Effects of Stabilization on Engineering Characteristics of Fly Ash as Pavement Subbase Material

Deepti Patel, Rakesh Kumar, Krupesh Chauhan and Satyajit Patel

Abstract Scarcity of natural resources is increasingly encountered around the world because of the increasing population. Fly ash is one of the problematic waste materials being generated in very large quantity in India by thermal power plants. The use of fly ash in road base, subbase, and subgrade layer provides an opportunity to use high volumes of the materials. In this study, engineering properties of different fly ash-lime (FAL) mixes and fly ash-cement (FAC) mixes were investigated for their effective use as subbase material for flexible pavements. The effect of binder content and curing period on unconfined compressive strength (UCS), CBR, and resilient modulus for all the mixes was studied. Fly ash with minimum 6% lime content and fly ash with minimum 6% cement content satisfy the minimum strength criteria recommended by Indian Road Congress (IRC) for their use in subbase layer. The resilient modulus of these mixes was found to be higher than that of conventional granular subbase (GSB). Finite element analyses of a five-layer flexible pavement system are carried out and the service life ratio of FAL and FAC mixes in relation to the conventional GSB layer is evaluated.

Keywords Unconfined compressive strength · CBR · Resilient modulus · Fly ash · Lime · Cement

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1 Introduction

Expeditious industrialization in India has resulted in the scarcity of naturally available construction materials. Investigating the feasibility of industrial wastes as a compatible construction material has become a vital area because of fast depleting natural construction resources. Industrial waste like fly ash can be effectively used in construction of highways and embankments, ensuing to the preservation of valuable land from colossal waste disposal subsequently averting the concomitant environmental problems. The annual generation of fly ash in India was reported to be 180 million tons in the year 2015–16 with a utilization rate of 60%. At the present generation rate, in the year 2025 fly ash generation will reach around 300 million tons. Fly ash is a waste material generated from thermal power plants which exhibit moderate pozzolanic characteristics. Fly ash utilization for stabilization purposes is always encouraged at locations where it is easily available. Class F fly ash is the least commonly used ash, mainly due to its self-cementations properties. It consists of siliceous and aluminous materials and usually being activated by lime or cement to create a stabilized mixture with augmented pozzolanic characteristics.

Kolias et al (2004) evaluated the mechanical properties of class C fly ash stabilized with cement, to avoid cracking of the stabilized layer and maintain the high modulus values and reduced the thickness of pavement layers. Kaniraj and Gayathri (2003) investigated the UCS strength till increased a certain curing period and then tended to decrease. The rate of increase in strength was high till about 14 days, decreased significantly during 28–90 days and became very small beyond 90 days. The role of lime and gypsum addition on strength behavior of fly ash was studied by Ghosh and Subbarao (2007), Consoli et al (2011) evaluated the strength parameters of sandy soil treated with fly ash and lime mixed for used in bases under pavements. UCS increased linearly with the amount of lime for soil–fly ash–lime mixtures (Sivapullaiah and Moghal 2011). Ghosh and Subbarao (2007) reported the UCS value of 6307 kPa at curing period of 3 months for fly ash stabilized with 10% lime and 1% gypsum. They developed the correlation of deviator stress at failure and cohesion with UCS values.

The resilient modulus in a repeated load test is defined as the ratio of the maximum deviator stress (σ_{d}) and the recoverable elastic strain (ε_{r}) as follows:

$$M_{\mathrm{r}} = \frac{\sigma_{\mathrm{d}}}{\varepsilon_{\mathrm{r}}} \tag{1}$$

The resilient modulus (M_{r}) of cemented stone aggregates for use as road material and their estimation using different empirical models is reported by Peerapong and Hamid (2009); and Puppala et al. (2011). M_{r} values increase with deviator stress due to strain-hardening phenomenon for unbound aggregates (Arulrajah et al. 2013) and stabilized base materials (Puppala et al. 2011; Patel and Shahu 2016).

The objective of this study is to investigate the beneficial use of Class F fly ash mixed with lime and cement in subbase layer of flexible pavement system. A series of tests, namely UCS, CBR, durability, resilient modulus tests, were conducted on different fly ash-lime mixes and fly ash-cement mixes. Finite element analyses of a five-layer flexible pavement system are carried out and the service life ratio of FAL and FAC mixes in relation to the conventional GSB layer is evaluated.

2 Experimental Program

2.1 Materials

Fly ash was collected from Hindalco Industries Ltd. (Unit: Birla Copper) Dahej, Gujarat. Fly ash satisfies all the physical requirements for use as a pozzolana in lime-fly ash concrete as per IRC: SP 20 (2002). In accordance with ASTM C 618 (1999), this fly ash belongs to Class F type. Hydrated lime with 64% CaO content was used for the present study. Cement used in the research work is 53 Grade Ordinary Portland cement.

2.2 Mix Proportions

In the present study, different percentages of lime (3, 6, 9, and 12%) and cement (4, 6, 8, and 10%) were mixed separately with fly ash to prepare fly ash-lime (FAL) mixes and fly ash-cement (FAC) mixes, respectively. The mix proportions and their designations are given in Table 1.

Table 1 Mix proportions and their designations

Mix proportions	Mix designations
Fly ash + 3% lime	FA3L
Fly ash + 6% lime	FA6L
Fly ash + 9% lime	FA9L
Fly ash + 12% lime	FA12L
Fly ash + 4% cement	FA4C
Fly ash + 6% cement	FA6C
Fly ash + 8% cement	FA8C
Fly ash + 10% cement	FA10C

2.3 Tests Performed

For the determination of UCS, lime and cement were mixed separately with fly ash in a required proportion in dry condition. A right amount of water (close to optimum moisture content) was added to give proper consistency to the mixture for easy molding. Cylindrical samples of 50-mm-diameter and 100 mm height were then prepared by compacting the mix at their corresponding maximum dry density. The samples were sealed in an airtight polythene bag and kept at a temperature of 27 ± 2 °C for different curing period. The unconfined compressive strength of these cured samples was then determined using a conventional compression testing machine at a constant strain rate of 0.6 mm/min as per IS: 2720 (Part X)-1991.

CBR value of a material is an important parameter to study its feasibility for the utilization in the subbase course of flexible pavements as per IRC: 37 (2012). Therefore, CBR tests were carried out on different fly ash-lime mixes and fly ash-cement mixes in accordance with IS: 2720 (Part-16) 1987. CBR specimens were first cured for 7 days and then soaked for 4 days prior to testing.

Durability tests adopted in the present study are applicable for the stabilized pavement materials. The tests were carried out in accordance with ASTM D 559 (2003). The specimens were first cured for 28 days and then subjected to several wetting and drying cycles. One wetting and drying cycle consists of 5 h soaking in water and 42 h of heating at a temperature of 72 °C in a thermostatically controlled oven. The weight loss of the specimens was determined after 12 such cycles of alternate wetting and drying.

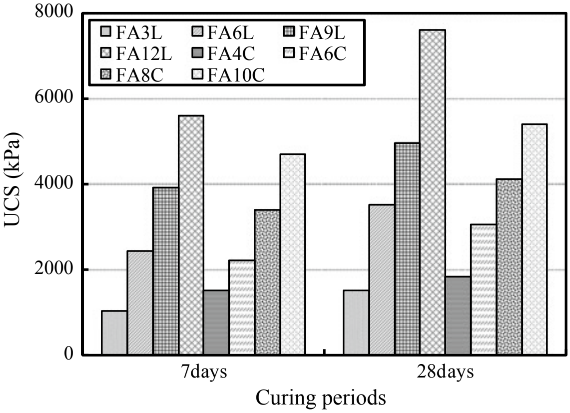
Resilient modulus (M_r) of different fly ash-lime mixes and fly ash-cement mixes was determined using a repeated load triaxial (RLT) test apparatus (Make: Geotechnical Digital System, UK) as per AASHTO T-307 (2000). Specimen preparation and curing procedure for RLT tests were similar to that for UCS tests. A haversine-shaped load pulse was applied to simulate the traffic wheel loading condition (Puppla et al. 2011). At each loading sequence, 100 repetitions of the corresponding cyclic load were applied using a haversine-shaped load (loading pulse of 0.1 s with a resting period of 0.9 s). Resilient modulus was calculated for 15 different stress combinations applicable for subbase materials as per AASHTO T-307 (2000).

3 Results and Discussion

3.1 Unconfined Compressive Strength

Specimens prepared for UCS test were cured for 7 and 28 days before the test. UCS values of different fly ash-lime mixes and fly ash-cement mixes are shown in Fig. 1. Compressive strength increases with the binder (lime and cement) content. The UCS values at 28 days curing were found to be 16–43% higher than that at 7 days curing.

Fig. 1 Variation of UCS with binder (lime and cement) content for 7 and 28 days of curing period



The strength development in fly ash-lime and fly ash-cement mixes happens mainly due to pozzolanic reaction of fly ash with lime and cement. In this reaction, calcium silicate hydrate (C–H–S) and calcium aluminosilicate hydrate (C–A–S–H), collectively called binding gels, are formed which bind the fly ash particles together resulting in a hardened mass. With an increase in binder (lime and cement) content, the quantity of gel formation increases which bind the particles more efficiently leading to an increase in the compressive strength. The pozzolanic reaction is a slow process. Therefore, the formation of binding gel and hence the compressive strength increases with an increase in curing period.

For a given binder content, the UCS values of fly ash-lime mix were found to be higher than that of fly ash-cement mix owing to the higher specific surface area of lime as compared to that of cement.

In accordance with IRC 20 (2002), the minimum laboratory UCS value of fly ash-lime mix after 28 days and fly ash-cement mix after 7 days should be 1.5 and 1.7 MPa, respectively, for their use as a subbase material in flexible pavements. Figure 1 shows that fly ash with minimum 6% lime content and fly ash with minimum 6% cement content satisfy the IRC criteria.

3.2 California Bearing Ratio (CBR)

The soaked CBR values obtained for different FAL mixes and FAC mixes after 7 days curing and 4 days soaking are given in Table 2. The broad trends observed for CBR values and the reasons for these trends are similar to those described earlier for UCS values.

Table 2 CBR values of different mixes

Mixes	CBR (%)	Mixes	CBR (%)
FA6L	64	FA6C	58
FA9L	89	FA8C	73

The minimum CBR value recommended by IRC: 37 (2012) is 30% for subbase course of flexible pavements. Hence, all the four mixes adopted in the present study with a minimum curing period of 7 days satisfy this criterion.

3.3 Durability

The loss of dry weight for FA6L, FA9L, FA6C, and FA8C mixes are obtained as 17.1, 16.2, 17.8, and 16.6%, respectively. Hence, all the four mixes satisfy the criterion for the maximum permissible percentage loss in weight (=30%) recommended by IRC: 89 (2010) for the stabilized mix to be used in pavement subbase course.

3.4 Resilient Modulus

Repeated load triaxial tests conducted on different FAL and FAC mixes to simulate the traffic wheel loading under different confining pressure. Figure 2 illustrates the resilient modulus of the mixes after 28 days curing period for six different stress combinations. M_r value increases with the confining pressure and deviator stress. This behavior is in consistent with the previous (Arulrajah et al. 2013; Puppala et al. 2011; Patel and Shahu 2016). Also, M_r increases with an increase in binder content. The broad trends observed for M_r values with binder content and curing period, and the reasons for these trends are similar to those described earlier for UCS values.

Figure 3 shows the effect of curing period on resilient modulus of various mixes and also compares their M_r values with those of conventional granular subbase layer. The resilient modulus of all the mixes after 28 days curing periods was found to be higher than that of GSB. This shows that the thickness of the subbase layer can be reduced if GSB is replaced by FAL and FAC mixes.

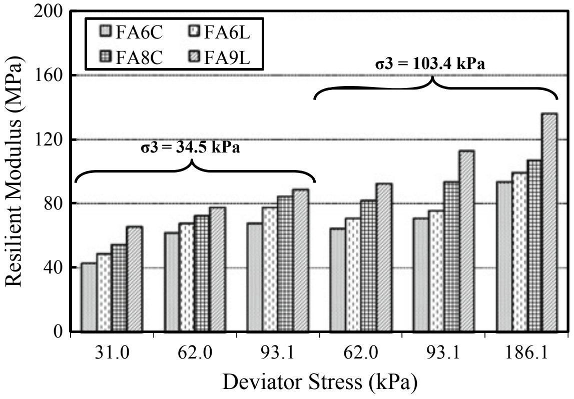


Fig. 2 Variation of resilient modulus with deviator stress and confining pressure at 28 days curing period

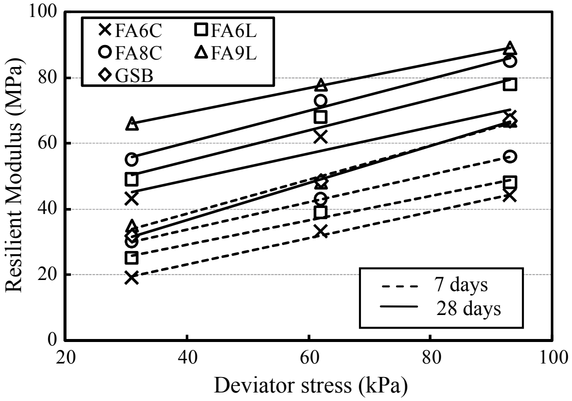


Fig. 3 Effect of deviator stress and confining pressure on resilient modulus of fly ash-lime and fly ash-cement mixes for 7 and 28 days curing period

3.5 Modeling of Resilient Modulus

In the present study, the performance of three stress-dependent models is compared to predict the resilient modulus of FAL and FAC mixes.

i. **Model 1**—The following two-parameter model is suggested by Witczak and Uzan (1988):

$$M_\mathrm{r} = k_1 \times \sigma_\mathrm{d}^{k_2} \tag{2}$$

ii. **Model 2**—The following two-parameter model, commonly known as $k - \theta$ model:

$$M_\mathrm{r} = k_3 \times \sigma_\mathrm{d}^{k_4} \tag{3}$$

iii. **Model 3**—The following three-parameter model is proposed by Puppala et al. (2011) and Patel and Shahu (2016) for stabilized specimens:

$$\frac{M_\mathrm{r}}{P_\mathrm{a}} = k_5 \times \left(\frac{\sigma_3}{P_a}\right)^{k_6} \times \left(\frac{\sigma_\mathrm{d}}{P_\mathrm{a}}\right)^{k_7} \tag{4}$$

where θ = bulk stress; σ_3 = confining stress; σ_d cyclic deviator stress; P_a = atmospheric pressure; and k_1 to k_7 = model constant.

The model constants k_1 to k_7 were obtained from the regression statistical analysis. The predicted $\mathrm{M_r}$ values were compared with the measured M_r values, and the coefficient of determination (R^2) for Model 1, Model 2, and Model 3 were determined as 0.93, 0.87 and 0.98, respectively, for FAL mixes; and 0.91, 0.86 and 0.95, respectively, for FAC mixes.

The highest R^2 values are obtained for Model 3, indicating three-parameter model provides the best prediction of resilient modulus for both FAL mixes and

FAC mixes. The advantage of the models lies in separating the effects of deviator stress and confining pressure on M_r values (Patel and Shahu 2016).

The plot between predicted and measured M_r values for all FAL and FAC mixes for Model 3 is shown in Figs. 4 and 5. The model constants (k_5, k_6, and k_7) obtained for all FAL and FAC mixes are presented in Table 3.

3.6 Service Life of Flexible Pavements

Service life of pavement was evaluated through finite element analysis of a five-layer flexible pavement system using a commercial finite element code, Plaxis. The thickness of different layers of the pavements was adopted as per IRC: 37 (2012) for traffic intensity of 100 million standard axles (MSA) and subgrade CBR of 3%. A linear elastic model is used for all the layers, such as Bituminus Concrete

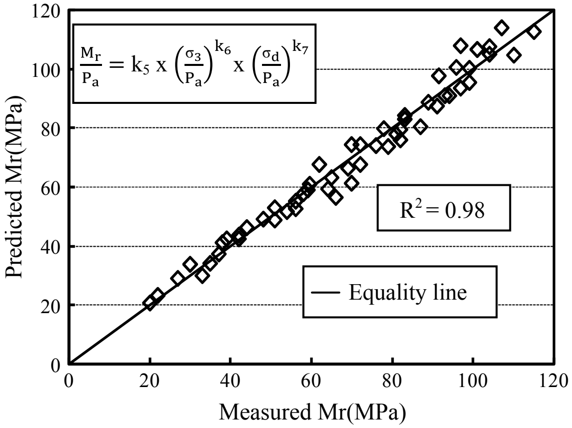


Fig. 4 Measured resilient modulus versus predicted resilient modulus using Model 3 for fly ash-lime mixes

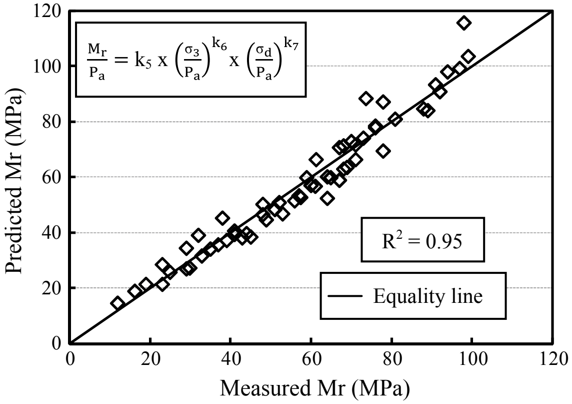


Fig. 5 Measured resilient modulus versus predicted resilient modulus using Model 3 for fly ash-cement mixes

Table 3 Model constants of FAL and FAC mixes after 7 and 28 days of curing period

Mixes	Curing days	$M_{\mathrm{R}} = k_5 \times \left(\frac{\sigma_3}{P_{\mathrm{a}}}\right)^{k_6} \times \left(\frac{\sigma_{\mathrm{d}}}{P_{\mathrm{a}}}\right)^{k_7}$		
		k_5	k_6	k_7
FA6L	7	0.629	0.129	0.545
	28	0.925	0.164	0.328
FA9L	7	0.764	0.174	0.541
	28	0.999	0.101	0.396
FA6C	7	0.500	0.179	0.565
	28	0.738	0.121	0.451
FA8C	7	0.523	0.075	0.535
	28	0.804	0.109	0.404

(BC), Dense Bituminous Macadam (DBM), base, subbase, and subgrade layers. The input parameters of different layers other than FAL and FAC mixes are taken from Patel and Shahu (2016). M_{r} values of FA6L, FA9L, FA6C, and FA8C mixes are adopted as 82, 91, 68, and 78 MPa, respectively, as determined experimentally corresponding to deviator stress of 93.1 kPa and confining pressure of 34.5 kPa. A uniform pressure of 575 kPa was applied on a circular contact area with radius of 150 mm, which is equivalent to the pressure caused by a single-axle wheel load of 40.80 kN (Fig. 6).

The service life ratio (SLR) of pavements with FAL and FAC mixes in the subbase course vis-a-vis the conventional GSB layer based on fatigue failure criteria is determined by the following equation:

$$\mathrm{SLR} = (\varepsilon_{t1} / \varepsilon_{t2})^{3.89} \tag{5}$$

where $\varepsilon_{\mathrm{t1}}$ and $\varepsilon_{\mathrm{t2}}$ are the maximum horizontal tensile strains developed at the bottom of DBM layer made up of conventional GSB and that of stabilized fly ash, respectively. The values of $\varepsilon_{\mathrm{t1}}$, $\varepsilon_{\mathrm{t2},}$ and maximum deformation δ at the pavement surface as obtained from the finite element analyses and service life ratios for various materials are given in Table 4. The pavement with FAL and FAC mixes in subbase layer has higher service life compared to the pavement with GSB layer.

The construction cost per cubic meter of FA6L, FA9L, FA6C, FA8C, and GSB subbase layer as per the current schedule of rates of Public Work Department (PWD) in Gujarat are obtained as 729, 843, 898, 1016, and 985 Indian Rupees, respectively. Hence, the construction cost can be saved up to 26% by replacing the conventional GSB with fly ash + 6% lime (FA6L) mix.

4 Conclusion

From the present study on engineering properties of fly ash-lime mix and fly ash-cement mix, the following conclusions are drawn.

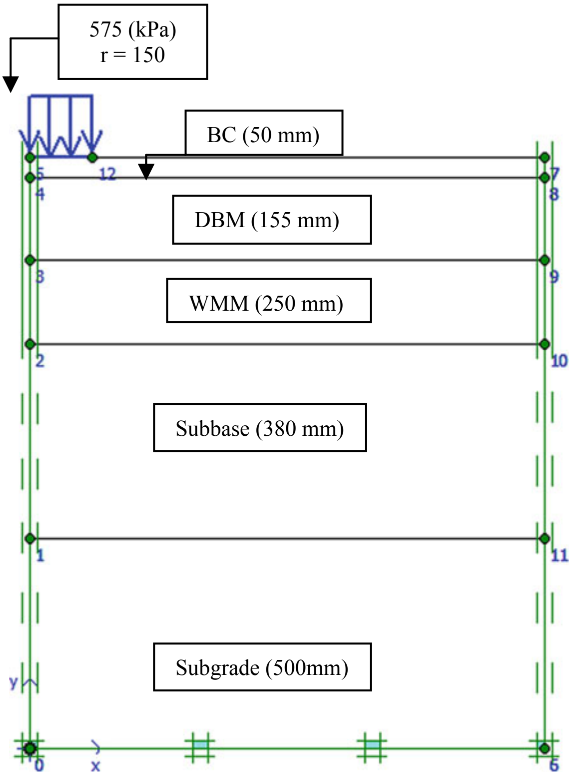


Fig. 6 Finite element analysis of flexible pavement system using plaxis for traffic intensity of 100 MSA and subgrade CBR of 3%

Table 4 Service life ratio (SLR) for various subbase materials for 3% subgrade CBR

Subbase material	δ (mm)	ε_{t1} or ε_{t2} (micron)	SLR	Construction cost per m^3 in INR
GSB	418	261.2	1.000	985
FA6L	405	255.4	1.107	729
FA9L	402	254.2	1.131	843
FA6C	413	257.5	1.067	898
FA8C	409	256.5	1.086	1016

δ = maximum deformation at the pavement surface

- UCS and resilient modulus increase with binder content and curing period for all the mixes. Fly ash with minimum 6% lime content and fly ash with minimum 6% cement content satisfy the IRC strength criteria for use in subbase course of flexible pavement.
- Durability test results showed the weight loss in the range of 16% to 18% for stabilized fly ash mixes. Hence, these mixes satisfied the durability criteria as per IRC: SP: 89-2010.

- The CBR value of only fly ash is 12. As per IRC: 37 (2012), the subbase materials should have minimum CBR value of 30% for traffic exceeding 2 MSA. The CBR value was found up to 89 and 73% for FAL and FAC mixes, respectively.
- A three-parameter model provides the best fit for the effects of both confining pressure and deviator stress on resilient modulus of FAL and FAC mixes.
- The pavement with FAL and FAC mixes in subbase layer has higher service life compared to the pavement with GSB layer. Construction cost can be saved up to 26% by replacing the conventional GSB with fly ash + 6% lime (FA6L) mix.

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