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ENGINEERING PROPERTIES OF BLACK COTTON SOIL-DOLIME MIX FOR ITS USE AS SUBBASE MATERIAL IN PAVEMENTS

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ABSTRACT: In this paper, an attempt is made to stabilize problematic expansive Black Cotton (BC) soil by dolime fines for its use in subbase course of flexible pavements. Atterberg limits, free swell index, compaction characteristics, unconfined compressive strength (UCS), soaked CBR, shear strength parameters and resilient modulus are evaluated for different trial mixes cured up to 28 days. BC soil stabilized with a minimum dolime content of 9% satisfies the criteria recommended by Indian Road Congress for utilization in subbase layer of flexible pavements. The effects of dolime content and curing period on the above geotechnical properties of the mixes were investigated. Empirical relationships are developed to estimate important design parameters such as deviator stress at failure and cohesion of the stabilized mix that can be used to determine dolime content to achieve a target strength within a given curing period. Different empirical models are proposed to estimate the resilient modulus of soil-dolime mixes and their performances for the prediction of resilient modulus are compared.

Keywords: CBR, Unconfined Compressive Strength, Repeated Load Triaxial Test, Resilient Modulus

1. INTRODUCTION

Due to economic growth, rapid development is occurring in the field of transportation, especially road sector in India. For construction, maintenance and widening of roads, huge quantity of construction material is required. However, due to various reasons such as depleting resources, environmental concerns, etc., there is scarcity of conventional materials such as sand and gravel for construction of subbase and base layers of flexible pavements. Consequently, the cost of good quality natural construction materials is increasing and they need to be hauled from distant quarries to the project site.

During a steel making process, electric arc furnaces use dolomite chips of size 20-40 mm as flux, which is obtained by crushing dolomite stones of larger sizes. During the crushing process, fine particles known as dolime fines are produced which are disposed off as waste material. The generation of dolime fines is about 20-40% by weight of dolomite stones and a huge quantity of dolime fines is generated every year. For example, a typical steel electric arc furnace in Surat, India produces over 23000 tonnes of dolime fines annually and there are more than 175 such electric arc furnace units in India. Disposal of dolime fines is costly and occupies precious land resources.

On the other hand, a large portion of India roughly equal to 0.8 million sq. km, which is about 20% of the total land area, is covered with expansive soil popularly known as Black Cotton (BC) soil. This soil is characterized by the presence of montmorillonite mineral that causes huge volumetric changes due to changes in water content. Black cotton soil is usually treated with pure lime (CaO) to reduce volumetric changes on addition of water [1]. However, impurities such as silica, alumina, or carbonates present in lime may reduce the reactivity of commercial lime but are not harmful. Dolomitic lime, which contains significant amounts of magnesium oxide, has much lesser reactivity. The dolime fines contain 51.5 % of calcium oxide (CaO), and there is a possibility that the material can be used as a binding agent. Various engineering properties of lime stabilized soil have been reported in the literature [2], [3] and [4]. However, no literature is available on strength and stiffness characteristics of BC soil-dolime mix.

Solanki et al. [5] and [6] observed an increase in resilient modulus of subgrade soils for each of three different additives, such as hydrated lime, class C fly ash and cement kiln dust. Ranjan et al. [7] observed an increase in resilient modulus on addition of lime and cement to three different types of subgrade soils. However, behavior of dolime stabilized BC soil under cyclic loading conditions has not been studied before.

In this paper, series of tests for Atterberg limits, free swell index, compaction, UCS, soaked CBR, shear strength parameters and resilient modulus on BCD mixes are presented. Based on these tests, empirical relationships are developed for determination of dolime percentage to achieve a target compressive strength within a given curing period. Correlations are proposed to evaluate important design parameters, namely, deviator stress at failure and cohesion as a function of unconfined compressive strength of BCD mix. The performances of four stress dependant models are compared for the prediction of resilient modulus of BC soil-dolime mixes.

2. EXPERIMENTAL PROGRAM

The experimental program is carried out in two parts. First, Atterberg limits, free swell index, compaction characteristics, unconfined compressive strength, CBR and repeated load triaxial test of different BC soil-dolime mixes are investigated and the optimum mix is determined. Next, monotonic triaxial tests and resilient modulus tests are carried out on the optimum mix for different curing period.

2.1 Materials

Dolime was procured from Essar Steel Limited, Surat and BC soil was collected from SVNIT campus, Surat. BC soil and dolime were air dried, pulverized and then passed through 4.75 mm sieve and 425 micron sieve, respectively. The soil was classified as high plastic clay (CH) as per Indian Standard. The chemical composition of dolime as obtained from Essar Steel Ltd. was as follows: CaO = 51.52%; MgO = 35.06%; SiO_2 = 1.39%; R_2O_3 = 1.43%; and Loss on ignition = 10.6%.

2.2 Atterberg Limits and Free Swell Index

Atterberg limits and free swell index for BC soil treated with different dolime contents (= 0, 3, 6, 9 and 12% by weight of soil) were determined. The compacted samples of the above mixes were first cured for 28 days. The mixes were then pulverized and used for the determination of Atterberg limits and free swell index.

2.3 Compaction Characteristics

Modified Proctor compaction test was conducted on BC soil with varying dolime contents (0 to 24% at 3% interval) to determine the optimum moisture content (OMC) and maximum dry density (MDD). The moist soil-dolime mix was kept in an airtight polythene bag for about 16 hours for moisture equalization before compaction.

2.4 Unconfined Compressive Strength (UCS)

Two different series of UCS tests were conducted. The first series of tests were conducted to evaluate the effect of dolime content and curing period on UCS values as follows: After thoroughly mixing optimum water content and required dolime content (0, 3, 6, 9, 12, 15, 18, 21 and 24%) to the soil, the moist soil-dolime mix was kept in an airtight polythene bag for about 16 hours for moisture equalization. Next, cylindrical specimens of 38 mm diameter and 76 mm high were compacted by a static press in three layers to achieve dry density equal to the maximum dry density of the mix obtained from modified Proctor compaction test. Immediately after preparation, the specimens were sealed in airtight polythene bags and kept at constant temperature (= 27±2^{0}C) for curing. To study the effect of curing period on unconfined compressive strength, the specimens were cured for 0, 7, 14 and 28 days. The values of unconfined compressive strength (q_u) of the cured specimens were then determined in a conventional compression testing machine at a constant strain rate of 0.6 mm/min. Because of a typical scatter in UCS data, three identical specimens were tested for each trial mix; if UCS of any specimen deviated by more than 10%, such UCS value was discarded and the test was repeated.

The second series of UCS tests were performed as per Indian Roads Congress (IRC): 51 [8] procedures to determine the optimum mix. In this series, the compacted specimens were first cured for three days and then soaked in water for four days prior to UCS testing.

2.5 CBR Test

California Bearing Ratio (CBR) tests were conducted on various BC soil-dolime mixes (0, 3, 6 and 9%). Immediately after compaction, the CBR specimens were sealed in airtight polythene bags and kept at a temperature of 27±2^{0}C for curing up to a required period. The CBR specimens were then soaked in water for 4 days before the test was performed.

2.6 Monotonic Triaxial Test

Unconsolidated Undrained (UU) triaxial tests were carried out on compacted specimens of 38 mm diameter and 76 mm high of the optimum combination of BC soil-dolime mix. Specimen preparation and curing for triaxial tests were similar to that for UCS tests. Triaxial tests were conducted after 0, 14 and 28 days of curing on a conventional triaxial test equipment at three different cell pressures (= 40, 80 and 120 kPa). The specimens were sheared immediately after application of cell pressure at a constant strain rate of 0.6 mm/min. From the stress-strain curves, elastic secant modulus (E) was determined corresponding to 0.3 times the deviator stress at failure σ_d as per BS EN 13286 [9].

2.7 Repeated Load Triaxial Test

Repeated load triaxial tests (RLTT) were carried out on compacted specimens of 50 mm diameter and 100 mm high of different soil-dolime mixes for 28 days curing period. To study the effect of curing period, the tests were conducted after 0, 7, 14 and 28 days of curing on the specimens corresponding to the optimum BCD mix. The test was carried out in accordance with AASTHO T 307 [10] method. First, the specimens were subjected to 3000 loading cycles during the conditioning phase and then tested for the determination of resilient modulus at fifteen different stress levels.

3. RESULTS AND DISCUSSION

3.1 Atterberg Limits

Table 1 shows the variation of Atterberg limits with dolime content for various BC soil-dolime mixes. With an increase in dolime content, the plasticity index decreases continuously owing to a decrease in liquid limit and an increase in plastic limit. At 12% dolime content, the mix becomes non-plastic.

A similar behavior on stabilization of high plasticity clay with lime has been reported by Hausmann [1]. When clay is treated with dolime, sodium and other cations adsorbed on the clay surface are exchanged with calcium ions. This cation exchange affects the way in which the components of the clay minerals are connected with each other. This cation exchange causes clay to coagulate and flocculate making it more friable, thus reducing the plasticity of clay.

Table 1 Atterberg limits and free swell index of BC soil-dolime mixes

Dolime (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Free swell index (%)
0	58.0	21.0	37.0	54.0
3	50.5	22.2	28.3	41.0
6	48.3	26.5	21.8	35.0
9	45.2	29.0	16.2	24.0
12	34.0	NP	-	17.0

NP- Non plastic

3.2 Free Swell Index

Free swell index of BC soil-dolime mixes decreases with increase in dolime content (Table 1). Dolime causes clay particles to coagulate and flocculate which reduces the total specific surface area of clay minerals, thereby decreasing the quantity of water that can be adsorbed to the clay mineral surfaces. Therefore, free swell index which is a measure of a soil's affinity to water decreases with an increase in dolime content.

3.3 Compaction Characteristics

Fig. 1 presents dry density-moisture content relationships for different BC soil-dolime mixes. With the increase in dolime content, while the optimum moisture content increases, the maximum dry density decreases; and the compaction curve becomes flatter. Dolime increases the optimum water content for compaction, which is an advantage when dealing with wet soil. Flocculation and cementation due to addition of dolime make the soil more difficult to compact, thereby reducing the maximum dry density that can be achieved with a particular compaction effort. The compaction curve for lime treated clay is generally flatter, making moisture control less critical and reducing the variability of the density produced.

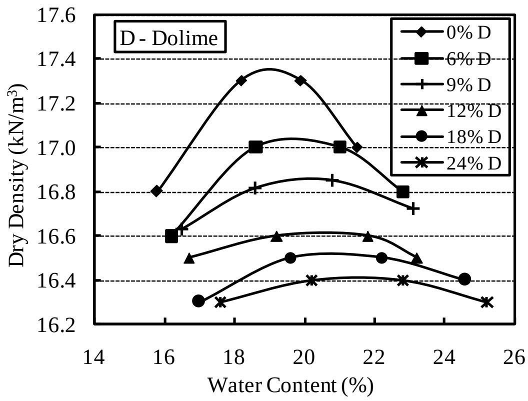

Fig. 1 Modified Proctor compaction curves for various BC soil-dolime mixes

3.4 Unconfined Compressive Strength

Figs. 2 and 3 show the variation of unconfined compressive strength with dolime content and curing period, respectively, for different BC soil-dolime mixes. The compressive strength increases with increase in dolime content up to 18% and decreases thereafter (Fig. 2). The UCS value increases continuously with curing period for all mixes (Fig. 3); however, the rate of gain of strength is high during the first 14 days, but slows down thereafter.

The strength gain in BC soil-lime mix is mainly due to the cementitious reaction which immediately begins by addition of lime in clay. The calcium ions of lime react with the silica and alumina present in the soil and form $CaO \cdot SiO_2 \cdot H_2O$ and $CaO \cdot Al_2O_3 \cdot H_2O$ known as C-S-H and C-A-H gel. These products act as a glue to bind the soil particles together resulting in a stabilized mass. With an increase in dolime content, the formation of quantity of gel increases, thus increasing the compressive strength. As the pozzolanic reaction is a slow reaction, with an increase in curing period, again the formation of quantity of gel increases, thus increasing the compressive strength.

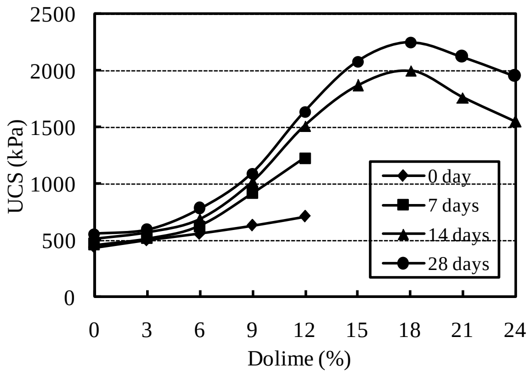

Fig. 2 Variation of UCS with dolime content for different curing periods

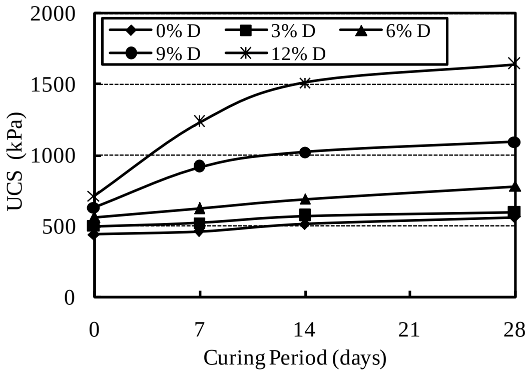

Fig. 3 Variation of UCS with curing period for different dolime contents

Next, an attempt is made to develop a generalized relationship between UCS values (q_u), dolime percent (D) and curing period (t) in days. For this purpose, UCS values are plotted against ($D \cdot t^{0.2}$) for all 18 mixes – 6 dolime contents (3, 6, 9, 12, 15 and 18%) and 3 curing periods (7, 14 and 28 days) – as shown in Fig. 4. A good correlation (R^2 = 0.975) was obtained with a linear relationship of the form:

$$q_u \text{ (kPa)} = 62 (D \cdot t^{0.2}) + 152 \quad (1)$$

where R^2 is the coefficient of determination.

For second series of UCS tests, 7-day (3 days curing and 4 days soaking in water) UCS values of BC soil with 6%, 9% and 12% dolime were 418, 788 and 980 kPa, respectively. The specimens with 0% and 3% dolime content collapsed during soaking in water. IRC: 51 [8] recommends a minimum 7-day UCS value of 700 kPa for soil-lime mix to satisfy strength and durability criteria for use in the subbase course. BC soil stabilized with a minimum dolime content of 9% satisfies these criteria; hence, BC soil + 9% dolime mix is recommended as the optimum mix for use in the subbase course.

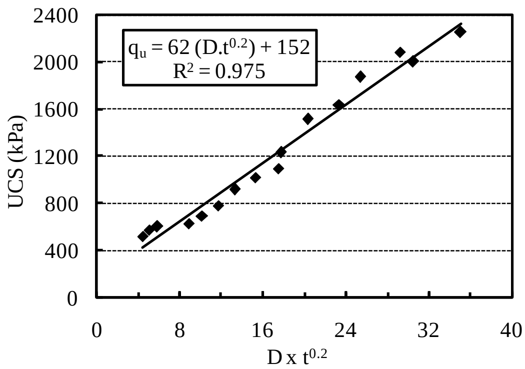

Fig. 4 Unique relationship accounting for the variation of UCS with dolime content and curing period

3.5 California Bearing Ratio (CBR)

The soaked CBR values obtained for various BC soil-dolime mixes are given in Table 2. The CBR values increase as dolime content and curing period increase. Dolime in the mix provides calcium ions for pozzolanic reaction giving rise to C-S-H gel which bind the particles efficiently and impart strength to the mix. With an increase in dolime content and curing period, the gel formation increases leading to higher CBR value.

Table 2 Soaked CBR values for BC soil-dolime mixes

Dolime (%)	Curing (days)*	CBR (%)
0	4	2.3
3	7	9
6	7	26
9	7	58
9	14	73

*Curing period includes 4 days soaking in water prior to testing

IRC: 51 [8] recommends a minimum of 30% CBR for soil-lime mix after 7-day (3 days curing + 4 days soaking in water) curing for its use in the subbase course of flexible pavements with traffic exceeding 2 million standard axles (msa). BC soil stabilized with a minimum dolime content of 9% satisfies this criterion. Hence, BC soil + 9% dolime mix is recommended as the optimum mix for use as a subbase material.

3.6 Triaxial Shear Strength

The deviator stress σ_d at failure and elastic secant modulus E for BC soil and optimum mix (BC soil + 9% dolime) at different curing periods as determined by UU triaxial tests are plotted against the cell pressure in Figs. 5 and 6, respectively. Both the deviator stress at failure and modulus of elasticity increase linearly with the cell pressure at all curing periods. As expected, an increase in confinement of the specimen increases its failure stress. Also, an increase in confinement of the specimen reduces the lateral strain and hence, the specimen can bear a given axial stress at a lower strain level resulting in a higher value of the elastic modulus. Because pozzolanic reaction is a slow process, an increasingly higher quantity of C-S-H gel is formed with an increase in curing period. Higher gel quantity binds the soil particles more efficiently leading to an increase in the stiffness and the failure stress.

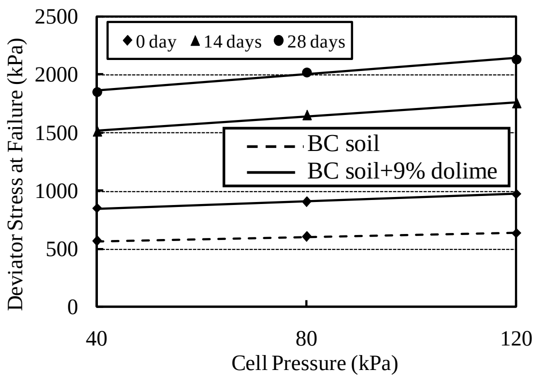

Fig. 5 Relationship between deviator stress at failure and cell pressure for different curing periods

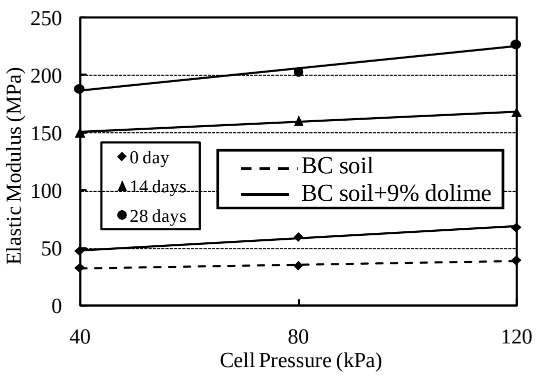

Fig. 6 Relationship between elastic modulus and cell pressure for different curing periods

Similar linear relationships for σ_d and E with cell pressure are reported for various subbase materials by Kumar et al. [11] and Sinha [12]. The deviator stress at failure and elastic modulus after 28 days of curing for the optimum mix (BC soil + 9% dolime) are found to be higher than that of the conventional subbase materials evaluated by Sinha [12].

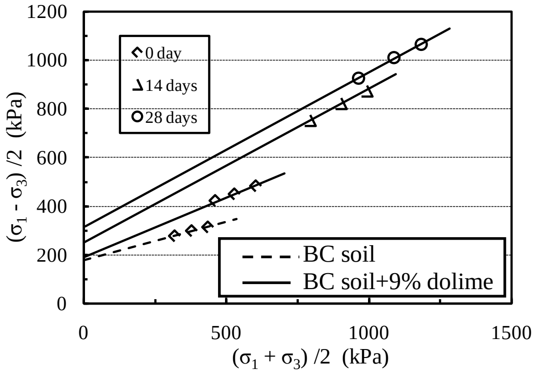

Fig. 7 Modified failure envelopes at various curing periods for the optimum mix and BC soil

Table 3 Cohesion and angle of friction for BC soil-dolime mixes

Dolime (%)	Curing (days)	Cohesion (kPa)	Angle of friction (degree)
0	0	188	18.4
9	0	208	29.0
9	14	315	39.3
9	28	403	39.6

Modified failure envelopes (k_f - line) for BC soil and optimum mix (BC soil + 9% dolime) at various curing periods are shown in Fig. 7 and the calculated total strength parameters are given in Table 3. The angle of friction for lime stabilized fine-grained soils has been reported to be 25°-35° in the literature [13]. The angle of internal friction of BC soil increases significantly with the addition of dolime up to first 14 days of curing but does not change much thereafter. The friction angle increases due to alterations in soil texture, essentially caused by a quick flocculation-agglomeration mechanism of lime stabilization [14]. On the other hand, cohesion does not show much variation with the addition of dolime in the beginning (at 0 days) but increases significantly with increasing curing period. The cohesion increases due to development of bonding between the soil particles owing to slow pozzolanic reaction. Similar behaviour of the strength parameters of soil-lime mix has been reported in literature [15].

3.7 Correlation of σ_d and c with UCS Values

An attempt is made to develop empirical correlations to determine the parameters obtained from triaxial tests such as failure deviator stress and cohesion as a function of unconfined compressive strength (UCS) values. Such an attempt, no doubt, is guided by the fact that the above mentioned triaxial test parameters are related to strength as do the UCS values.

The deviator stress at failure σ_d as obtained from undrained triaxial tests on all 12 mixes (BC soil at 0 day curing and BC soil + 9% dolime mix at 0, 14 and 28 days curing for 3 confining pressures) is plotted against UCS values in Figure 8. The figure shows that σ_d can be expressed as a linear function of UCS for all confining pressures. A similar relationship obtained by Ghosh and Subbarao [16] for fly ash stabilized with lime (0 to 10%) and gypsum (0 to 1%) for 28 days curing period is also shown in this figure. Based on Figure 8, an empirical correlation for σ_d (kPa) is developed as a function of unconfined compressive strength q_u (kPa) and confining pressure σ_3 (kPa) as given below:

$$\sigma_d = 1.95q_u + 2\sigma_3 - 457.7, \quad R^2 = 0.94 \qquad (2)$$

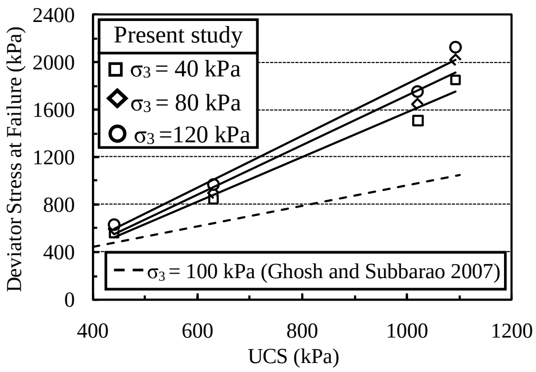

Fig. 8 Relationship between deviator stress at failure and UCS

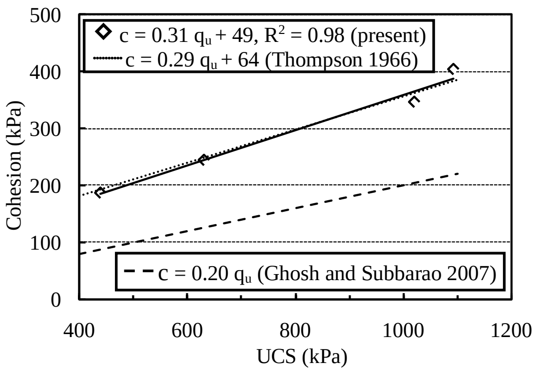

Fig. 9 Relationship between cohesion and UCS

Similarly, a linear relationship between cohesion (c) and UCS (q_u) is obtained in Figure 9 for BC soil-dolime mixes as given below:

$$c = 0.31q_u + 49, R^2 = 0.98 \qquad (3)$$

where c and q_u are in kPa. A similar relationship between UCS and c was reported by Thompson [15] for lime stabilized soils and by Ghosh and Subbarao [16] for fly ash-lime-gypsum mix.

3.8 Resilient Modulus

Resilient modulus (M_r) of various trial mixes was determined for fifteen different stress levels applicable for base/subbase layers as per AASHTO T-307 [10] test procedure. The AASHTO test procedures recommend analysis of resilient modulus test results by using different regression models. Several constitutive models are available in the transportation literature for M_r calculation and prediction. Four stress-dependent models as shown in Table 4 are considered in this study.

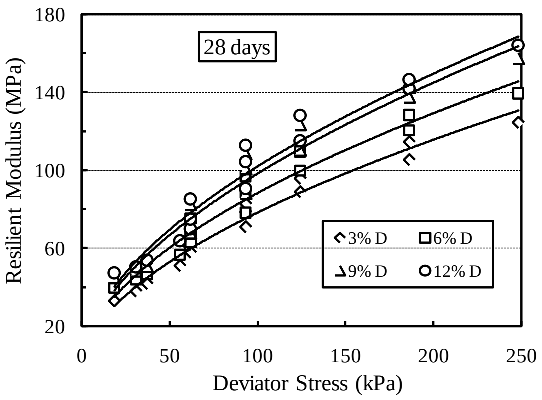

Fig. 10 Variation of resilient modulus with deviatoric stress for different dolime contents at 28 day curing period

Resilient modulus test results are plotted against deviator stress, major principal stress and bulk stress in Figs. 10, 12 and 13, respectively, for different soil-dolime mixes. The influence of deviatoric stress on resilient modulus (M_r) of the optimum mix for different curing periods is shown in Fig. 11. There is an increase in M_r values with increase in dolime content. However, the rate of increase is high in the beginning and slows down after 9% dolime content. The resilient modulus of soil-dolime mixes increases continuously with curing period. The amount of gel formation in the pozzolanic reaction increases with increase in curing period which binds the soil particles more efficiently resulting in higher stiffness.

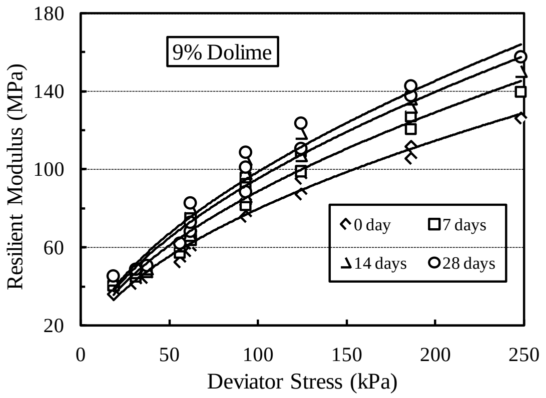

Fig. 11 Variation of resilient modulus with deviatoric stress for different curing periods at 9% dolime content

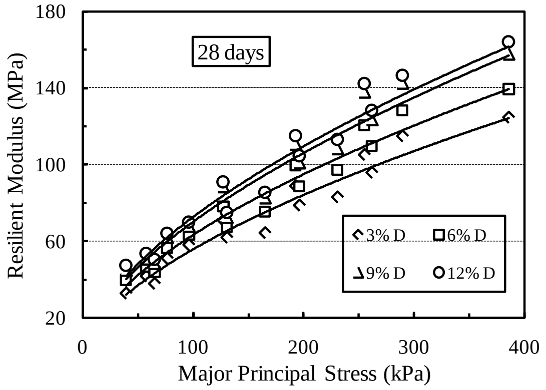

Fig. 12 Variation of resilient modulus with major principal stress for different dolime contents at 28 day curing period

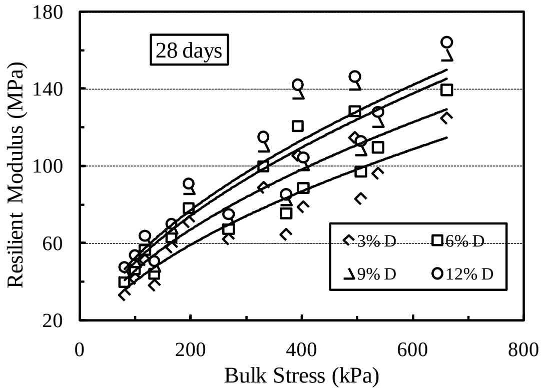

Fig. 13 Variation of resilient modulus with bulk stress for different dolime contents at 28 day curing period

The residual sum of squares (rss) and the coefficient of determination (R^2) obtained from the non-linear regression analysis were used to compare the "goodness of fit" for the four models. The regression constants obtained were used for determining the predicted resilient modulus of the mixes. A graph was drawn between measured resilient modulus and predicted resilient modulus, and the corresponding R^2 and rss values were determined as shown in Table 4. Comparison between the four models shows that the three parameter model provided a best fit regression equation for the determination of resilient modulus of dolime stabilized soil.

Table 4 Stress based models with R^2 and rss values

Model	R^2	rss
$\frac{M_r}{P_a} = k_1\left(\frac{\sigma_3}{P_a}\right)^{k_2}\left(\frac{\sigma_d}{P_a}\right)^{k_3}$	0.988	1264
$M_r = k_4\,\sigma_d^{k_5}$	0.963	3896
$M_r = k_6\,\sigma_1^{k_7}$	0.954	4566
$M_r = k_8\,\theta^{k_9}$	0.804	17240

P_a is atmospheric pressure equals to 101.3 kPa
k_1, k_2, k_3, k_4, k_5, k_6, k_7, k_8 are model constants

Table 5 Model constants of three parameter model for different dolime content and curing period

$\frac{M_r}{P_a} = k_1\left(\frac{\sigma_3}{P_a}\right)^{k_2}\left(\frac{\sigma_d}{P_a}\right)^{k_3}$				
Curing days	Dolime (%)	k_1	k_2	k_3
28	3	0.817	0.112	0.478
28	6	0.930	0.141	0.443
28	9	1.037	0.143	0.452
28	12	1.074	0.145	0.444
0	9	0.829	0.108	0.444
7	9	0.929	0.129	0.445
14	9	1.002	0.142	0.447

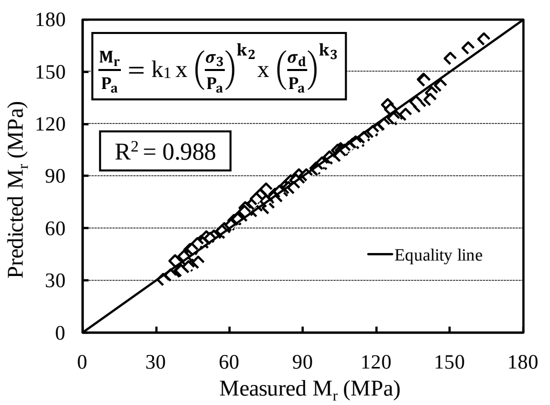

Fig. 14 Predicted M_r versus measured M_r for three parameter model

Model constants (k_1, k_2 and k_3) of the three parameter model obtained for different soil-dolime mixes were given in Table 5. Figure 14 shows the graph between predicted M_r using three parameter model and actual M_r of all the soil-dolime mixes for fifteen different stress levels.

4. CONCLUSIONS

The geotechnical characteristics of compacted

BC soil-dolime mix are studied for different curing periods. Empirical correlations are developed to estimate UCS, triaxial test shear strength parameters and resilient modulus. The following conclusions are drawn:

- With the increase in dolime content, optimum moisture content of the mix increases, maximum dry density decreases and the compaction curve becomes flatter. UCS values increase with an increase in dolime content up to 18% and decrease thereafter. UCS increases rapidly with the increase in curing period up to first 14 days for all mixes. However, the rate of gain of strength decreases thereafter.
- The soaked CBR value of BC soil increases from 2.3 to 73 with the addition of 9% dolime. Based on UCS and CBR test results, BC soil + 9% dolime mix is recommended as the optimum mix for use in subbase course of flexible pavement. Elastic modulus and deviator stress at failure in the triaxial test on the optimum mix after 28 days of curing were higher than that of conventional subbase materials.
- The deviator stress at failure and modulus of elasticity increase linearly with the cell pressure at all curing periods. Simple relationships are proposed to estimate design parameters such as deviator stress at failure and cohesion from UCS test results.
- Resilient modulus of the soil-dolime mixes increases with the increase in dolime content and curing period. The performance of four stress based models were compared and observed that the three parameter model outperformed the other models with high coefficient of determination values providing good fit model constants for the prediction of resilient modulus.

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