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Engineering Properties of Bentonite Stabilized with Lime and Phosphogypsum

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Abstract - **The paper presents the engineering properties such as compaction, unconfined compressive strength, consistency limits, percentage swell, free swell index, California bearing ratio and consolidation of bentonite stabilized with lime and phosphogypsum. The content of lime and phosphogypsum was varied from 0 to 10% to check the improvement in the engineering properties. The results of this study reveal that the dry unit weight and optimum moisture content of bentonite + 8% lime increased with the addition of 8% phosphogypsum. The dry unit weight and optimum moisture content of bentonite + 8% lime increased with the addition of 8% phosphogypsum. The percentage swell increased and 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 increase in curing period up to 14 days. Beyond a phosphogypsum content of 8%, the unconfined compressive strength decreased. The liquid limit and plastic limit of bentonite + 8% lime increased where as the plasticity index remains constant with the addition 8 % phosphogypsum. The California bearing ratio, modulus of subgrade reaction, secant modulus increased for the bentonite stabilized with lime and phosphogypsum. The coefficient of consolidation of bentonite increased with the addition of 8% lime and no change with the addition of 8 % phosphogypsum. The improved behaviour of the bentonite-lime-phosphogypsum mixture will boost the construction of road pavements on such problematic soils.**

Keywords: **Bentonite, Lime, Phosphogypsum, Consistency limits, Compaction, Consolidation, Unconfined compressive strength, CBR, Free swell index**

I. Introduction

With the globalization of Indian economy and emphasis on development of infrastructure, the requirement of materials for the earth work in the construction of the base 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. In India states like Rajasthan, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka and Tamilnadu have adequate deposit of black cotton soil, bentonite, mar and kabar (Ameta *et al*, 2007). These soils exhibit high swelling, shrinkage, compressibility and poor strength in contact with water leading to cracks in overlying pavements. The best alternative approach is to modify the properties of these soils with some additives lime and phosphogypsum to make them suitable for the construction of overlying pavement. In the present paper, an attempt has been made to study the engineering properties of bentonite stabilized with lime and phosphogypsum so that it may not cause any serious damage to the overlying pavements.

II. Background

Many studies are available on stabilization of expansive soils using lime alone and very limited studies with phosphogypsum in literature. The content of lime required stabilizing expansive soils range from 2 to 8 % by weight (Chen, 1975). The liquid limit of expansive clay decreases with the increase in lime content (Wang *et al,* 1963; Bell, 1988). The plastic limit of expansive soils increases with the increase in lime content (Herrin and Mitchell, 1961). Similar observations were made by Barker *et al*. (2006). The plasticity index increases with the increase in lime content (Clare and Cruchley, 1957; Prakash *et al*., 1989; Bell, 1996). The liquid limit, plasticity index and swell potential (4 to 0.2 %) decreased with the addition of 6% lime (Adam *et al*, 2012). Mateos (1964) reported that modifications of expansive soils with lime can effectively control the swelling. Similar observations were reported by Bhasin *et al*. (1978). The optimum moisture content decreased and maximum dry unit weight increased with the increase in lime content in expansive soils (Neeraja, 2010). Researchers like 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 stabilize the expansive soil but also induce cementation due to pozzolanic reactions leading to increase in strength and long-term performance whereas researchers like Hilt and Davidson (1960); Herrin and Mitchell (1961); Bell (1996) and Kumar *et al* (2007) have reported that increase in lime content beyond a threshold leading to decrease in strength. Ameta et al, (2007) conducted the study on bentonite mixed with lime and gypsum and reported that addition of 2% Lime + 4% Gypsum is adequate for reducing the plasticity and swelling of the bentonite. Degirmenci *et al* (2007) conducted a study on expansive soil stabilized with phosphogypsum and reported decrease in plasticity index, increase in dry unit weight, decrease in optimum moisture content and increase in unconfined compressive strength with the addition of phosphogypsum. From the literature study it is evident that the engineering properties such as compaction, unconfined compressive strength, consistency limits, free swell index, swelling pressure, California bearing ratio and consolidation of bentonite stabilized with lime and phosphogypsum has not been studied extensively. The present study tries to fill this gap. In the present work, the results of the effect of lime and phosphogypsum on the engineering properties such as compaction, unconfined compressive strength, consistency limits, free swell index, California bearing ratio and consolidation of bentonite is reported.

III. Material Used and Experimental Procedure

The bentonite used in this study was having a specific gravity, liquid limit, plastic limit, dry unit weight and optimum moisture content 2.30, 220% and 39.74%, 13.95 kN/m^3 and 27.98% respectively. As per Universal Soil Classification System, the clay was classified as clay of high compressibility. Hydrated lime and phosphogypsum used in this study was procured from the local market at Hamirpur, Himachal Pradesh, India. The specific gravity of lime and phosphogypsum was 2.37 and 2.20 respectively. The content of lime and phosphogypsum was varied from 0 to 10 %.

The standard proctor compaction tests were conducted as per IS 2720-Part-VII (1980) on bentonite-lime and bentonite-lime-phosphogypsum mixtures by varying the content of 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 size 38 mm inner diameter and 76 mm long, with additional detachable collars at both ends were used to prepare cylindrical specimens. Required quantity of bentonite, lime and phosphogypsum were mixed and water corresponding to optimum moisture content was added and the mix was 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 IS 2720-Part-X (1991).

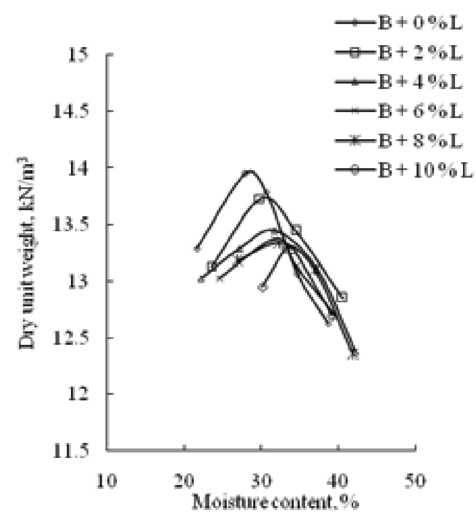
The liquid limit and plastic limit tests were conducted using percussion method and thread rolling method respectively. The sample was prepared by mixing together required quantity of bentonite, lime and phosphogypsum and tap water was added to make slurry of uniform consistency. The liquid limit and plastic limit tests were conducted as per IS 2720-Part-V (1985). The consolidation test was carried out in a conventional odometer apparatus for determination of the coefficient of consolidation of bentonite-lime-phosphogypsum mixtures. From the dry unit weight of bentonite-lime-phosphogypsum mixtures and known volume of consolidation ring, the required oven dry quantity of bentonite was calculated. Then the required quantity of lime and phosphogypsum was added to the bentonite. Water corresponding to 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 the consolidation ring of 60 mm internal diameter and 25.9 mm height in three layers. The specimen in consolidation ring was allowed to saturate for five days under a surcharge load of 5 kPa prior to consolidation test. The consolidation tests were conducted as per IS 2720-Part-XV (1986). The specimen was prepared in the conventional odometer in the similar way as for the consolidation test and was applied a seating load of 3.89 kPa. The odometer was then placed in a container containing water and was allowed to swell for 15 days. Free swell test were conducted as per the procedure reported in IS 2720-Part-XL (1977) using 100 cc graduated glass jar using distilled water in one & kerosene in the other jar. About 15g of bentonite was mixed in distilled water and stirred thoroughly before pouring the mix in the jar and was allowed to swell. The observations were recorded after 24 hours from the start of the test.

For CBR tests on bentonite-lime-phosphogypsum mixture, a thin layer of grease was applied on the internal surfaces of the CBR mould in an attempt to minimize the side friction. The bentonite-lime-phosphogypsum were compacted on the top of the CBR mould (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 25.5N 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 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 penetration up to a total penetration of 12.5 mm. The California bearing ratio tests were conducted as per IS 2720-Part-XVI (1987).

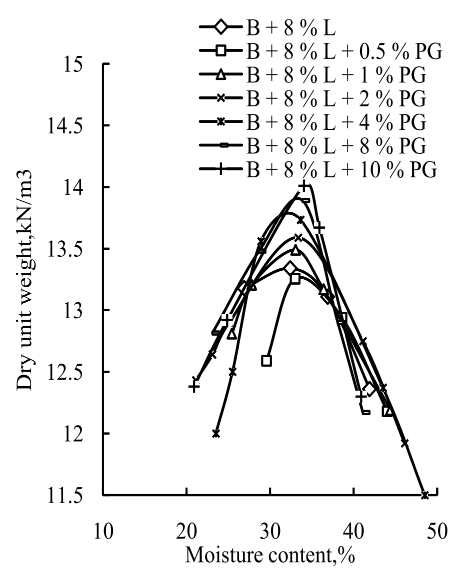
IV. Result

A. Compaction

The dry unit weight and moisture content curves for bentonite with varying percentages of lime are shown in the Fig. 1(a).



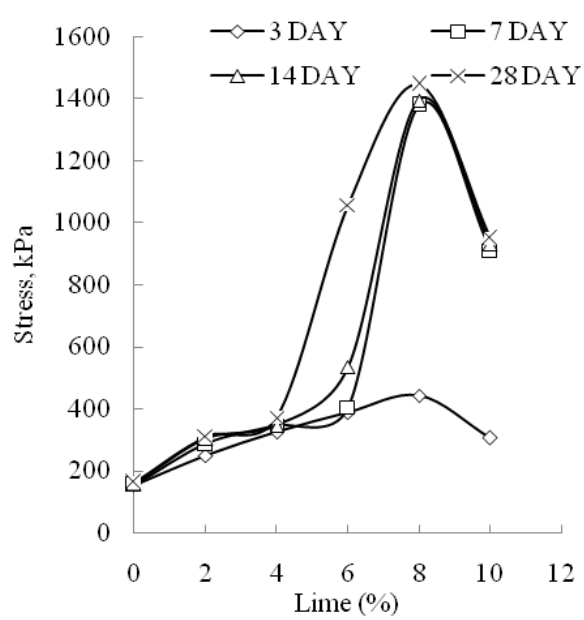
(a)



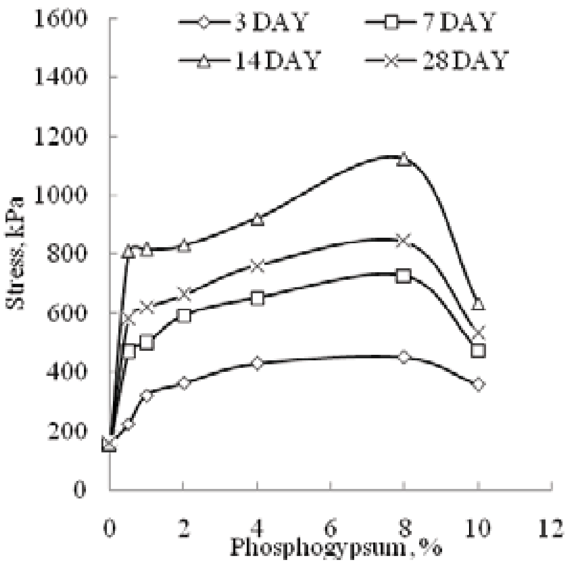
(b)

Fig.1. Compaction curves for (a) bentonite with varying percentage of lime (b) bentonite + 8 % lime with varying percentage of phosphogypsum

The study of Fig. 1 (a) reveals that the maximum dry unit weight for the bentonite was 13.95 kN/m^3 which decreased to 13.72 kN/m^3, 13.45 kN/m^3, 13.37 kN/m^3, 13.34 kN/m^3 and 13.29 kN/m^3 respectively with the addition of 2, 4, 6, 8 and 10 % lime. The decrease in dry unit weight is attributed to the fact that lime reacts quickly with bentonite resulting Base Exchange aggregation and flocculation which leads to increase in void ratio of the mixture leading to 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). Study of Fig. 1 (a) further reveals that the optimum moisture content of the bentonite 27.98 % which increased to 29.88 %, 31.71 %, 31.90 %, 32.40 % and 33.20 % respectively with the addition of 2, 4, 6, 8 and 10 % lime. This increase in optimum moisture content is attributed to the fact that additional water held within the flocs resulting from flocculation due to 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 bentonite and lime, it was decided to conduct unconfined compressive strength tests. 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 kPa, 325.25 kPa, 387.47 kPa, 442.77 kPa with the addition of 2, 4, 6, 8 % lime and decreased to 306.54 kPa with the addition of 10 % lime 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. 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 phosphogypsum. The results of dry unit weight and moisture content for bentonite + 8% lime with varying percentages of phosphogypsum are shown in the Fig. 1(b). The study of Fig. 1 (b) reveals that the maximum dry unit weight for the bentonite + 8% lime was 13.34 kN/m^3 which increased to 13.41 kN/m^3, 13.49 kN/m^3, 13.59 kN/m^3, 13.72 kN/m^3, 13.89 kN/m^3 and 14.01 kN/m^3 respectively with the addition of 0.5, 1, 2, 4, 8 and 10 % phosphogypsum. The increase in dry unit weight is attributed to the fact that the phosphogypsum fills up the void spaces left out after quick reaction of bentonite with lime resulting Base Exchange aggregation and flocculation. Study of Fig. 1 (b) further reveals that the optimum moisture content of the bentonite + 8 % lime was 32.40 % which increased to 32.98%, 33.05%, 33.38%, 33.65%, 33.89% and 34.05% respectively with the addition of 0.5, 1, 2, 4, 8 and 10% phosphogypsum. The effect of addition of 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). 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 the optimum mix of bentonite-lime-phosphogypsum, it was decided to conduct unconfined compressive strength tests. 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, 450.24kPa with the addition of 0.5, 1, 2, 4, 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. 2 (b). Therefore on the basis of the results shown in Fig. 2 (b), a reference mix of bentonite + 8% lime + 8% phosphogypsum was chosen for further study.



(a)



(b)

Fig. 2.Variation of unconfined compressive strength of (a) bentonite with varying percentage of lime and curing period (b) bentonite+8% lime with varying percentage of phosphogypsum and curing period

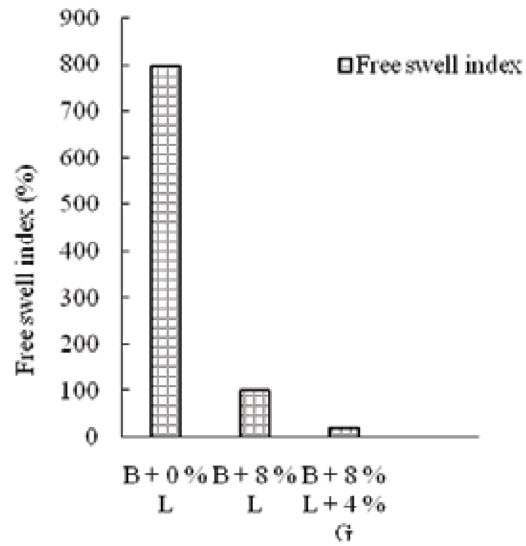


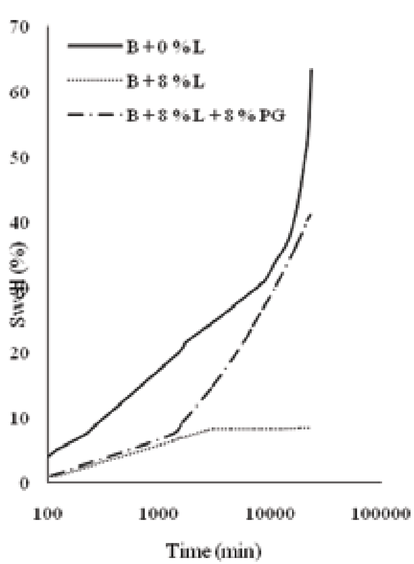
Fig. 3 Variation of (a) percentage swell with time (b) free swell index for the mixes

TABLE I SUMMARY OF PERCENTAGE SWELL FOR 15 DAYS DURATION

Mixes	Percentage swell	Free swell index (%)
B + 0 % L	53.42	795.45
B + 8 % L	8.44	100
B + 8 % L + 8 % PG	39.84	72.5

B. Swell Potential and Free Swell Index

The results of swell potential (percentage swell (expressed as a percentage increase in specimen height) of a laterally confined soaked specimen compacted at maximum dry unit weight at optimum moisture content and under a surcharge pressure of 3.89 kPa) and free swell index are presented in Fig. 3(a) and Fig. 3(b) for the mixes. The percentage swells for 15 days duration and free swell index for all the mixes is shown in Table I.

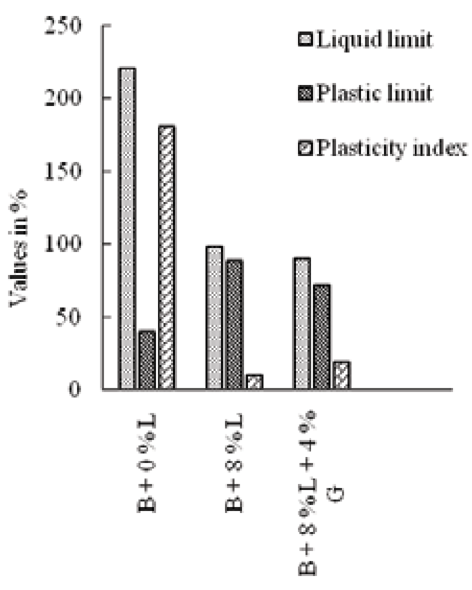


Study of Table I reveals that the percentage swell and free swell index of the bentonite is decreased with the addition of 8% lime. For example, the percentage swell and free swell index of the bentonite was 53.42% and 795.45% respectively which decreased to 8.44% and 100% with the addition of 8% lime. The decrease in percentage swell and free swell index due to addition of 8% lime is attributed to the fact that bentonite cations are substituted by calcium leading to 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 to 39.84% and decreased to 72.5% with the addition of 8% phosphogypsum. The increase in percentage swell of bentonite + 8% lime with the addition of 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 increase in percentage swell. The decrease in free swell index of bentonite + 8% lime with the addition of 8% phosphogypsum is attributed to the fact that the cementing effect of the reaction products of bentonite-lime-phosphogypsum binds the clay particles together leading to decrease in free swell index. Thus from the above discussion it is concluded that the percentage swell increased and free swell index decreased with the addition of 8 % phosphogypsum to the bentonite + 8% lime mix.

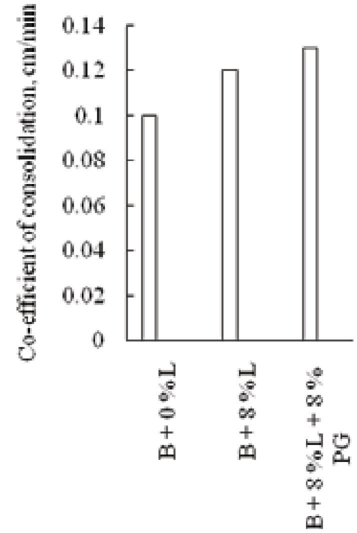
C. Consistency limits and Coefficient of Consolidation

The variation of liquid limit and plastic limit for the mixes studied is shown in Fig. 4(a). A study of Fig. 4(a) reveals that the liquid limit and plastic limit of the bentonite was 220 % and 39.74 % respectively which decreased to 98.04 % and increased to 88.20 % respectively when the bentonite is mixed with 8 % lime. The decrease in the liquid limit with the addition of lime was attributed to the fact that release of Ca^+ ions into the pore fluid increases the electrolyte concentration of pore water leading to decrease in the thickness of diffuse double layer around the bentonite particles and ultimately the liquid limit. Similar observations were reported by Dash and Hussain (2012).

The increase in plastic limit with the addition of 8 % lime content is attributed to the fact that flocculated fabric resulted from lime stabilization requires more water for thread formation leading to increase in plastic limit. Abdelmadjid and Muzahim (2008) also observed the increase in plastic limit with the addition of lime in expansive soil. The liquid limit and plastic limit of the bentonite + 8% lime mix increased to 107.04% and 97.98% respectively with the addition of 8% phosphogypsum. Fig. 4(a) further reveals that the plasticity index of the bentonite was 180.26% which decreased to 9.84% when the bentonite is mixed with 8 % lime. The decrease in plasticity index of bentonite with the addition of 8% lime is attributed to the increasingly granular nature of the bentonite with lime. These observations are in agreement with Abdelmadjid and Muzahim (2008). The plasticity index of the bentonite + 8% lime mix marginally decreased to 9.06% with the addition of 8% phosphogypsum which means that the addition of phosphogypsum makes the bentonite + 8% lime mix more granular and the same is reflected in the marginal decrease in plasticity index. The change in plasticity index is with the experimental error and for all practical purposes it concluded that there is no change in the plasticity index with the addition of 8% phosphogypsum to bentonite + 8% lime mix. The coefficient of consolidation for the mixes studied is shown in Fig. 4(b). A study of 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 is mixed with 8% lime. The increase in coefficient of consolidation of bentonite with the addition of 8% lime is attributed to the increasingly granular nature of the bentonite with lime resulting higher porosity and increase in coefficient of consolidation. There was no change in



(a)

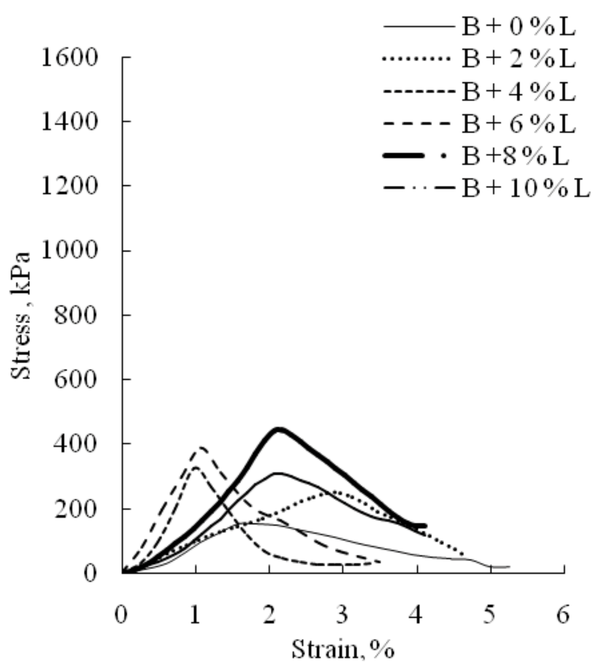


(b)

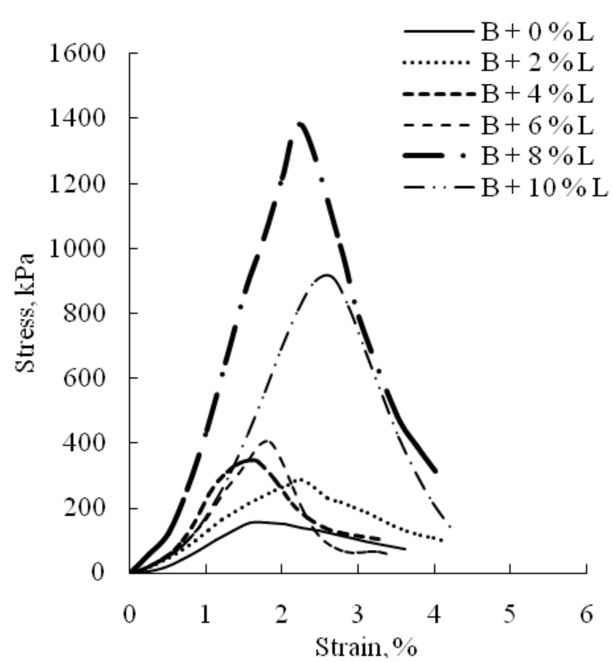
Fig. 4 Variation of (a) consistency limits (b) coefficient of consolidation for the mixes coefficient of consolidation of the bentonite + 8% lime mix with the addition of 8% phosphogypsum. This is attributed to the fact that the phosphogypsum fills up the void spaces left out after quick reaction of bentonite with lime resulting Base Exchange aggregation and flocculation leading to no change in the coefficient of consolidation of the mixture. Thus from the above discussion it can be concluded that the coefficient of consolidation of bentonite increased with the addition of 8% lime and no change with the addition of 8% phosphogypsum.

D. Unconfined Compressive Strength

The axial stress-strain curve of the bentonite with varying percentage of lime and cured for 3, 7, 14, 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. Study of Fig. 5 (a) to (d) reveals that the axial stress at failure of the bentonite does not improve appreciably with the increase in curing period. For example, the axial stress at failure of the bentonite cured for 3 days was 154.25 kPa which marginally increased to 154.263 kPa, 158.89 kPa and 162.03 kPa respectively after 7, 14 and 28 days of curing. The improvement in unconfined compressive strength with 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. Further examination of Fig. 5 (a) to (d) reveals that the axial stress at failure increased with the increase in curing period. For example, for the bentonite + 2% lime mix cured for 3 days, the axial stress at failure was 248.25 kPa which increased to 287.51 kPa, 303.60 kPa and 311.01 kPa with the increase in curing period to 7, 14 and 28 days respectively. The increase in axial stress at failure with the curing period is attributed to the pozzolanic reactions of lime with the bentonite leading to increase in axial stress at failure. Similar trend of increase in axial stress at failure was observed for a lime content of 4, 6, 8 and 10%. A close examination of Fig. 5 (a) to (d) reveals that the axial stress at failure increased with the increase in lime content up to a content of 8%. For example, for the bentonite + 2% lime mix cured for 3 days, the axial stress at failure was 248.25 kPa which increased to 325.25 kPa, 387.47 kPa, 442.47 kPa and decreased to 311.01 kPa with the increase in lime content to 4, 6, 8 and 10 % respectively. The decrease in 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). Similar trend of increase in axial stress at failure was observed for other curing periods of 7, 14 and 28 days as evident from Fig. 5 (a) to (d).



(a)



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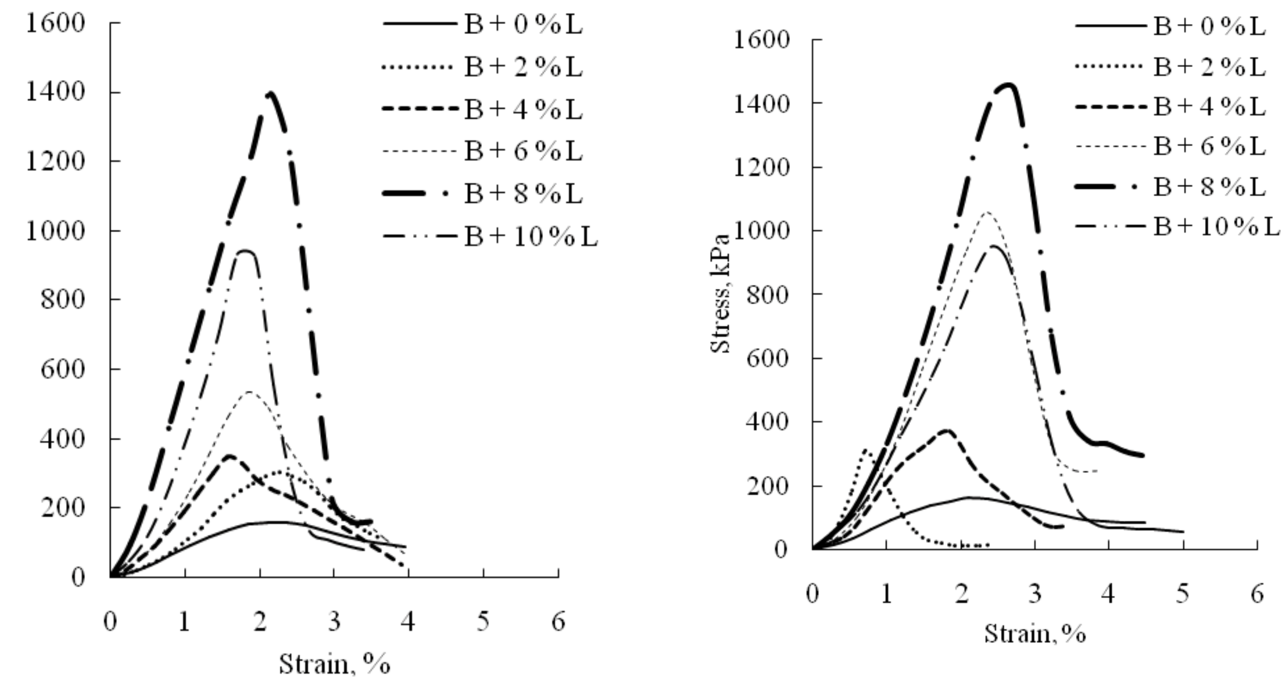
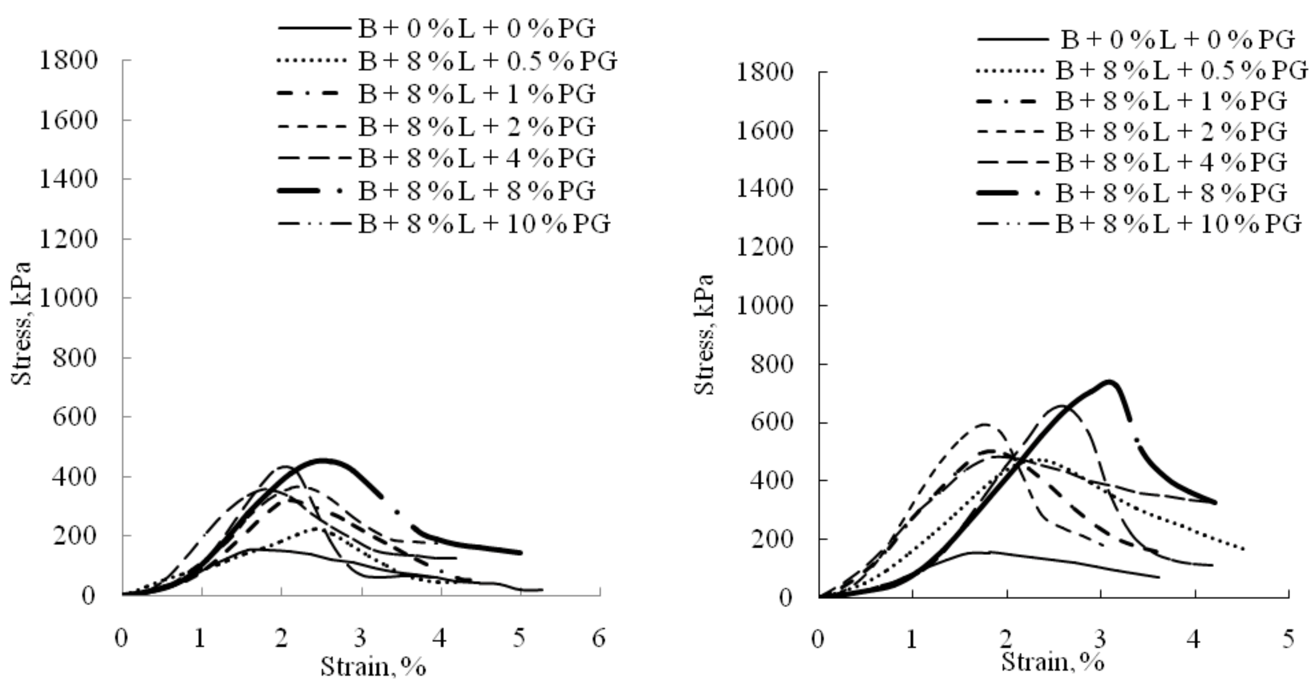
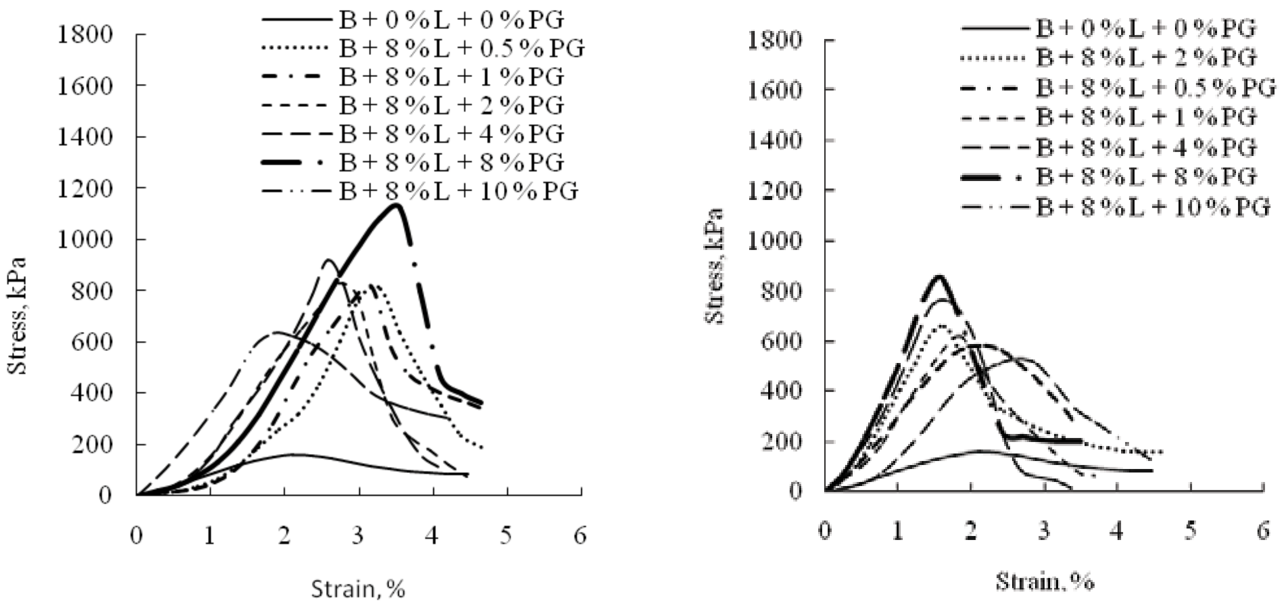


(c) (d)

Fig. 5 Variation of axial stress for bentonite mixed with varying percentage of lime at (a) 3 days (b) 7 days (c) 14 days (d) 28 days



(a) (b)



(c) (d)

Fig. 6 Variation of axial stress for bentonite + 8% lime with varying percentage of phosphogypsum at (a) 3 days (b) 7 days (c) 14 days (d) 28 days

The axial stress-strain curve of the bentonite + 8% lime mixture with varying percentage of phosphogypsum and cured for 3, 7, 14, 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. Study of Fig. 6 (a) to (d) reveals that the axial stress at failure increased with the increase in curing period up to 14 days. For example, for the bentonite + 8 % lime + 0.5 % phosphogypsum cured for 3 days, the axial stress at failure was 225.15 kPa which increased to 592.26 kPa, 810.00 kPa and decreased to 661.91 kPa with the increase in curing period to 7, 14 and 28 days respectively. The increase in axial stress at failure with the curing period is attributed to the acceleration in the pozzolanic reactions of lime with the bentonite in the presence of phosphogypsum leading to increase in axial stress at failure. Similar trend of increase in axial stress at failure was observed for a phosphogypsum content of 1, 2, 4, 8 and 10 %. A close examination of Fig. 6 (a) to (d) reveals that the axial stress at failure increased with the increase in phosphogypsum content up to 8%. Beyond this content there was a decrease in axial stress at failure. For example, for the bentonite + 8% lime + 0.5% phosphogypsum mix cured for 3 days, the axial stress at failure was 225.15 kPa which increased to 321.67 kPa, 362.53 kPa, 429.19 kPa, 450.24 kPa and decreased to 357.65 kPa at a phosphogypsum content of 1, 2, 4, 8% and 10% respectively at the same curing period. Similar trend of increase in axial stress at failure was observed for other curing periods of 7, 14 and 28 days as evident from Fig. 6 (a) to (d). The decrease in 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 do not change with the increase in curing period. The unconfined compressive strength of the bentonite + 8% lime increased with the addition of 8% phosphogypsum as well as increase in curing period up to 14 days. Beyond 8%, the unconfined compressive strength decreased.

E.CBR Behaviour

The load deformation curve for bentonite, bentonite + 8% lime and bentonite + 8% lime + 8% phosphogypsum as obtained from CBR test is shown in Fig. 7. The variation of CBR for the bentonite, bentonite + 8% lime and bentonite + 8% lime + 8% phosphogypsum is shown in Table II.

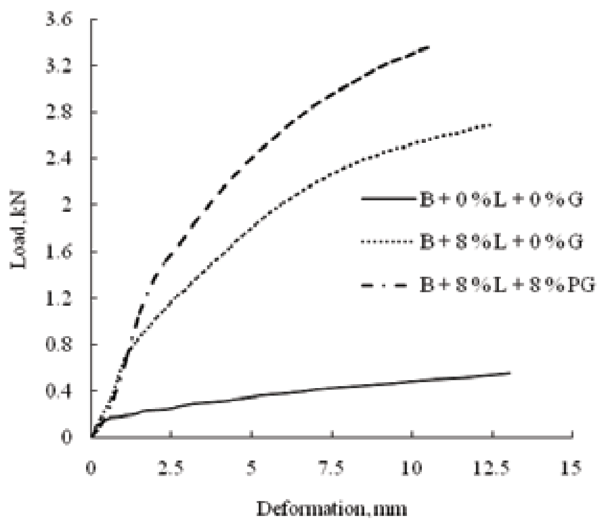


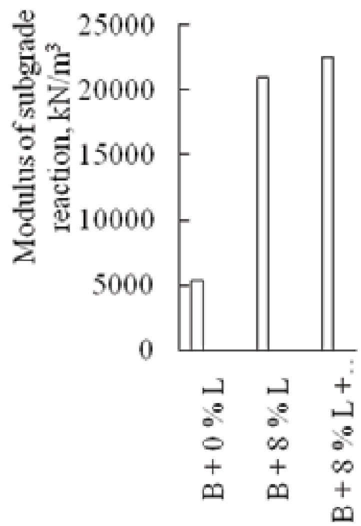
Fig. 7 Load vs. Deformation curves obtained in CBR.

TABLE II CBR OF MIXES

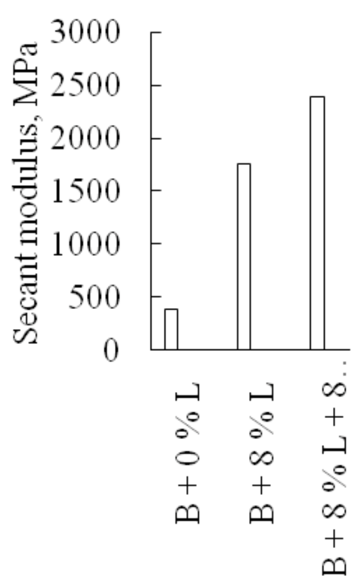
	CBR (%) at a deformation of	
Mix	2.5mm	5mm
Bentonite	1.87	1.73
Bentonite + 8 % Lime	8.62	8.92
Bentonite + 8% Lime + 8% Phosphogypsum	11.71	11.89

A study of Table II reveals that the CBR of the bentonite was 1.88% and 1.73% which increased to 8.62% and 8.92% when the bentonite is mixed with 8% lime at a deformation of 2.5 mm and 5 mm respectively. The increase in CBR of bentonite with the addition of 8 % lime is attributed to the fact that all the lime is taken up by the bentonite at the early stages thus modifying the behaviour of bentonite leading to increase in CBR of the mix. The CBR of the bentonite + 8% lime mix further increased to 11.71% and 11.89% at a deformation of 2.5 mm and 5 mm respectively with the addition of 8% phosphogypsum. The increase in CBR of 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 quick reaction of bentonite with lime resulting Base Exchange aggregation and flocculation leading to increase in the CBR of the mixture.

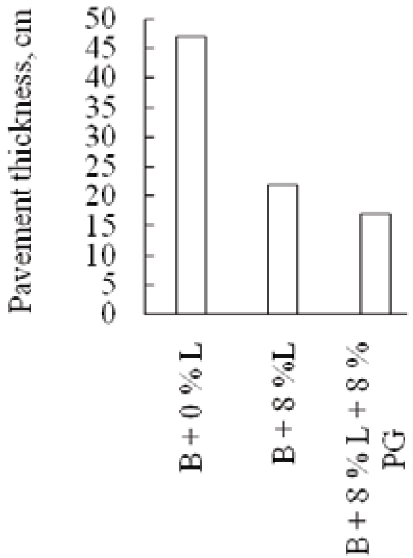
Modulus of subgrade reaction is the reaction pressure sustained by the soil sample under a rigid plate of standard diameter per unit settlement measured at a specified pressure or settlement. Modulus of subgrade reaction is obtained corresponding to 1.25 mm penetration from load penetration curve and actual subgrade modulus is obtained after applying correction for plate size. The variation of modulus of subgrade reaction for the mixes studied is shown in Fig. 8(a).



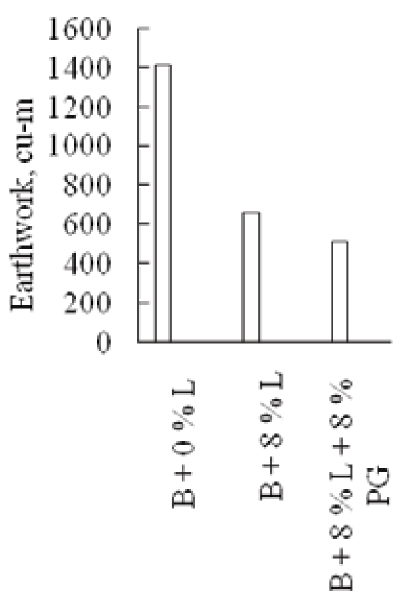
(a)



(b)



(c)



(d)

Fig. 8 Variation of (a) modulus of subgrade reaction (b) secant modulus (c) pavement thickness (d) earth work for the mixes

A study of Fig. 8(a) reveals that the modulus of subgrade reaction of the bentonite was 5378.16 kN/m^3 which increased to 20969.17 kN/m^3 when the bentonite is mixed with 8% lime. The modulus of subgrade reaction of the bentonite + 8% lime mix further increased to 22544.82 kN/m^3 with the addition of 8% phosphogypsum. To ascertain the performance of modified bentonite, secant modulus corresponding to the penetration of 2.5 mm has been calculated. The secant modulus is obtained from load deformation curve by dividing the load at 2.5 mm penetration with plunger area and deformation (0.0025m) respectively. The variation of secant modulus of bentonite, bentonite + 8% lime and bentonite + 8% lime + 8% phosphogypsum is shown in Fig. 8(b). The secant modulus for bentonite was 382.54 MPa which increased to 1757.00 MPa with the addition of 8 % lime. The secant modulus further increased to 2385.54 MPa with the addition of 8% phosphogypsum to the bentonite + 8% lime mix. Further to check the saving in bentonite subgrade thickness, the pavement thickness was calculated using CBR design chart (recommended by IRC: 37-1970) for 15-45 commercial vehicles per day exceeding 3 tonnes laden weight. Curve B has been used for this load. The pavement thickness required for subgrade bentonite stabilized with Lime & phosphogypsum shown in Fig. 8(c). A study of Fig. 8(c) reveals that the pavement thickness requirement for the bentonite was 47 cm which decreased to 22 cm with the addition of 8 % lime. The pavement thickness requirement for bentonite + 8% lime mix further decreased to 17 cm with the addition of 8% phosphogypsum. The saving in material per kilometer length for a village road of 3 m width for the bentonite stabilized with lime and phosphogypsum is shown in Fig. 8(d). A study of Fig. 8(d) reveals that the earth work required for the subgrade bentonite was 1410 cum which decreased to 660 cum when the bentonite is mixed with 8% lime. The earth work required for subgrade bentonite + 8% lime mix further decreased to 510 cum with the addition of 8% phosphogypsum. Thus from the above discussion it is concluded that the California bearing ratio, modulus of subgrade reaction, secant modulus increased for the bentonite stabilized with lime and phosphogypsum. This improved behaviour lead to reduction in earth work and required thickness of subgrade bentonite.

V. Conclusion

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

1. The dry unit weight and optimum moisture content of bentonite + 8% lime increased with the addition of 8 % phosphogypsum.
2. The percentage swell increased and free swell index decreased with the addition of 8% phosphogypsum to the bentonite + 8% lime mix.
3. The unconfined compressive strength of the bentonite + 8 % lime increased with the addition of 8% phosphogypsum as well as increase in curing period up to 14 days. Beyond a phosphogypsum content of 8%, the unconfined compressive strength decreased.
4. The liquid limit and plastic limit of bentonite + 8% lime increased where as the plasticity index remains constant with the addition 8% phosphogypsum.
5. The California bearing ratio, modulus of subgrade reaction, secant modulus increased for the bentonite stabilized with lime and phosphogypsum. This improved behaviour lead to reduction in earth work and required thickness of subgrade bentonite.
6. The coefficient of consolidation of bentonite increased with the addition of 8 % lime and no change with the addition of 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.

VI. Notation

B = Bentonite

L= Lime

PG = Phosphogypsum

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