Strength of Lime-Treated Fly Ash Using Bentonite

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ABSTRACT: Fly ash has many bulk applications; but Class 'F' fly ash being non-cohesive, has to be strengthened or reinforced when used in structural fills. Portland cement and lime are the usual additives for strengthening fly ash. The strength from such additions comes from pozzolanic reactions. In this study, bentonite was used to augment pozzolanic reactions of fly ash with lime, producing very high unconfined compressive strength exceeding 7000 kPa. The strength increased by 88% because of 20% addition of bentonite at the optimum lime content of 13% by weight. There was no adverse effect in terms of swell after adding bentonite. The addition of bentonite also increased the elastic modulus of fly ash-lime combine.

KEYWORDS: Fly ash, Lime treatment, Bentonite, Unconfined compressive strength, Soil stabilisation

1. INTRODUCTION

Fly ash is a coal combustion product (CCP). It forms about 80-85% of all the CCPs produced. Worldwide production of CCPs was approximately 780 million tonnes (MT) in 2011. With 395 MT of production, China is the highest producer of CCPs. The USA and India are the second and third highest producer of CCPs, with annual output of 118MT and 105 MT respectively (Heidrich et al. 2013). The enormous volume of fly ash generated mainly from the coal-based power plants posed serious environmental problems. It was disposed in dumps and low lying areas, which occupied large areas of land. Being very light, fly ash is blown far away by wind in the dry season, creating hardship for surrounding habitations.

Through concerted efforts, several utilities of fly ash were developed and promoted throughout the world. Some such uses of fly ash are – as landfill, as admixture in concrete, as a pozzolanic material in combination with lime to stabilise soil, for immobilisation of contaminants in soils, as raw material for brickmaking, etc. In recent years, the cement industry has been using a large quantity of fly ash as a raw material for making fly ash-based Portland pozzolana cement (PPC). In 2008-09, India produced about 182 MT of cement, out of which 67% was PPC (Anonymous 2011).

As of 2011, globally about 53% of the total production of CCPs was effectively utilised, although this rate varies widely with countries. The highest reported effective utilisation rate was 96.4%, in Japan. The European countries together utilise about 91% of their CCPs. The rate of utilisation of CCPs by the largest producers i.e. China, the USA and India are 67%, 42% and 14% respectively (Heidrich et al. 2013). So, a lot is yet to be done for full utilisation of CCPs, particularly fly ash.

The physical and chemical properties of fly ash depend upon the composition of the parent coal, combustion process, efficiency of the fly ash collection devices, and the storage and handling processes. Fly ash is generally finer than Portland cement and consists of minute aluminous silicious glassy spheres. Fly ash particles are spherical, have a large specific area (2000-10000 cm^2/gm), low specific gravity, no plasticity, and generally fall in the category 'silt' as per the United Soil Classification System (Joshi 2000). The major chemical components of fly ash are silica (SiO_2) and alumina (Al_2O_3). Some oxides of calcium (CaO) and iron (Fe_2O_3) and various other trace oxides of alkalies, titanium, etc. may also be present. SiO_2 and Al_2O_3 participate in the strength-giving pozzolanic reactions in presence of lime. If CaO is present in fly ash, such reactions take place without adding lime.

Based on the self-cementitious properties, fly ashes are divided in to Class C and Class F categories as per ASTM C618-08a. Class C fly ash has generally higher CaO content (more than 15%) and is self-cementitious. It has high pH value and low loss-on-ignition (i.e. less unburnt carbon). The usual sources of Cass C fly ashes are sub-bituminous and lignite coals. The Class F fly ash is not self-cementitious. Its pH value is usually less than 11 and it contains more unburnt carbon and hence more loss on ignition (Joshi 2000). Because of the self-cementitious property, the Class C fly ash is preferred for use in earthfill and embankments, flowable fills, soil stabilisation, etc.

Every year, enormous quantities of earthwork are required for construction of structural fills such as road and rail embankments, road and airport subgrade, river embankments, dams, and various containment barriers. In India alone, approximately 108 thousand kilometre of new road was added in 2011 (Anonymous 2012), which required construction of comparable length of highway embankments. These can be a major area for utilizing huge volumes of fly ash. When non-self-cementing fly ash is to be used in structural fill, it has to be either confined within strong supports such as embankments of natural cohesive soil, masonry, reinforced earth, etc., or strengthened with other additives. Small amount of cement may be used to impart the necessary strength to fly ash, particularly when the fly ash is non-self-cementing. Researchers have reported on various aspects of cement addition with fly ash (Kaniraj and Havanagi 1999, Lav and Lav 2000, Hanehara et al. 2001, Pandian and Krishna 2002, Arora and Aydilek 2005, Zabielska-Adamska 2008, Li et al. 2010, Chang et al. 2011, Sivapullaiah and Moghal 2011). It is possible to obtain high strength from cement treated fly ash. Kaniraj and Havanagi (1999) achieved a 58-day strength of 1400 kPa from Rajghat (Delhi)-fly ash with 6% OPC. The trend was increasing at that point.

Fly ash is pozzolanic in nature, and both of its major components SiO_2 and Al_2O_3 react with lime. Therefore, lime is also used to stabilise and strengthen fly ash (Shi 1996, Heath et al. 1999, Zhou et al. 2002, Chand and Subbarao 2006, Sivapullaiah and Moghal 2011). Lav and Lav (2000) observed that the reaction products of Class F fly ash for both cement and lime treatments were similar. Both produced about the same amount of hydration products upon stabilisation. However, lime stabilisation yielded lower unconfined compressive strength (UCS) than cement. At 90 days, cement stabilisation gave about 5500 kPa strength, while lime stabilisation resulted in a UCS of about 3000 kPa.

Lime is more widely used to stabilise clay soils. Long-term strength in excess of about 1400 kPa is expected when lime is added to a reactive soil, usually clay. In some particular clay soils, ultimate compressive strength values above 7000 kPa can be reached. Such increase in strength provides significant structural enhancement to the pavement or embankment. In addition to this, lime provides the benefit of autogenous healing to soil, whereby, strength is regained even after periods of environmental or load damage providing long-term durability of lime-treated soil (Little 1999).

Basing upon the available information as cited above, an attempt was made in the present study for higher increase in the strength of lime-stabilised no-self-cementing fly ash by adding a second pozzolanic material to react with lime. Bentonite was chosen as the other reactive material because lime has very high affinity for the clay mineral montmorillonite (Bell 1996), which is the active component in bentonite. Addition of bentonite was expected to initially add cohesion to fly ash, and hence the immediate strength for fly ash to support itself. It was also expected to enhance the pozzolanic reactions, giving higher strength to the fly ash fill in the long run.

The objective of this study was to find out yet another mass re-use of fly ash, which would yield a very strong material and which would withstand high loads, for example in airport pavement subgrades. Even in normal highway embankments, a very strong subgrade may result in reduced thicknesses of flexible pavement layers.

2. MATERIALS AND METHOD

The fly ash used in this study is a waste product disposed from the Farakka Thermal Power Station in West Bengal, India. The ash is well-graded, with the D_{90}, D_{50} and D_{10} sizes being 120µ, 51µ and 12µ respectively. Figure 1 shows the image of fly ash obtained from scanning electron microscopy (SEM). The used fly ash had silica content of 50-55% and alumina content of 25-34%. It had a CaO content of less than 1.3% and had no self-adhesion properties.

Quick lime was used to strengthen fly ash by initiating pozzolanic reaction. Laboratory grade lime (CaO) powder was used with or without addition of bentonite.

To bind the fly ash particles for immediate strength, and to augment the pozzolanic reaction, a commercial bentonite is used in this study. The SEM image of bentonite is shown in Figure 2. The particles are aggregates of smaller scaly particles. The properties of the materials used are presented in the Tables 1–3. Based on the liquid limit and plasticity index (Table 2), the bentonite is classified as a clay of high compressibility (CH).

The experimental programme comprised characterisation tests and strength tests. The characterisation tests included tests for determination of physico-chemical properties (specific gravity, particle size and pH value), tests for index properties (liquid limit, plastic limit), scanning electron micrography (SEM) with EDX for microstructure and atomic composition, and X-ray diffraction (XRD) for mineral composition. The powder XRD patterns for the fly ash and bentonite used are shown in Figure 3 and Figure 4. Major minerals present in the materials were identified by matching the obtained XRD peaks with those of powder diffraction library files and also with the peaks from pre-published data.

Initial consumption of lime (ICL) was determined from the pH tests on fly ash and bentonite. Both the materials – fly ash and bentonite have pH values above 7.0. The pH tests were done on soil slurries with soil:water ratio of 1:5. Figures 5-6 show that the pH values of both the materials shoots up on addition of even 1% lime. In case of bentonite, further increase in pH is gradual from 11.5 at 1% lime content up to the saturation level at 5% lime content. However, in case of fly ash, very little increase in pH is seen beyond 1% lime content, and we can say that lime has become nearly saturated after 1% addition of lime. The maximum attained pH values are less than 12.4, as solubility of lime reduces at higher temperatures. During the period of tests, the temperature was in the range of 27-30°C.

Unconfined compression (UC) tests were conducted to measure the strength performance before and after the treatment. These tests provide a reliable and quick method of measurement of strength particularly when a large number of samples are to be tested (Awoleye et al. 1991, Kalkana and Akbulut 2004, Sariosseiri and Muhunthan 2009). The tests were done in unsoaked condition.

The UC test samples were prepared at maximum dry density. For this purpose, light compaction tests (Standard Proctor's tests) were carried out to determine maximum dry density and optimum moisture content.

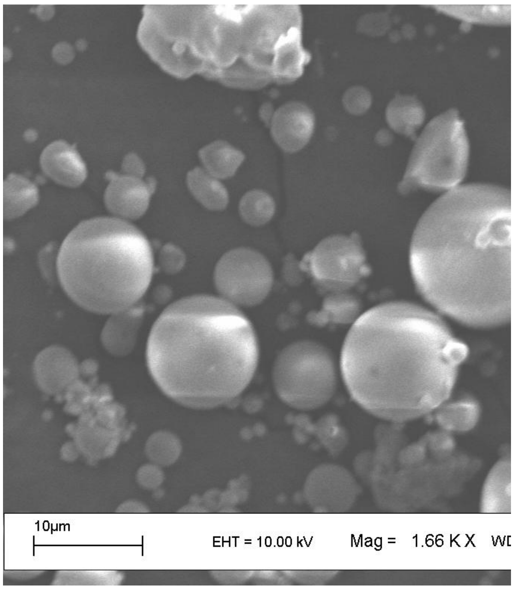

Figure 1 SEM image of fly ash

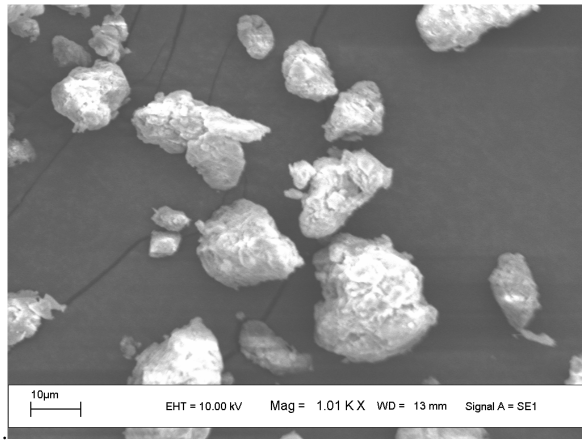

Figure 2 SEM image of bentonite

Table 1 Physico-chemical properties of fly ash and bentonite

Property	Fly ash	Bentonite
Specific gravity	2.12	2.54
Particle size distribution	<632 µ. However, fraction finer than 425 µ was used for tests.	1.12µ to 399µ. 97% of the particles were finer than 75µ
Specific surface area (*SSA*)	0.92 m^2/g	65.79 m^2/g
Cation exchange capacity (*CEC*)		45 meq
pH value	9.00	8.79
Initial consumption of lime (ICL)	1%	4%

Table 2 Index properties of bentonite

Property	Value
Liquid Limit	265%
Plastic Limit	42%
Plasticity Index	223%
Shrinkage Limit	33%

Table 3 Properties of lime

Property	Value
Chemical formula	CaO
Make	S.D. Fine Chem, India
Specific gravity	3.1
Minimum assay	95 %

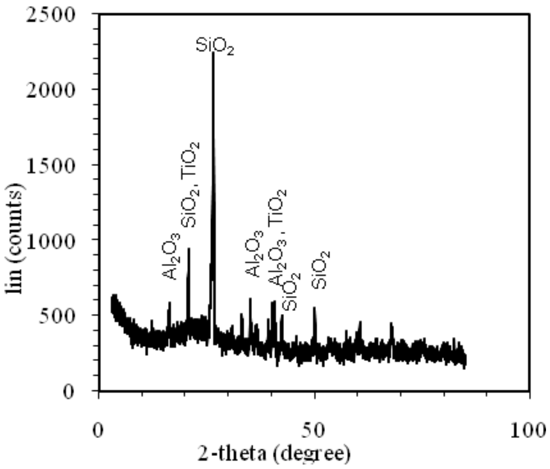

Figure 3 X-Ray Diffraction pattern of fly ash

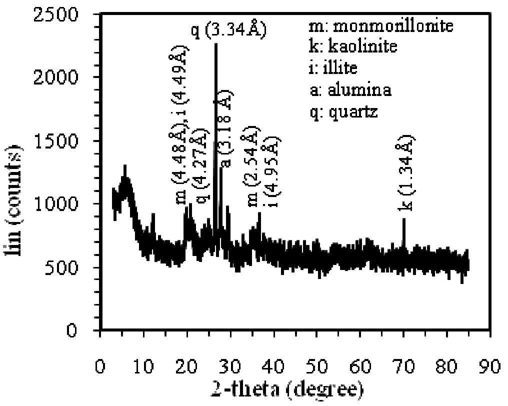

Figure 4 X-Ray Diffraction pattern of bentonite

One of the materials being bentonite, which is highly expansive, swell tests were also conducted in oedometers as per IS 2720 Part XLI, to see if the bentonite-mixed samples exhibit unacceptable levels of swelling.

For observation of strength behaviour, samples were prepared with fly ash-bentonite mixtures at various proportions. These soil samples were designated as F80, F60, etc., where the numerical value in the sample designation implies the percentage by weight of fly ash in the fly ash-bentonite mixture before adding lime. Thus, the sample designation F80 denotes that the sample is composed of 80% by weight fly ash and 20% by weight bentonite. These samples were treated with lime at various lime contents (1%, 3%, 5%, 9%, 13% and 17% by weight).

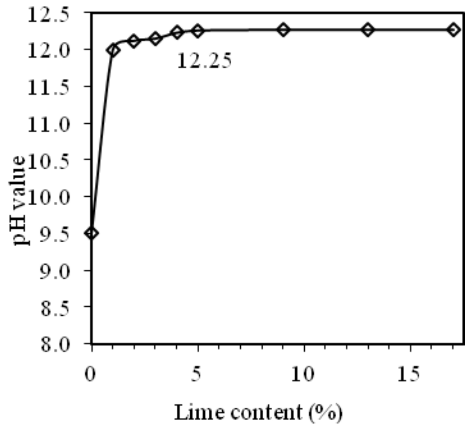

Figure 5 Variation of pH of fly ash with lime content

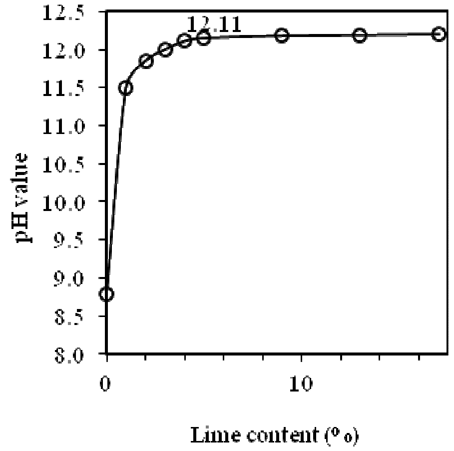

Figure 6 Variation of pH of bentonite with lime content

Samples with 38mm diameter were prepared in moulds at optimum moisture content and maximum dry density and tested for unconfined compressive strength as per IS 2720 (Part 10). Since lime stabilisation of soils involves time-dependent pozzolanic reactions, the UC tests were conducted on samples cured for different curing periods of 0, 1, 3, 7, 15, 30, 60 and 90 days. The test programmes are summarised in Table 4.

3. RESULTS AND DISCUSSION

Figure 7 shows the stress-strain responses of the fly ash-bentonite mixes without lime addition. Although the 100% fly ash samples (F100) lack cohesion, the binding action created by the surface tension of water and suction during deformation provided enough strength (54 kPa) to test it under unconfined condition. Addition of bentonite has increased the strength of fly ash through the cohesion of bentonite and resulting binding effect on fly ash particles. With 20% addition of bentonite, the strength has increased to almost four times that of fly ash without binders, although this is not yet much of an improvement. The F0 sample (i.e. 0% fly ash, 100% bentonite) has been included in the figure just to demonstrate that strengths of some of the fly ash-bentonite mixtures have surpassed the strength of bentonite alone.

Bentonite exhibits very high swelling with water. Addition of bentonite makes the fly ash susceptible to some swelling, which however becomes negligible on addition of lime (Figure 8). Because of cation exchange, Na^+ ions from the space between of montmorillonite mineral sheets are replaced by Ca^{2+} ions. It produces stronger bonds between the negatively charged surfaces of clay mineral sheets and Ca^{2+} ions, so that intruding water particles cannot push the mineral sheets apart (Sivapullaiah et al., 2000).

Table 4 Summary of tests conducted

Tests	Material	Fly ash: bentonite ratio in sample	Lime added (%)	Curing period (days)
Characterisation tests:				
Sp.Gr., particle size distribution, pH, Sp. Surface	Fly ash, bentonite	-	-	-
SEM-EDX, XRD	Fly ash, bentonite	-	-	-
Consistency Limits	Bentonite	-	-	-
Engg. Properties:				
Compaction	Fly ash, bentonite and their mixes	100:0, 80:20, 60:40, 40:60, 20:80, 0:100	0, 1, 3, 5, 9, 13, 17	-
Oedometer swell tests	Fly ash, bentonite and their mixes	100:0, 80:20, 60:40, 40:60, 20:80, 0:100	0, 1, 3, 5, 9, 13, 17	-
UC Tests	Fly ash, bentonite and their mixes	100:0, 80:20, 60:40, 40:60, 20:80, 0:100	0, 1, 3, 5, 9, 13, 17	1, 3, 7, 15, 30, 60, 90

Addition of bentonite to fly ash also changes its compaction characteristics. It is seen that maintaining the maximum dry density (MDD) of fly ash (F100) is very difficult as a slight change in moisture content from the optimum moisture content (OMC) reduces the dry density noticeably from the MDD (Figure 9). Addition of 20% bentonite makes the compaction characteristics flatter. As a result, the dry density can be maintained near the MDD value over range of moisture content of about 20-24% near the OMC, making the MDD achievable and maintainable. Addition of lime, however, drastically changes the OMC and MDD values of the bentonite-mixed fly ash. Addition of even small amount of lime significantly reduces MDD, and higher lime content further reduces the MDD slightly. This is because of flocculation of the bentonite particles by lime. Additional calcium cations, which are not consumed in cation exchange, crowd onto the surface of clay particles. These charge concentrations make clay particles to create flocs/agglomerations. These flocs resist reorientation of particles during compaction to some extent, resulting in less MDD. It should be mentioned here that the compaction tests on lime treated samples were done immediately after mixing, and only the initial lime reactions, and not pozzolanic reactions, could take place. The change in MDD and OMC of lime treated samples are shown in Figure 10-11.

The stress-strain responses of the fly ash on addition of lime for different curing periods are shown in Figures 12-15. The stress-strain responses exhibited mostly ductile response and the strength gain is visibly less at relatively low lime content. The strength gain is low at moderate curing even with higher addition (i.e. ≥ 5%) of lime. Only after long curing periods (i.e. 60-90 days) the specimens turned brittle and the strength gain became high. Ghosh and Subbarao (2001) reported that the interaction between fly ash and lime is complex and the pozzolanic reactions are very slow. At high pH levels induced by the lime, alumina and silica get dissolved from the edges of the soil particles. These react with calcium and hydroxyl ions to produce various forms of calcium silicate hydrates

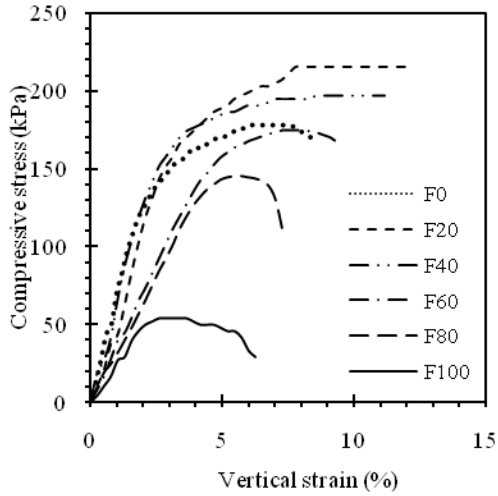

Figure 7 Effect of bentonite addition on stress-strain response of fly ash, without lime

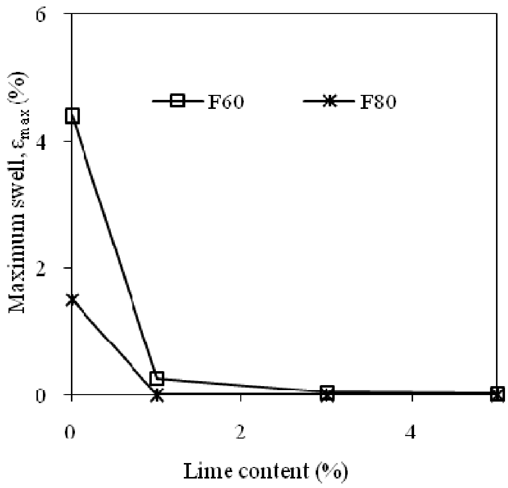

Figure 8 Effect of lime on swell behaviour of swell of fly ash-bentonite mixtures in oedometers

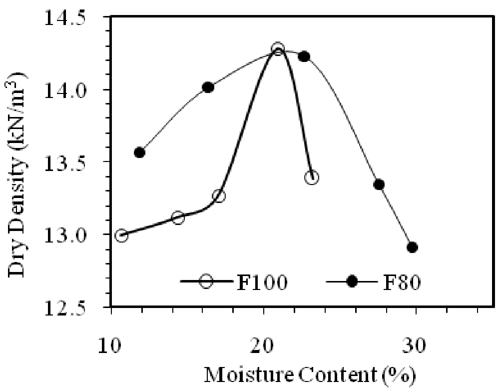

Figure 9 Change in compaction characteristics of fly ash because of bentonite addition

(CSH) and calcium aluminate hydrates (CAH). These reticulous and gel-like substances solidify with time to become hard and bind the soil particles (Eades and Grim 1960, Rajasekaran and Narasimha Rao 1998, Lav and Lav 2000, Ghosh and Subbarao 2001, Dermatas and Meng 2003).

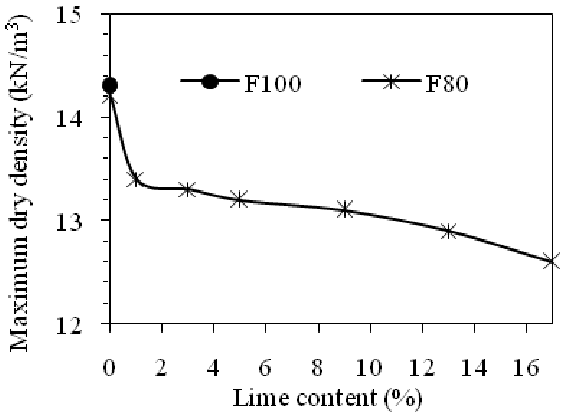

Figure 10 Change in maximum dry density of fly ash-bentonite mixture because of lime addition

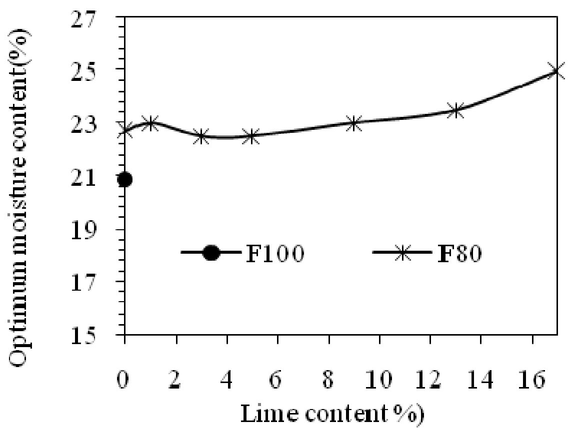

Figure 11 Change in optimum moisture content of fly ash-bentonite mixture because of lime addition

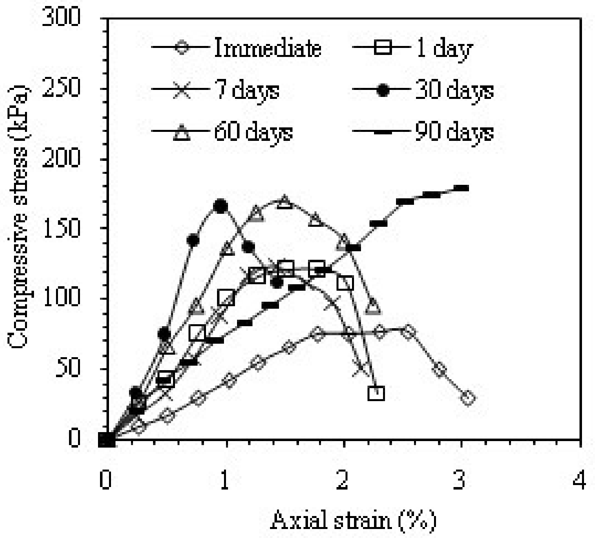

Figure 12 Stress-strain responses of fly ash treated with 1% lime

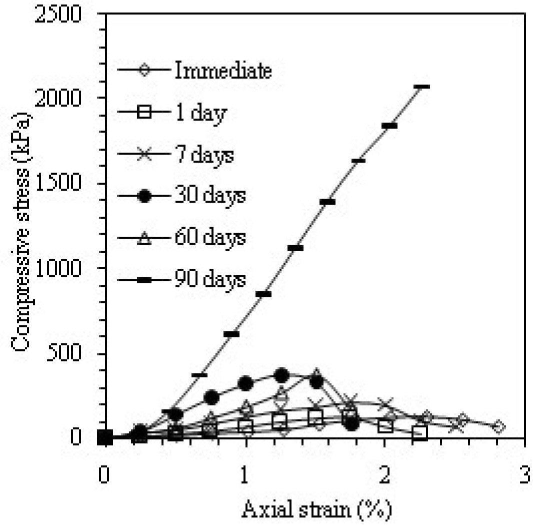

Figure 13 Stress-strain responses of fly ash treated with 5% lime

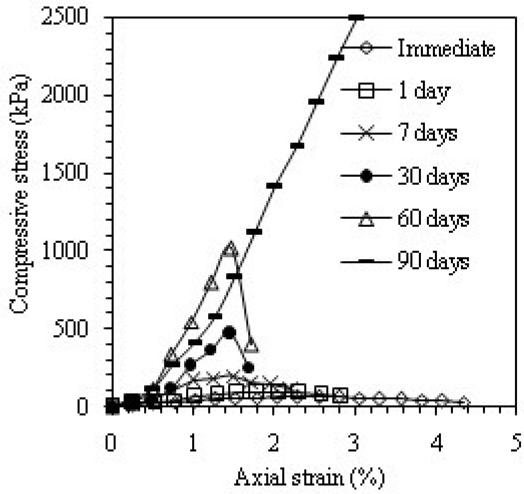

Figure 14 Stress-strain responses of fly ash treated with 9% lime

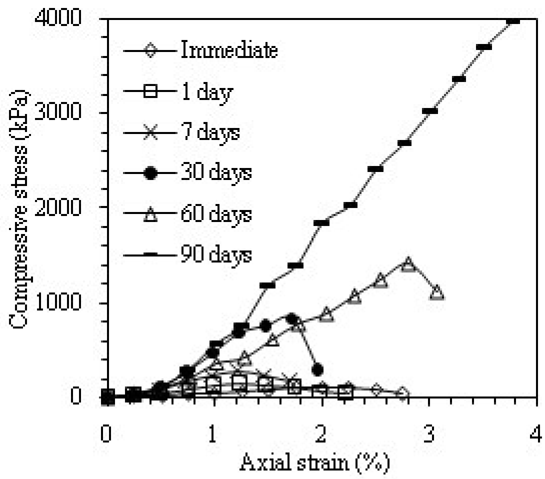

Figure 15 Stress-strain responses of fly ash treated with 13% lime

The stress-strain characteristics of the samples with prolonged curing are also linear and steep up to the failure point, which clearly indicates that along with the unconfined compressive strength, the elastic modulus also increases on application of high amount of lime. This has been reflected in Figure 22.

Similarly, when 20% bentonite is mixd with fly ash and then lime is added, the stress-strain response is ductile for short curing periods (Figures 16-19). However, with longer curing period, the mixes showed brittle failure, indicating solidification of the sample. This trend is more prominent with high percentage of fly ash and lime. Here also, the stress-strain characteristics of the fully cured samples are linear and steep up to the failure point, showing clearly the gain in the unconfined compressive strength as well as the elastic modulus. This indicates that deformation under load will be much less in fly ash mixed with bentonite and treated with high dose of lime.

UC tests were also conducted for the combination of 60% fly ash + 40% bentonite (mix F60). The variation of UCS with lime content for various fly ash-bentonite mixes, at different curing periods are shown in Figures 20–22. In general, the strength improvement is marginal with short curing time (i.e. ≤ 7 days) even at a high lime content. Significant increase in strength is observed only after about 15 days of curing. The UCS continues to increase with increase in lime content. As the pozzolanic reactions continue, lime in solution is consumed and more lime must be dissolved to maintain the solution equilibrium. Increase in lime concentration, at least up to 10%, is favorable in terms of strength development, despite the fact that only very small amount of lime is sufficient to saturate the pore-water solution (Locat et al. 1990). In addition to the lime content, the dispersion of solid lime in excess may have a strong influence on stabilisation. Higher is the lime content better is the dispersion of it, the shorter the average distance between the reacting soil and lime particles, thus producing a more efficient molecular diffusion of calcium within the interconnected and saturated portion of the porous soil system (Locat et al. 1990). However, beyond about 13% lime content strength is seen to reduce for all combinations of fly ash and bentonite (Figures 20-22). Hence it can be said that, for the tested material, 13% lime content is the optimum amount that gives maximum increase in strength. Small lumps of calcium carbonate were also formed beyond this limit, showing wastage of lime. Similar reduction in strength was also observed by Kampala and Horpibulsuk (2013), and Liu et al. (2012).

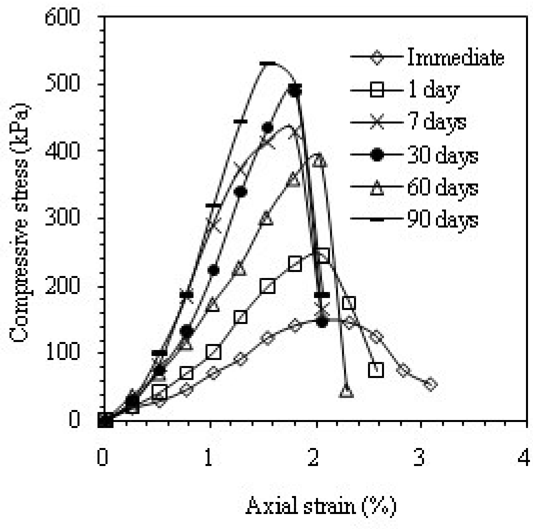

Figure 16 Stress-strain responses of fly ash-bentonite mix F80 treated with 1% lime

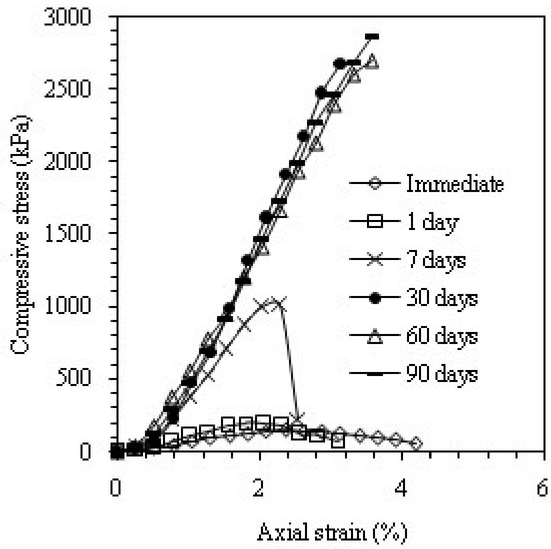

Figure 17 Stress-strain responses of fly ash-bentonite mix F80 treated with 5% lime

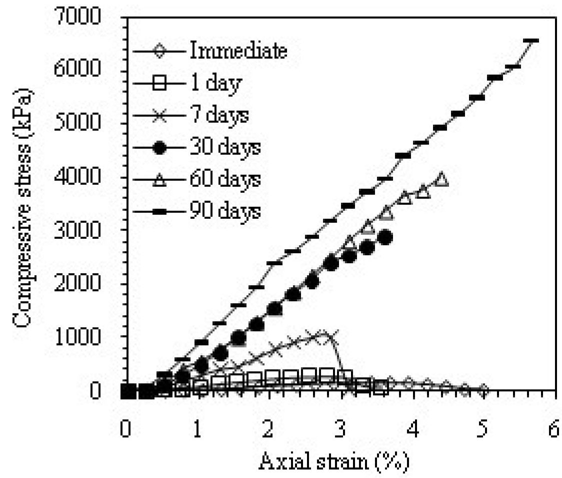

Figure 18 Stress-strain responses of fly ash-bentonite mix F80 treated with 9% lime

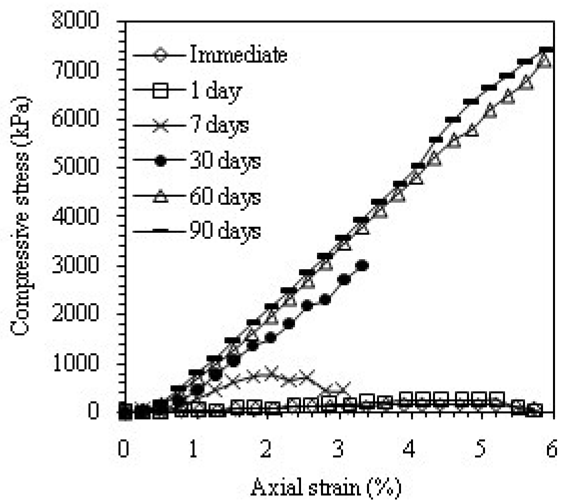

Figure 19 Stress-strain responses of fly ash-bentonite mix F80 treated with 13% lime

When high percentage of lime is added in soil, which is prepared at OMC and cured without further addition of moisture, the moisture content may be insufficient to allow complete hydrolysis of the lime. So, all the lime may not add to the strength, but remains as it is throughout the sample. As lime does not have appreciable cohesion or angle of internal friction as compared to soil, its presence becomes disadvantageous to strength (Liu et al. 2012).

The 90 day-UCS for the optimum content of lime (13%) for different mixes are presented in Figure 20. When 20% bentonite is added to fly ash (i.e. mix F80), the compressive strength has increased to the maximum i.e. 7440 kPa. In comparison, with fly ash alone without bentonite, the peak strength is 3875 kPa for the same lime content and curing period. In case of 9% lime addition, the UCS for fly ash and F80 mix are about 2800 kPa and 6500 kPa respectively. It demonstrates that the addition of bentonite maximises the strength of fly ash under lime treatment. Increase in strength of lime-treated fly ash on adding bentonite was also observed by Dermatas and Meng (2003). This finding opens up the possibility of utilizing the fly ash in large quantity for geotechnical applications such as building highway and railway embankments, dams, etc. This finding may be particularly useful in constructing pavements which are subjected to very heavy loads e.g. airstrips.

The 90-day waiting period for strength development may be considered too long for some situations. Figure 21 shows that the 60-day strength for F80 and 13% lime is only slightly less than the 90-day strength for the same combination. So, the 60-day strength may be conveniently used for design. If further reduction in construction time is essential, a 30-day curing period may be adopted, but in this case F80 with 13% lime produces only about half of the 90-day strength (i.e. approx. 3000 kPa). However, in such case, the same strength may be obtained using much lower lime content of approximately 5%. So, if gain of strength upto the maximum limit (i.e. 7440 kPa) is not required, then 5% lime content with 20% replacement of fly ash with bentonite will be more practical.

Figure 23 shows the variation strength of fly ash-bentonite compositions at the optimum lime content of 13%. It is seen that addition of 20% bentonite to fly ash is optimum for the tested materials in terms of strength gain. Figure 24 also shows that 20% bentonite addition is also optimum for elastic modulus. The 90-day strength and elastic modulus properties for different proportions of fly ash-bentonite and for different lime additions are summarised in Table. 5.

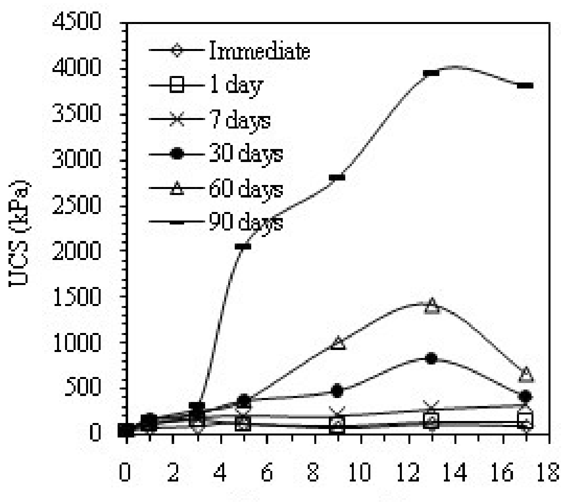

Figure 20 Unconfined compressive strength variations with lime content for fly ash

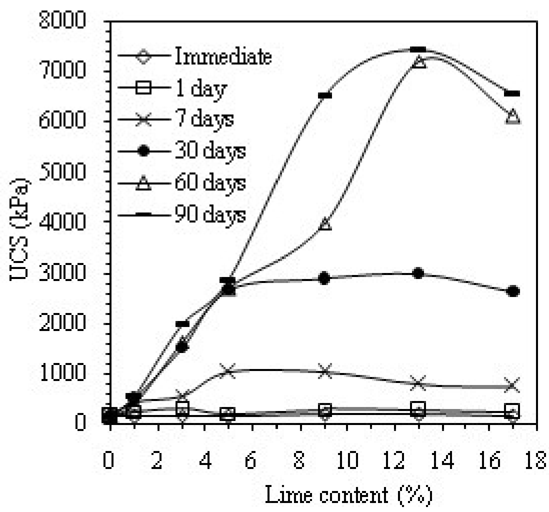

Figure 21 Unconfined compressive strength variations with lime content for F80

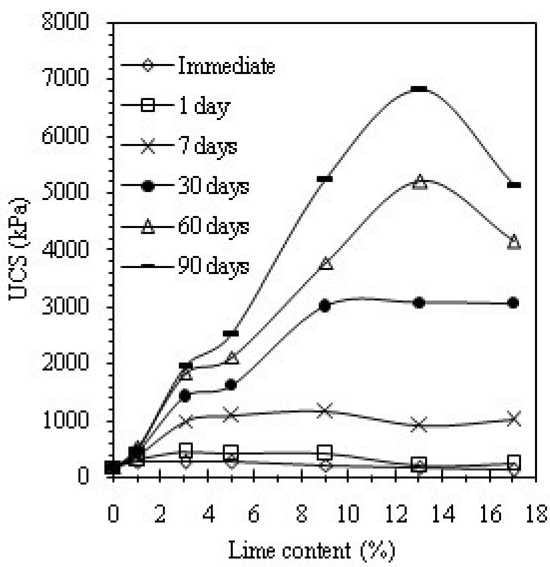

Figure 22 Unconfined compressive strength variations with lime content for F60

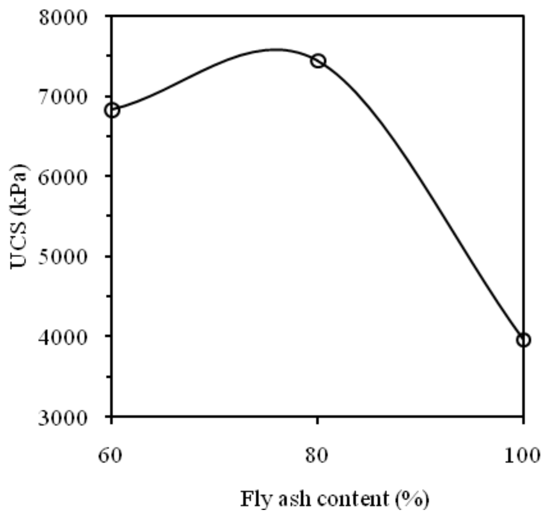

Figure 23 Unconfined compressive strength of fly ash-bentonite mixes corresponding to 13% lime and 90 days curing

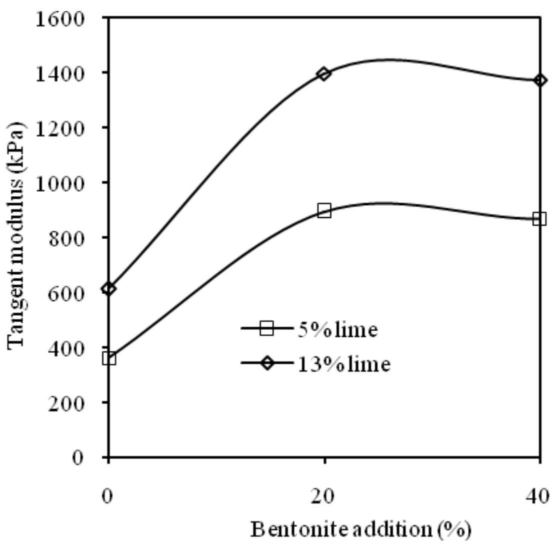

Figure 24 Elastic modulus for 60-day curing

Table 5 Summary of test results for various mixes

Fly ash: bentonite proportion	Lime added (%)	UCS (kN/m^2) at 90 days	Elastic modulus (kN/m^2) at 90 days
100:0	1	178	-
	5	2064	862
	9	2818	1147
	13	3962	1334
80:20	1	530	491
	5	2860	1000
	9	6542	1237
	13	7440	1604
60:40	1	468	264
	5	2520	934
	9	5251	1140
	13	6826	1444

4. SUMMARY AND CONCLUSION

This study has brought out the influence of bentonite addition on the strength of fly ash under lime treatment. A series of unconfined compression tests have been carried out on fly ash by varying the bentonite content, lime content, and curing period. The test results indicate that :

- Addition of bentonite to non-self-cementing fly ash adds cohesion, acts as a binder, and increases its initial strength by a small factor. If only bentonite is mixed, it makes the soil mix susceptible to swelling. However, the swelling is neutralised by addition of lime.
- Upon long-term curing (e.g. 90 days) after lime treatment, fly ash alone or along with bentonite gains a lot of strength because of pozzolanic reactions. However, compared to fly ash alone, the mixtures of fly ash-bentonite yields better long term strength upon lime treatment.
- There is an optimum percentage of lime that gives maximum strength improvement. Here, at the optimum replacement of fly ash with bentonite (i.e. 20%), the optimum addition of lime is 13% of total dry weight.
- There is also an optimum content of bentonite which further increases the strength.
- Very high strengths of over 7000 kPa could be obtained by addition of bentonite and treatment with sufficient quantity of lime.
- In addition to the UCS, the elastic modulus also increases on addition of bentonite and lime, as a result of which less deformation will occur under heavy loads.
- This creates potential for use in situations where high loads are expected and deformations are to be minimised.

In this study, the material selected as additive was bentonite because of its accelerated reactions with lime. Since bentonite has many other commercial applications and is a sought-after mineral, cost-wise it may not be cheap to use it as an admixture with fly ash. However, almost all clays react with lime, of course in a lesser scale as compared to bentonites. So, other types of easily available clays may also be tried as admixtures with fly ash and lime so as to supplement the lime-fly ash reactions. This is a further scope of extending this study.

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