2001) and Horpibulsuk et al. (2005) have demonstrated that it would be advantageous to have a parameter to reflect the combined effects of clay, cement and water in the analysis of strength and deformation of cement admixed clays. This parameter is designated as clay-water/cement ratio, w_c/C, which is defined as the ratio of clay-water content to cement content. The cement content is the ratio of dry weight of clay to weight of cement. It is a structural parameter reflecting the effect of the fabric and cementation bond. It helps to control the cement content corresponding to the requirement of strength and stress~strain characteristics as the water content of the clay varies over a wide range. The application of the w_c/C to predict the strength development in cement admixed clays is successfully done by Horpibulsuk et al. (2003).

The clay-water/cement ratio hypothesis (Miura et al., 2001) would be used as a fundamental framework for development of strength prediction model for cement-biomass fly ash admixed clay. By considering that the input of fly ash can be equivalent to cement content (Papadakis and Tsimas, 2002), the equivalent cement content (C_e) is equal to kF where k is efficiency factor and F is fly ash content. The cement content (C) is thus the summation of input of cement and equivalent cement content.

MATERIAL USED AND METHODOLOGY

Kaolinite from a commercial company was taken for this investigation to represent a low swelling clay. Its initial water content is 1.5% and the consistency limits of this clay are liquid limit, w_L = 42.5% and plastic limit, w_P = 33.5%. The specific gravity of this clay is 2.78. The biomass fly ash taken from Thai Power supply Company Limited in Chachoenngsao Province, Thailand was passed through sieve No.325. The particle sizes of the biomass fly ash were then broken down by Los Angeles Abrasion Machine. This biomass fly ash is referred to as "off-specification" fly ash because it does not meet the class C or class F criteria in ASTM C 618. Chemical compounds of the biomass fly ash, Portland cement and kaolinite are summarized in Table 1.

The compositional fuel formula of the fly ash is 36% rice hush, 24% bark, 6% board wood, 23% fined Eucalyptus wood, and 11% seed husk. Grain size distribution curves of the kaolinite, Portland cement and biomass fly ash are shown in Fig.1. Grain size distributions of cement and biomass fly ash were obtained from laser particle size analysis.

Water content of the kaolinite was adjusted to attain different levels of liquidity indices from 1.0 to 2.0. This intentional increase in water content is to simulate possible increase that takes place during mixing in the wet method of dispensing cement admixture or due to inevitable increase which occurs in jet grouting.

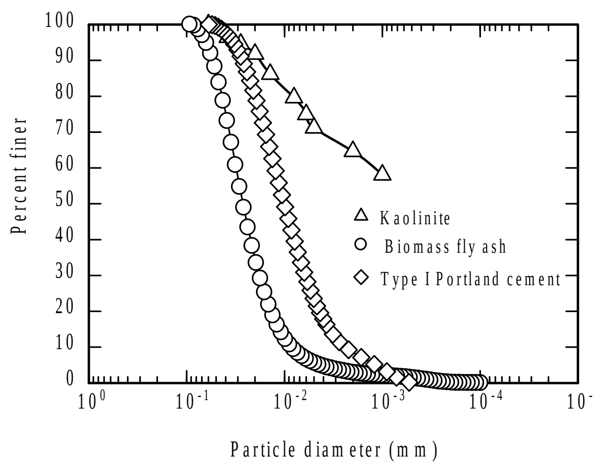


Fig.1 Grain size distribution of kaolinite, the biomass fly ash and Portland cement

Table 1 Chemical compound of biomass fly ash, Portland cement and kaolinite

Chemical compounds	Biomass fly ash	Type I Portland cement	Kaolinite
SiO_2 (%)	74.12	20.90	59.79
Al_2O_3 (%)	0.57	4.76	31.84
Fe_2O_3 (%)	0.88	3.41	1.59
MgO (%)	1.54	1.25	-
CaO (%)	5.91	65.41	-
Na_2O (%)	3.33	0.24	-
K_2O (%)	1.71	0.35	3.05
SO_3 (%)	0.50	2.71	0.05
G_s	1.95	3.15	2.78
LOI	7.45	0.96	3.68

Table 2 Summary of the program for unconfined compression tests

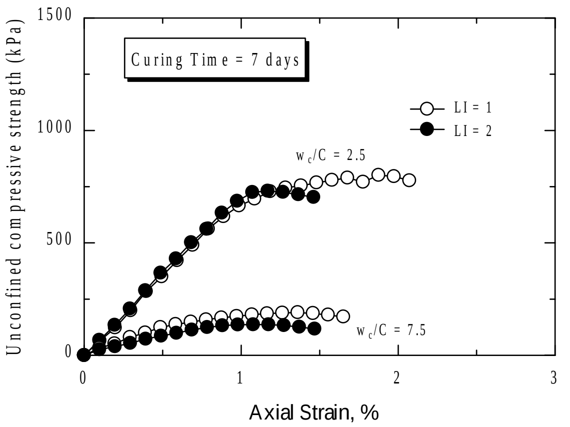
Type of stabilization	LI	w_c/C or w_c/B	Amount of biomass fly ash (%)	Curing time, (days)
Type A	1, 2	2.5, 5.0, 7.5	0	7, 14, 28, 60
Type B	1, 2	2.5, 5.0, 7.5	10, 30	7, 14, 28, 60

Remark:
Type A = Cement admixed kaolinite
Type B = Cement-biomass fly ash admixed kaolinite

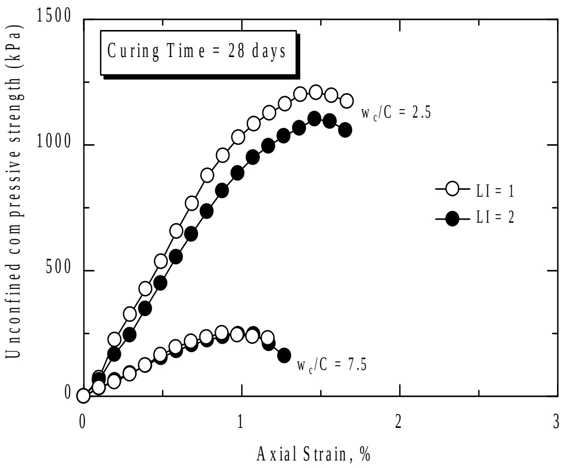
The clay with its water content of 42.5% to 51.6% (LI = 1 -2) was mixed with cement and fly ash to attain the w_c/B values of 2.5, 5.0, and 7.5, where B is the binder content (cement + fly ash). The replacement ratio of the biomass fly ash is 10% and 30% by weight of cement (Cement:Biomass fly ash = 90:10 and 70:30). Through mixing for a period of 10 minutes was reported to have uniform dispersion of the cementing agent (Miura et al., 2001). Such uniform paste was transferred to split molds for cylindrical samples of 50 mm diameter and 100 mm in height, taking care to prevent any air entrapment. All these samples were controlled by total unit weight for the consistency, wrapped in vinyl bags and stored at constant temperature and humidity in a controlled room until different curing periods had lapsed. Samples were cured for a period of 7, 14, 28 and 60 days. Unconfined compression tests in accordance with ASTM D2166-85 were carried out on samples cured for different periods. For the stabilized clay at high cement content as done in this investigation, the unconfined compression test is simpler and more practical than triaxial test for geotechnical design. This is because the high cement content yields the high yield stress where in-situ effective confining pressure acting on the DMM column is generally much lower. For such condition, the strength development is mainly dependent on the cementation bond strength and irrespective of effective confining pressure (Horpibulsuk et al., 2004a). The rate of loading displacement in unconfined compression test is 1 mm/min. The test program is summarized in Table 2. Based on the test result, the strength prediction method is proposed. The method is verified by the separate test results of cement-fly ash admixed kaolinite at water contents of 43.1% and 50.9% and replacement ratios of 15% and 20% of biomass fly ash.

TEST RESULTS

Figure 2 depicts typical stress-strain relationship of cement admixed kaolinite at 7 and 28 days of curing. The relationship is the same pattern with practically the same strength level even of different initial water contents, w_c (at LI = 1 and 2) for each clay-water/cement ratio. These results are in agreement with the previous investigation (Papadakis, 2000 and Horpibulsuk et al., 2003 and 2005).

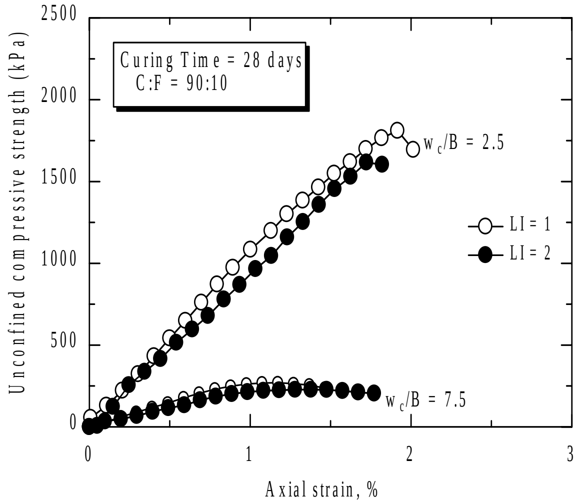


a) 7 days

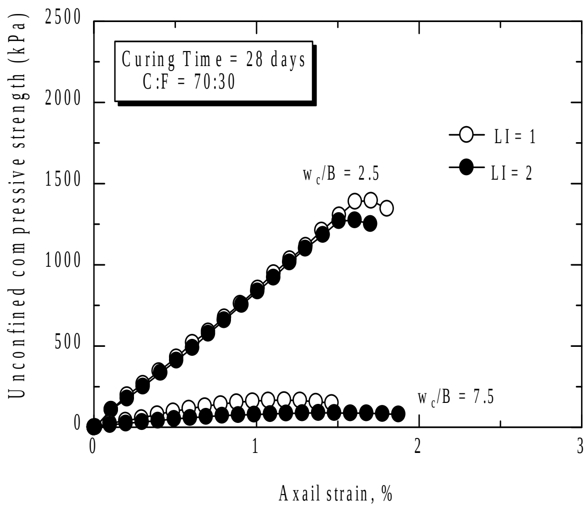


b) 28 days

Fig.2 Stress-strain relationship of cement admixed kaolinite at 7 and 28 days of curing



a) Cement : Biomass fly ash = 90:10

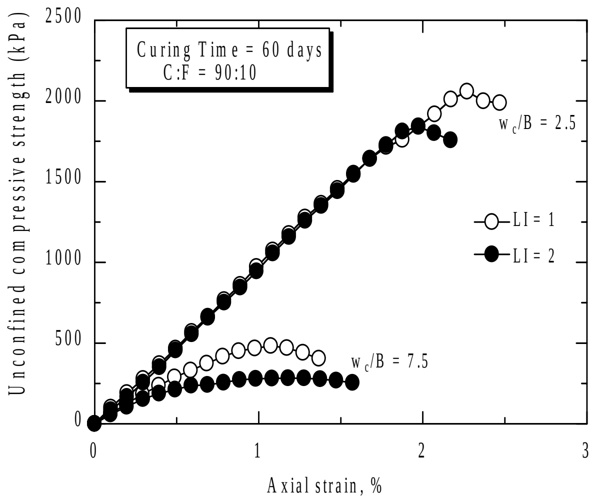


b) Cement : Biomass fly ash = 70:30

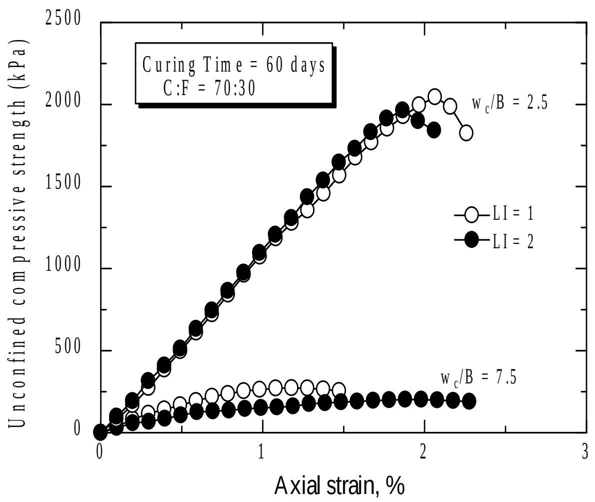
Fig.3 Stress-strain relationship of binder admixed kaolinite at 28 days of curing

The 28 day strength of curing is higher than at 7 day strength due to the hydration reaction. In case of cement-fly ash stabilization at a particular replacement ratio, and curing time, it is found that w_c/B is the prime parameter as illustrated in Figs. 3 and 4 for 28 and 60 days of curing, respectively. For a particular curing time, the lower the w_c/B, the greater the strength. At a particular replacement ratio, the strength development of cement-fly ash admixed kaolinite increases with time due to the pozzolanic reaction.

Influence of replacement ratio at a particular curing time is illustrated in Fig.5. It is observed that 10% replacement ratio gives the highest strength for all clay-water/binder ratios, w_c/B and curing times. The 30% replacement ratio strength is higher than 0% replacement ratio strength only when w_c/B equal to 2.5 and 5.0 after 28 days of curing.



a) Cement : Biomass fly ash = 90:10



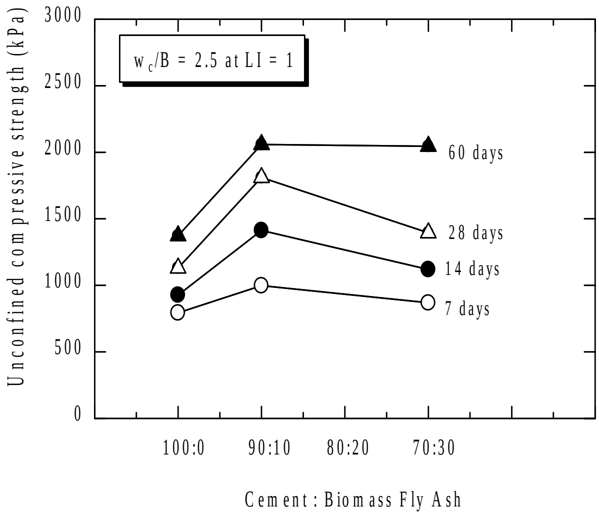
b) Cement : Biomass fly ash = 70:30

Fig.4 Stress-strain relationship of binder admixed kaolinite at 60 days of curing

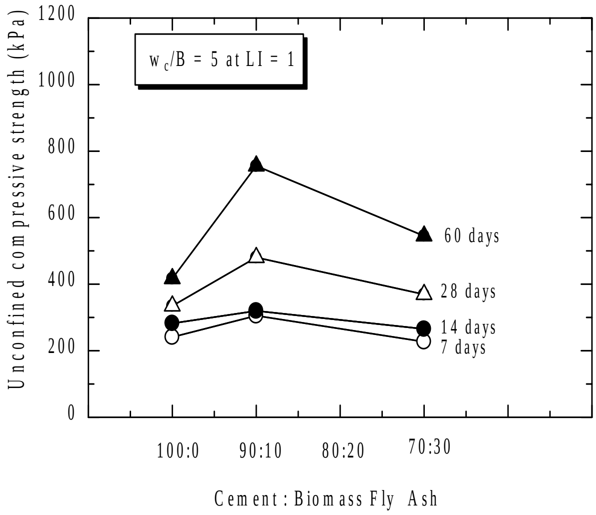
The high fly ash content at early time gives lower strength possibly due to less $Ca(OH)_2$ for pozzolanic reaction. It is concluded from this investigation that the replacement ratio, w_c/B and curing time are the influencing factors controlling strength development of cement-biomass fly ash admixed kaolinite. These three factors are considered in analysis of strength development in the following section.

ANALYSIS OF STRENGTH DEVELOPMENT

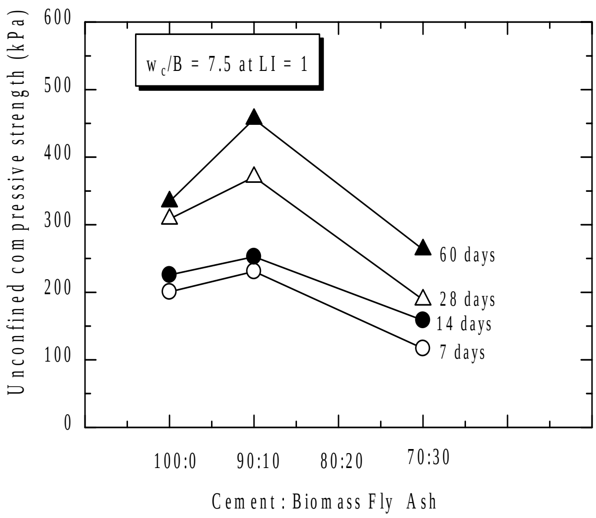
By considering that the strength development depends on inverse clay-water/cement ratio, C/w_c at a particular curing time (Nagaraj et al., 1998 and Horpibulsuk et al., 2003). The strength equation is expressed as follows.



a) at w_c/B = 2.5



b) at w_c/B = 5



c) at w_c/B = 7.5

Fig.5 Unconfined compressive strength with binder content

$$q_u = A\left(\frac{C}{w_c}\right) + E \quad (1)$$

where q_u is the compressive strength of cement admixed kaolinite at a specific curing time, C/w_c is the inverse clay–water/cement ratio and A and E are empirical constants dependent on type of soil and curing time. The higher the curing time, the greater the A and E values.

In the case of blended cement (cement+fly ash), the above concept can be employed. It is assumed that the efficiency of biomass fly ash to partially replace Type I Portland cement can be expressed by kF where k is the efficiency factor, indicating the degree of the cementation bond induced by fly ash replacement related to that of cement and F is the fly ash content. If the k-factor is around unity ($k \approx 1$), it means that the specific pulverized fly ash can substitute equivalently for Portland cement. The prime parameter for blended cement stabilization is thus $(C_i+kF)/w_c$, where C_i is the input of cement content. As such, Eq. (1) is modified as follows

$$q_u = A\left(\frac{C_i + k.F}{w_c}\right) + E \quad (2a)$$

$$q_u = A\left(\frac{C_i}{w_c}\right) + A_2\left(\frac{F}{w_c}\right) + E \quad (2b)$$

where A_2 is the empirical constant obtained from multi-linear regression analysis. It is dependent on type of fly ash, clay mineral, curing time and replacement ratio. From the above equations, k can be determined from A_2/A. In order to estimate the k-factor, the multi-linear regression is adopted. The proposed relation can well fit the test results as shown in Fig. 6. From the linear regression, it is found from this investigation that A and

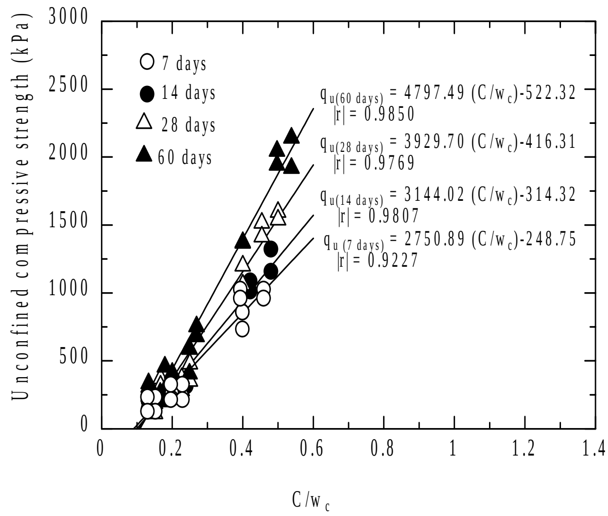


Fig.6 Strength development with time of cement-biomass fly ash admixed kaolinite

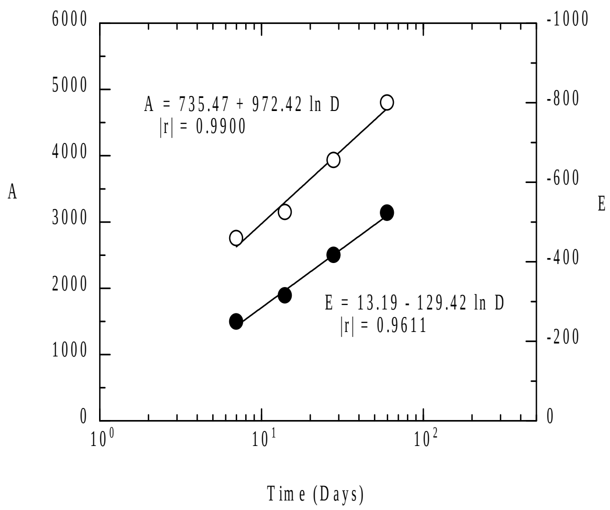


Fig.7 Relationship between A and E versus time of cement-biomass fly ash admixed kaolinite

E can be expressed in terms of the natural logarithm of curing time as shown in Fig. 7 and following equations

$$A = 735.47 + 972.42 \ln D \quad (3)$$

$$E = 13.19 - 129.42 \ln D \quad (4)$$

It is noted that the A and E values are the same for cement stabilization with and without fly ash. The k-value is dependent upon curing time and replacement ratio, irrespective of clay water content and binder content.

Table 3 summarizes the k-values for different replacement ratios, and curing times. At the same curing time, the higher replacement ratio (30% of the biomass fly ash), the lower k-value. The k-value increases with time for each replacement ratio. By considering the curing time (days) in natural logarithmic scale, the relationship between k-value and curing time can be expressed as linear variation in the form:

Table 3 k -value of the biomass fly ash admixed kaolinite

C:F	Curing time, days	Multi-Linear Regression		R^2	k-value
		A	A_2		
90:10	7	2609.0	6511.6	0.957	2.50
	14	3065.3	9281.2	0.955	3.03
	28	3663.3	12844.9	0.954	3.51
	60	4469.2	19876.3	0.978	4.45
70:30	7	2424.9	2309.7	0.970	0.95
	14	3067.9	3609.7	0.961	1.18
	28	3978.2	5751.2	0.951	1.45
	60	4902.1	8855.9	0.962	1.81

For 10% replacement ratio;

$$k_{(90:10)} = 0.696 + 0.890 \ln D \quad (5)$$

For 30% replacement ratio;

$$k_{(70:30)} = 0.146 + 0.40 \ln D \quad (6)$$

where $k_{(90:10)}$ is the k for 90% cement and 10% biomass fly ash, $k_{(70:30)}$ is the k for 70% cement and 30% biomass fly ash and D is the curing time (days).

It is of interest to mention that even though the k-values are dependent upon replacement ratio, the change rate with time is practically the same as shown by the normalized plot in Fig.8. Taking the 28 day- k value as a reference normalized k-value can be performed in terms of curing time for LI = 1-2 in the form

$$\frac{k_D}{k_{28}} = 0.150 + 0.265 \ln D \quad (7)$$

where k_D is the k after D days of curing, k_{28} is the 28 day-k-value and D is the curing time (days) with the coefficient of correlation of 0.990. This equation is useful for predicting the k-value at any cuing time from a known k-value at a specific curing time and replacement ratio.

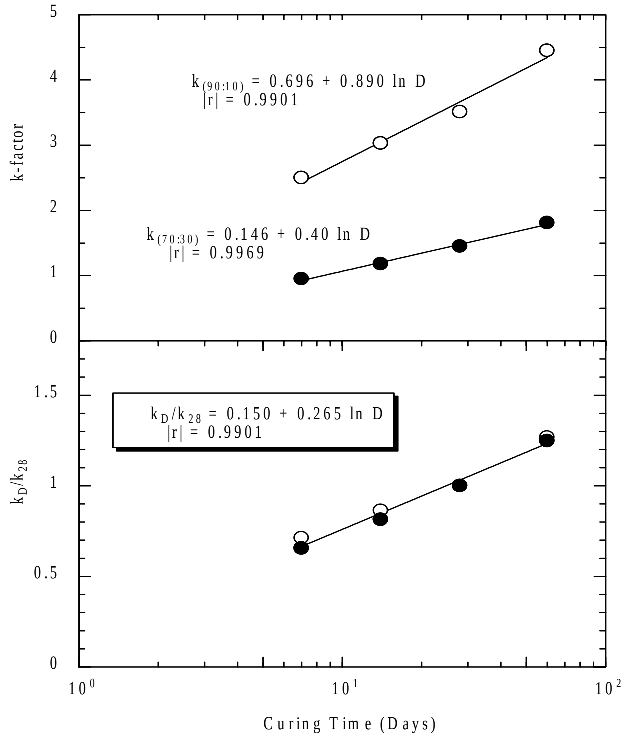


Fig. 8 The k-factor development with time and its generalization at 10% and 30% replacement ratio of the biomass fly ash

Table 4 Strength prediction of the cement-biomass fly ash admixed kaolinite at 7 days of curing (w_L = 43.10% and w_P = 33.5%)

C :F	w_c (%)	C_i (%)	F (%)	k-value	Predicted strength, q_{up} (kPa)	Laboratory strength, q_{ul} (kPa)	$\frac{\lvert q_{up}-q_{ul}\rvert}{q_{ul}} \times 100$ (%)
100:0	43.1	12.3	0.0	1.00	512	642	20.25
	50.9	14.5	0.0	1.00	512	627	18.34
	58.7	16.8	0.0	1.00	512	591	13.22
	43.1	6.6	0.0	1.00	165	245	32.65
	50.9	7.8	0.0	1.00	165	221	25.34
	58.7	9.0	0.0	1.00	165	209	21.05
85:15	43.1	10.5	1.8	2.11	637	580	9.83
	50.9	12.4	2.2	2.11	637	574	10.98
	58.7	14.3	2.5	2.11	637	588	8.33
	43.1	5.6	1.0	2.11	232	269	13.75
	50.9	6.7	1.2	2.11	233	219	6.39
	58.7	7.7	1.4	2.11	233	172	35.47
85:20	43.1	9.8	2.5	1.73	621	551	12.70
	43.1	5.3	1.3	1.73	224	207	8.21
	50.9	6.3	1.6	1.73	224	197	13.71
	58.7	7.2	1.8	1.73	224	183	22.40
Mean Absolute Percent Error, MAPE							17.04 %

(MAPE $= \frac{1}{n}\sum_{i=1}^{n}\frac{\lvert q_{up}-q_{ul}\rvert}{q_{ul}} \times 100$)

From this investigation, it is possible to use the clay-water/cement ratio and *k*-value as prime factors to assess the strength development at any replacement ratio between 10 and 30% and any curing time. Table 4 shows the prediction of the strength development of cement-fly ash admixed kaolinite. For simplicity, the *k*-values for any replacement ratio were approximated from the interpolation of the *k*-values shown in Fig. 8 and the *A* and *E* values were determined from Eqs. (3) and (4). It is found that the predicted and measured values are in good agreement with an engineering acceptable range.

CONCLUSIONS

This paper deals with the investigation of utilizing the biomass fly ash as a pozzalanic material. The phenomenological model of assessing the strength development of blended cement admixed low swelling clay is proposed. The model proposed is within the framework of the clay-water/cement ratio hypothesis and the concept of an efficiency factor. The effect of replacement ratio on the strength development is taken care by the efficiency factor (*k*-factor). It is found that the *k*-factor is dependent on curing time and replacement ratio of biomass fly ash, irrespective of binder content. This proposed method of predicting strength is useful in estimating the strength of blended cement admixed clay wherein the water content and cement content vary over a wide range of liquidity indexes of 1 to 2.

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