# Resilient modulus and permanent strain behaviour of Fly Ash as Pavement Subbase Material

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ABSTRACT: 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), resilient modulus and permanent strain 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 FAL and FAC mixes increased with increase in curing condition and confining pressure. Different Models for the measured data of resilient modulus and permanent strain are comared and for the best fitting model were compared. 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, Resilient Modulus, Permanent strain, Fly ash, Lime, Cement.

## 1. Introduction

Expeditious industrialization in India has resulted to 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 exhibits 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 aluminious 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 stabilised 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 behaviour 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 ($\sigma_d$) and the recoverable elastic strain ($\varepsilon_r$) as follows:

$$M_r = \frac{\sigma_d}{\varepsilon_r} \qquad (1)$$

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, durability, resilient modulus, permanent deformation 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 (6 % and 9 %) and cement (6% and 8% 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 + 6% lime | FA6L |
| Fly ash + 9% lime | FA9L |
| Fly ash + 6% cement | FA6C |
| Fly ash + 8% cement | FA8C |

### *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 $27 \pm 2^0$ 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.

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 (Puppala et al. 2011). At each loading sequences, 100 repetitions of the corresponding cyclic load were applied using a haversine-shaped load (loading pulse of 0.1 second with a resting period of 0.9 second). Resilient modulus was calculated for 15 different stress combinations applicable for subbase materials as per AASHTO T-307 (2000).

In modeling the long-term behavior of pavements, it is necessary to take into account the influence of load repetitions and stress conditions on the gradual accumulation of permanent deformation in pavement structures. Therefore, permanent strain testing was carried out for different mixes after 28 days of the curing period at three stages; each stage was performed at a constant confining pressure with different deviator stresses up to 10,000 load repetitions following Arulrajah et al. (2013) and Peerapong and Hamid (2009). A constant confining pressure ($\sigma_3$) of 34.5 kPa and deviator stresses of 100, 200, and 300 kPa were applied at Stage 1, Stage 2, and Stage 3, respectively.

## 3. Results and Discussion

### *3.1 Unconfined compressive strength*

Specimens prepared for UCS test were cured for 7, 28 and 48 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 and curing period. The hydration process was found to progress with time, creating a stronger bond between the materials.

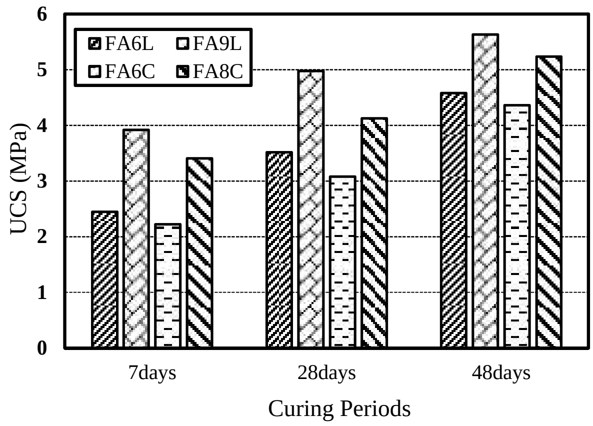


Fig. 1 Variation of UCS with binder (lime and cement) content for different curing period

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 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 was 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 MPa and 1.7 MPa, respectively, for their use as a subbase material in flexible pavements. Fig. 1 shows that fly ash with minimum 6% lime content and fly ash with minimum 6% cement content satisfy the IRC criteria.

### *3.2 Resilient modulus*

In pavement design resilient modulus ($M_r$) is an important factor of the materials under different confining pressures ($\sigma_c$). Fig. 2 and Fig. 3 illustrates resilient modulus of FA6L and FA6C specimens. It shows that the resilient modulus increases as the confining pressure increases. This could be due to that the materials get denser as the confinement increases and hence, low recoverable deformations resulted in higher resilient modulus. So, the material under a constant confining pressure under different deviator stress levels $M_r$ increases with increasing deviator stress (Mohammadinia et al 2014). The resilient modulus increases as the curing period increases. Similar figures are not shown here for other mixes.

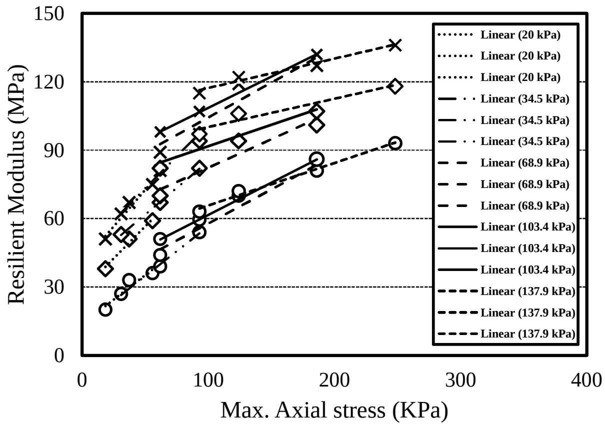


Fig. 2 Resilient modulus result after 7, 28 and 48 days curing for fly ash + 6% lime (FA6L) content

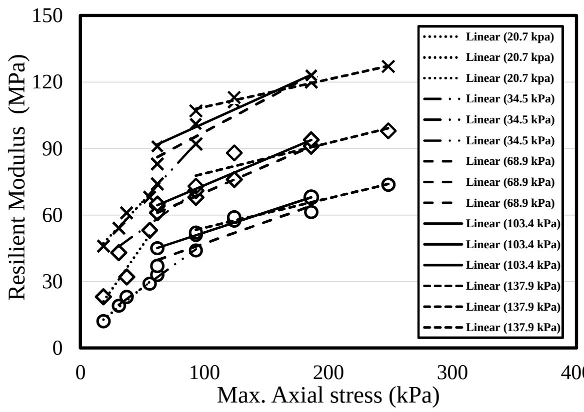


Fig. 3 Resilient modulus result after 7, 28 and 48 days curing for fly ash + 6% cement (FA6C) content

### *3.3 Modelling of resilient modulus*

In the present study the performance of three stress- dependent models are 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):

$$M_r = k_1 \times \sigma_d^{k_2} \quad (1)$$

ii. **Model 2** - The following two-parameter model, commonly known as k-θ model:

$$M_r = k_3 \times \theta^{k_4} \quad (2)$$

iii. Model 3- The following three-parameter model known as Octahedral Shear Stress Model is recommended by AASHTO 2008 Mechanistic–Empirical Pavement Design Guide:

$$\frac{M_r}{P_a} = k_5 \times \left(\frac{\theta}{p_a}\right)^{k_6} \times \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_7} \quad (3)$$

where bulk stress, $\theta = \sigma_d + 3\sigma_3$; $\sigma_3$ is confining stress; $\sigma_d$ is cyclic deviatoric stress; $P_a$ is atmospheric pressure (= 100 kPa); $\tau_{oct}$ is octahedral shear stress = 1/3 $\{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\}^{1/2}$; and $k_1$ to $k_7$ are model constants.

In Fig. 5 and Fig. 6 resilient modulus increases with increasing deviator stresses. Same as in Fig. 7 and Fig. 8 resilient modulus increases with increasing bulk stress. The limitation of bulk stress model is not predict the volumetric strain of the materials under repeated triaxial loading. The limitation of the bulk and deviatior stress model the three parameter model has been suggested by AASHTO (2008). The model constants $k_1$ to $k_7$ were obtained from the regression statistical analysis. The predicted $M_r$ 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 0.95 respectively, for FAL mixes; and 0.91, 0.86 and 0.92 respectively, for FAC mixes.

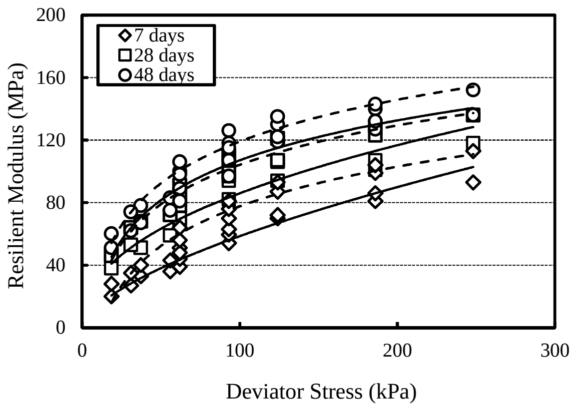


Fig. 4 Measured resilient modulus versus predicted resilient modulus using model 1 for fly ash-lime mixes

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).

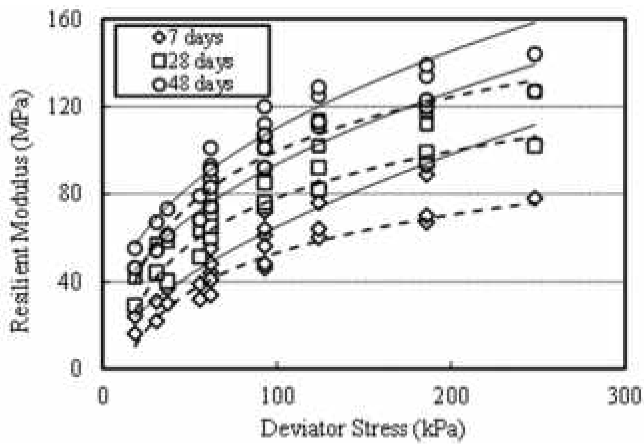


Fig. 5 Measured resilient modulus versus deviator stress using model 1 for fly ash-cement mixes

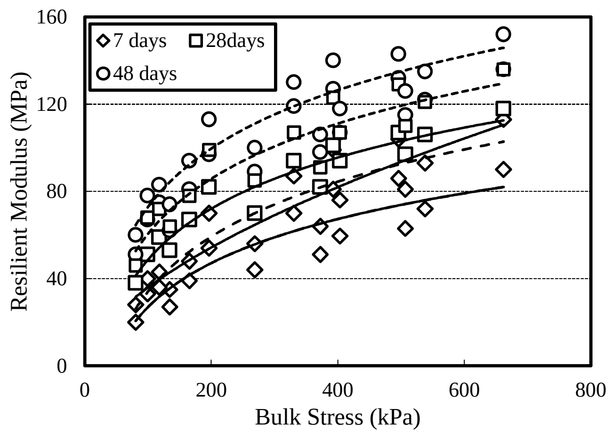


Fig. 6 Measured resilient modulus versus Bulk stress using model 2 for fly ash-lime mixes

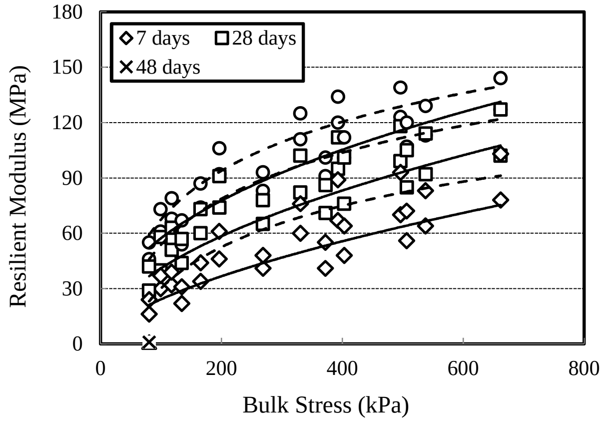


Fig. 7 Measured resilient modulus versus Bulk stress using model 2 for fly ash-cement mixes

Table 2 Model constants of FAL and FAC mixes after 7, 28 and 48 days of curing period

| **Mixes** | **Curing days** | $\frac{M_r}{P_a} = k_5 \times \left(\frac{\theta}{P_a}\right)^{k_6} \times \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_7}$ | | |
|---|---|---|---|---|
| | | $\boldsymbol{k_5}$ | $\boldsymbol{k_6}$ | $\boldsymbol{k_7}$ |
| FA6L | 7 | 0.242 | 0.331 | 1.150 |
| | 28 | 0.465 | 0.346 | 0.494 |
| | 48 | 0.520 | 0.312 | 0.572 |
| FA9L | 7 | 0.314 | 0.349 | 1.03 |
| | 28 | 0.563 | 0.265 | 0.650 |
| | 48 | 0.631 | 0.279 | 0.537 |
| FA6C | 7 | 0.208 | 0.330 | 1.137 |
| | 28 | 0.397 | 0.324 | 0.666 |
| | 48 | 0.446 | 0.340 | 0.597 |
| FA8C | 7 | 0.274 | 0.314 | 1.016 |
| | 28 | 0.507 | 0.319 | 0.561 |
| | 48 | 0.575 | 0.291 | 0.572 |

The plot between predicted and measured $M_r$ values for all FAL and FAC mixes for Model 3 is shown in Fig. 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.

### *3.4 Permanent Strain Characteristics*

Fig. 5 presents the effect of load repetitions and deviator stress on the permanent strain (εp) of different FAL and FAC mixes. εp values increased with increasing σd values at a constant σ3 of 34.5 kPa. However, the responses were found to be plastic in the beginning for a finite number of load cycles, i.e., $\varepsilon_p$ values increased rapidly with an increase in load repetition, but after completion of the postcompaction period, the $\varepsilon_p$ values remain almost constant indicating that the response becomes entirely resilient. This behavior of FAL and FAC mixes is in agreement with the literature (Arulrajah et al. 2013; Peerapong and Hamid 2009).

### *3.5 Modeling of Permanent Strain Response*

Several models dependent on load repetitions and stress conditions are available in the literature for the estimation of plastic strain of pavement materials. In this study, the performance of the following four models is compared:
Model 1—A two-parameter logarithmic model suggested by
Bennert et al. (2000):

$$\varepsilon_p = \alpha_1 + \alpha_2 \log_e(N)$$

Model 2—A two-parameter power model proposed by Peerapong and Hamid (2009) for cement-treated aggregates:

$$\varepsilon_p = \alpha_3 N^{\alpha_4}$$

Model 3—A three-parameter model recommended by Ulldit (1993) to account for the influence of deviator stress:

$$\varepsilon_p = \alpha_5 \left(\frac{\sigma_d}{P_a}\right)^{\alpha_6} N^{\alpha_7}$$

where N = number of load repetitions; and $\alpha_1$ to $\alpha_{10}$ are model constants.

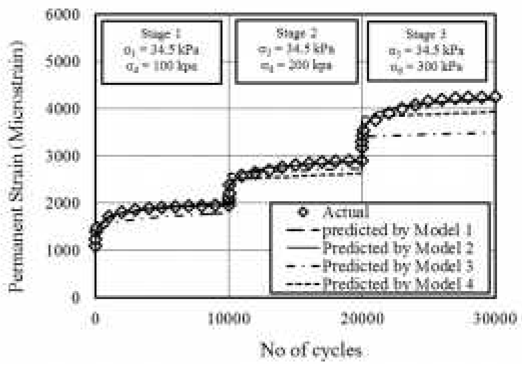


Fig. 8 Comparison of different models for the prediction of permanent strain for fly ash + 6% lime mix

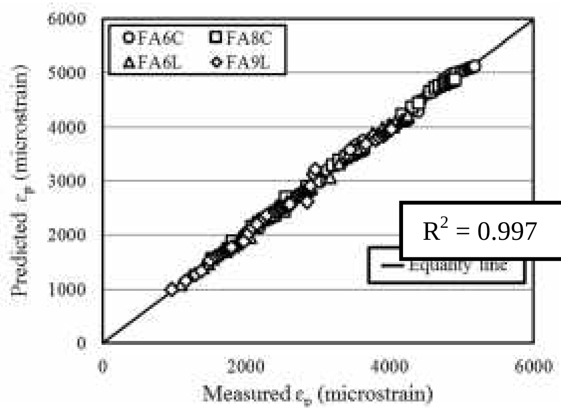

Fig. 9. Measured permanent strain versus predicted permanent strain using model 1 for different mixes

From the measured data of $\varepsilon_p$ values, the model constants $\alpha_1$ to $\alpha_7$ were determined using a multiple linear regression analysis, and permanent strain were back-calculated for different deviator stresses and load cycles for all trial mixes. Fig. 8 show the comparison of the predicted $\varepsilon_p$ values using the above three models with the measured $\varepsilon_p$ values for FAL mixes, respectively. The permanent strain predicted by Model 1 and Model 2 is very close to the measured permanent strain (Fig. 8)

The predicted permanent strain is plotted against the measured permanent strain for FAL and FAC mixes is shown in Fig. 5.9 for Model 2 (best performing model). The model constants $\alpha_3$ to $\alpha_4$ for different deviator stresses determined for FAL and FAC mixes are given in Table 2.

The coefficient of determination ($R^2$) values were determined for Model 1, Model 2, and Model 3 as 0.996, 0.997, and 0.918 respectively. Model 2 was found to be the best performing model for the estimation of permanent strain for all mixes. A significant influence of stress levels on the development of permanent strain has been reported in the literature (Arulrajah et al. 2013). Model 1 and Model 2 do not account for the effect of stress level on permanent strain and hence, the model constants of these two models are dependent on the applied deviator stress.

Table 2. Model 2 constants for permanent strain of fly ash-lime mixes and fly ash-cement mixes for best fit model

| Mixes | $\sigma_d$ = 100 kPa | | $\sigma_d$ = 200 kPa | | $\sigma_d$ = 300 kPa | |
|---|---|---|---|---|---|---|
| | $\alpha_3$ | $\alpha_4$ | $\alpha_3$ | $\alpha_4$ | $\alpha_3$ | $\alpha_4$ |
| FA6L | 1038 | 101 | 1228 | 102 | 3017 | 129 |
| FA9L | 954 | 87 | 1861 | 76 | 2548 | 154 |
| FA6C | 1556 | 129 | 1951 | 105 | 4257 | 92 |
| FA8C | 1514 | 95 | 2383 | 132 | 3982 | 96 |

## 4. Cost analysis

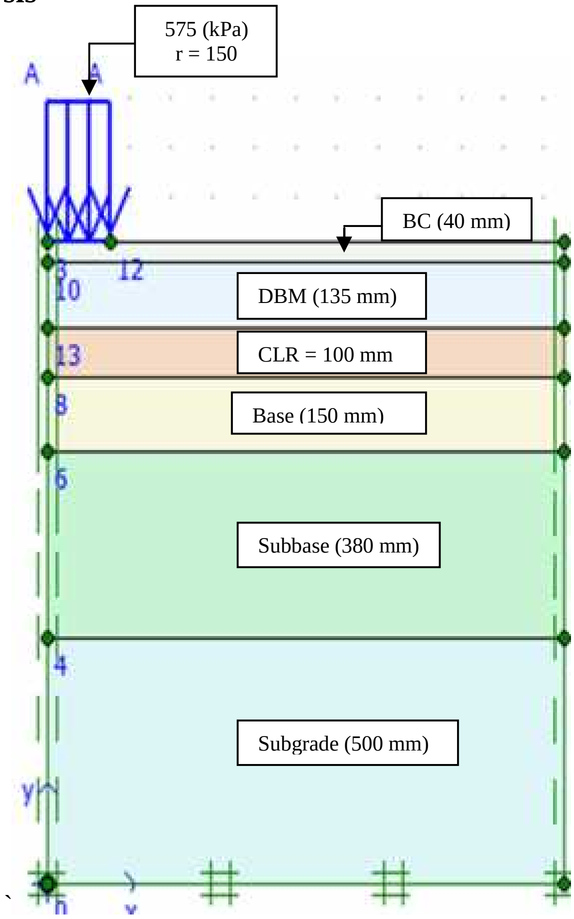


Fig. 10. Finite-element analysis of flexible pavement system using plaxis for traffic intensity of 50 MSA and subgrade CBR of 3%

The pavements in the present study are designed for different types of subbase materials. The design traffic is 50 million standard axle (msa) and subgrade CBR is 3%. The thicknesses of all layers of the control section are decided based on IRC: 37-2012 is shown in Fig. 10 and that of the pavement with waste materials in subbase layer are decided based on finite element analysis using Plaxis. Cost of preparing subgrade is common in all cases of design. Similarly, cost of laying 40 mm BC and 135 mm DBM will remain unchanged. The conventional GSB was replaced with fly ash-6% lime (FA6L), fly ash-9% lime (FA9L), fly ash-6% cement (FA6C) and fly ash-8% cement (FA8C) mixes. WMM is also adopted as crack relief layer (CRL) to be provided above the cemented base layer as recommended by IRC 37 – 2012. The schedule rates for Surat district in the state of Gujarat (India) was followed to carry out the cost analysis for these layers.

Finite element analysis of the pavement with different combinations of thickness of WMM and FA6L / FA9L / FA6C / FA8C was carried out and the optimum thickness of these materials are determined. Cost saving of Rs 24,94,377.20, Rs 27,19,603.00, Rs 15,81,995.20 and Rs 11,25,877.20 per km length of 7 m wide road was obtained by using FA6L, FA9L, FA6C, and FA8Cmix in the subbase layer of the flexible pavement, respectively.

Table 3 Service life ratio (SLR) of pavement with FAL and FAC mixes in Subbase layer

| parameters | Control section | Pavement with FA6L as subbase | Pavement with FA9L as subbase | Pavement with FA6C as subbase | Pavement with FA8C as subbase |
|---|---|---|---|---|---|
| $\delta$ | 493.78 | 476.82 | 463.10 | 488.53 | 465.53 |
| $\varepsilon_t$ | 325.9 | 322.1 | 318.7 | 325.6 | 318.6 |
| $\varepsilon_v$ | 490.7 | 490.5 | 488.8 | 487.2 | 485.2 |
| $SLR_f$ (Fatigue failure) | - | 1.047 | 1.091 | 1.004 | 1.092 |
| $SLR_r$ (Rutting failure) | - | 1.002 | 1.018 | 1.033 | 1.052 |

## 5. Conclusion

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

- 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 sub base course of flexible pavement.
- 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.
- Models 1 and 2 do not account for the effect of stress level on permanent strain and hence the model constants of these two models are dependent on the applied deviator stress. Model 2 was found to be the best-performing model for the estimation of permanent strain for both FAL and FAC mixes.
- Construction cost reduces by saving of 14-16% in FAL mix and 7 - 9% in FAC mix used in the subbase layer of the flexible pavement.

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