ENGINEERING PROPERTIES OF BENTONITE STABILIZED WITH LIME AND PHOSPHOGYPSUM

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Abstract

Engineering properties such as compaction, unconfined compressive strength, consistency limits, percentage swell, free swell index, the California bearing ratio and the consolidation of bentonite stabilized with lime and phosphogypsum are presented in this paper. The content of the lime and phosphogypsum varied from 0 to 10 %. The results reveal that the dry unit weight and optimum moisture content of bentonite + 8 % lime increased with the addition of 8 % phosphogypsum. The percentage of swell increased and the free swell index decreased with the addition of 8 % phosphogypsum to the bentonite + 8 % lime mix. The unconfined compressive strength of the bentonite + 8 % lime increased with the addition of 8 % phosphogypsum as well as an increase in the curing period up to 14 days. The liquid limit and plastic limit of the bentonite + 8 % lime increased, whereas the plasticity index remained constant with the addition of 8 % phosphogypsum. The California bearing ratio, modulus of subgrade reaction, and secant modulus increased for the bentonite stabilized with lime and phosphogypsum. The coefficient of the consolidation of the bentonite increased with the addition of 8 % lime and no change with the addition of 8 % phosphogypsum.

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1 INTRODUCTION AND BACKGROUND

With the globalization of the Indian economy and an emphasis on the development of its infrastructure, the requirement of materials for earthwork in the construction of bases and sub-grades is increasing day by day. In order to utilize the locally available expansive clays, different treatment techniques have been developed across the world. Indian states such as Rajasthan, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka and Tamil Nadu have adequate deposits of black cotton soil, bentonite, mar and kabar (Ameta et al., 2007). These soils exhibit a high degree of swelling, shrinkage, compressibility and poor strength in contact with water, thereby leading to cracks in the overlying pavements. The best alternative approach is to modify the properties of these soils with some additives such as lime and phosphogypsum to make them suitable for the construction of the overlying pavement. In the present paper, an attempt has been made to study the engineering properties of bentonite stabilized with lime and phosphogypsum (an industrial by-product generated by the phosphoric fertilizer industry), so that it may not cause any serious damage to the overlying pavements.

Many studies are available on the stabilization of expansive soils using lime alone and very limited studies using phosphogypsum in the literature. The content of lime required for stabilizing expansive soil ranges from 2 to 8 % by weight (Chen, 1975). The liquid limit of expansive clay decreases with increases in the lime content (Wang et al, 1963; Bell, 1988). The plastic limit of expansive soil increases

with increases in the lime content (Herrin and Mitchell, 1961). Similar observations were made by Barker et al. (2006). The plasticity index increases with increases in the lime content (Clare and Cruchley, 1957; Prakash et al., 1989; Bell, 1996). The liquid limit, plasticity index and swell potential (4 to 0.2 %) decreases with the addition of 6 % lime (Adam et al, 2012). Mateos (1964) reported that modifications of expansive soil with lime can effectively control any swelling. Similar observations were reported by Bhasin et al. (1978). The optimum moisture content decreases, and the maximum dry unit weight increases with an increase in lime content in expansive soil (Neeraja, 2010). Researchers such as Bell (1996); Rajasekaran and Rao (2000); Consoli et al. (2011); Rogers et al. (2006); and Khattab et al (2007) reported that lime stabilization not only stabilizes expansive soil but also induces cementation due to pozzolanic reactions that lead to increases in strength and long-term performance, whereas researchers such as Hilt and Davidson (1960); Herrin and Mitchell (1961); Bell (1996) and Kumar et al. (2007) have reported that increases in lime content beyond a certain threshold leads to a decrease in strength. Ameta et al, (2007) conducted a study on bentonite mixed with lime and gypsum and reported that the addition of 2 % lime + 4 % gypsum is adequate for reducing the plasticity and swelling of bentonite. Degirmenci et al. (2007) conducted a study on expansive soil stabilized with phosphogypsum and reported a decrease in the plasticity index, an increase in the dry unit weight, a decrease in the optimum moisture content, and an increase in the unconfined compressive strength with the addition of phosphogypsum. From studying the literature it is evident that engineering properties such as compaction, unconfined compressive strength, consistency limits, the free swell index, swelling pressure, the California bearing ratio, and the consolidation of bentonite stabilized with lime and phosphogypsum has not been studied extensively. The present study is trying to fill this gap. In the present work, the results of the effect of lime and phosphogypsum on engineering properties such as compaction, unconfined compressive strength, consistency limits, the free swell index, the California bearing ratio and the consolidation of bentonite are reported.

2 MATERIALS AND METHODS

The bentonite used in this study had a specific gravity, liquid limit, plastic limit, dry unit weight and optimum moisture content of 2.30, 220 % and 39.74 %, 13.95 kN/m³ and 27.98 % respectively. As per the Universal Soil Classification System, the bentonite was classified as a clay of high compressibility. The hydrated lime used in this study was procured from a local market in Hamirpur, Himachal Pradesh, India. The phosphogypsum was procured from Ludhiana, Punjab, India. The specific gravity of the lime and phosphogypsum was 2.37 and 2.20 respectively. The content of the lime and phosphogypsum varied from 0 to 10 %. The chemical composition provided by the manufacturer indicates that the phosphogypsum contains 92 − 95 % $CaSO_4$.

The standard proctor compaction tests were conducted as per IS 2720-Part-VII (1980) on the bentonite-lime and bentonite-lime-phosphogypsum mixtures by varying the content of the lime and phosphogypsum from 2 to 10 % and 0.5 to 10 % respectively, and water was added as needed to facilitate the mixing and compaction process. For the unconfined compressive strength tests, a metallic mould having a size 38 mm inner diameter that was 76 mm long, with additional detachable collars at both ends was used to prepare the cylindrical specimens. The required quantity of bentonite, lime and phosphogypsum was mixed, and water corresponding to the optimum moisture content was added; the mix was placed inside the mould. To ensure uniform compaction, the specimen was compressed statically from both ends till the specimen just reached the height of 76 mm. Then the specimen was extracted with a hydraulic jack and placed in airtight polythene bags, which were placed inside a 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. The strain rate of 1.2 mm/min was chosen for the unconfined compressive strength test, which is basically an undrained test. Smaller strain rates are desirable for the drained tests (triaxial tests) on clay. The unconfined compressive strength tests were conducted as per IS 2720-Part-X (1991).

The liquid limit and plastic limit tests were conducted using the percussion method and thread rolling method respectively. The sample was prepared by mixing together the required quantities of bentonite, lime and phosphogypsum; tap water was added to make a slurry of a uniform consistency. The liquid limit and plastic limit tests were conducted as per IS 2720-Part-V (1985). The consolidation test was carried out in a conventional oedometer apparatus for the determination of the coefficient of the consolidation of the bentonite-lime-phosphogypsum mixtures. From the dry unit weight of the bentonite-lime-phosphogypsum mixtures and the known volume of the consolidation ring, the required oven-dry quantity of bentonite was calculated. Then the required quantity of the lime and phosphogypsum was added to the bentonite. Water corresponding to the optimum moisture content was added to the bentonite-lime-phosphogypsum mixtures. The mix was divided into three parts and compacted using a rubber tamper in a consolidation ring with a 60 mm internal diameter that was 25.9 mm in height in three layers. Care was taken for the oedometer to be away from any machine as vibrations or any kind of human movements would affect the results. The specimen in the consolidation ring was allowed to saturate for five days under a surcharge load of 5 kPa prior to the consolidation test. The consolidation tests were conducted as per IS 2720-Part-XV (1986). For the swell potential test, the specimen was prepared in a conventional oedometer in a similar way as for the consolidation test, and a seating load of 3.89 kPa was applied. The oedometer was then placed in a container containing water and was allowed to swell for 15 days. The swelling was measured over time. A free swell test was conducted as per the procedure reported in IS 2720-Part-XL (1977) using a 100 cc graduated glass jar with distilled water in one jar and kerosene in the other jar. About 15 g of the bentonite was mixed in the distilled water and stirred thoroughly before pouring the mix in the jar; it was allowed to swell. The observations were recorded after 24 hours from the start of the test.

For the CBR tests on the bentonite-lime-phosphogypsum mixture, a thin layer of grease was applied to the internal surfaces of the CBR mould in an attempt to minimize the side friction. The bentonite-lime-phosphogypsum was compacted on the top of the CBR mould (a rigid metal cylinder with an inside diameter of 152 mm and a height of 178 mm) at a respective optimum moisture content by the standard procedure by giving 56 blows of a 25.5 N rammer dropped from a distance of 310 mm. A manual loading machine equipped with a movable base that traveled at a uniform rate of 1.2 mm/min and a calibrated load-indicating device was used to force the penetration piston of a diameter of 50 mm into the specimen. A surcharge plate of 2.44 kPa was placed on the specimen prior to testing. The loads were carefully recorded as a function of the penetration up to a total penetration of 12.5 mm. The California bearing ratio tests were conducted as per IS 2720-Part-XVI (1987).

3 RESULTS

3.1 Compaction

The dry unit weight and moisture content curves for the bentonite with varying percentages of lime are shown in Fig. 1(a). The study in Fig. 1 (a) reveals that the maximum dry unit weight for the bentonite decreased with the addition of lime. The decrease in the dry
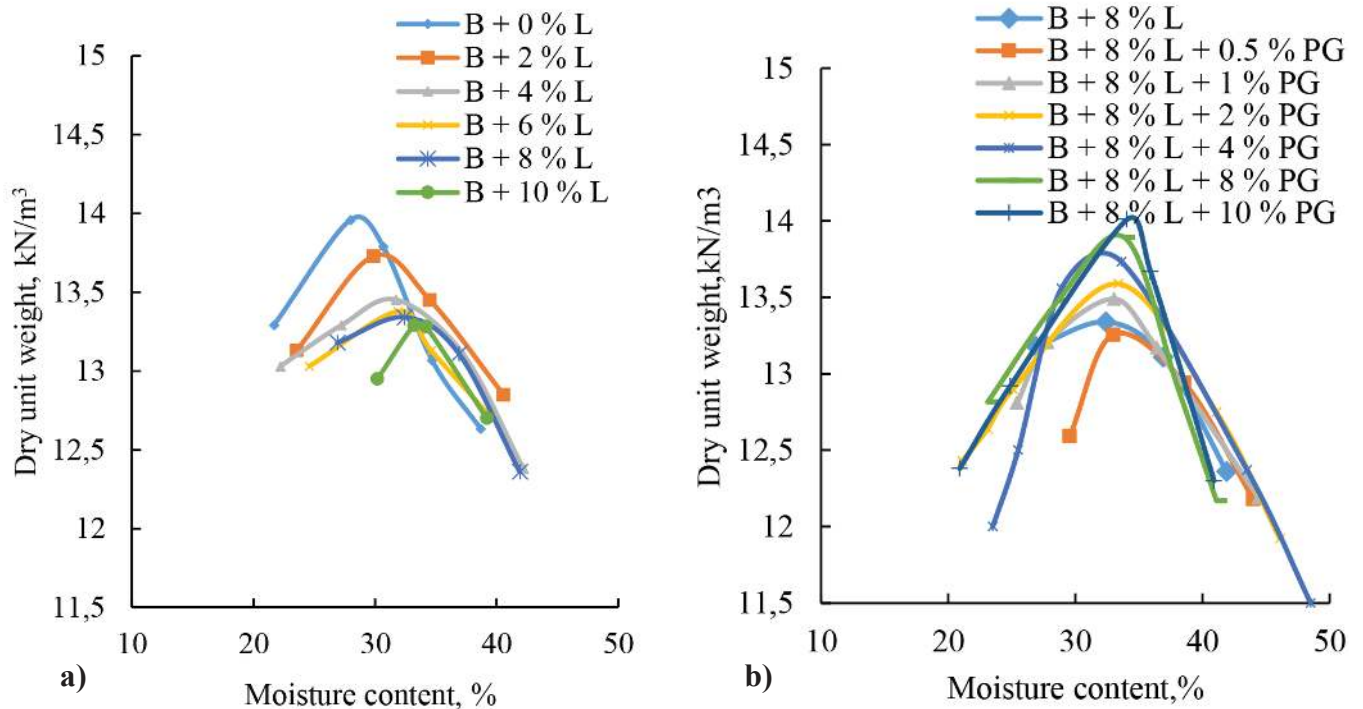
Fig. 1 *Compaction curves for (a) bentonite with varying percentages of lime (b) bentonite + 8 % lime with varying percentages of phosphogypsum.*

unit weight is attributed to the fact that lime reacts quickly with the bentonite resulting in a Base Exchange aggregation and flocculation, which leads to an increase in the void ratio of the mixture and leads to a decrease in the dry unit weight of the bentonite-lime mixture.

These observations are in agreement with Kumar et al. (2007) and Rao and Rao (2004). The study in Fig. 1 (a) further reveals that the optimum moisture content of the bentonite increased with the addition of lime. This increase in the optimum moisture content is at-

tributed to the fact that the additional water was held within the flocs resulting from the flocculation due to the lime reaction. These observations are in agreement with Kumar et al. (2007) and Rao and Rao (2004). In order to decide the optimum mix of the bentonite and lime, it was decided to conduct unconfined compressive strength tests. A similar procedure was adopted by Kumar et al. (2007) for fixing the optimum mix with lime. The unconfined compressive strength of the bentonite cured for 3 days was 154.25 kPa, which increased to 248.25
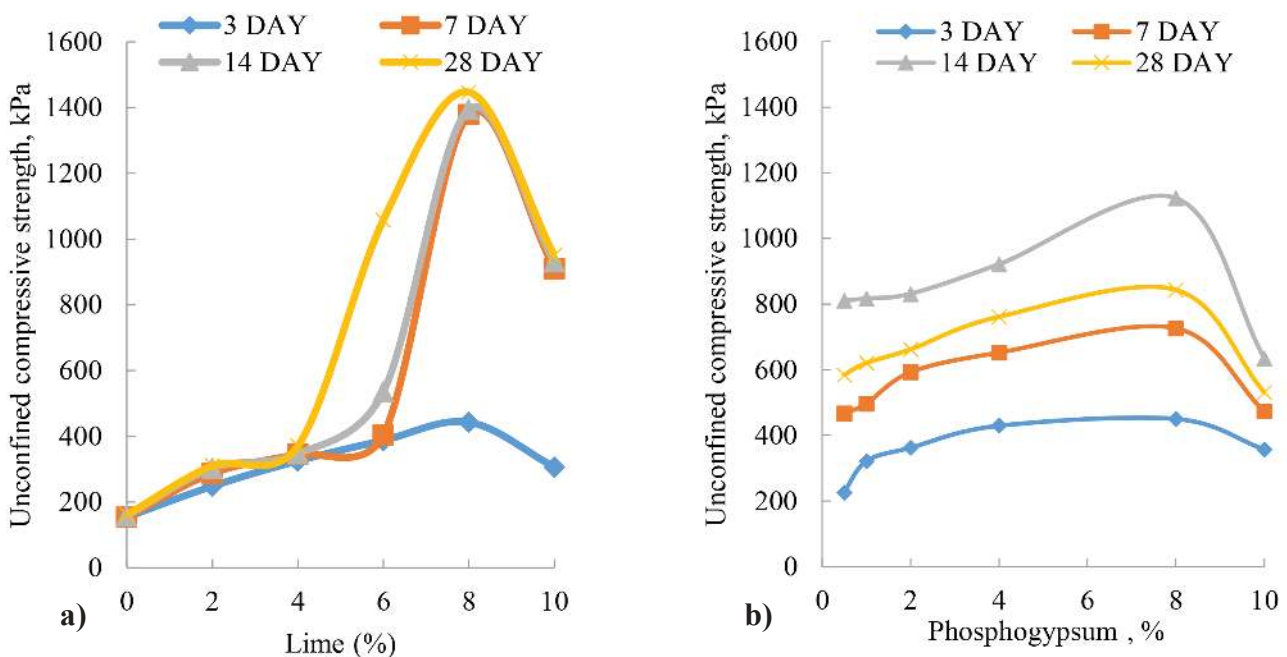

Fig. 2 *Variations of the unconfined compressive strength of (a) bentonite with varying percentages of lime and curing periods (b) bentonite+8% lime with varying percentages of phosphogypsum and curing periods.*
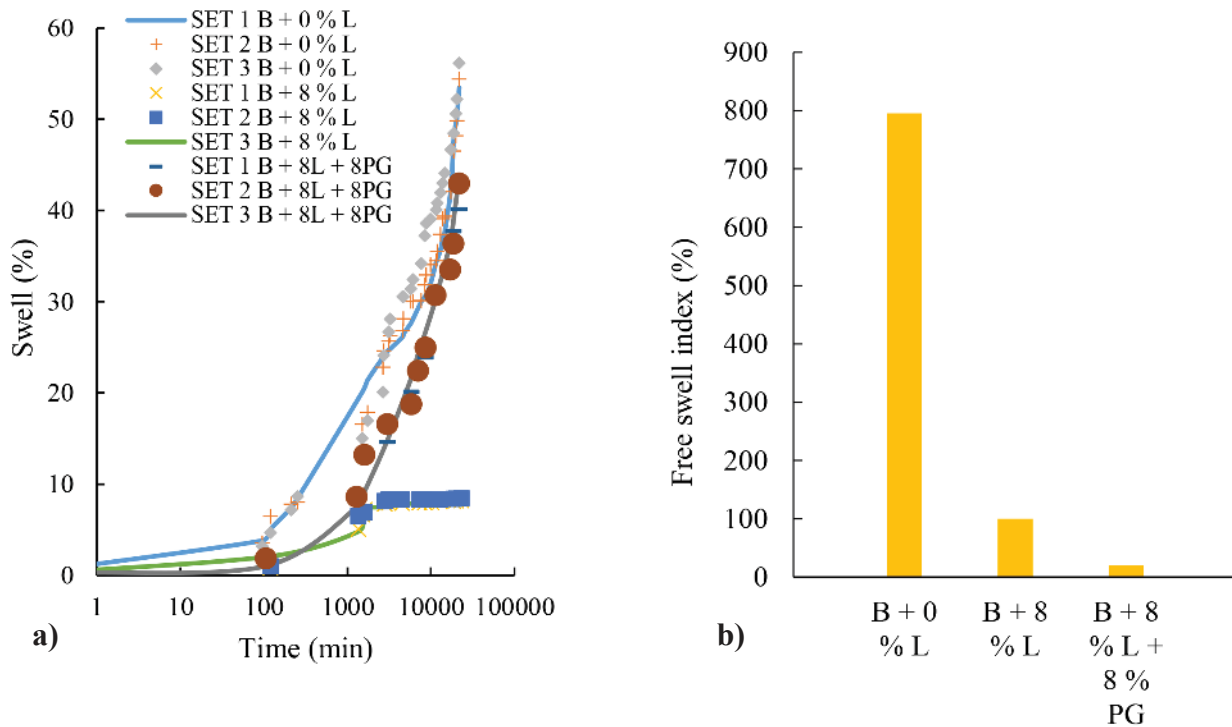
Fig. 3 *Variation of (a) the percentage swell over time (b) free swell index for the mixes.*

kPa, 325.25 kPa, 387.47 kPa, and 442.77 kPa with the addition of 2, 4, 6 and 8 % lime and decreased to 306.54 kPa with the addition of 10 % lime in the same curing period. A similar trend was observed for other curing periods of 7, 14 and 28 days, and the results are shown in Fig. 2 (a). Therefore, on the basis of the results shown in Fig. 2 (a), a mix of bentonite + 8 % lime was chosen for studying the compaction behaviour by varying the content of the phosphogypsum. The results of the dry unit weight and moisture content for the bentonite + 8 % lime with varying percentages of phosphogypsum are shown in Fig. 1(b). The study in Fig. 1 (b) reveals that the maximum dry unit weight for the bentonite + 8 % lime increased with the addition of phosphogypsum. The increase in the dry unit weight is attributed to the fact that the phosphogypsum fills up the void spaces left out after the quick reaction of the bentonite with the lime, resulting in the Base Exchange aggregation and flocculation. The study in Fig. 1 (b) further reveals that the optimum moisture content of the bentonite + 8 % lime increased with the addition of the phosphogypsum. The effect of the addition of the phosphogypsum to the bentonite + 8 % lime is to produce a greater maximum dry unit weight and optimum moisture content. These observations are in agreement with Wild et al. (1996), where gypsum was added to the expansive clay. Thus from the above discussion, it is concluded that the dry unit weight and optimum moisture content of bentonite + 8 % lime increased with the addition of 8 % phosphogypsum.

In order to decide on the optimum mix of bentonite-lime-phos-phogypsum, it was decided to conduct unconfined compressive strength tests. A similar procedure was adopted by Kumar et al. (2007) for fixing the optimum mix with lime. The unconfined compressive strength of the bentonite + 8 % lime cured for 3 days was 442.77 kPa, which changed to 225.15 kPa, 321.67 kPa, 362.53 kPa, 429.19 kPa, and 450.24kPa with the addition of 0.5, 1, 2, 4 and 8 % phosphogypsum and decreased to 357.65 kPa with the addition of 10 % phosphogypsum in the same curing period. A similar trend was observed for other curing periods of 7, 14 and 28 days, and the results are shown in Fig. 2 (b). Therefore, on the basis of the results shown in Fig. 2 (b), a reference mix of bentonite + 8 % lime + 8 % phospho-gypsum was chosen for further study.

3.2 The Swell Potential and Free Swell Index

The results of the swell potential (percentage swell expressed as an increase in the percentage of the specimen's height) of a later-ally-confined soaked specimen compacted at a maximum dry unit weight, at an optimum moisture content, under a surcharge pressure of 3.89 kPa, and a free swell index are presented in Figs. 3(a) and 3(b) for the mixes. Fig. 3(a) also contains the results of a larger size oedometer (SET-2 with a 70-mm diameter and a sample height of 26 mm and SET-3 with a 99.5 mm diameter and a sample height of 26.3 mm). The percentage swell for 15 days' duration and the free

Tab. 1 *Summary of the percentage swell for 15 days' duration.*

MIXES	PERCENTAGE SWELL					FREE SWELL INDEX (%)
	SET 1	SET 2	SET 3	Std. Deviation	Std. Error Mean	
B + 0 % L	53.46	54.39	56.15	1.57367	0.90856	795.45
B + 8 % L	8.18	8.44	8.77	0.29557	0.17065	100
B + 8 % L + 8 % PG	40.16	42.97	41.35	1.40622	0.81188	72.5

swell index for all the mixes are shown in Tab. 1. Tab. 1 reveals that the percentage swell and free swell index of the bentonite decreased with the addition of 8 % lime. The decrease in the percentage swell and free swell index due to the addition of 8 % lime is attributed to the fact that bentonite cations are substituted for by calcium, leading to the formation of calcium silicate and aluminate hydrates. The decreased affinity for water of the Ca-saturated bentonite and the formation of a cementitious matrix resists swelling and thus decreases the percentage swell and free swell index. The percentage swell and free swell index of the bentonite + 8 % lime increased with the addition of 8 % phosphogypsum. The increase in the percentage swell of the bentonite + 8 % lime with the addition of the 8 % phosphogypsum is attributed to the fact that the ettringite crystals nucleate and grow on the surface of the bentonite plates, within a colloidal calcium silicate and aluminate hydrates product, leading to an increase in the percentage of the swell. The decrease in the free swell index of the bentonite + 8 % lime with the addition of the 8 % phosphogypsum is attributed to the fact that the cementing effect of the reaction products of the bentonite-lime-phosphogypsum binds the clay particles together and leads to a decrease in the free swell index.

3.3 Consistency limits and the Coefficient of Consolidation

The variation of the liquid limit, plastic limit, and plasticity index for the various mixes studied is shown in Fig. 4(a). Fig. 4(a) reveals that the liquid limit of the bentonite decreased with the addition of the 8 % lime. A further examination of Fig. 4(a) reveals that the liquid limit of the bentonite + 8 % lime mix increased with the addition of the 8 % phosphogypsum. Fig. 4(a) reveals that the plastic limit of the bentonite increased with the addition of the 8 % lime, and the plastic limit further increases when the 8 % phosphogypsum is mixed with the bentonite + 8 % lime. Fig. 4(a) further reveals that the plasticity index of the bentonite decreased with the addition of the 8 % lime. The decrease in the plasticity index of the bentonite with the addition of the 8 % lime is attributed to the increasingly granular nature of the bentonite with the lime. These observations are in agreement with Abdelmadjid and Muzahim (2008), where the effect of hydrated lime on the engineering behavior and microstructure of highly expansive clay were studied. The plasticity index of the bentonite + 8 % lime mix marginally decreases with the addition of the 8 % phosphogyp-

sum, which means that the addition of the phosphogypsum makes the bentonite + 8 % lime mix more granular, and the same is reflected in the marginal decrease in the plasticity index. The change in the plasticity index is within the experimental error and, for all practical purposes it is concluded that there is no change in the plasticity index with the addition of the 8 % phosphogypsum to the bentonite + 8 % lime mix. The coefficient of consolidation for the mixes studied is shown in Fig. 4(b). Fig. 4(b) reveals that the coefficient of consolidation of the bentonite was 0.10 cm/min, which increased to 0.125 cm/min when the bentonite was mixed with the 8 % lime. The increase in the coefficient of consolidation of the bentonite with the addition of 8 % lime is attributed to the increasingly granular nature of the bentonite with the lime resulting in higher porosity and an increase in the coefficient of consolidation. There was no change in the coefficient of consolidation of the bentonite + 8 % lime mix with the addition of the 8 % phosphogypsum. This is attributed to the fact that the phosphogypsum fills up the void spaces left out after the quick reaction of the bentonite with lime resulting in the Base Exchange aggregation and flocculation, which led to no changes in the coefficient of the consolidation of the mixture.

3.4 Unconfined Compressive Strength

The axial stress-strain curve of the bentonite with varying percentages of lime and cured for 3, 7, 14 and 28 days respectively is shown in Fig. 5. Fig. 5 also contains the axial stress-strain curves for the bentonite cured for 3, 7, 14 and 28 days respectively. Figs. 5 (a) to (d) reveal that the axial stress at the failure of the bentonite does not improve appreciably with an increase in the curing period. The improvement in the unconfined compressive strength with the curing period is within the experimental error. Hence, for all practical purposes it is concluded that there is no change in the unconfined compressive strength of the bentonite with the curing period. A further examination of Figs. 5 (a) to (d) reveals that the axial stress at failure increased with the increase in the curing period. The increase in the axial stress at failure with the curing period is attributed to the pozzolanic reactions of the lime with the bentonite, leading to an increase in the axial stress at failure. A similar trend of an increase in axial stress at failure was observed for a lime content of 4, 6, 8 and 10 %. A close examination of Figs. 5(a) to (d) reveals that the axial stress at failure increased with the increase in lime content up to a content of 8 %;
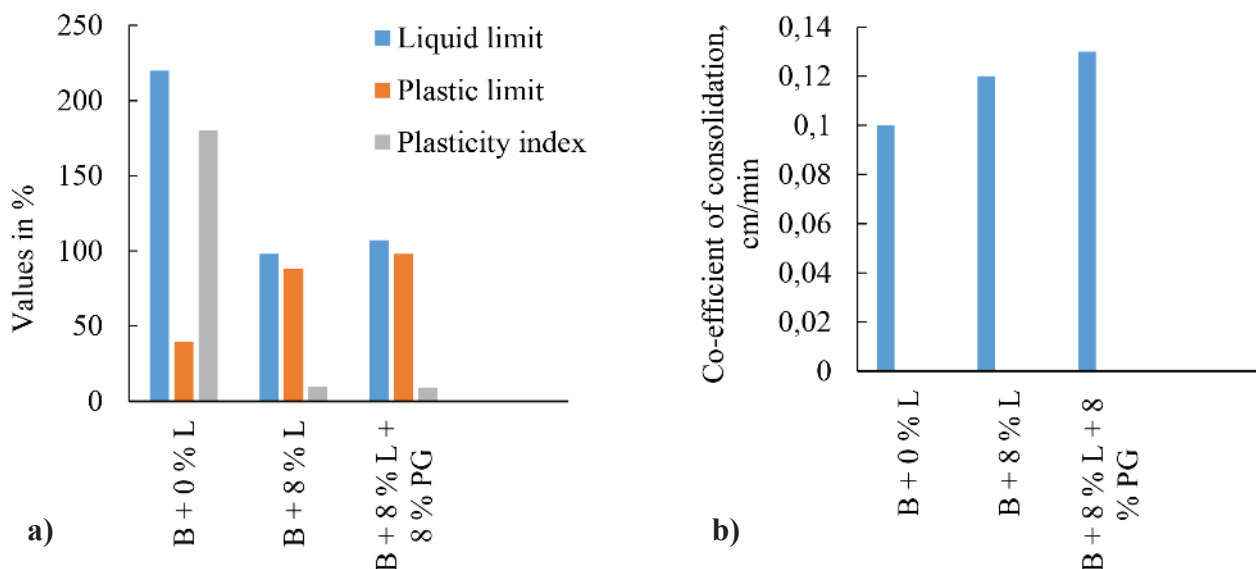

Fig. 4 *Variation of the (a) consistency limits (b) coefficient of consolidation for the mixes.*
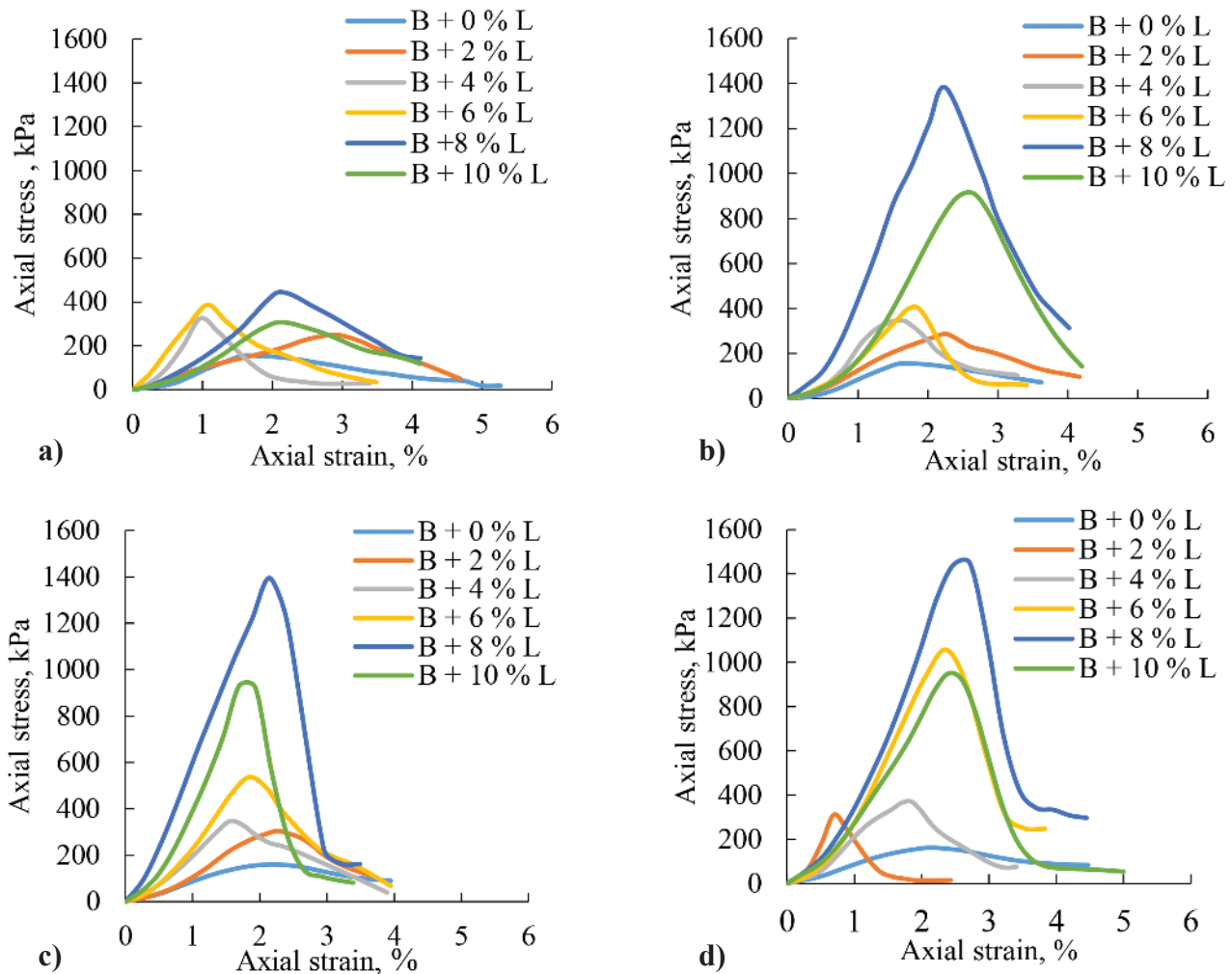
Fig. 5 *Variations of axial stress for bentonite mixed with varying percentages of lime at (a) 3 days (b) 7 days (c) 14 days (d) 28 days.*

thereafter, the trends were reversed. The decrease in the axial stress at failure beyond a lime content of 8 % is attributed to the platy shapes of the unreacted lime particles in bentonite. These observations are in agreement with the earlier study reported by Kumar et al. (2007). A similar trend of an increase in the axial stress at failure was observed for the other curing periods of 7, 14 and 28 days as is evident from Figs. 5(a) to (d). The axial stress-strain curve of the bentonite + 8 % lime mixture with varying percentages of phosphogypsum and cured for 3, 7, 14 and 28 days respectively is shown in Fig. 6. Fig. 6 also contains the axial stress-strain curves for the bentonite and bentonite + 8 % lime mixture cured for 3, 7, 14 and 28 days respectively. Figs. 6(a) to (d) reveal that the axial stress at failure increased with the increase in the curing period up to 14 days. The increase in the axial stress at failure with the curing period is attributed to the acceleration in the pozzolanic reactions of the lime with the bentonite in the presence of phosphogypsum, leading to an increase in the axial stress at failure.

A close examination of Figs. 6(a) to (d) reveals that the axial stress at failure increased with the increase in the phosphogypsum content up to 8 %. Beyond this content there was a decrease in the axial stress at failure. The decrease in the axial stress at failure beyond a phosphogypsum content of 8 % is perhaps attributed to the platy shapes of the unreacted lime particles in bentonite, even in the presence of phosphogypsum. Thus from the above discussion it is concluded that the unconfined compressive strength of bentonite does not change with an increase in the curing period. The unconfined

compressive strength of the bentonite + 8 % lime increased with the addition of 8 % phosphogypsum as well as an increase in the curing period up to 14 days. Beyond 8 %, the unconfined compressive strength decreased.

3.5 California Bearing Ratio

The load deformation curve for the bentonite, bentonite + 8 % lime, and bentonite + 8 % lime + 8 % phosphogypsum as obtained from the bearing ratio test is shown in Fig. 7. The variations of the bearing ratio for the bentonite, bentonite + 8 % lime, and bentonite + 8 % lime + 8 % phosphogypsum are shown in Tab. 2.

Tab. 2 *Bearing ratio of the mixes.*

Mixes	CBR (%) at a deformation of	
	2.5 mm	5 mm
B + 0 % L	1.87	1.73
B + 8 % L	8.62	8.92
B + 8 % L + 8 % PG	11.71	11.89

Tab. 2 reveals that the bearing ratio of the bentonite increased with the addition of 8 % lime. This increase in the bearing ratio is
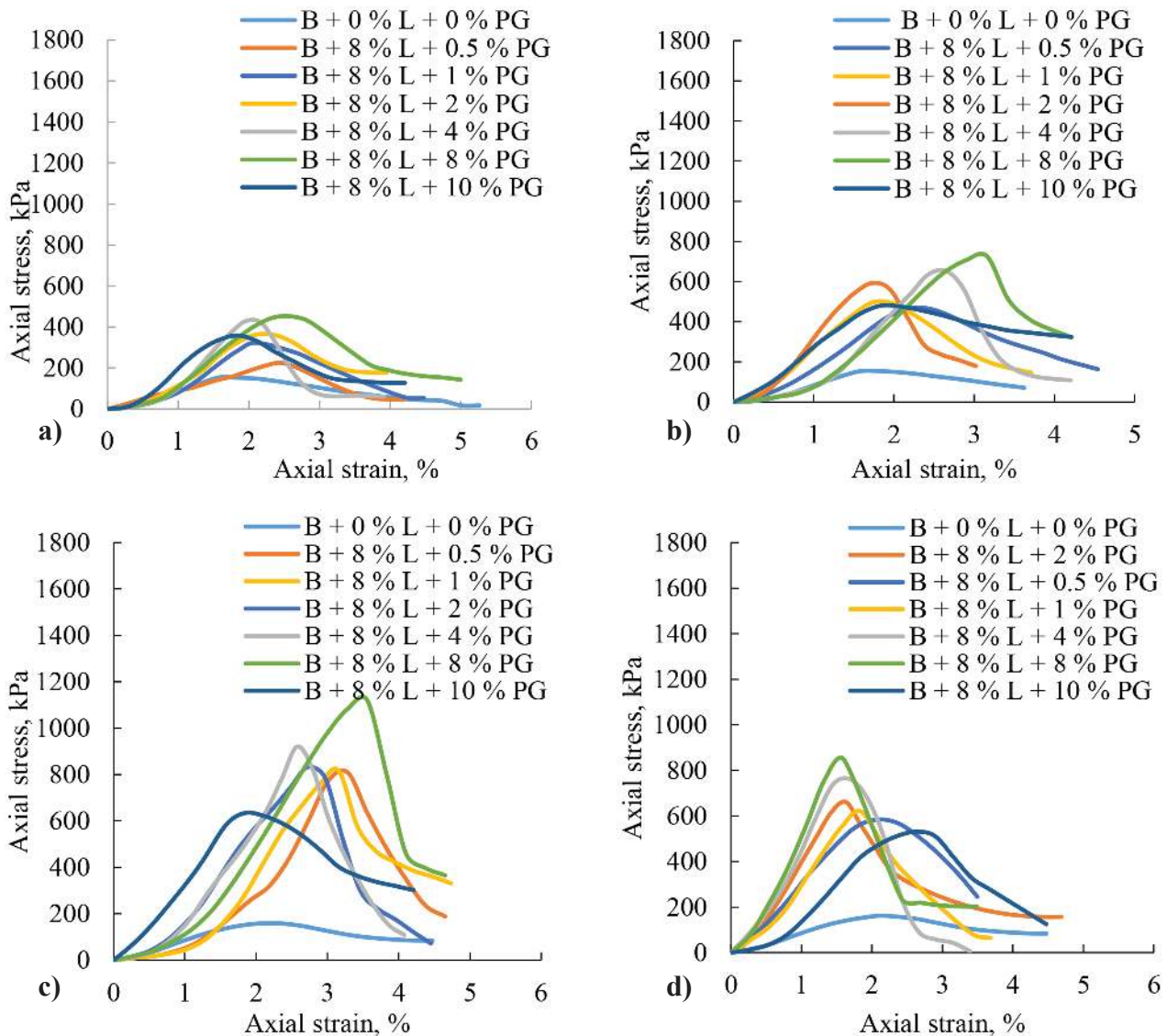
Fig. 6 *Variations of the unconfined compressive strength of bentonite + 8 % lime with varying percentages of phosphogypsum at (a) 3 days (b) 7 days (c) 14 days (d) 28 days.*

attributed to the fact that all the lime is taken up by the bentonite at the early stages, thus modifying the behaviour of the bentonite leading to an increase in the bearing ratio of the mix. The bearing ratio of the bentonite + 8 % lime mix further increases with the addition of the 8 % phosphogypsum. The increase in the bearing ratio of the bentonite + 8 % lime with the addition of 8 % phosphogypsum is attributed to the fact that the phosphogypsum fills up the void spaces left out after the quick reaction of the bentonite with the lime, resulting in the Base Exchange aggregation and flocculation, which leads to an increase in the bearing ratio of the mixture.

3.5.1 Economic Analysis

The modulus of the subgrade reaction is the reaction pressure sustained by a soil sample under a rigid plate of a standard diameter per unit settlement measured at a specified pressure or settlement. The modulus of the subgrade reaction is obtained corresponding to a 1.25 mm penetration from the load penetration curve, and the actual subgrade modulus is obtained after applying a correction for the plate size. The variations of the modulus of the subgrade reaction
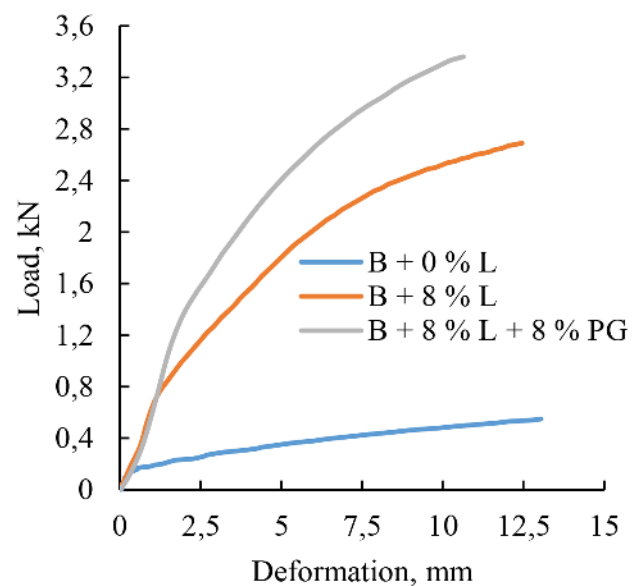
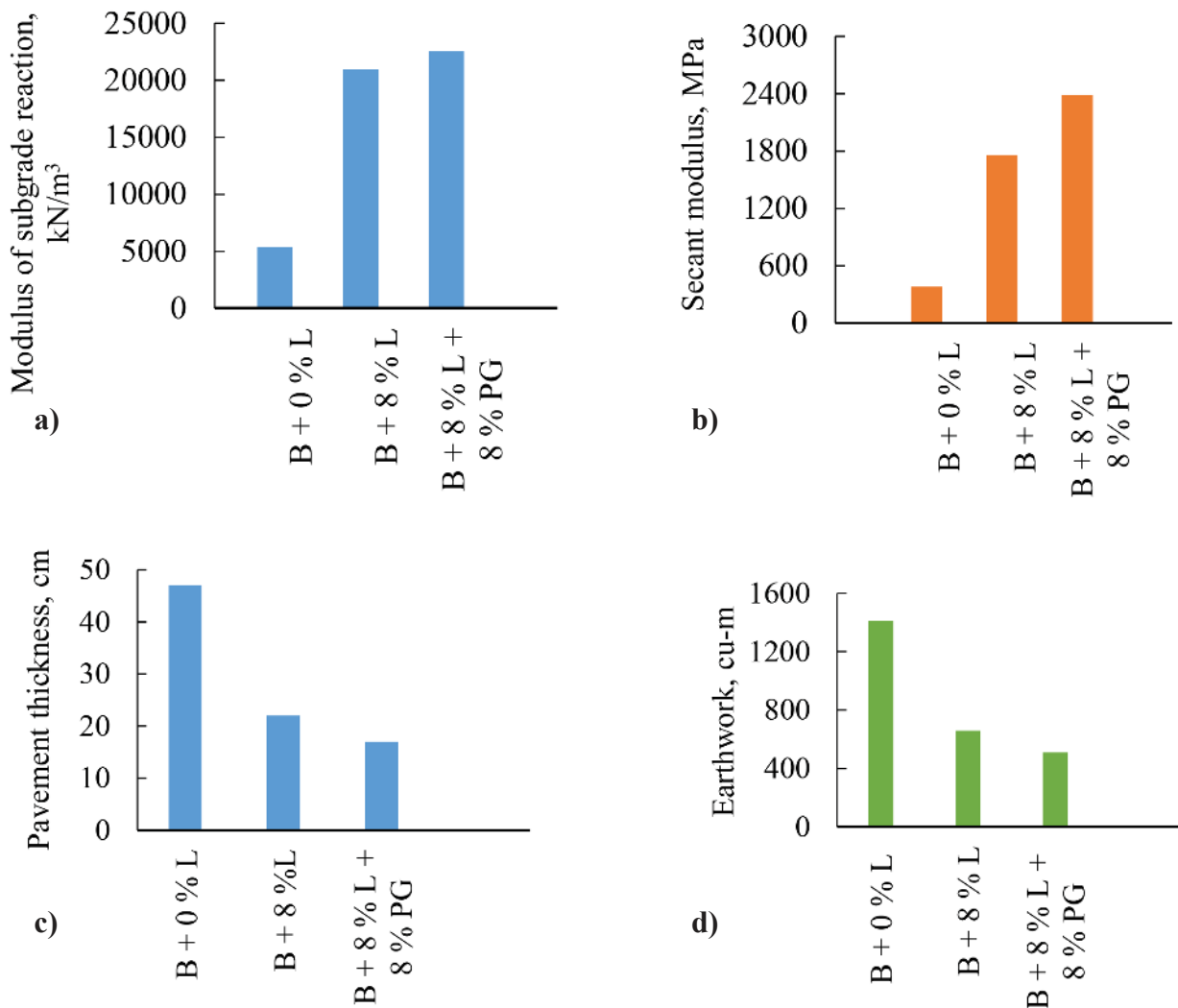**Fig. 7** *Load vs. deformation curves obtained in CBR.*

Fig. 8 *Variations of the (a) modulus of the subgrade reaction (b) secant modulus (c) pavement thickness (d) earthwork of the mixes.*

for the mixes studied is shown in Fig. 8(a). Fig. 8(a) reveals that the modulus of the subgrade reaction of the bentonite was 5378.16 kN/m³, which increased to 20969.17 kN/m³ when the bentonite was mixed with 8 % lime. The modulus of the subgrade reaction of the bentonite + 8 % lime mix further increased to 22544.82 kN/m³ with the addition of the 8 % phosphogypsum. To ascertain the performance of the modified bentonite, the secant modulus corresponding to a penetration of 2.5 mm has been calculated. The secant modulus is obtained from the load deformation curve by dividing the load at a 2.5 mm penetration with the plunger area and the deformation (0.0025m) respectively. The variations of the secant modulus of the bentonite, bentonite + 8 % lime, and bentonite + 8 % lime + 8 % phosphogypsum is shown in Fig. 8(b). The secant modulus for the bentonite was 382.54 MPa, which increased to 1757.00 MPa with the addition of the 8 % lime.

The secant modulus further increased to 2385.54 MPa with the addition of the 8 % phosphogypsum to the bentonite + 8 % lime mix. To check the savings in the bentonite subgrade's thickness, the pavement thickness was calculated using the California bearing ratio design chart (recommended by IRC: 37-2001) for 15-45 commercial vehicles per day exceeding 3 tonnes of laden weight. Curve B was used for this load. The pavement thickness required for subgrade

bentonite stabilized with lime & phosphogypsum is shown in Fig. 8(c). Fig. 8(c) reveals that the pavement thickness requirement for the bentonite was 47 cm, which decreased to 22 cm with the addition of the 8 % lime. The pavement thickness requirement for the bentonite + 8 % lime mix further decreased to 17 cm with the addition of the 8 % phosphogypsum. The savings in material per kilometer length for a village road of a 3 m width for the bentonite stabilized with lime and phosphogypsum is shown in Fig. 8(d). Fig. 8(d) reveals that the earthwork required for the subgrade bentonite was 1410 cum, which decreased to 660 cum when the bentonite was mixed with 8 % lime. The earthwork required for the subgrade bentonite + 8 % lime mix further decreased to 510 cum with the addition of the 8 % phosphogypsum.

4 CONCLUSIONS

An experimental study was carried out to investigate engineering properties such as compaction, unconfined compressive strength, consistency limits, percentage swell, free swell index, California bearing ratio and the consolidation of bentonite stabilized with lime and phosphogypsum. The study resulted in the following conclusions.

1. The dry unit weight and optimum moisture content of the bentonite + 8 % lime increased with the addition of the 8 % phosphogypsum.
2. The percentage swell increased and the free swell index decreased with the addition of the 8 % phosphogypsum to the bentonite + 8 % lime mix.
3. The unconfined compressive strength of the bentonite + 8 % lime increased with the addition of the 8 % phosphogypsum as well as with the increase in the curing period. Beyond a phosphogypsum content of 8 %, the unconfined compressive strength decreased.
4. The liquid limit and plastic limit of the bentonite + 8 % lime increased, whereas the plasticity index remained constant with the addition of the 8 % phosphogypsum.
5. The California bearing ratio, the modulus of the subgrade reaction, and the secant modulus increased for the bentonite stabilized with lime and phosphogypsum. This improved behaviour leads to a reduction in earthwork and the required thickness of subgrade bentonite.

6. The coefficient of consolidation of the bentonite increased with the addition of the 8 % lime, but no change occurred with the addition of the 8 % phosphogypsum.

On the whole, this study has attempted to provide an insight into the compaction, unconfined compressive strength, consistency limits, percentage swell, free swell index, California bearing ratio, and consolidation of bentonite stabilized with lime and phosphogypsum. The improved behaviour of the bentonite-lime-phosphogypsum mixture will boost the construction of pavements on such problematic soils.

5 NOTATION

B = Bentonite
L= Lime
PG = Phosphogypsum

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