International Journal of Engineering and Technology Innovation, vol. 6, no. 4, 2016, pp. 294 - 304

Effect of Lime and Gypsum on Engineering Properties of Badarpur Fly Ash

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Received 29 January 2016; received in revised form 02 May 2016; accepted 13 May 2016

Abstract

The present study was conducted to investigate the performance of Badarpur fly ash stabilized with lime and gypsum. The work investigates the effect of lime (4%, 8%, 12% and 16% by mass of dry fly ash) and gypsum (1%) on compaction (in terms of density/moisture relationship), unconfined compressive strength (UCS), California bearing ratio (CBR), split tensile strength, and resilient modulus of fly ash. Based on strength, fly ash stabilized using 12% lime and 1% gypsum was observed as the highest strength mix. The microstructural development of the stabilized mix was studied through SEM and XRD. The results showed that Badarpur fly ash acquired UCS of 4697 kPa, CBR of 73% after 28 days of curing, split tensile strength of 630 kPa, and resilient modulus of 651 kPa. The strength increases with curing period and the composite achieved strength of 6150 kPa after 90 days of curing. This stabilized Badarpur fly ash can be utilized as road construction material.

Keywords: fly ash, gypsum, lime, strength, microstructural development

1. Introduction

India is witnessing a sustained growth in infrastructure build up. The constructional sector is a major employment driver, being the second largest employer in the country, next only to agriculture. To meet the demand of huge construction of infrastructure projects, the conventional construction materials are over exploited and becoming scarce. On the other hand, a large amount of industrial wastes are generated, which could be utilized in construction al sector effectively. One such potential waste material is fly ash which is produced from thermal power stations in bulk amount. India generated about 184 million tons of FA in the year 2014-2015 of which approximately 55% was consumed in various construction applications [1]. In India majority of fly ashes are class F and are pozzolanic in nature. Hence, they can be stabilized with cement or lime to achieve the required strength for use as construction materials. Stabilization is one of the promising methods to transform fly ash into a potential road construction material [2]. It was reported that when Dadri fly ash was stabilized with different cement content, the highest strength of 3000 kPa was acquired at 15% cement content for 28 days curried specimen [3]. It has been reported that lime can be used advantageously over cement for fly ash stabilization. Lime was used for fly ash stabilization and reported that the Kolaghat fly ash modified with 10% lime and 1% gypsum attained strength of 4000 kPa at 28 days curing [4]. Different lime content was added to fly ash, and it was observed that maximum strength of 2750 kPa was achieved by Nayeveli fly ash with stabilized with 5% lime and 1% gypsum at 28 days curing [5]. Road sector provides an opportunity to utilize bulk amount of such waste materials for long time. Hence, the present work was carried out to examine the suitability of Badarpur fly ash modified with lime and gypsum to be used as base/sub-base course material in flexible pavement.

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The objectives of the present study are as follows:

(1) Physical, chemical, morphological and mineralogical characterization of Badarpur fly ash

(2) Influence of lime and gypsum content on compaction characteristics, UCS, split tensile strength and CBR of fly ash

(3) Microstructural development and durability of the optimum composite selected after trial studies

2. Experimental program

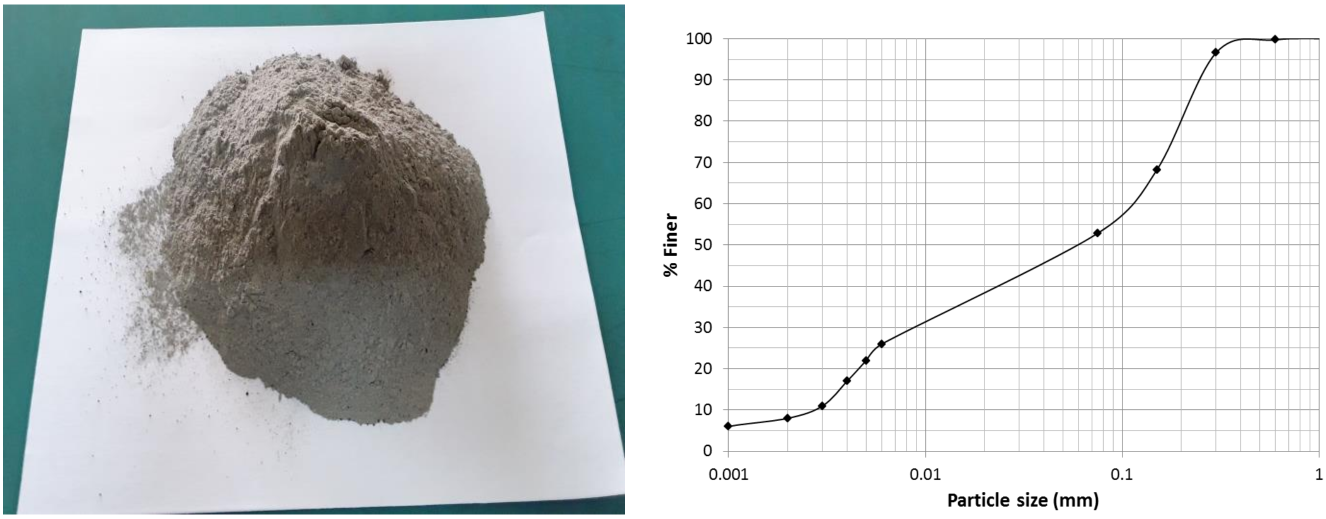
2.1. Material

Fly ash used in the present work is collected from Badarpur thermal power plant, Delhi (Fig. 1a). Commercial lime Ca $(OH)_2$ and gypsum were used to stabilize fly ash .The specific gravity of the fly ash is 2.2. The chemical composition (% by dry weight) of the fly ash is shown in Table 1.

Table 1 Chemical composition of fly ash

Element	Fly ash
SiO_2	57.9
Al_2O_3	31.78
Fe_2O_3	4.2
CaO	0.87
TiO_2	0.81
MgO	0.51
P_2O_5	0.44
MnO	0.32
K_2O	0.28
Na_2O	0.15
SO_3	0.075
Free Cao	0.87

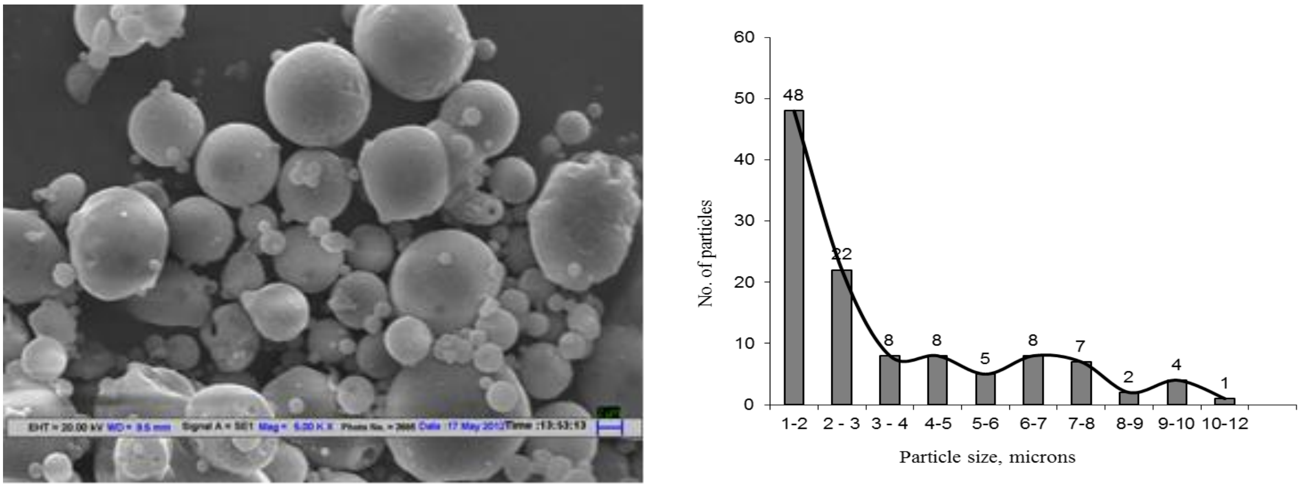
It is observed that the sum of oxides of Silicon (SiO_2), Aluminium (Al_2O_3) and Iron (Fe_2O_3) in Badarpur fly ash is 96% which is more than 70% (minimum limit) as specified by ASTM C618 for class F fly ash. The free lime content in FA is very low as 0.87% only. The particle-size distribution curve of fly ash is also shown in Fig. 1 (b).



(a) Fly ash used in the present study

(b) Particle size distribution

Fig. 1 Fly ash and its particle size distribution



(a) SEM of fly ash (b) Histogram showing particle size distribution

Fig. 2 SEM and histogram showing particle size distribution of fly ash

The morphological characteristic of fly ash was studied by scanning electron microscopic (SEM) technique. Fig. 2 (a) showed the presence of spherical and smooth particles of various size ranges in the fly ash. The distribution of particles is shown as histogram in Fig. 2 (b). It is observed that 10 micron size particles were present in abundance. Similarly, the Dadri fly ash was reported to have more particles of 10 µm size [3]. According to [6], the occurrence of cenospheres and plerospheres is limited in Indian fly ashes.

The various minerals present in fly ash were studied by X-ray diffraction (XRD) studies. It shows the presence of crystalline phases quartz (SiO_2) and mullite (Fe_2O_3) in fly ash (Fig. 3).

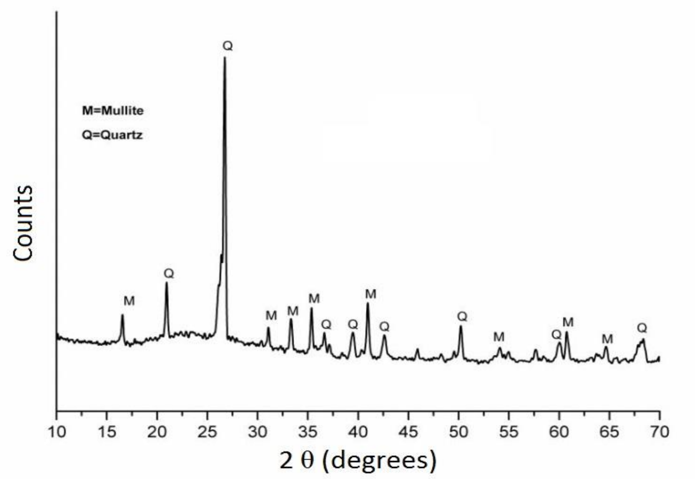


Fig. 3 X-Ray diffraction pattern of Badarpur fly ash

2.2. Method of mixing

The fly ash was stabilized using the lime dosage of 4%, 8%, 12% and 16% and gypsum dosage of 1%. The experimental program was conducted for various combinations of fly ash, lime and gypsum. The specimens were prepared at their respective density. The required amounts of fly ash, lime and gypsum were weighed and mixed together in the dry state. Required amount of water was added and again mixed properly. Precautions were taken to prepare homogeneous mixtures at each stage of mixing. The samples were compacted using static compaction technique. The samples were sealed properly in airtight polythene bags and kept in humidity chamber at 95% humidity and 25°C temperature cured for 7, 28, 56, 90 days. Here the mixes are designated with a common coding system. The first term FA shows fly ash, and other terms are used to denote the percentage of lime and gypsum respectively. Details of mixes are shown in table 2. Five identical specimens were prepared for each mix, particular test and curing period.

Table 2 Details of the mixes

Designation	FA (%)	L (%)	G (%)
FA+0L+0G	100	0	0
FA+4L+0G	96	4	0
FA+8L+0G	92	8	0
FA+12L+0G	88	12	0
FA+16L+0G	84	16	0
FA+4L+1G	95	4	1
FA+8L+1G	91	8	1
FA+12L+1G	87	12	1
FA+16L+1G	83	16	1

2.3. *Compaction test*

The relation between moisture content and dry density was determined by Standard Proctor compaction test in accordance with ASTM D 698-92 [7]. The compaction curve of fly ash modified with 0%, 4%, 8%, 12% and 16% lime are illustrated in Fig. 4.

2.4. *Unconfined compressive strength test*

For unconfined compressive strength (UCS) test, cylindrical specimens of diameter 38 mm and height 76 mm were used. Automatic compacter and extruder equipment were used to compact and extrude the cylindrical specimens. After each curing period they were tested for strength in a compression testing machine as per ASTM D1633 [8]. All the specimens failed in shear.

2.5. *Brazilian tensile strength test*

Brazilian tensile strength is an important parameter to check whether a stabilized fly ash is appropriate to serve as a base course material in road construction. The traffic load applies continuous tensile stresses on the pavement layers, and hence, failure is initiated due to the formation and propagation of tensile cracks. Hence, it is an important parameter to check the suitability of stabilized fly ash construction material. [9]. Therefore, tensile strength needs to be determined. It can be measured through direct test which is complexin nature. Other simple and easy procedure to determine tensile strength is through indirect tensile strength test [10, 11]. As per the test, the ratio of specimen diameter to height is generally two. In the present work, the specimen with diameter 38 mm and height 76 mm was used. The specimen was laid diametrically on the Universal testing machine. The sample fails in tension when load is applied. The indirect tensile strength is calculated as

$$\sigma_t = 2P/\pi DL \qquad (1)$$

where P = failure load; D = diameter of specimen; L = length of specimen

2.6. *California bearing ratio test*

The CBR test provides the bearing capacity of the material and was performed as per the ASTM standard [12]. The samples were compacted to 95% of their maximum density in CBR mould. The specimens were cured for 7 and 28 days in the humidity chamber for unsoaked conditions. To simulate the worst field conditions, the specimens were soaked in water for 4 days, and then CBR values were determined.

2.7. *Resilient modulus*

Pavement materials are typically characterized by their resistance to deformation under load, which can be either a measure of their strength or stiffness. A basic layer stiffness/strength characterization is resilient modulus (M_R). This test requires significant resources including high level of technical capability to conduct. Some agencies consider the cost, time, complication, and sampling resolution required for meaningful resilient modulus testing to be too cumbersome for its application in less critical projects. Because of this, correlations were desired for estimating resilient modulus and it was found that resilient modulus can be estimated with the help of simple UCS test. Thompson (1966) [13] developed a correlation between the conventional unconfined compression and the resilient modulus for fine grained soils. It was recommended that the design resilient modulus (M_R) for lime stabilized subgrades can be approximated from the results of unconfined compressive strength tests using Thompson’s correlation [14]. Based on eq. 2, M_R was determined for all composites.

$$M_R\ (\text{MPa}) = 0.124 q_u\ (\text{kPa}) + 68.8 \tag{2}$$

2.8. *Triaxial shear strength test*

The compacted specimen of the optimum composite was tested for triaxial shear strength at three different confining pressures ($\sigma_3 = 100, 200, 300$ kPa) after 0, 7, 14 and 28 days of curing. Immediately, after the application of the confining pressure, the specimens were sheared at a constant strain rate of 0.6 mm/min.

2.9. *Durability test*

The selected composite mix was subjected to twelve cycles of alternate wetting and drying as per the standard procedure based on ASTM D559-2003. This method helps to check the durability of the composite mix as road base course material. IRC [15] specifies that for any stabilized mix to be used in pavement base course the permissible percentage loss in weight should not be more than 20%.

3. Result and Discussion

3.1. *Compaction characteristics*

The compaction curves for the fly ash mixed with 4%, 8%, 12% and 16% lime is shown in Fig. 4. The compaction characteristics of fly ash stabilized with commercial lime (4% to 16%) ranged between 1414 kg/m^3 to 1345 kg/m^3. As the lime content increases the maximum dry density decreases, but the trend for moisture content is revered. It increases with the lime content and confirms to similar observations for fly ash-lime mixtures [2].

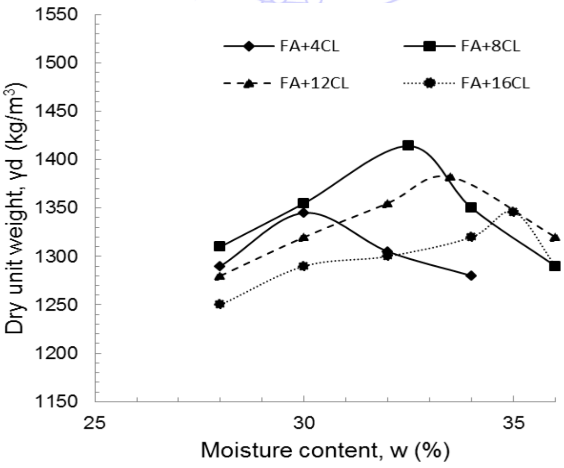


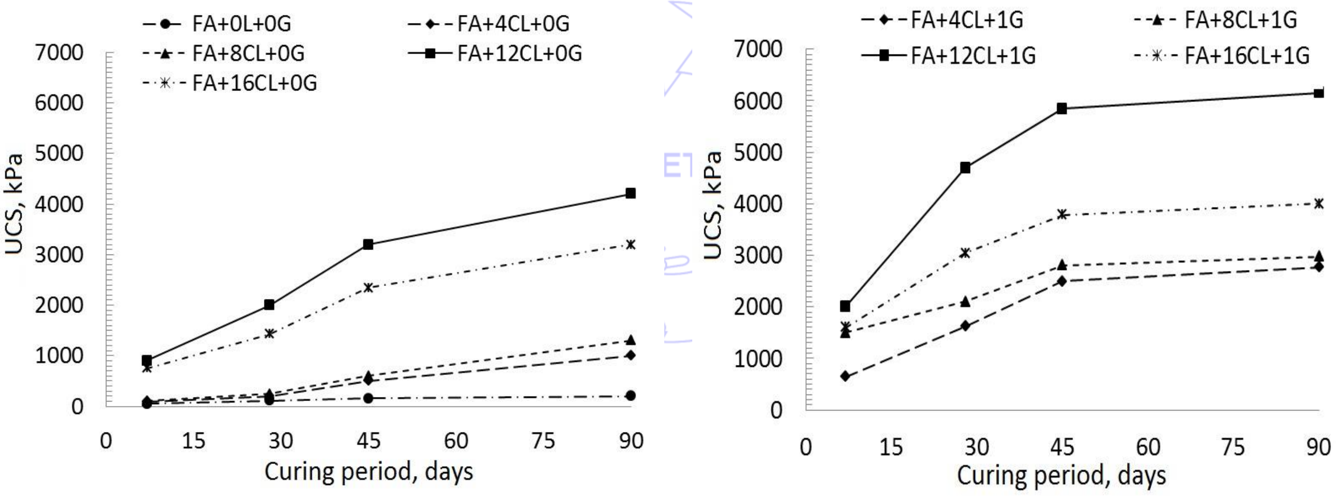
Fig. 4 Proctor compaction curves for various fly ash-lime mixes

3.2. *Unconfined compressive strength (UCS)*

It is observed from Fig. 5a that as the lime content increases the rate of strength gain also increases, however it can be noted that at 16% lime content the strength reduced. The reason for strength gain with lime content is the increased pozzolanic reaction due to the availability of more lime. However some lime remain unutilized when 16% lime content was added to fly ash as majority of the reactive silica and alumina of fly ash has already been utilized in pozzolanic reactions. Fly ash modified with 12% lime acquired strength of 3715 kPa at 90 days curing and is highest among various compositions. All the composite mixes were kept for 7, 28, 45 and 90 days. For all the various composites types, the rate of gain in strength with curing period increases from 7 to 90 days. The reason for continuous rapid increase in strength may be the slow pozzolanic reaction and the amount of gel formed in the mix which increases with an increase in curing period. It is observed that the percentage increase in UCS increases with lime content and it was maximum at 12% lime.

It was observed that different fly ash acquire different strength upon stabilization. Ghosh and Subbarao [4] reported UCS of 6000 kPa after 90 days of curing for Kolaghat fly ash stabilized with 10% lime. It was observed that addition of minor amount of gypsum (0.5% - 1%) contributes to strength at early stages of curing [4]. Hence to extend the present studies, 1% gypsum was also added to the fly ash-lime mix. It is observed that addition of 1% gypsum increases the strength of lime stabilized fly ash, further the influence of gypsum on UCS at lower lime content is more pronounced than higher content (Fig. 5b). Hence 1% gypsum addition was sufficient for significant strength gain. It was reported that 1% gypsum addition increased the strength of the fly ash-lime mix and UCS of 6500 kPa was achieved after 90 days of curing for fly ash modified with 10% lime and 1% gypsum [4]. The design manual of Electric Power Research Institute (EPRI) [16] specifies that the lime stabilized base courses should acquire minimum UCS of 3790 kPa after 28 days of curing. Hence fly ash mixed with 1% gypsum and 12% CL acquired strength of 4697 kPa after 28 days of curing is selected as optimum mix.

After 28, 45 and 90 days of curing, the MDD of the mixes and their UCS is shown in Fig 6. It can be seen that no definite relation can be drawn from this. However it is observed that maximum UCS is obtained at MDD of 1380 kg/m^3.



(a) UCS of fly ash with different lime content at different curing period

(b) UCS of fly ash with different lime and gypsum content at different curing period

Fig. 5 UCS of fly ash-lime mix and fly ash-lime-gypsum mix at different curing period

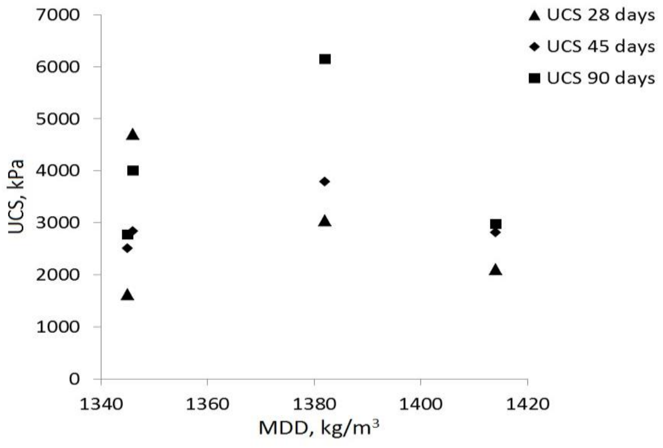


Fig. 6 MDD and UCS of various mixes

3.3. Brazilian tensile strength test

Fig. 7 illustrates the split tensile strength for lime (4%, 8%, 12%, and 16%) and gypsum content (1%). Fly ash with 4% and 8% lime showed very less values after 28 days of curing. It increased with curing period. The addition of 1% gypsum enhanced the strength values for all composition and all curing period. It is observed that the addition of gypsum has more influence on the tensile strength for shorter curing period as compared to higher curing period (90 days). It may be due to the fact that the lime stabilized mixes achieve considerable tensile strength at higher curing period, while the increase in strength due to the addition of gypsum is not significant. It was reported that the Kolaghat fly ash modified with 10% lime and 1% gypsum attained split tensile strength of 500 kPa and 1150 kPa after 28 days and 90 days of curing respectively [17]. It was concluded that a tensile strength of 469 kPa or above is required for road bases to resist freeze–thaw cycles [18]. This study shows that fly ash with 12% lime and 1% gypsum attained split tensile strength of 630 kPa after 28 days of curing, and therefore, can be suggested for base course layer of pavement.

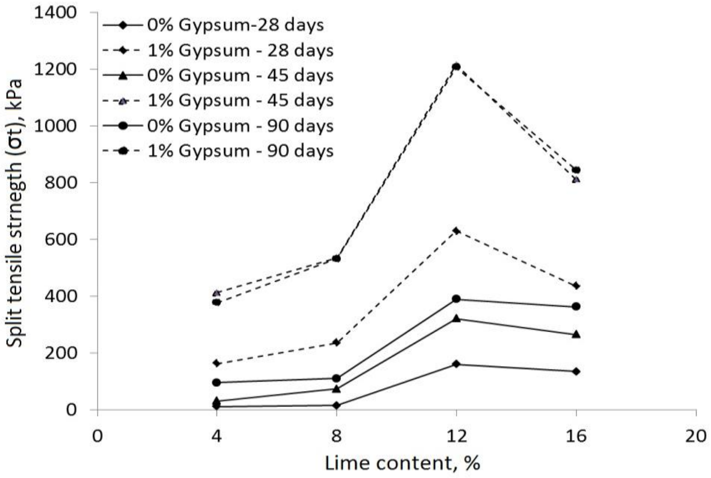


Fig. 7 Split tensile strength for all composition and curing period

3.4. California bearing ratio

It is observed from the results (Fig. 8) that the CBR values increased from 25% to 83% and from 34% to 95% at 7 and 28 days of curing respectively. It is also revealed that the CBR values increased with lime content and curing period. This may be due to the hydration process in the presence of lime which forms calcium silicate hydrate gels and increases the CBR value and the amount of gel formation increases with curing of the samples. The CBR values decreased upon soaking for all lime content. The addition of gypsum further increased the CBR value for 7 and 28 days cured samples (Fig. 9). The maximum CBR value of 119% was acquired at 16% lime and 1% gypsum composite cured for 28 days. The gypsum binds the particles together and makes the matrix dense and increases the CBR.

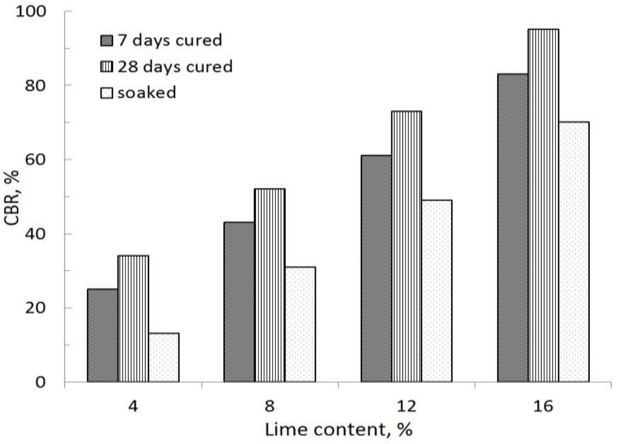


Fig. 8 CBR for lime stabilized fly ash

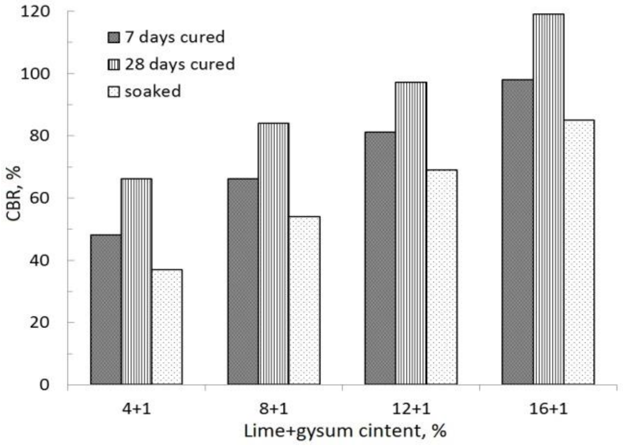


Fig. 9 CBR for lime and gypsum stabilized fly ash

3.5. *Resilient modulus*

The UCS based on resilient modulus was determined for all compositions cured for 28 days. The value of M_R of fly ash stabilized with lime only and with lime and gypsum is illustrated in Fig 10. It is observed that maximum value of 651 MPa was observed for fly ash stabilized with 12% lime and 1% gypsum. Generally for unbound aggregate base materials, the resilient modulus will vary between 105 MPa and 415 MPa. Thus, all the compositions with lime and gypsum have shown M_R above 250 MPa.

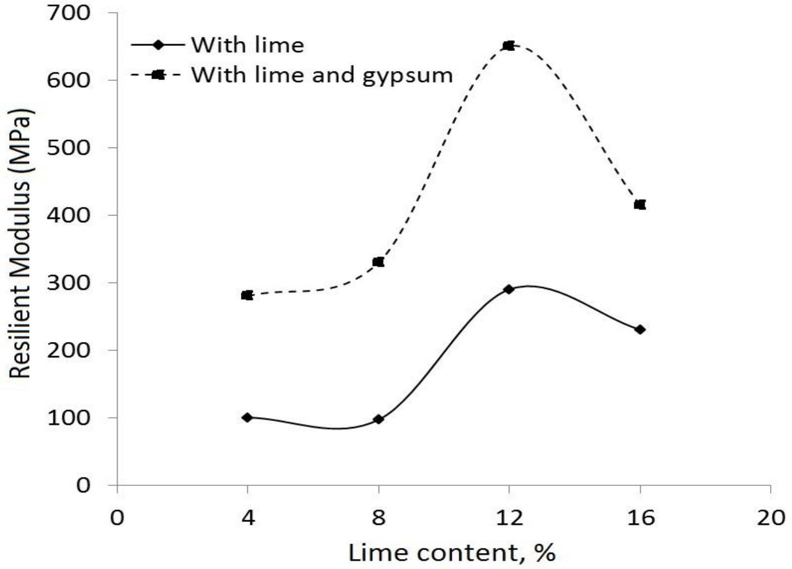


Fig. 10 Resilient modulus for lime and gypsum stabilized fly ash

3.6. *Triaxial shear strength test*

Fig. 11 shows the plot of deviator stress at failure (σ_d) and the confining pressure at different curing periods. The deviator stress and confining pressure shows linear relationship for all curing periods. The confinement of the fly ash mix increased upon lime and gypsum addition, and hence, the resistance to failure has also increased.

Fig. 12 shows the relationship between modulus of elasticity (E) and confining pressure for different curing periods. It can be seen that for all curing periods, E also varies linearly with the confining pressure. As the fly ash mix has confined with lime and gypsum addition, the strain has reduced and thus the sample can sustain any particular axial stress at a lower strain value and thus it results in a higher value of E. It is observed that both σ_d, and E increases with curing period.

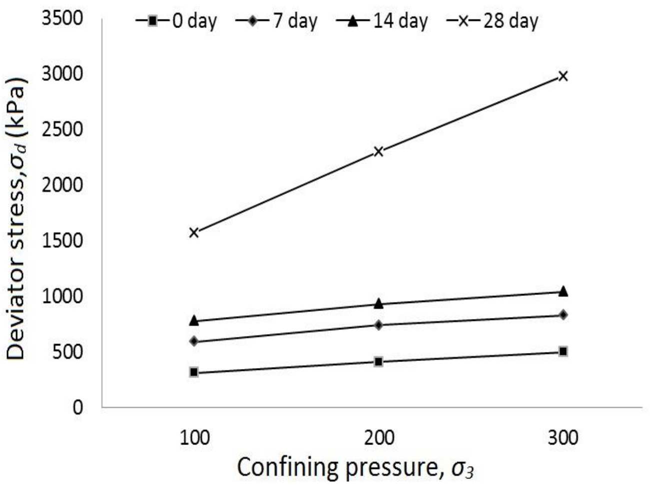


Fig. 11 Relationship between deviator stress at failure with confining pressure

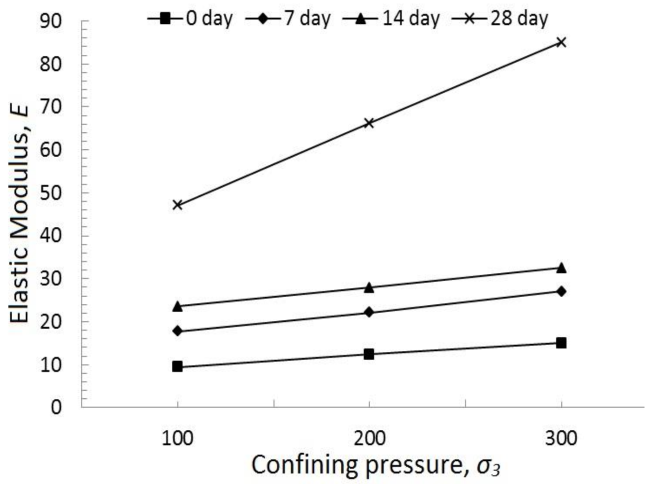


Fig. 12 Relationship between elastic modulus with confining pressure

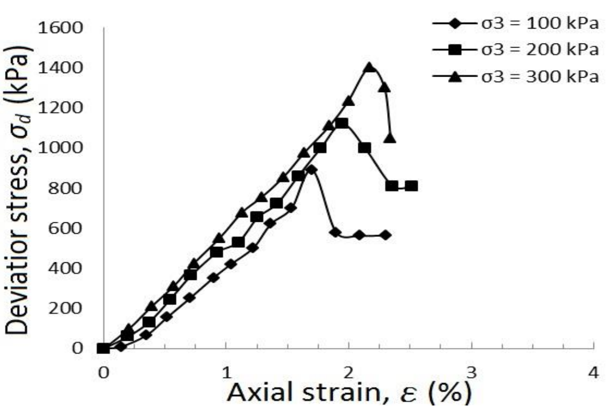


Fig. 13 Stress strain behaviour of 28 days cured specimen

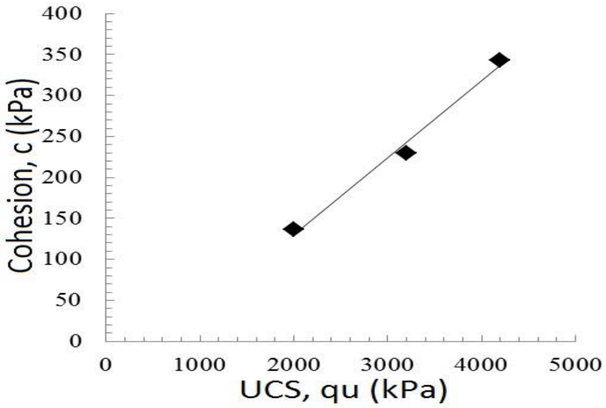


Fig. 14 Relationship between cohesion and UCS

Additionally, the stress strain behaviour of the selected composite mix cured for 28 days was studied (Fig. 13). It is observed that the peak deviator stress, σ_d for all the specimens was attained at axial strains varying between 3% and 4%. An empirical relationship is developed to compute the parameters such as deviator stress (σ_d) and cohesion (c) obtained from triaxial test as function of UCS (q_u). The empirical relationship is as follows:

$$\boldsymbol{\sigma}_d = 0.290q_u + 0.976\sigma_3 \text{ with } R^2 = 0.928 \tag{4}$$

Similar relationship was proposed by Schnaid et al. [19] for cemented sand. Such relationships were also reported for lime stabilized fly ash and fly ash-copper slag mix stabilized with dolime [4, 20]. Similarly, the total cohesion was observed to have a linear relationship with UCS (q_u) and is presented in Fig. 14. The empirical relationship of total cohesion c (kPa) and unconfined compressive strength, q_u (kPa) is presented as follows:

$$c = 0.0768q_u,\ R^2=0.9538 \tag{5}$$

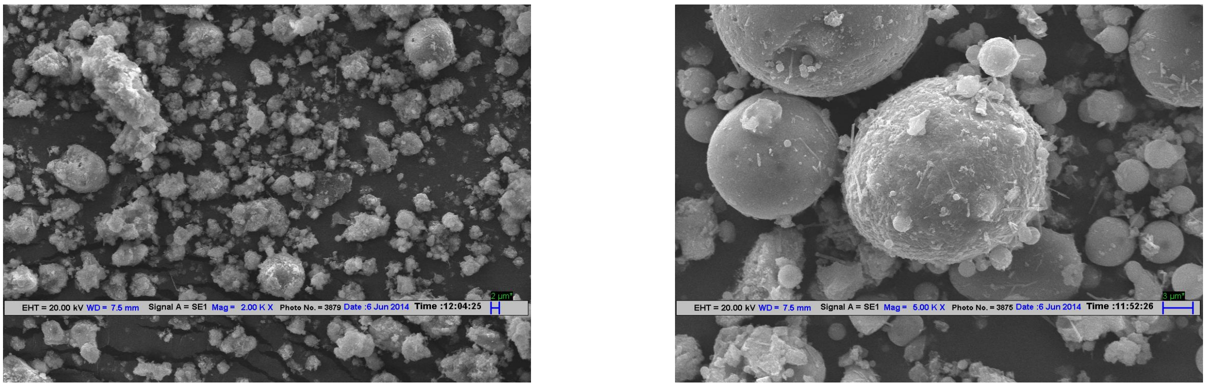
Similar relationship was observed for lime stabilized soils, fly ash stabilized with 10% lime and 1% gypsum and for fly ash-slag mix stabilized with 15% dolime [4, 13, 20].

3.7. *Durability characteristics*

The sample was subjected to twelve alternate wet and dry cycles. After the test, the loss of dry weight of the optimum mix was observed to be 5 %. The optimum composite mix in the present study satisfies the durability criterion of IRC, and hence, was found durable as road base material.

3.8. *Microstructural development*

The SEM (Fig. 15) of the composite (28 days & 90 days cured) shows the formation of pozzolanic reaction products which makes a dense matrix and fly ash acts as a nucleation site for them. The XRD (Fig. 16) of the composite shows the formation of calcium silicate hydrate (CSH) compounds responsible for strength gain of stabilized fly ash.



(a) SEM of 28 days cured optimum composite

(b) SEM of 90 days cured optimum composite

Fig. 15 SEM of 28 days and 90 days cured optimum composite

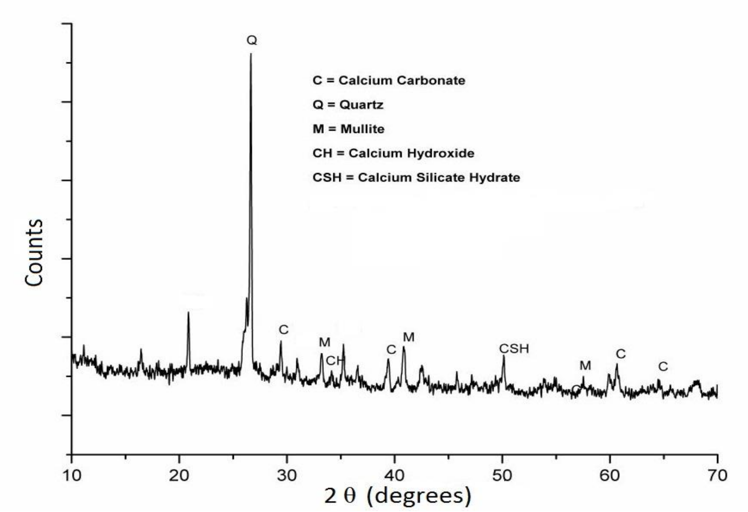


Fig. 16 XRD of optimum composite

4. Conclusions

In order to reuse the industrial solid waste materials widely produced and distributed in India, a composite material consist of fly ash and commercially available lime and gypsum is prepared which can be suggested as road base material. This can solve the disposal problem of fly ash and can also reduce the harmful effects on environmental due to its disposal. The following are the main conclusions drawn from the study:

(1) The maximum dry density decreases and moisture content increases with the increase in lime content (4% to 16%).

(2) The UCS increases with increase in lime content and curing period upto 12% lime addition.

(3) Enhancement of strength was shown by the fly ash-lime sludge mix at the addition of 1% gypsum.

(4) Fly ash stabilized with 12% lime and 1% gypsum acquired UCS of 4697 kPa, split tensile strength of 630 kPa after 28 days of curing.

(5) It showerd CBR value of 93% for 28days cured specimen and the resilient modulus was 651 kPa.

(6) The optimum mix was found to be durable with only 5% weight loss after twelve alternate wet and dry cycles.

(7) The deviator stress at failure (σ_d) and elastic modulus (E) increases linearly with the confining pressure (σ_3) at all curing periods.

(8) Based on the present study, fly ash stabilized with 12% lime and 1% gypsum was selescted as an optimum composite that can be used as a base course layer material in pavement with requisite engineering properties.

References

[1] Central Electricity Authority. CEA, “Report on fly ash generation at coal/lignite based thermal power stations and its utilization in the country for the year 2011-2011,” New Delhi, 2015.

[2] A. Ghosh and C. Subbarao, “Fly ash management by stabilization,” Journal of Solid Waste Technology and Management, vol. 24, no. 3, pp. 126-130, 1997.

[3] S. R. Kaniraj and V. Gayathri, “Permeability and consolidation characteristics of compacted fly ash,” Journal of Energy Engineering, vol. 130, no. 1, pp. 18-43, 2004.

[4] A. Ghosh and C. Subbarao, “Strength characteristics of class F fly ash modified with lime and gypsum,” Journal of Geotechnical and Geoenvironmental Engineering, vol. 133, no. 7, pp. 757-766, 2007.

[5] P. Sivapullaiah and A. A. B. Moghal, “Role of gypsum in the strength development of fly ashes with lime,” Journal of Material in Civil Engineering, vol. 23, no. 2, pp. 197-297, 2011.

[6] A. K. Chatterjee, “Manufacture of PPC in India: effective use of fly ash as a blending material,” Proc. of the National Seminar on Utilization of Fly Ash in Water Resources Sector, Central Soil and Materials Research Station, New Delhi, India, 2001, pp. 29-41.

[7] ASTM C 618, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. American Society for Testing Materials, Philadelphia, 2008.

[8] ASTM D1633. Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders, American Society for Testing Materials, Philadelphia, 2007.

[9] K. Sobhan and M. Mashnad, “Tensile strength and toughness of soil–cement–fly-ash composite reinforced with recycle high-density polyethylene strips,” Journal of Materials in Civil Engineering, vol. 14, no. 2, pp. 177-184, 2002.

[10] J. A. Franklin and M. B. Dusseault, Rock engineering, International ed. New York: McGraw-Hill, 1996.

[11] B. M. Das, S. C. Yen, and R. N. Dass, “Brazilian tensile strength test of lightly cemented sand,” Canadian Geotechical Journal, vol. 32, pp. 166-171, 1995.

[12] ASTM D1833. Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils. American Society for Testing Materials, Philadelphia, 2007.

[13] M. R. Thompson, “Shear strength and elastic properties of lime soil mixtures,” Highway Research Board, Univ. of Illinois, Champaign, IL, pp. 1-14, 1996.

[14] J. Mallela, H. Von Quintus, and K. L. Smith, “Consideration of lime-stabilized layers in mechanistic-empirical pavement design,” Rep. prepared for The National Lime Association, National Lime Association, Arlington VA, 2004.

[15] IRC: 89. Guidelines for soil and granular material stabilization using cement lime and fly ash. Indian Roads Congress, special publication, New Delhi, 2010.

[16] P. E. Glogowski, J. M. Kelly, R. J. McLaren and D. L. Burns, “Fly ash design manual for road and site applications,” RP2422-2. Report prepared for Electric Power Research Institute, GAI Consultants, Monroeville, Pa, 1992.

[17] A. Ghosh and C. Subbarao, “Strength characteristics of class F fly ash modified with lime and gypsum ,” Journal of Geotechnical and Geoenvironmental, vol. 133, no. 7, pp. 757-766.

[18] G. Cumberledge, G. L. Hoffman and A. C. Bhajandas, “Curing and tensile strength characteristics of aggregate-lime-pozzolan,” Transportation Research Record 559, Transportation Research Board, Washington, D.C., pp. 21-29, 1976.

[19] F. Schnaid, P. D. M. Prietto, N. C. and Consoli, “Characterization of cemented sand in triaxial compression,” Journal of Geotechical and Geoenvironmental Enginering, vol. 127, no. 10, pp. 857-868, 2001.

[20] J. T. Shahu, S. Patel, S. and A. Senapati, “Engineering properties of copper slag-fly ash-dolime mix and its utilization in base course of flexible pavement,” Journal of Materials in Civil Engineering, vol. 25, no. 12, pp. 1871-1879, 2013.