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RESEARCH ARTICLE

Potential of Bentonite-lime-mix Modified with Phosphogypsum and Reinforced with Sisal Fibres

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Abstract

The paper presents the potential of bentonite-lime-phosphogypsum mix reinforced with sisal fibre in effectively reducing the pavement thickness in an extremely problematic sub-soil condition intended for road construction. In view of which, compaction, unconfined compressive strength and California bearing ratio tests were conducted. The content of lime, phosphogypsum and sisal fibre was varied from 0 to 10%, 0 to 10% and 0 to 2% respectively. The specimens were prepared at their respective optimum moisture content and maximum dry unit weight for conducting the unconfined compressive strength and bearing ratio tests and were cured for 3 to 28 days. The results of this study reveal that the unconfined compressive strength and bearing ratio of the bentonite-lime-phosphogypsum mix increased with the increase in curing period. Addition of sisal fibres to the bentonite-lime-phosphogypsum mix changes the behaviour of the composite from brittle to ductile in the post peak region. Scanning electron micrographs and energy-dispersive X-ray analysis confirms the improvement in unconfined compressive strength and bearing ratio. The improved behaviour of the composite indicates that the sisal fibres have the potential for use in road pavements.

Keywords

Bentonite · lime · phosphogypsum · compaction · unconfined compressive strength · California bearing ratio · SEM-EDAX

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1 Introduction

With the increase in world population and land costs, engineers are resorting to construction on land having problematic soils. Many countries like Unites states, Greece, Australia, Russia, Ukraine, Turkey and China have vast deposits of bentonite with India covering a 36% area of expansive soils which exhibit high swelling, shrinkage, compressibility and poor strength in contact with water. To control the swell-shrink behaviour and to improve the strength and life of the constructions on these problematic soils, chemical stabilization using lime, cement, fly ash and gypsum has been tried by many investigators across the globe. On the other hand, a large quantity of industrial by-product such as phosphogypsum is being generated leading to disposal, environmental and health problems. The mechanical properties of the stabilised problematic soils can further be improved by reinforcing them with variety of polymeric fibres having long life, do not undergo biological degradation and liable to create environmental problem from its manufacture till the end use [1]. In effecting this, the use of sisal fibres holds promise and are gaining popularity in India. These fibres are biodegradable in nature and do not cause any environmental problem. The paper presents the results of the unconfined compressive strength and bearing ratio, scanning electron micrographs and energy-dispersive X-ray spectroscopy of bentonite-lime-phosphogypsum mix reinforced with sisal fibre and brought out its potential in road application.

2 Background

Past study has shown that the optimum moisture content, dry unit weight and unconfined compressive strength of bentonite are 41.8%, 11.21 kN/m^3 and 58.7 kPa respectively [2]. Improvement in engineering properties of expansive soils with the addition of lime is reported by [3]. Lime stabilization is an environmental friendly, economical and technically feasible construction practice for roads [4]. Researchers [5–8] reported that lime stabilization not only stabilize the expansive soil but also induce cementation due to pozzolanic reactions leading to increase in strength and long-term performance whereas researcher [9] has reported that increase in lime content beyond a threshold leads to decrease in strength. An appreciable increase (16 to 21 times) in the soaked bearing ratio after lime stabilization, which reduced the requirement of the upper layer thickness of the roads is reported by [10]. An increase of 191% in bearing ratio of the clay with the increase in lime content from 0 to 4% and with the addition of 12% rice husk ash was reported by [11]. Other researchers [2, 12–14] and [15] have advocated the use of additives rich in sulphates in their studies. The increase in maximum dry unit weight, optimum moisture content, unconfined compressive strength and bearing ratio of the bentonite stabilized with 8% lime and modified with 4% gypsum was reported by [16]. The increase in unconfined compressive strength of the expansive soil mixed with cement and stabilized with phosphogypsum was reported by [13]. The unconfined compressive strength of the phosphogypsum was 1789.5 kPa [17]. The phosphogypsum produced in India reported by [18] was having a radioactivity less than 13.5 pCu/g as specified by [19]. Researchers [12, 20, 21] reported studies on clay-lime-gypsum mixes and reported increase in the formation of ettringite with the increase in gypsum content. Fibre inclusion changed the brittle behavior of lime treated soil to more ductile one [22]. Black cotton soil reinforced with 0.5% sisal fibre of length 25 mm results an improvement of 14.21% and 7.98 times in bearing ratio and unconfined compressive strength respectively as reported by [23]. An increase in unconfined compressive strength and bearing ratio was reported by [24] for the black cotton soil reinforced with sisal fibres and stabilized with lime. From the literature study it is evident that the study on the potential of bentonite-lime-phosphogypsum mix reinforced with sisal fibres has not been reported so far. The present study tries to fill this gap.

3 Materials Used and Experimental Procedure

Commercially available bentonite was used in this study. The specific gravity, liquid limit, plastic limit, optimum moisture content and maximum dry unit weight of the bentonite was 2.30, 220%, 39.74%, 27.98% and 13.95 kN/m^3 respectively. The bentonite was classified as clay of high compressibility. Hydrated lime and phosphogypsum was used in this study The specific gravity of lime and phosphogypsum was 2.37 and 2.20 respectively. Thee specific gravity, diameter, length and tensile strength of thee sisal fibres used in this study were 1.40, 0.25 mm, 15 mm and 405.2 N/mm^2 respectively. In order to assess the elemental changes occurring due to mixing of bentonite, lime, phosphogypsum and sisal fibres, the elemental composition was determined through scanning electron micrographs and energy-dispersive X-ray *(SEM-EDAX)* and the results are shown in Table 1. Materials such as lime, phosphogypsum and sisal fibres have been chosen to improve the strength of the bentonite and to improve the toughening behavior of the modified bentonite-lime-phosphogypsum mix. Therefore, compaction, unconfined compressive strength and California bearing ratio tests were thus performed. The standard proctor compaction tests were conducted as per [25] on bentonite-lime and bentonite-lime–phosphogypsum and bentonite-lime–phosphogypsum-sisal fibre mixtures by varying the content of lime , phosphogypsum and sisal fibre from 2 to 10%, 0.5 to 8 % and 0.5 to 2% respectively and water was added as needed to facilitate the mixing and compaction process. For the unconfined compressive strength tests, a metallic mould having size 38 mm inner diameter and 76 mm long, with additional detachable collars at both ends were used to prepare cylindrical specimens.

Required quantities of bentonite, lime, phosphogypsum and sisal fibres were mixed in dry state. The sisal fibres have the tendency to lump together. Therefore a considerable care and time was spent to separate them to get an even distribution of the fibres in the mixture. The dry bentonite-lime-gypsum–sisal fibre mixture was then mixed with the required amount of water corresponding to optimum moisture content. All mixing was done manually and proper care was taken to prepare homogeneous mixtures at each stage of mixing. The mix was then placed inside the mould. To ensure uniform compaction, specimen was compressed statically from both ends till the specimen just reached the dimensions of the mould. Then the specimen was extracted with the hydraulic jack and was placed in air tight polythene bags which were placed inside the dessicator for curing for 3, 7, 14 and 28 days. The specimen was taken out of the dessicator and polythene bag after the desired period of curing and tested for unconfined compressive strength using a strain rate of 1.2 mm/min. The unconfined compressive strength tests were conducted as per [26]. The California bearing ratio tests were conducted as per [27]. A metallic mould having size 152 mm inner diameter and 178 mm long, with additional detachable collars at the top end was used to prepare the specimen for testing. A base plate was used at the bottom. The quantity of bentonite, lime, phosphogypsum and sisal fibre corresponding to the dry weight of bentonite was mixed thoroughly and the required quantity of water was added to the mix. The mix was compacted in three layers by giving 56 blows to each layers and the mould was then placed inside the polythene bag which was then placed inside the desiccator for curing for 3, 7, 14 and 28 days. Failed specimens of unconfined compression tests were powdered and sieved through a 45 μm sieve and gold-coated prior too scanning electron micrographs and energy-dispersive X-ray spectroscopy (*SEM-EDAX*) tests.

The equipment used for testing unconfined compressive strength is shown in Fig. 1.

For easy reference and identification of specimen, specific codification was used. Specimens containing only bentonite and lime (without sisal fibre) were designated by four letter codification. The first letter of codification indicates bentonite; the next three digits indicate percent lime. For example, code B08L will indicate bentonite mixed with 8% lime. For specimens containing bentonite-lime-phosphogypsum (without sisal fibre) was designated by nine letter codification. The first letter of codification indicates bentonite, the next three digits and next to next

Tab. 1. Elemental composition of bentonite, lime, phosphogypsum and sisal fibre

Element	Materials (%)			
	Bentonite	Lime	Phosphogypsum	Sisal Fibre
C	10.67	18.98	5.38	38.03
N	5.86	20.31	6.40	24.61
O	56.08	47.99	68.57	33.35
F	ND	ND	ND	ND
Na	2.02	ND	0.05	0.04
Mg	0.77	0.11	0.01	0.15
Al	7.61	0.05	0.05	0.72
Si	15.01	0.03	0.65	1.77
P	ND	ND	0.22	ND
S	ND	ND	9.16	ND
Cl	ND	0.02	0.04	0.02
K	0.19	0.05	0.04	0.18
Ca	0.03	12.24	0.00	0.26
Cr	0.02	ND	9.16	0.03
Fe	1.68	0.00	0.04	0.55
Zn	ND	0.24	0.01	0.23
Pb	ND	ND	ND	ND
As	0.05	ND	ND	ND
I	ND	ND	0.09	0.09

Note: ND → Not detected

Fig. 1. Pictorial view of equipment used to determine unconfined compressive strength and bearing ratio test

five digits indicates the percent lime and percent phosphogypsum respectively. For example, code B08L005PG will indicate bentonite mixed with 8% lime and 0.5% phosphogypsum. For specimens containing sisal fibres, a thirteen letter codification scheme was used. The first letter of codification indicates bentonite; the second three digits and third five digits indicate percent lime and phosphogypsum content respectively. The next four digits indicate the percent sisal fibres. For example, code B08L005PG05SF will indicate bentonite mixed with 8% lime, 0.5% phosphogypsum, 0.5% sisal fibres.

4 Testing Results and Analyses

4.1 Compaction and Unconfined Compressive Strength

In order to decide the optimum mix for the bentonite-lime-phosphogypsum-sisal fibre, the compaction tests were conducted. The variations of the maximum dry unit weight and the optimum moisture content of the bentonite mixed with varying percentages of lime is shown in Fig. 2(a). Fig. 2(a) reveals that the maximum dry unit weight for the bentonite decreased whereas the optimum moisture content increased with the addition of 2, 4, 6, 8 and 10% lime. As no optimum mix could be fixed on the basis of the results of the compaction tests, it was decided to conduct unconfined compressive strength tests on the bentonite-lime mixes. The variation of unconfined compressive strength of the bentonite with varying percentages of lime and cured for 3, 7, 14 and 28 days is shown in Fig. 3(a). Fig. 3(a) reveals that the unconfined compressive strength of the bentonite cured for 3 days increased with the addition of 2, 4, 6, 8% lime and decreased with the addition of 10% lime at the same curing period. The trend was consistent at other curing periods also as evident from Fig. 3(a). Fig. 3(a) further reveals that there is not much change in the unconfined compressive strength up to 6% lime and 4% lime for a shorter curing periods (up to 14 days) and longer curing periods (28 days) respectively. This is attributed to the fact that the initial 6% lime and 4% lime at shorter (up to 14 days) and longer (28 days) curing period respectively is absorbed by the bentonite for cationic exchange reaction and beyond 6% lime and 4% lime at shorter (up to 14 days) and longer (28 days) curing period respectively is available for pozzolanic reactions. Therefore a mix B08L was chosen for studying the compaction behavior by varying the content of phosphogypsum. The results of the variation of the maximum dry unit weight and the optimum moisture content for the mix B08L with varying percentages of phosphogypsum are shown in the Fig. 2(b). Fig. 2(b) reveals that the maximum dry unit weight and the optimum moisture content for the mix B08L increased with the addition of 0.5, 1, 2, 4, 8 and 10% phosphogypsum. The effect of addition of phosphogypsum to the mix B08L is to produce a greater maximum dry unit weight and optimum moisture content. As no optimum mix could be fixed on the basis of the results of the compaction tests, it was decided to conduct unconfined compressive strength tests on the bentonite-lime-phosphogypsum mix.

The unconfined compressive strength of the mix B08L cured for 3 days was 442.77 kPa which increased to 450.24 kPa with the addition of 8% phosphogypsum and decreased to 357.65 kPa with the addition of 10% phosphogypsum at the same curing period. Similar trend was observed for other curing periods of 7, 14 and 28 days and the results are shown in Fig. 3(b). Fig. 3(b) further reveals that the unconfined compressive strength of the bentonite-lime-phosphogypsum mix increased with the increase in curing period up to a curing period of 14 days. The increase in unconfined compressive strength of bentonite-lime-phosphogypsum mixes cured for short curing periods is due to the dominant effect of formation of pozzolanic compounds. While, in the mixes cured for longer curing periods, the effect of impurities and sulphates becomes dominant and effect of formation of pozzolanic compound decreases. Similar trend of increase in unconfined compressive strength was observed at other content of phosphogypsum. A study in Fig. 3(b) reveals that the unconfined compressive strength increased with the increase in phosphogypsum content up to 8%. Beyond this content there was a decrease in unconfined compressive strength. Similar trend of increase in unconfined compressive strength was observed for other curing periods of 7, 14 and 28 days as evident from Fig. 3(b). The decrease in unconfined compressive strength beyond a phosphogypsum content of 8% is perhaps attributed to the increase in the phosphates, fluorides and sulphates present in phosphogypsum which in turn is responsible for the increased formation of ettringite crystals Therefore on the basis of the results shown in Fig. 3(b), a reference mix B08L080PG was chosen for further studying the compaction behavior by varying the sisal fibre content and the variation of the maximum dry unit weight and the optimum moisture content is shown in Fig. 2(c). Fig. 2(c) reveals that the maximum dry unit weight of the reference mix decreases whereas the optimum moisture content increases with the increase in sisal fibre content As no optimum mix could be fixed on the basis of the results of the compaction tests, it was decided to conduct unconfined compressive strength tests on the reference mix mixed with sisal fibre. The unconfined compressive strength of the reference mix cured for 3 days was 450.24 kPa which increased to 515.48 kPa and decreased to 289.20 kPa with the addition of 1 and 2% sisal fibre respectively at the same curing period. Similar trend was observed for other

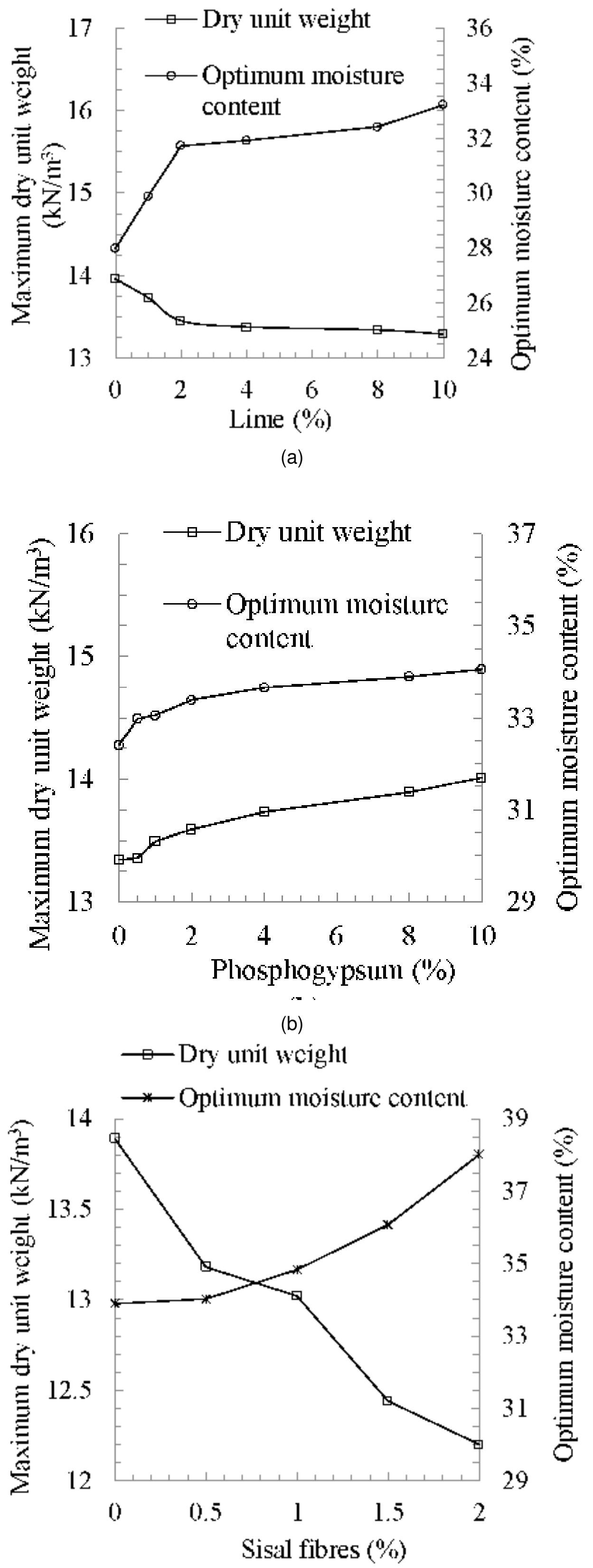
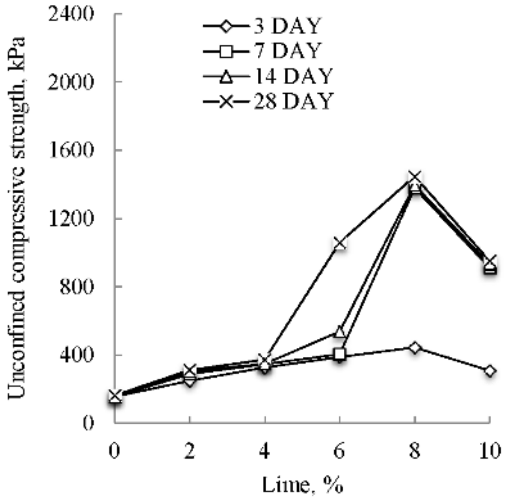
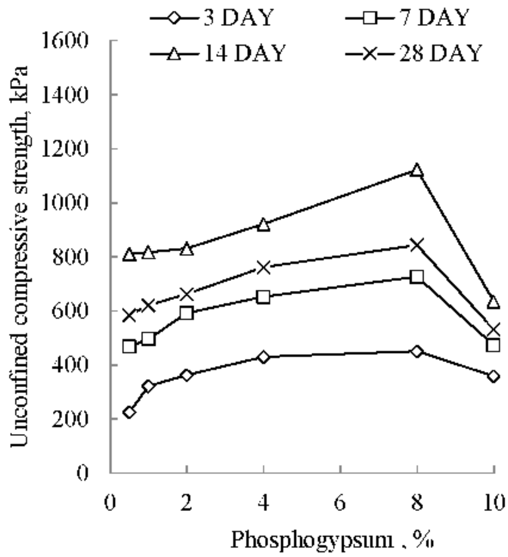


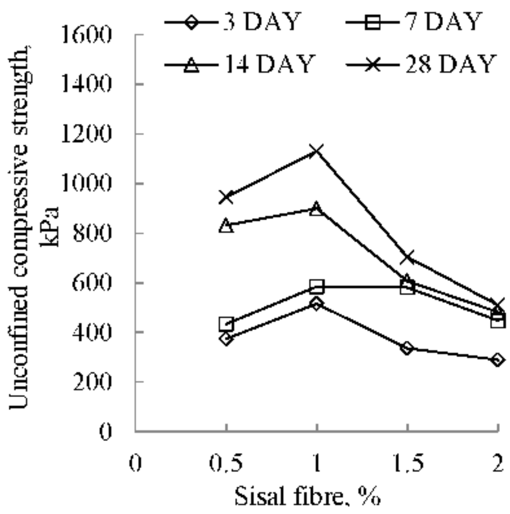
Fig. 2. Variation of maximum dry unit weight and optimum moisture content of(a) bentonite with varying lime content (b) mix B08L with varying phosphogypsum content (c) mix B08L080PG with varying sisal fibre content



(a)



(b)



(c)

Fig. 3. Variation of unconfined compressive strength of (a) bentonite with varying lime content and curing period (b) mix B08L with varying phosphogypsum content and curing period (c) mix B08L080PG with varying sisal fibre content and curing period

curing periods of 7, 14 and 28 days and the results are presented in Fig. 3(c). Fig. 3(c) reveals that the increase in unconfined compressive strength with the addition of sisal fibres up to a fibre content of 1.0% is attributed to the fact that the cementing gel formed due to the reaction of bentonite with lime, binds the sisal fibres with the bentonite particles leading to enhancement in the unconfined compressive strength. The decrease in unconfined compressive strength beyond a fibre content of 1.0% is attributed to the fact that formation of lump of fibres due to excessive adhesion and poor contact of fibres with bentonite particles results in decrease in unconfined compressive strength. More details on the above study are reported elsewhere [28]. Failed specimens of unconfined compressive strength of the mixes are shown in Fig. 4. A close observation of Fig. 4(a), Fig. 4(b) and Fig. 4(c) indicate brittle failure of bentonite-lime-phosphogypsum mixes. The addition of sisal fibres to the reference mix B08L080PG shows the ductile behavior as evident from Fig. 4(d).

4.1.1 Post-peak behavior

In order to study the post peak behaviour, the stress axis of the unconfined compressive stress- strain curve was normalized with respect to the peak axial stress, and the strain axis was normalized with respect to the strain at the peak axial stress. Fig. 5 shows the normalized stress-strain curves of the reference mix B08L080PG with varying percentages of sisal fibres. Study of Fig. 5 reveals that the brittle failure of the bentonite, mix B08L and B08L080PG for the curing periods of 3, 7, 14 and 28 days. Addition of sisal fibres to these mixes induces a ductile behaviour which becomes evident with the increase in the curing periods. Thus, sisal fibres improve the ductility of the mix in the post peak region.

4.2 California Bearing Ratio

The load-displacement behavior of various mixes such as bentonite, B08L, B08L080PG and B08L080PG10SF cured for 0, 3, 7, 14 and 28 days are shown in Fig. 6(a) to Fig. 6(e) respectively. The summary of variation of bearing ratio of the mixes along with curing period is given in Table 2. Table 2 reveals that the bearing ratio of the bentonite increases with the addition of 8% lime as well as increase in the curing period. This increase in bearing ratio is attributed to the formation of cementing compounds due to pozzolanic reaction. For example, at a curing period of 28 days, an 18.34 fold increase in the bearing ratio of the bentonite was observed with the addition of 8% lime. Further, the bearing ratio of the mix B08L increased with the addition of 8% phosphogypsum up to a curing period of 14 days. This increase is due to the dominant effect of the formation of cementing compounds and the trend is reversed after a curing period of 14 days. For example, the bearing ratio of the bentonite increased 15.95 fold with the addition of 8% phosphogypsum to the mix B08L after a curing period of 14 days. The decrease in the *bearing ratio* beyond a curing period of 14 days of the mix B08L080PG as compared to the mix B08L is due to the action of

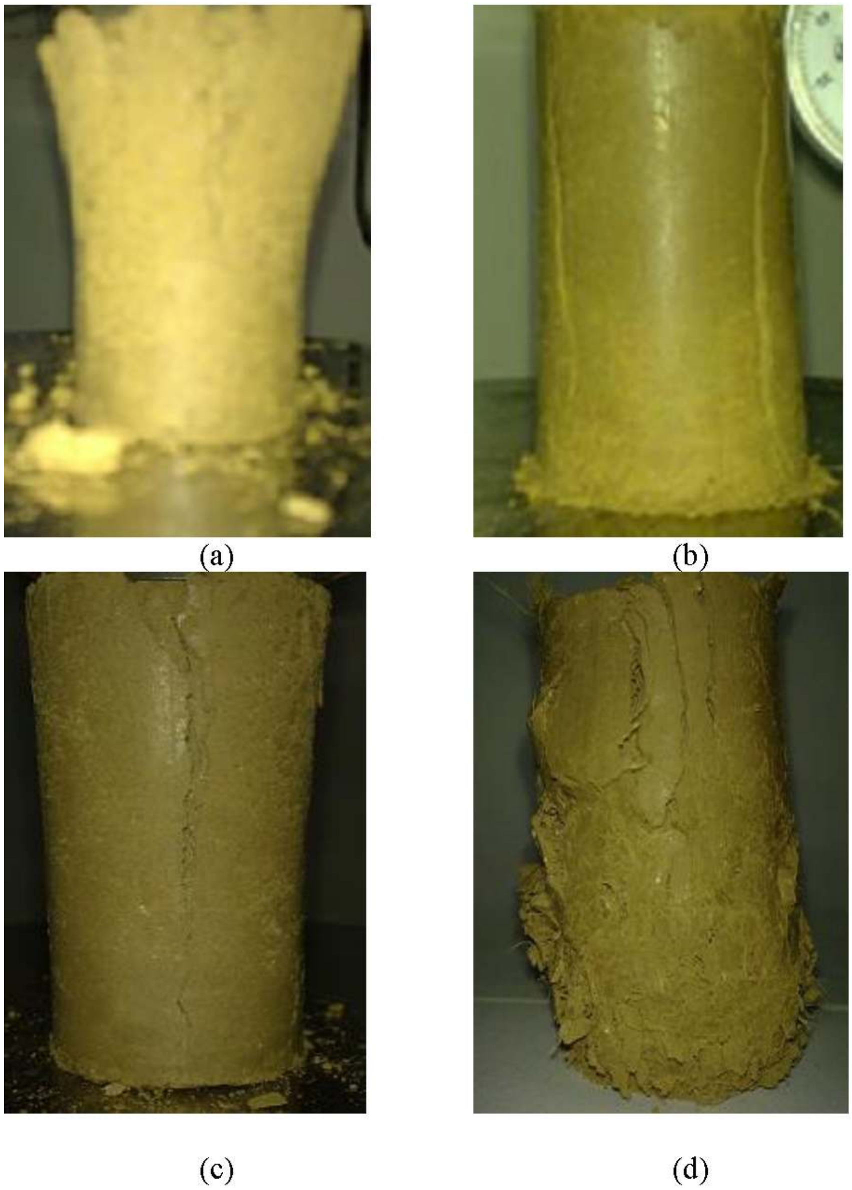


Fig. 4. Failed specimens of unconfined compressive strength test of (a) bentonite (b) B08L (c) B08L080PG (d) B08L080PG10SF

impurities and sulphate present in the phosphogypsum. Further from Table 2, it is observed that there was no significant increase in the bearing ratio of the mix B08L080PG with the addition of 1% sisal fibres

Tab. 2. Summary of bearing ratio of various mixes with curing period

Curing period, days	Bearing ratio,%			
	Bentonite	B08L	B08L080PG	B08L080PG10SF
	1.87	8.92	11.90	6.58
3	1.88	14.83	16.48	17.43
7	1.89	18.63	19.46	20.12
14	2.00	25.04	29.82	25.62
28	2.07	34.29	25.67	29.73

4.3 Scanning Electron Micrograph Study

Scanning electron micrographs (*SEM*) of the bentonite and the mix B08L (cured for 7 and 28 days) are shown in Figs. 7(a) to 7(c). Study of Fig. 7(a) reveals the particles of bentonite. Fig. 7(b) reveals the formation of compact matrix (cementing gel) around the bentonite particle with the addition of 8% lime and cured for 7 days. The formation of cementing gel increased with the increase in curing period to 28 days as shown in Fig. 7(c). The *SEM* of the mix B10L at a curing period of 28 days is shown in the Fig. 7(d). Fig. 7(d) reveals lesser formation of cementing gel in comparison to Fig. 7(c). The *SEM* of the mix B08L080PG with the curing period of 7, 14 and 28 days is shown in Fig. 7(e) to 7(g). Study of these figures reveals the formation of needle like interlocking matrix and pozzolanic products. The effect of the later is dominant up to a curing period of 14 days. But, with the increase in curing period to 28 days, the former dominate the later leading to decrease in the bearing ratio of the mix B08L080PG as evident from Table 2.

4.4 Energy Dispersive X-Ray Spectroscopy Analysis

The energy-dispersive X-ray diffraction (*EDAX*) of the mixes such as bentonite, B08L (cured for 7 and 28 days), B10L (cured

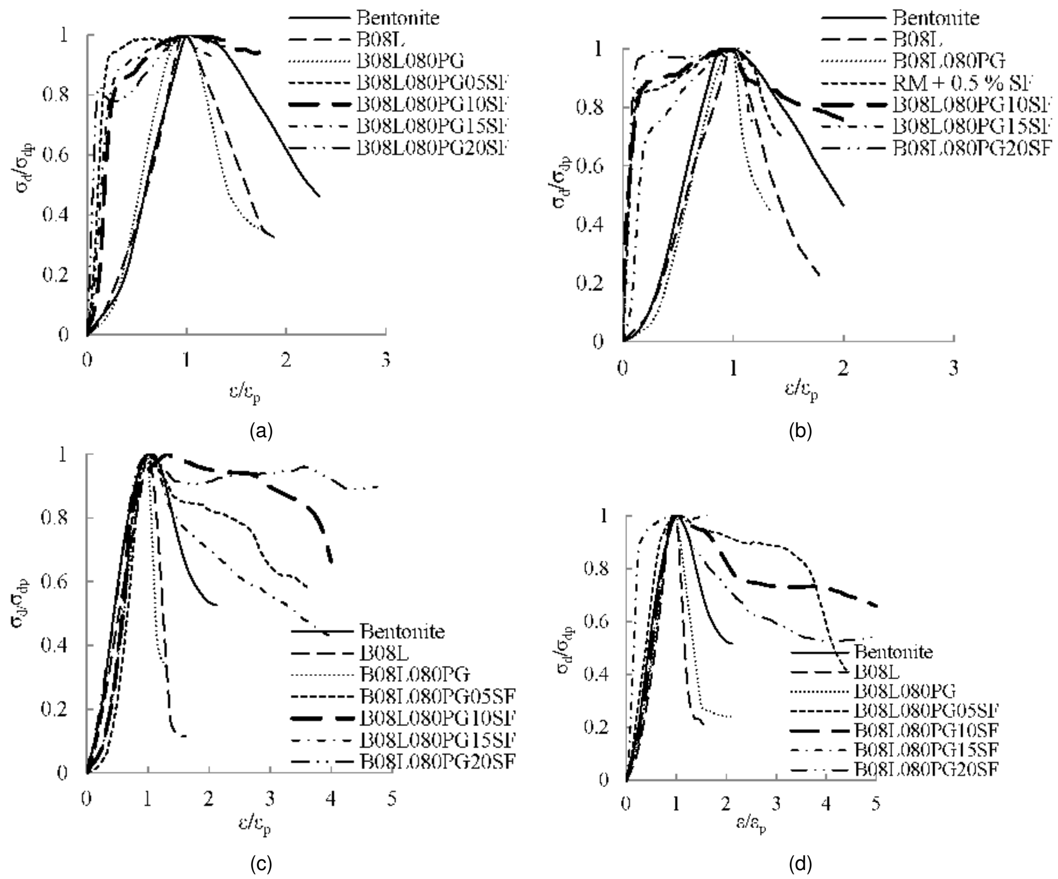


Fig. 5. Normalized stress-strain curve for the various mixes at a curing period of (a) 3 days (b) 7 days (c) 14 days (d) 28 days

for 28 days), B08L080PG (cured for 7, 14 and 28 days) , and B08L100PG (cured for 28 days) are shown in Figs. 8(a) to 8(d) and Figs. 9(a) to 9(d) respectively. Summary of the *EDAX* analysis is given in the Table 3. Study of Table 3 reveals an increase in the *Ca: Si* ratio and decrease in the *Si: Al* ratio of bentonite with the addition of 8% lime as well as with the increase in curing period. The increase in *Ca: Si* ratio and decrease in *Si: Al* ratio indicates an improvement in the bearing ratio. The emissions of Ca, Si and O confirm the formation of cementing compound like $C-S-H$ leading to increase in the bearing ratio of the bentonite with the addition of lime as evident from Table 2.

Tab. 3. Summary of *EDAX* analysis

Mixes	Curing period, days	*Ca: Si* ratio	*Si: Al* ratio
Bentonite	-	0.0002	2.2696
B08L	7	0.1727	2.1556
	28	0.2577	1.8765
B10L	28	0.2198	1.9766
B08L080PG	7	0.2351	2.0000
	14	0.40000	1.9557
	28	0.2706	1.8300
B08L100PG	28	0.3026	2.0242

Energy-dispersive X-ray diffraction of the mix B10L cured for 28 days shows the decrease in *Ca: Si* ratio and increase in *Si: Al* ratio of the bentonite with the addition of 10% lime as compared to the mix B08L in the same curing period. This resulted in the decrease in unconfined compressive strength of the bentonite with the addition of 10% lime as evident from Fig. 3(a). Study of the *EDAX* of the reference mix with the curing period reveals that the *Ca:Si* ratio of B08L increased with the addition of 8% phosphogypsum and with the increase in curing period leading to improvement in unconfined compressive strength and bearing ratio as mentioned in Section 4.1 and 4.2 respectively. The *Si: Al* ratio of B08L was 2.1556 and 1.8765 at a curing period of 7 and 28 days respectively. The Si:Al ratio changed to 2.15, 1.95 and 2.06 with the addition of 8% phosphogypsum to B08L mix at a curing period of 7, 14 and 28 days respectively. The decrease in *Si: Al* ratio continued up to a curing period of 28 days leading to improvement in unconfined compressive strength. The *Si: Al* ratio decreased up to a curing period of 14 days indicating appreciable improvement in unconfined compressive strength and bearing ratio due to the accelerated formation of cementation products in the presence of sulphates from phosphogypsum, this can be observed from the strong emissions of Ca, Al, S and O. The further increase in the *Si: Al* ratio at a curing period of 28 days shows the decrease in the unconfined compressive strength and bearing ratio of B08L080PG due to increased formation of ettringite crystals responsible for decrease in the strength. The *EDAX* of the B08L100PG cured for 28 days shows a further increase in the *Si: Al* ratio and decrease in the *Ca: Si* ratio as compared to the reference mix cured for 14 days.

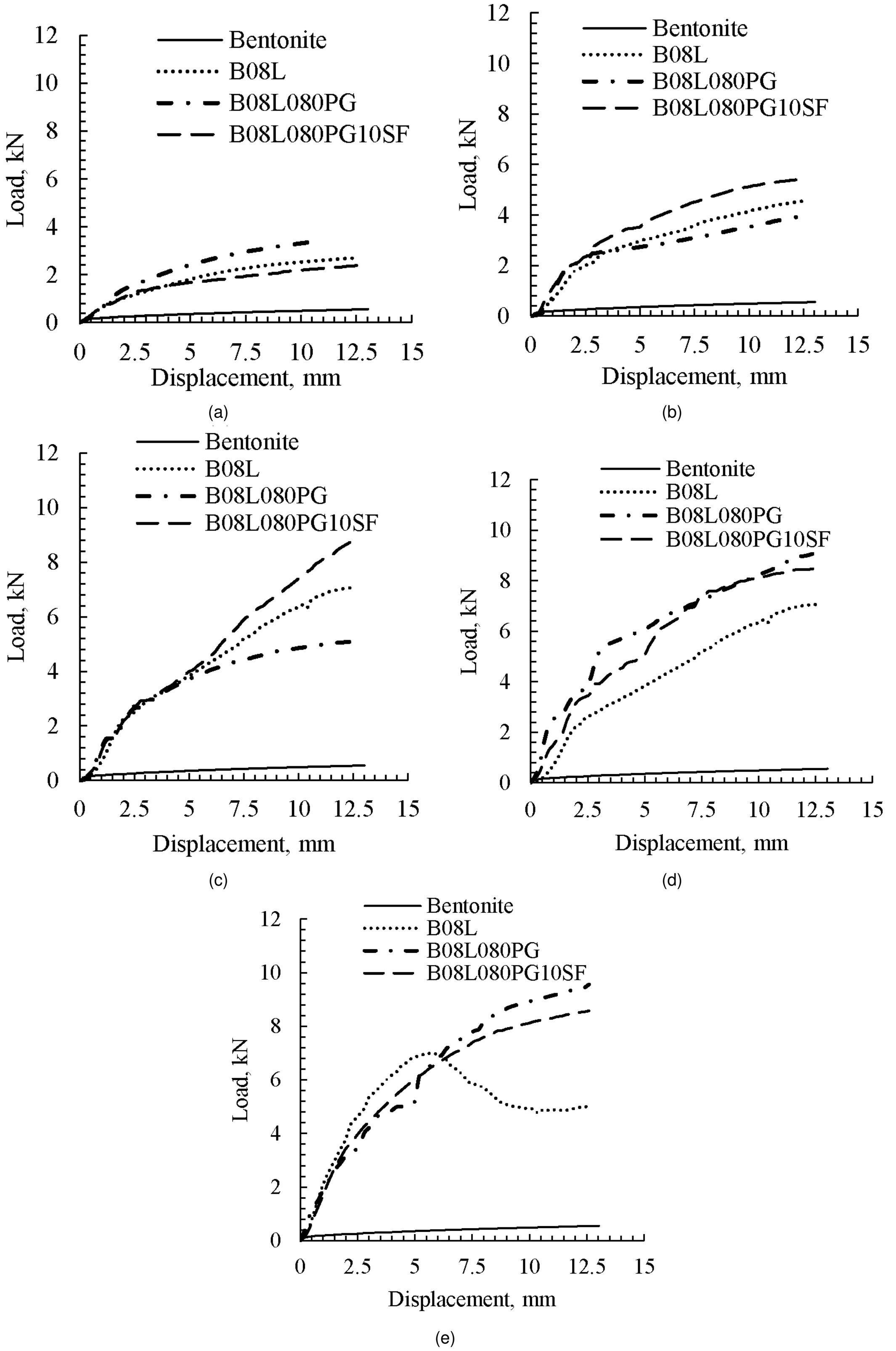


Fig. 6. Load-displacement curves of various mixes at a curing period of (a) 0 days (b) 3 days (c) 7 days (d) 14 days (e) 28 days

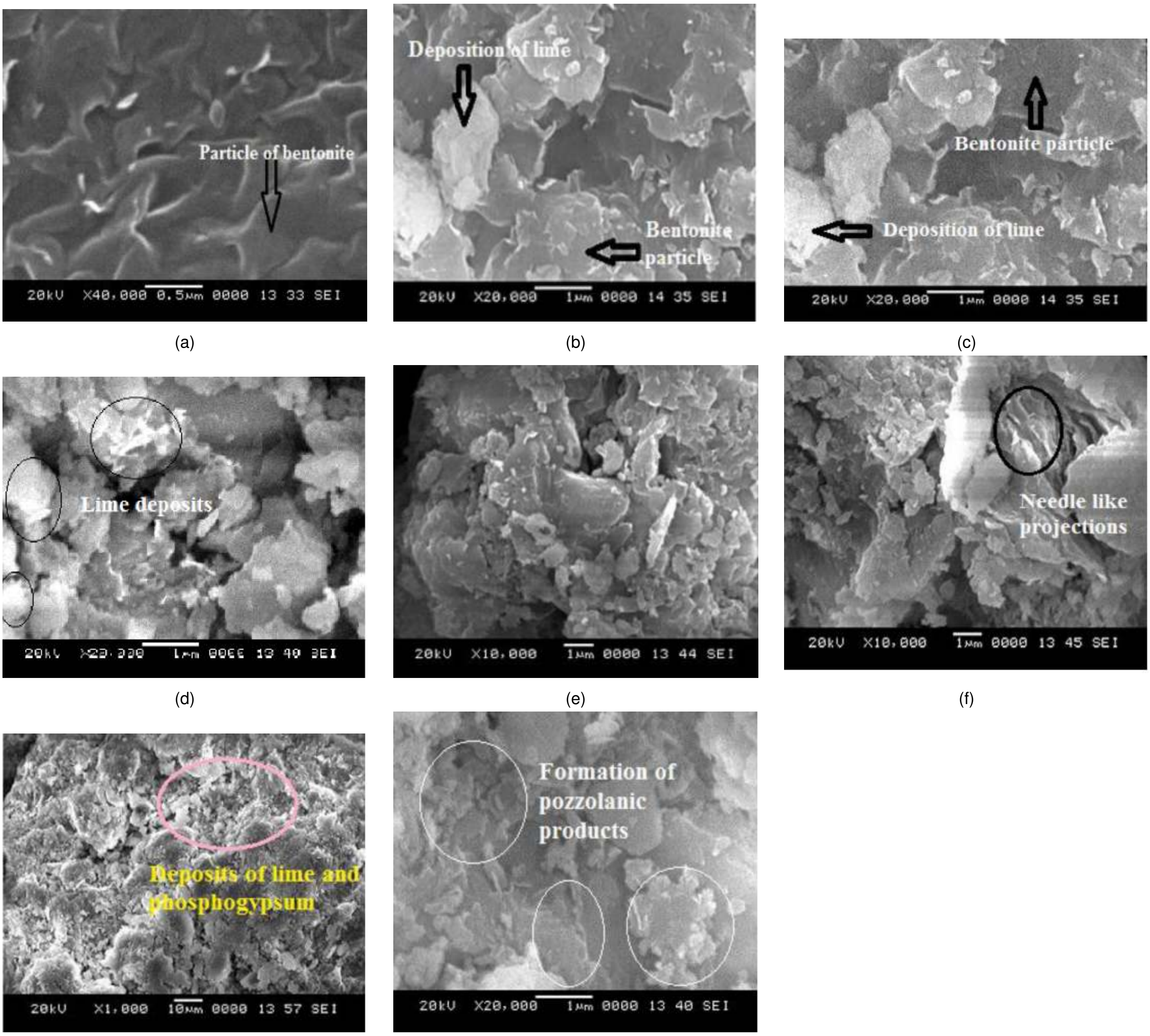


Fig. 7. *SEM* of (a) bentonite (20kV, 40000x) (b) mix B08L 7 days curing (20kV, 20000x) (c) mix B08L 28 days curing (20kV, 20000x) (d) mix B10L 28 days curing (20kV, 20000x) (e) mix B08L080PG 7 days curing (20kV, 10000x) (f) mix B08L080PG 14 days curing (20kV, 10000x) (g) mix B08L080PG 28 days curing (20kV, 1000x) (h) mix B08L100PG 28 days curing (20kV, 20000x)

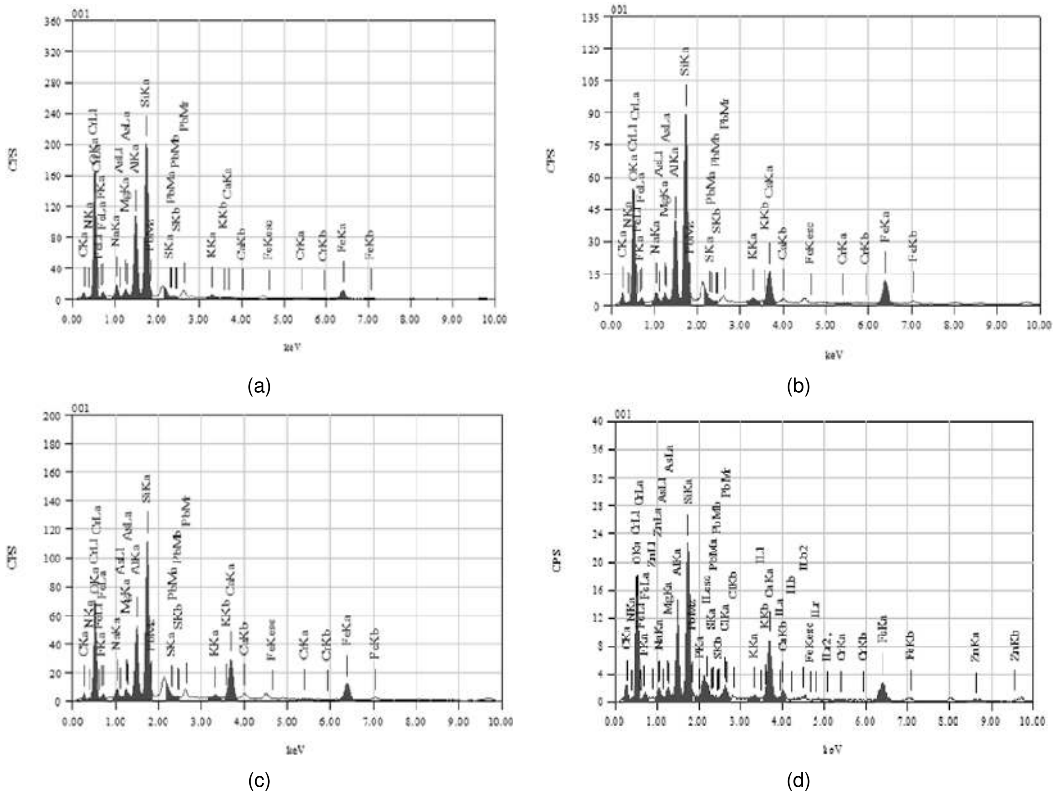


Fig. 8. *EDAX* of (a) bentonite (b) mix B08L at 7 day of curing (c) mix B08L at 28 day of curing (d) mix B10L at 28 day of curing

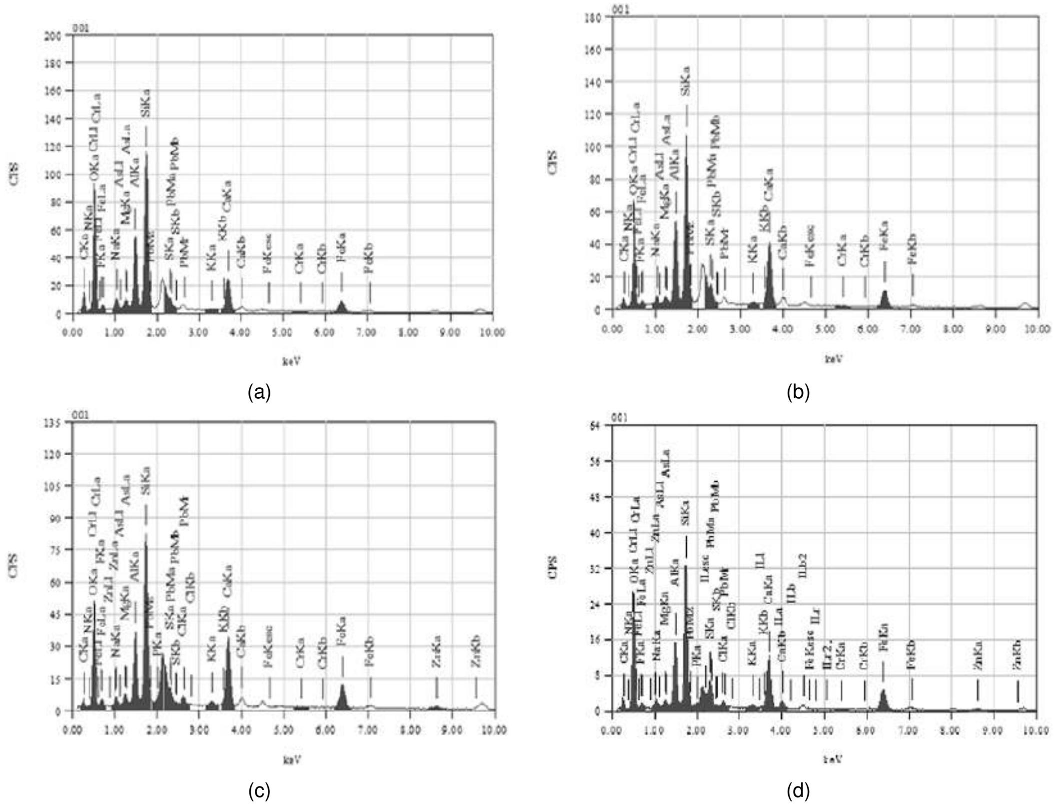


Fig. 9. *EDAX* of mix (a) B08L080PG at 7 days of curing (b) B08L080PG at 14 days of curing (c) B08L080PG at 28 days of curing (d) B08L100PG at 28 days of curing

This proves the decrease in the unconfined compressive strength of the B08L100PG

4.5 Application to Road Pavement

In this section an attempt has been made to use the experimental results to assess the potential of bentonite-lime-phosphogypsum mix reinforced with sisal fibres. For the analysis, a traffic survey shows that the average daily traffic of commercial vehicles per day on a proposed major district road was 1200. The expected annual growth of the traffic is estimated to be 8% and the pavement construction is to be completed in 3 years after the last traffic count. The pavement thickness for this case was calculated using *bearing ratio* design chart (recommended by [29]). The number of commercial vehicles per day for the design (laden weight textgreater 3 tons) was calculated using the formula as given in (Eq. (1)).

$$A = P\left(1 + \frac{r}{10}\right)^{(n+10)} \quad (1)$$

where A is the number of heavy vehicles per day design (laden weight >3 tons), P is the number of heavy vehicles per day at least count, r is the annual rate of increase of heavy vehicles and n is the number of years between the last count and the year of completion of construction. The estimated number of commercial vehicles per day was 3260. Keeping in view the number of commercial vehicles, a Curve F recommended by [29] for use in India was chosen for the design as the design traffic volume is in range 1500 - 4500 commercial vehicle per day. The requirement of pavement thickness for subgrade bentonite modified with lime–phosphogypsum and sisal fibres along with the curing period is shown in Fig. 10(a). The pavement thickness of bentonite reduced to 17.72%, 20.89% and 20.25 % with the addition of lime, phosphogypsum and sisal fibres respectively. The saving in material per kilometer length for a major district road of 4.5 m width for the bentonite, mixes B08L, B080L080PG and B08L080PG10SF with the curing period is shown in Fig. 10(b).

A study of Fig. 10(b) reveals that the earth work required for the subgrade bentonite decreases by 82%, 79% and 79.7% with the addition of lime, lime-phosphogypsum and lime-phosphogypsum-sisal fibres respectively. This improved reduction in the earthwork is due to the increased bearing ratio and reduced pavement thickness of the bentonite after chemical modification and subsequent reinforcement from sisal fibres.

The durability of sisal fibres conditioned in tap water was studied by [30] and the results indicated that after 420 days, sisal fibres retained 83.3 % of their original strength. Further study is required to make an assessment for the durability of sisal fibres in bentonite-lime-phosphogypsum matrix for the actual implementation of the results in the field. The cost economics is beyond the scope of this study. However, the authors of this paper are of the opinion that the use of this composite material

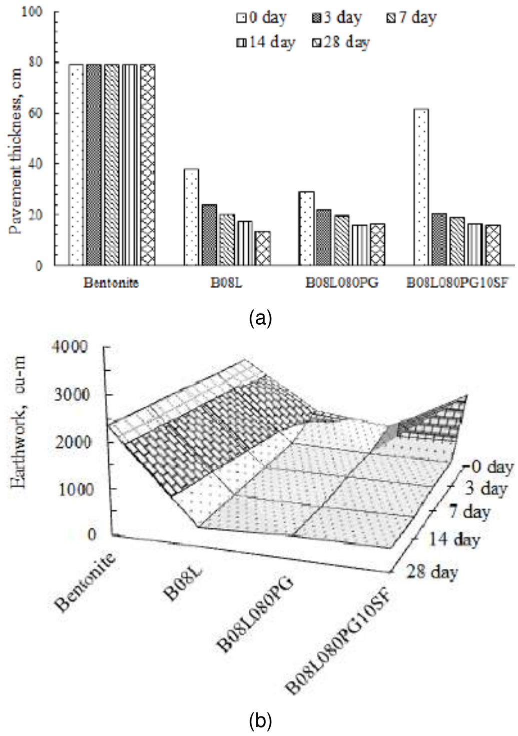


Fig. 10. Variation of (a) pavement thickness of the mixes with the curing period (b) volume of earth work of the mixes with the curing period

can be more economical in those areas where these materials are available in the nearby places.

5 Conclusion

An experimental study is carried out to investigate the potential of bentonite stabilized with lime and modified with phosphogypsum reinforced with sisal fibre. For this, compaction, unconfined compressive strength and California bearing ratio tests were conducted on the mixes. The study brings forth the following conclusions.

1 The dry unit weight and optimum moisture content of the mix B08L increased with the addition of 8% phosphogypsum. The dry unit weight of the mix B08L080PG decreased with the addition of 1.0% sisal fibres. The optimum moisture content of the mix B08L080PG increased with the addition of 1.0% sisal fibres.

2 The unconfined compressive strength of the mix B08L increased with the addition of 8% phosphogypsum. Beyond 8%, the unconfined compressive strength decreased. The unconfined compressive strength of the bentonite-lime-phosphogypsum mix increased with the increase in curing period. The unconfined compressive strength of the bentonite-lime-phosphogypsum increased with the addition of sisal fibres. However, the increase was highest with the addition of 1.0% sisal fibres and decreased later on. Addition of sisal fibres to the mix B08L080PG improves the ductility in the post peak region.

3 The bearing ratio of the mix B08L increased with the addi-

tion of 8% phosphogypsum. The bearing ratio of bentonite increased with the addition of 8% phosphogypsum and 1.0% sisal fibres.

4 The *SEM-EDAX* studies proved the formation of cementation compounds like *CSH* and *CAH* and ettringite compounds with the addition of lime and phosphogypsum to the bentonite respectively. These compounds were responsible for the improvement of strength with the increase in the curing period.

5 The addition of lime-phosphogypsum-sisal fibres to bentonite decreases the pavement thickness and reduces the volume of earthwork in road application.

Notations

B	Bentonite
L	Lime
PG	Phosphogypsum
SF	Sisal Fibre
RM	Reference mix
CAH	Calcium Aluminate Hydrate
CSH	Calcium Silicate Hydrate
SEM	Scanning Electron Micrograph
EDAX	Electron Dispersive Absorption X-Ray spectroscopy

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