

Engineering Properties of Bentonite Modified with Lime and Gypsum

Vidya Tilak, B.^{1)*}, *Rakesh Kumar Dutta*²⁾ and *Bijayananda Mohanty*³⁾

¹⁾ PG Student, Department of Civil Engineering, National Institute of Technology, Hamirpur – 177005, Himachal Pradesh, India. E-Mail: vidyatilakb@gmail.com

* Corresponding Author.

²⁾ Professor, Department of Civil Engineering, National Institute of Technology, Hamirpur – 177005, Himachal Pradesh, India.

³⁾ Assistant Professor, Department of Civil Engineering, National Institute of Technology, Hamirpur – 177005, Himachal Pradesh, India.

ABSTRACT

This paper presents the engineering properties such as compaction, unconfined compressive strength, consistency limits, free swell index, California bearing ratio and consolidation of bentonite stabilized with lime and modified with gypsum. The content of lime and gypsum was varied from 0 to 10% and from 0.5 to 8%, respectively, to check the improvement in the engineering properties. The results of this study revealed that the dry unit weight and optimum moisture content of bentonite + 8% lime increased with the addition of 4% gypsum. The unconfined compressive strength of bentonite did not change with the increase in curing period. The unconfined compressive strength of bentonite + 8% lime increased with the addition of 4% gypsum. Beyond 4%, the unconfined compressive strength decreased. The unconfined compressive strength of bentonite-lime-gypsum mix increased with the increase in curing period. The liquid limit, plastic limit and free swell index of bentonite + 8% lime decreased; whereas the plasticity index increased with the addition of 4% gypsum. The California bearing ratio and modulus of subgrade reaction increased for bentonite stabilized with 8% lime and modified with 4% gypsum leading to reduction in earth work and required thickness of subgrade bentonite. The coefficient of consolidation of bentonite increased with the addition of 8% lime and did not change with the addition of 4% gypsum. The swell potential of bentonite + 8% lime increased with the addition of 4% gypsum. The improved behaviour of the bentonite-lime-gypsum mixture will boost the construction of road pavements on such problematic soils.

KEYWORDS: Bentonite, Lime, Gypsum, Consistency limits, Compaction, Consolidation, Unconfined compressive strength, CBR, Free swell index, Swell potential.

INTRODUCTION

Expansive soils pose serious problems to civil engineering structures such as roads constructed on them in terms of differential settlements, poor strength and high compressibility. Several states in India such as Rajasthan, Madhya Pradesh, Gujarat, Andhra

Pradesh, Karnataka and Tamilnadu have vast deposit of expansive soils. The various types of expansive soils found in these regions are black cotton soil, bentonite, mar and kabar (Ameta et al., 2007). Among all, bentonite soil is a highly expansive as it exhibits high swelling, shrinkage, compressibility and poor strength in contact with water, especially during rainy season leading to cracks in overlying road pavements. The best alternative approach is to modify the properties of

these soils with some admixtures such as lime and gypsum to make them suitable for the construction of overlying road pavements. The present study is an attempt to study the engineering properties of bentonite modified with lime and gypsum so that it may not cause any serious damage to the overlying road pavements.

BACKGROUND

Stabilization of expansive soils with additives has been used in road pavements since long. There are numerous studies on the stabilization of expansive soils using lime alone and very limited studies with gypsum. TRB (1976) reported that stabilization of expansive clay with lime has gained popularity as it lowers the volume change characteristics. Chen (1975) reported that the content of lime required for stabilizing expansive soils ranges from 2% to 8% by weight. He further reported that with the increase in lime content in expansive soils, there is an apparent reduction in clay content and a corresponding increase in the percentage of coarse particles. Wang et al. (1963) and Bell (1988) reported that the liquid limit of expansive clay decreases with the increase in lime content. Herrin and Mitchell (1961) and Barker et al. (2006) reported an increase in plastic limit with the increase in lime content in expansive clay. Other researchers (Clare and Cruchley, 1957; Prakash et al., 1989; Bell, 1996) reported an increase in plasticity of expansive soil with the increase in lime content. Adam et al. (2012) reported the decrease in liquid limit and plasticity index with the addition of 6% lime. Degirmenci et al. (2007) conducted a study on expansive soil stabilized with phosphogypsum and reported a decrease in plasticity index. 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 of bentonite. Expansive soils exhibit high swelling, shrinkage, compressibility and poor strength in contact with water, especially during rainy seasons leading to cracks in overlying road

pavements. Mateos (1964) and Bhasin et al. (1978) reported that modifications of such soils with lime can effectively control swelling. Adam et al. (2012) reported a decrease in swelling pressure (4 to 0.2%) with the addition of 6 % lime. Ameta et al. (2007) conducted the study on bentonite mixed with lime and gypsum and reported that the addition of 2% lime + 4% gypsum is adequate for reducing swelling of expansive soils. Neeraja (2010) conducted a compaction study on expansive soil modified with different percentages of lime and reported that the optimum moisture content decreased and maximum dry unit weight increased with the increase in lime content. Degirmenci et al. (2007) conducted a study on expansive soil stabilized with phosphogypsum and reported an increase in dry unit weight and a decrease in optimum moisture content with the addition of phosphogypsum. Many researchers (Bell, 1996; Rajasekaran and Rao, 2000; Consoli et al., 2011; Rogers et al., 2006; Khattab et al., 2007) reported that lime stabilization not only stabilizes the expansive soil but also induces cementation due to pozzolanic reactions leading to an increase in strength and long-term performance. Other researchers (Hilt and Davidson, 1960; Herrin and Mitchell, 1961; Bell, 1996; Kumar et al., 2007) have reported that the increase in lime content beyond a threshold leads to a decrease in strength of lime stabilized expansive soils. Degirmenci et al. (2007) conducted a study on expansive soil stabilized with phosphogypsum and reported an increase in unconfined compressive strength with the addition of phosphogypsum. From literature, it is evident that the engineering properties such as: compaction, unconfined compressive strength, consistency limits, free swell index, California bearing ratio and consolidation of bentonite stabilized with lime and modified with gypsum have not been extensively studied. The present study tries to fill this gap. In the present work, the effect of lime and gypsum on the engineering properties such as: compaction, unconfined compressive strength, consistency limits, free swell index, California bearing ratio and

consolidation of bentonite stabilized with lime and modified with gypsum is investigated.

METHODOLOGY

The geotechnical characteristics of bentonite-lime and bentonite-lime-gypsum mixes were studied. The content of lime and gypsum was varied from 2 to 10% and from 0.5 to 8% by dry weight of bentonite, respectively. Consistency limits, compaction, consolidation, unconfined compressive strength, CBR, free swell index and swell potential tests were carried out on the test specimens. Unconfined compression strength tests were also conducted on cured specimens. Three specimens were prepared for unconfined compressive strength tests for each percentage of lime and gypsum. For CBR, free swell test, swell potential and consolidation, one specimen was prepared for each lime and gypsum content. About 165 specimens were prepared and tested in six different types of tests. The results obtained from these tests are presented and discussed in this paper.

MATERIAL USED AND EXPERIMENTAL PROCEDURE

Commercially available bentonite was used in this study. The physical and engineering properties of bentonite are given in Table 1.

Table 1. Physical and engineering properties of bentonite

Property	Value
Specific gravity	2.30
Liquid limit, %	220
Plastic limit, %	39.74
Optimum moisture content, %	27.98
Maximum dry density, kN/m ³	13.95
Type	CH

Hydrated lime and gypsum used in this study were

procured from the local market at Hamirpur, Himachal Pradesh, India. The specific gravity tests were conducted as per IS 2720-Part-III (1980) on lime and gypsum. The specific gravity of lime and gypsum was 2.37 and 2.89, respectively.

The standard proctor compaction tests were conducted as per IS 2720-Part-VII (1980) on bentonite-lime and bentonite-lime-gypsum mixtures by varying the content of lime and gypsum from 2 to 10% and from 0.5 to 8%, respectively, and water was added as needed to facilitate the mixing and compaction process.

For unconfined compressive strength tests, a metallic mould with 38 mm inner diameter and 76 mm length, with additional detachable collars at both ends, was used to prepare cylindrical specimens. Required quantities of bentonite, lime and gypsum were mixed and water corresponding to optimum moisture content was added and 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 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 the required quantities of bentonite, lime and gypsum and tap water was added to make a slurry of uniform consistency. The liquid limit and plastic limit tests were conducted as per IS 2720-Part-V (1985).

Free swell test was conducted as per the procedure reported in IS 2720-Part-XL (1977) using 100 cc graduated glass jars with distilled water in one jar and kerosene in the other jar. About 15 g 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-gypsum 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-gypsum mixture was 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 25.5 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 were used to force the penetration piston with 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 penetration up to a total penetration of 12.5 mm. The California bearing ratio tests were conducted as per IS 2720-Part-XVI (1987).

The consolidation test was carried out in a conventional odometer apparatus for determination of the coefficient of consolidation of bentonite-lime-gypsum mixtures. From the dry unit weight of bentonite-lime-gypsum mixtures and known volume of consolidation ring, the required oven dry quantity of bentonite was calculated. Then, the required quantities of lime and gypsum were added to the bentonite. Water corresponding to optimum moisture content was added to the bentonite-lime-gypsum 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 the 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). For the swell potential tests, the specimen was prepared in the conventional odometer in the similar way as for the

consolidation tests and a seating load of 5 kPa was applied. The odometer was then placed in a container containing water and was allowed to swell for 15 days.

RESULTS

Compaction

The dry unit weight and moisture content curves for bentonite with varying percentages of lime are shown in Fig. 1(a). The study of Fig. 1 (a) reveals that the maximum dry unit weight for bentonite was 13.95 kN/m³ which decreased to 13.72 kN/m³, 13.45 kN/m³, 13.37 kN/m³, 13.34 kN/m³ and 13.29 kN/m³, 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 in base exchange aggregation and flocculation leading to an increase in the void ratio of the mixture, causing 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).

Study of Fig. 1 (a) further reveals that the optimum moisture content of bentonite was 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 was 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 bentonite cured for 3 days was 154.25 kPa which increased to 248.25 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 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 gypsum. The results of dry unit weight and moisture content for bentonite + 8% lime with varying percentages of gypsum are shown in Fig. 1(b). The

study of Fig. 1 (b) reveals that the maximum dry unit weight for bentonite + 8% lime was 13.34 kN/m³ which increased to 13.39 kN/m³, 13.45 kN/m³, 13.50 kN/m³, 13.60 kN/m³ and 13.70 kN/m³, respectively, with the addition of 0.5, 1, 2, 4 and 8% gypsum. The increase in dry unit weight is attributed to the fact that

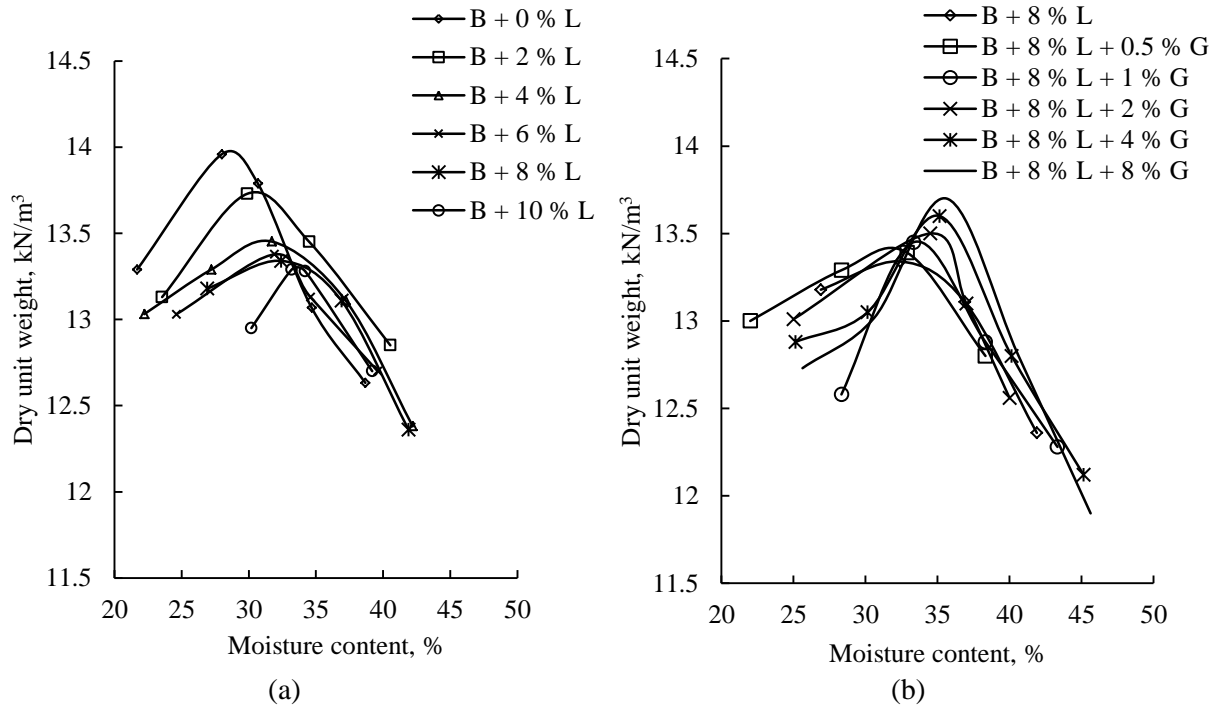


Figure (1): Compaction curves for (a) bentonite with varying percentage of lime (b) bentonite + 8% lime with varying percentage of gypsum

gypsum fills up the void spaces left out after a quick reaction of bentonite with lime resulting in base exchange aggregation and flocculation. Study of Fig. 1 (b) further reveals that the optimum moisture content of bentonite + 8% lime was 32.40% which increased to 32.90%, 33.33%, 34.50%, 35.15% and 35.63%, respectively, with the addition of 0.5, 1, 2, 4 and 8% gypsum. The effect of addition of gypsum to 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).

The dry unit weight and optimum moisture content of bentonite + 8% lime increased with the addition of 4% gypsum. In order to decide the optimum mix of bentonite-lime-gypsum, 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 bentonite + 8% lime cured for 3 days was 442.77 kPa which increased to 531.79 kPa, 573.30 kPa, 637.18 kPa and 648.72 kPa with the addition of 0.5, 1, 2 and 4% gypsum and decreased to

551.25 kPa with the addition of 8% gypsum 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 + 4% gypsum was chosen for further study.

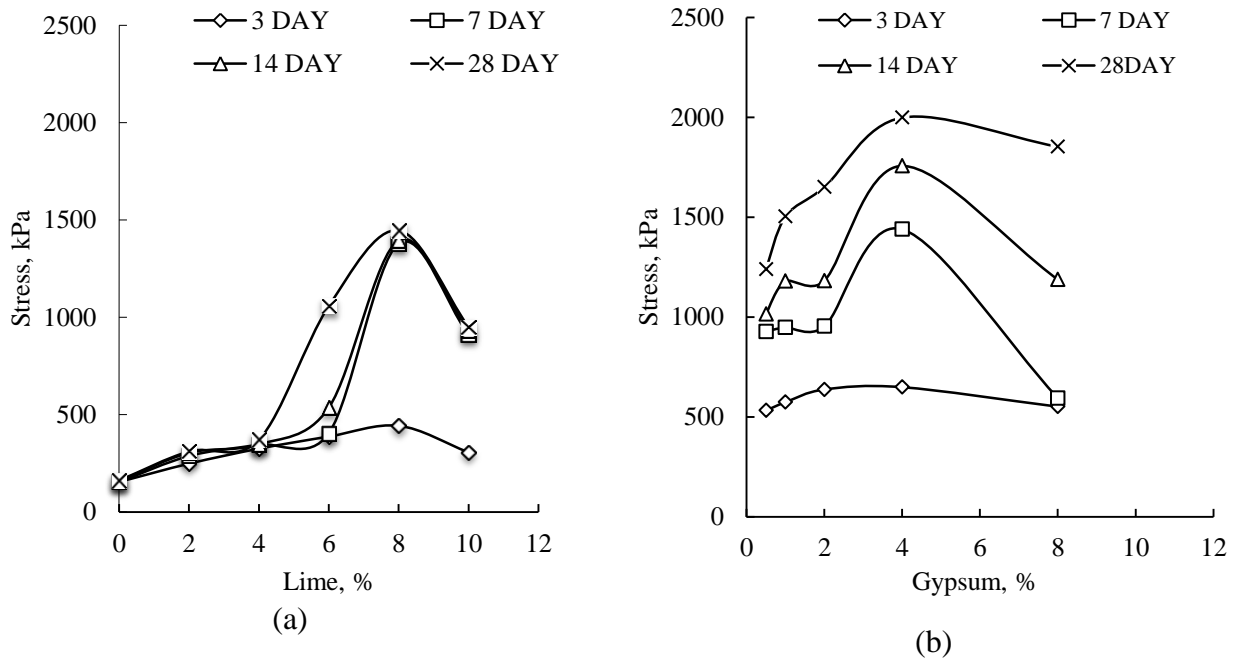


Figure (2): Variation of unconfined compressive strength of (a) bentonite with varying percentage of lime and curing period (b) bentonite + 8% lime with varying percentage of gypsum and curing period

Unconfined Compressive Strength

The axial stress-strain curve of bentonite with varying percentage of lime and cured for 3, 7, 14 and 28 days, respectively, is shown in Fig. 3. Fig. 3 also contains the axial stress-strain curves for bentonite cured for 3, 7, 14 and 28 days, respectively.

Study of Fig. 3 (a) to (d) reveals that the axial stress at failure of bentonite does not improve appreciably with the increase in the curing period. For example, the axial stress at failure of 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 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 bentonite with the curing period. Further examination of Fig. 3 (a) to (d) reveals that the axial stress at failure increased with the increase in curing period. For example, for 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

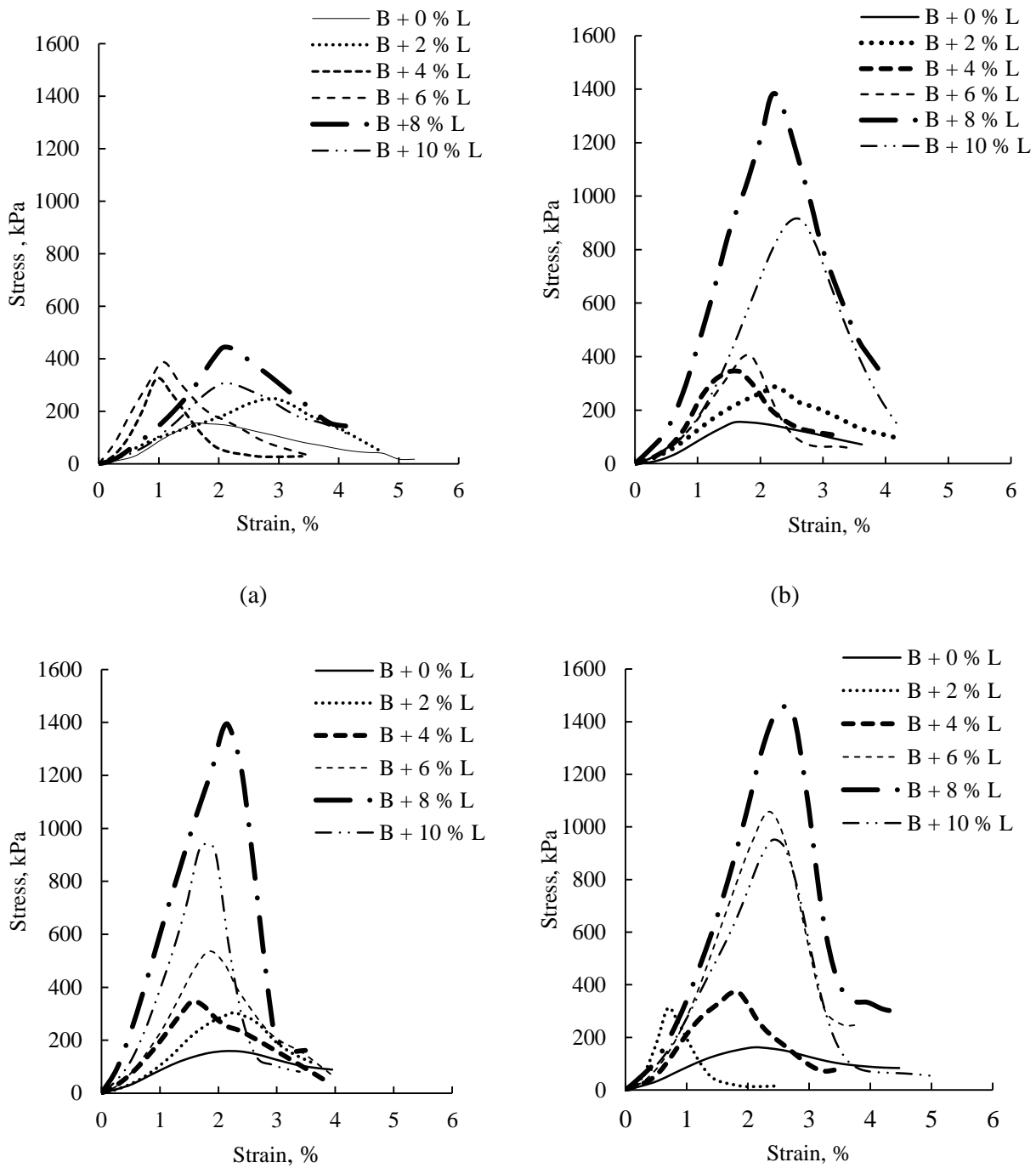


Figure (3): Variation of unconfined compressive strength for bentonite mixed with varying percentage of lime at (a) 3 days (b) 7 days (c) 14 days (d) 28 days

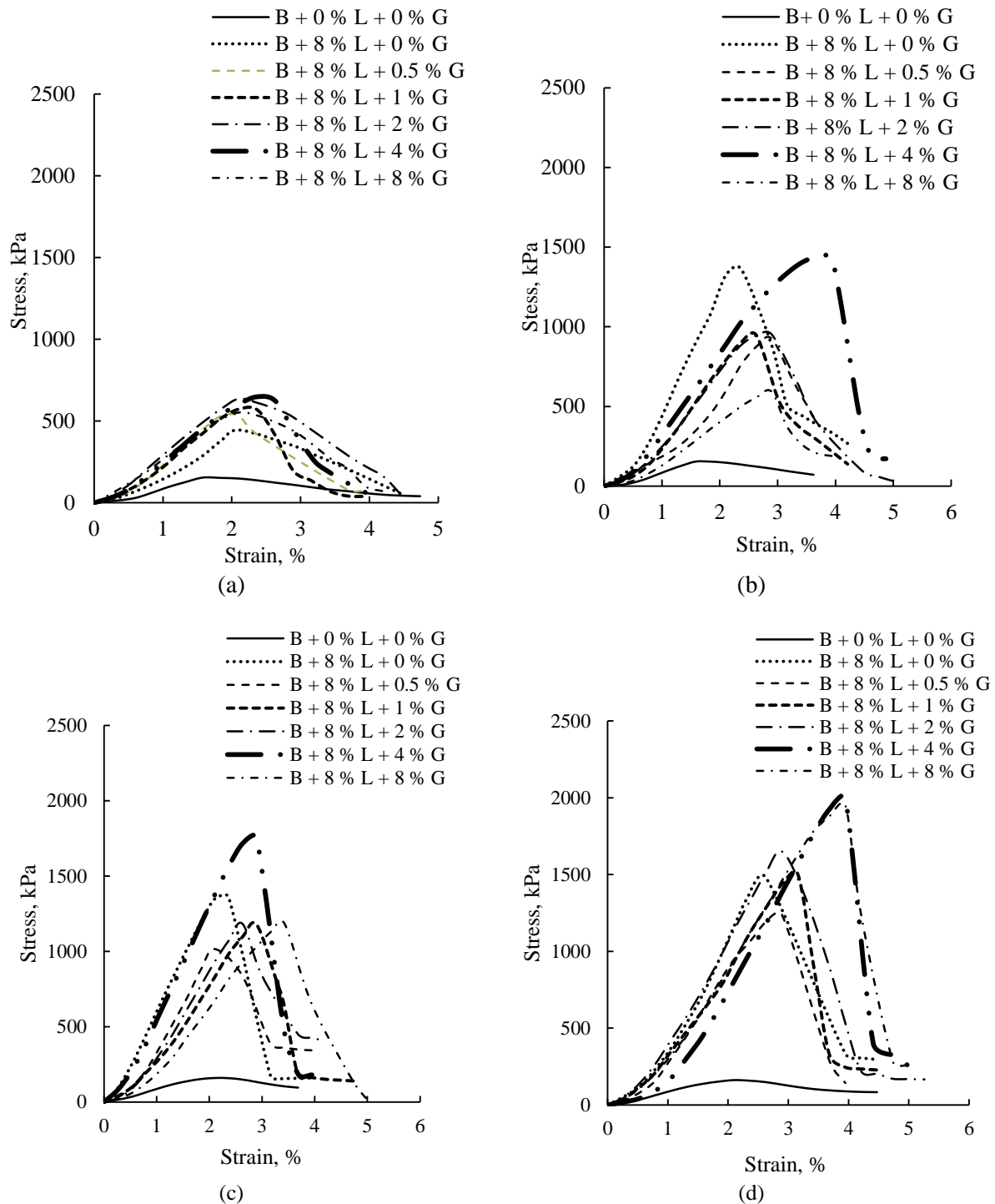


Figure (4): Variation of unconfined compressive strength for bentonite + 8% lime with varying percentage of gypsum at (a) 3 days (b) 7 days (c) 14 days (d) 28 days

reactions of lime with bentonite leading to an 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. 3 (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 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 an 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. 3 (a) to (d).

The axial stress-strain curve of bentonite + 8% lime mixture with varying percentage of gypsum and cured for 3, 7, 14 and 28 days, respectively, is shown in Fig. 4. Fig. 4 also contains the axial stress-strain curves for bentonite and bentonite + 8% lime mixture cured for 3, 7, 14 and 28 days, respectively. Study of Fig. 4 (a) to (d) reveals that the axial stress at failure increased with the increase in the curing period. For example, for bentonite + 8% lime + 0.5% gypsum cured for 3 days, the axial stress at failure was 531.794 kPa which increased to 926.57 kPa, 1014.95 kPa and 1283.63 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 bentonite in the presence of gypsum leading to an increase in axial stress at failure. Similar trend of increase in axial stress at failure was observed for a gypsum content of 1, 2, 4 and 8%. A close examination of Fig. 4 (a) to (d) reveals that the axial stress at failure increased with the increase in gypsum content up to a content of 4%. For example, for bentonite + 8% lime + 0.5% lime mix cured for 3 days, the axial stress at failure was 531.79 kPa which increased to 573.30 kPa, 637.18 kPa, 648.73

kPa and decreased to 511.25 kPa with the increase in gypsum content to 1, 2, 4 and 8%, respectively. The decrease in axial stress at failure beyond a gypsum content of 4% is perhaps attributed to the platy shapes of the unreacted lime particles in bentonite even in the presence of gypsum. 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. 4 (a) to (d). Thus, from the above discussion, it is concluded that the unconfined compressive strength of bentonite does not change with the increase in the curing period. The unconfined compressive strength of bentonite + 8% lime increased with the addition of 4% gypsum. Beyond 4%, the unconfined compressive strength decreased. The unconfined compressive strength of the bentonite-lime-gypsum mix increased with the increase in the curing period.

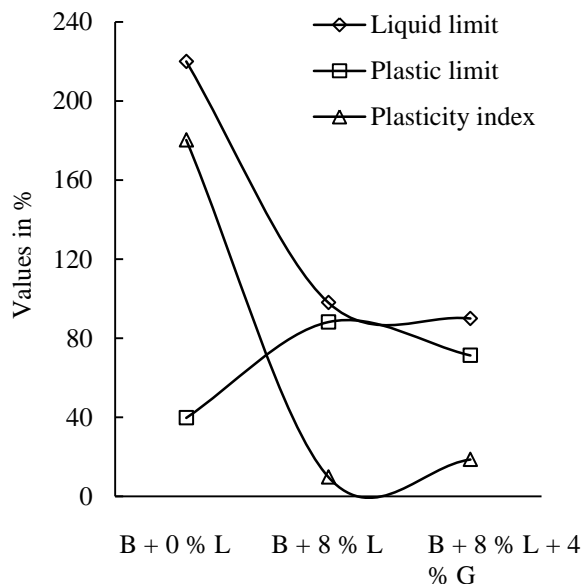
Consistency Limits and Free Swell Index

The variations of liquid limit and plastic limit for the mixes studied are shown in Fig. 5 (a). A study of Fig. 5 (a) reveals that the liquid limit and plastic limit of the bentonite were 220 % and 39.74%, respectively, which decreased to 98.04% and increased to 88.20%, respectively, when bentonite is mixed with 8% lime. The decrease in the liquid limit with the addition of lime was attributed to the fact that the release of Ca^+ ions into the pore fluid increases the electrolyte concentration of pore water leading to a decrease in the thickness of diffuse double layer around the bentonite particles and ultimately in the liquid limit. Similar observations were reported by Dash and Hussain (2012).

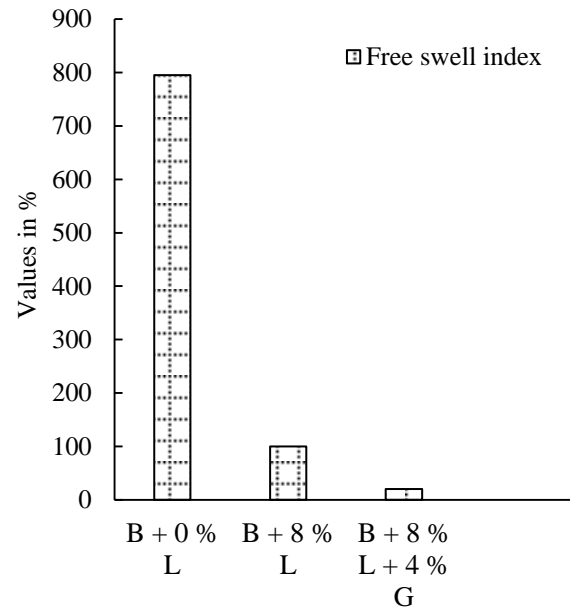
The increase in plastic limit with the addition of 8% lime content is attributed to the fact that flocculated fabric resulting from lime stabilization requires more water for thread formation leading to an increase in plastic limit. Abdelmadjid and Muzahim (2008) also observed the increase in plastic limit with the addition of lime in expansive soil. The liquid limit and plastic limit of the bentonite + 8% lime mix decreased to 90% and 71.32%, respectively, with the addition of 4%

gypsum. The decrease in the liquid limit and plastic limit with the addition of 4% gypsum to bentonite + 8% lime mix was attributed to the fact that the inert particles of the gypsum only act as filler and do not attract water molecules, owing to the fact that it is fully saturated with water leading to a decrease in liquid limit and plastic limit. Fig. 5 further reveals that the plasticity index of bentonite was 180.26% which decreased to 9.84% when bentonite was 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 bentonite with lime. These observations are in agreement with Abdelmadjid and Muzahim (2008). The plasticity index of bentonite + 8% lime mix increased to 18.68% with the addition of 4% gypsum which means that the addition of gypsum makes bentonite + 8% lime mix more plastic and the same is reflected in the increase in plasticity index.



(a)



(b)

Figure (5): (a) Variation of consistency limits with the best mixes. (b) Variation of free swell index with the best mixes

The variation of free swell index for the mixes studied is shown in Fig. 5 (b). A study of Fig. 5 (b) reveals that the free swell index of bentonite was 795.45% which decreased to 100% when bentonite was mixed with 8% lime. The decrease in free swell index due to the 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 Ca-

saturated bentonite and the formation of a cementitious matrix resist swelling and thus decrease the free swell index. The free swell index of bentonite + 8% lime mix further decreased to 20% with the addition of 4% gypsum. The decrease in free swell index of bentonite + 8% lime with the addition of 4% gypsum is attributed to the fact that the cementing effect of the reaction products of bentonite-lime-gypsum binds the clay particles together leading to a decrease in free

swell index. Thus, from the above discussion, it is concluded that the liquid limit, plastic limit and free swell index of bentonite decreased; whereas the

plasticity index increased with the addition of 8% lime and 4 % gypsum.

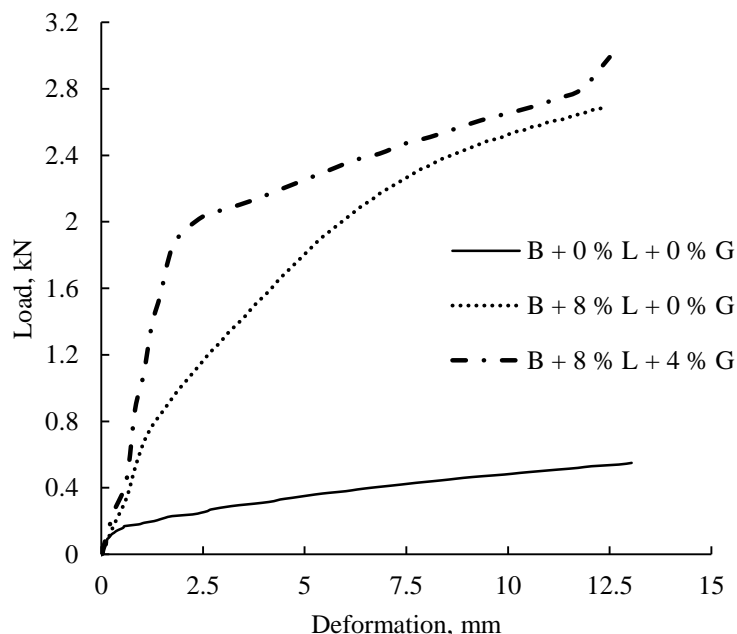


Figure (6): Load vs. deformation curves obtained in CBR

CBR Behaviour

The load deformation curve for bentonite, bentonite + 8% lime and bentonite + 8% lime + 4% gypsum as obtained from CBR test is shown in Fig. 6. The variation of CBR for bentonite, bentonite + 8% lime and bentonite + 8 % lime + 4% gypsum is shown in Table 2.

A study of Table 2 reveals that the CBR of bentonite was 1.87 % and 1.73 % which increased to 8.62% and 8.92% when bentonite was 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 an increase in CBR of the mix. CBR of the bentonite + 8

% lime mix further increased to 15.06% and 11.13% at a deformation of 2.5 mm and 5 mm, respectively, with the addition of 4% gypsum. The increase in CBR of bentonite + 8 % lime with the addition of 4 % gypsum is attributed to the fact that the gypsum fills up the void spaces left out after quick reaction of bentonite with lime resulting in base exchange aggregation and flocculation leading to an increase in the CBR of the mixture.

Modulus of Subgrade Reaction

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. 7.

A study of Fig. 7 reveals that the modulus of

subgrade reaction of bentonite was 5378.16 kN/m^3 which increased to 20969.17 kN/m^3 when bentonite was mixed with 8% lime. The modulus of subgrade reaction of bentonite + 8% lime mix further increased to 53516.80 kN/m^3 with the addition of 4% gypsum.

Table 2. CBR of mixes

Mix	CBR (%) at a deformation of	
	2.5 mm	5 mm
Bentonite	1.87	1.73
Bentonite + 8 % Lime	8.62	8.92
Bentonite + 8 % Lime + 4 % Gypsum	15.06	11.13

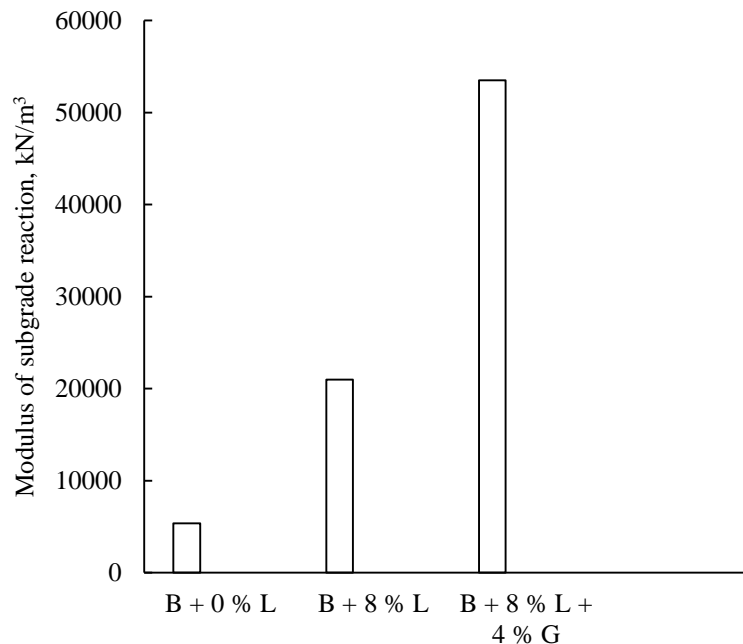


Figure (7): Variation of modulus of subgrade reaction of the best mixes

Pavement Thickness and Saving in Earth Work

Pavement thickness is calculated by 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 modified with lime and gypsum is shown in Fig. 8.

A study of Fig. 8 reveals that the pavement thickness requirement for 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 15 cm with the addition of 4% gypsum. The saving in material per kilometer length for a village road of 3 m width for bentonite stabilized with lime and modified with gypsum is shown in Fig. 9.

A study of Fig. 9 reveals that the earth work required for subgrade bentonite was 1410 cum which decreased to 660 cum when bentonite was mixed with

8% lime. The earth work required for subgrade bentonite + 8% lime mix further decreased to 450 cum with the addition of 4 % gypsum. Thus, from the above discussion, it is concluded that California bearing ratio and modulus of subgrade reaction increased for bentonite stabilized with lime and modified with gypsum. This improved behaviour led to a reduction in earth work and in required thickness of subgrade bentonite.

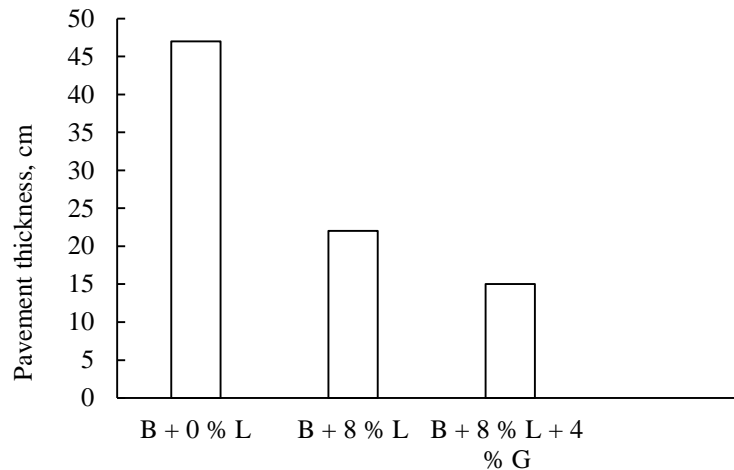


Figure (8): Variation of pavement thickness of the best mixes

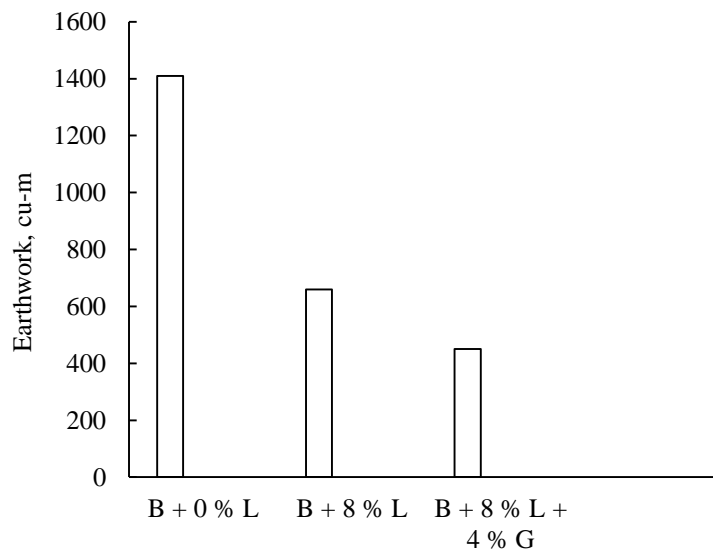


Figure (9): Variation of earth work with the best mixes

Consolidation and Swell Potential

The coefficient of consolidation for the mixes studied is shown in Fig. 10. A study of Fig. 10 reveals that the coefficient of consolidation of bentonite was 0.10 cm/min which increased to 0.125 cm/min when the bentonite was 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 bentonite with lime resulting in a higher porosity and an increase in the coefficient of consolidation.

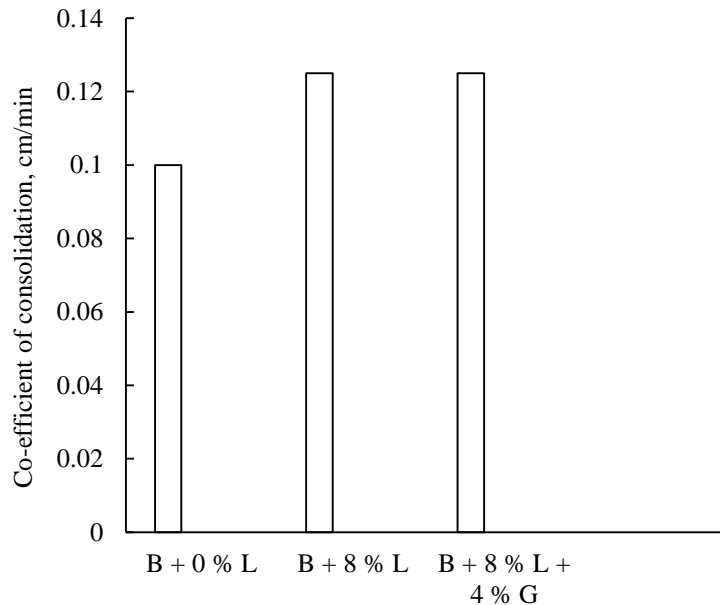


Figure (10): Variation of coefficient of consolidation with the best mixes

The coefficient of consolidation of the bentonite + 8% lime mix further increased to 0.125 cm/min with the addition of 4 % gypsum. The increase in the coefficient of consolidation of bentonite + 8% lime with the addition of 4 % gypsum is attributed to the fact that gypsum fills up the void spaces left out after quick reaction of bentonite with lime resulting in 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 occurred with the addition of 4% gypsum.

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 5 kPa are presented in Table 3 in the form of percentage swell for bentonite, bentonite + 8% lime and bentonite + 8% lime + 4% gypsum for a time duration of 15 days.

Table 3. Summary of percentage swell for a time duration of 15 days

MIX	% SWELL
B + 0 % L	53.42
B + 8 % L	8.44
B + 8 % L + 4 % G	26.98

Study of Table 3 reveals that the percentage swell of bentonite decreased with the addition of 8% lime. For example, the percentage swell of bentonite at a time duration of 15 days was 53.42 which decreased to 8.44 with the addition of 8 % lime. The percentage swell of bentonite + 8% lime at a time duration of 15 days increased to 26.89 with the addition of 4% gypsum. Thus, from the above discussion, it is concluded that the percentage swell increased with the addition of 4% gypsum to the bentonite + 8% lime mix.

CONCLUSIONS

An experimental study is carried out to investigate the engineering properties such as compaction, unconfined compressive strength, consistency limits, free swell index, California bearing ratio and consolidation of bentonite stabilized with lime and modified with gypsum. 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 4% gypsum.
2. The unconfined compressive strength of bentonite did not change with the increase in the curing period. The unconfined compressive strength of bentonite + 8% lime increased with the addition of 4% gypsum. Beyond 4%, the unconfined compressive strength decreased. The unconfined compressive strength of the bentonite-lime-gypsum mix increased with the increase in the curing

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period.

3. The liquid limit, plastic limit and free swell index of bentonite + 8% lime decreased; whereas the plasticity index increased with the addition of 4% gypsum.
4. The California bearing ratio and modulus of subgrade reaction increased for bentonite stabilized with 8% lime and modified with 4% gypsum. This improved behaviour led to a reduction in earth work and required thickness of subgrade bentonite.
5. The coefficient of consolidation of bentonite increased with the addition of 8% lime, and no change occurred with the addition of 4% gypsum. The swell potential of bentonite + 8% lime increased with the addition of 4% gypsum.
6. The optimum value of lime content and gypsum content in bentonite- lime- gypsum mixtures may be taken as 8 % and 4%, respectively.

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

Notation

B = Bentonite

L= Lime

G = Gypsum

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