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Comprehensive Review on Strength Characteristics of Bentonite-Lime-Gypsum Mix Reinforced

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ABSTRACT

This paper presents the strength characteristics of a reference mix containing bentonite, lime and gypsum and reinforced with coir fibre. The content of lime, gypsum and coir fibre was varied from 0 to 10%, 0 to 10% and 0 to 2%, respectively. The curing period was varied from 3 to 28 days. Cylindrical specimens were prepared for conducting the unconfined compressive strength and unconsolidated undrained triaxial tests. The results reveal that the addition of 8% lime to bentonite increased the deviator stress, friction angle and cohesion. Addition of 4% gypsum to bentonite +8% lime mix increased the deviator stress, decreased the friction angle and increased the cohesion. Further, addition of coir fibres to the reference increased the unconfined compressive strength, deviator stress and cohesion up to a fibre content of 1.5%. The two parameter hyperbolic model can be used for predicting the stress–strain response of bentonite-lime-gypsum-coir fibre mix with appropriate selection of model parameters. The scanning electron micrographs and energy-dispersive X-ray studies confirms the formation of cementing compounds responsible for the improved behaviour. The improved strength characteristics of the reference-coir fibre mix can be used for short term stability related problems.

Keywords: Bentonite, lime, gypsum, strength characteristics, constitutive relationship, SEM–EDAX studies

INTRODUCTION

In India, adequate deposit of black cotton soil, bentonite, mar and kabar exists in a state like Rajasthan, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka and Tamilnadu (Ameta et al., 2007). These soils exhibit high swelling, shrinkage, compressibility and poor strength in contact with water leading to cracks in overlying temporary roads. The current practices to deal with these soils are to modify the properties with the use of some additives like lime and gypsum/phosphogypsum. To further improve the mechanical properties of these soils, a variety of materials are used as reinforcement such as metallic elements, geosynthetics and other materials. The majority of reinforcement materials available in the market are polymeric in composition. These products generally have a long life and do not undergo biological degradation, but are liable to create environmental problems from their manufacture till the end use. In the light of this, the use of biodegradable natural fibers is gaining popularity in India. In the present paper, an attempt has been made to study the unconfined compressive strength of bentonite-lime phosphogypsum mixture reinforced with sisal fibers for possible use in ground improvement.

Reinforced soil is a composite material, where soil is reinforced by the elements which can take tension. The incorporation of reinforcement in the soil mass is aimed at either reducing or suppressing the tensile strain which might develop tensile stresses due to the movement of traffic on temporary roads. As such, soils possess very low tensile strength which may be significantly improved by providing reinforcement in the direction of tensile strains. Many researchers (Andersland and Khattack, 1979; Maher and Ho, 1994; Al-Wahab and El-Kedrah, 1995; Nataraj and McManis, 1997; Zeigler et al., 1998; Feuerharmel, 2000; Kumar and Tabor, 2003; Casagrande et al., 2006) in the past have shown that fiber reinforcement can significantly improve engineering properties of clay. Maher and Ho (1994) reported that the peak compressive strength of kaolinite clay increased by the inclusion of randomly distributed paper pulp fibers. Al-Wahab and El-Kedrah (1995) reported that fiber reinforcement decreased the swelling potential of low plasticity clay. Casagrande et al. (2006) reported that the inclusion of randomly distributed fibers increased the peak shear strength of bentonite. The use of sisal fibers as soil reinforcement is a cost-effective method of soil improvement in countries like India and Bangladesh, where it is cheap and locally available.

Krishna and Sayida (2009) reported the improvement in unconfined compressive strength of black cotton soil with the addition of sisal fibers. Manjunath et al. (2013) studied the effect of random inclusion of sisal fibers on strength behavior of lime treated black cotton soils and reported an increase in unconfined compressive strength of lime treated expansive soil with the addition of sisal fibers and with the curing period. Priya and Girish (2010) studied the effect of sisal fibers on the compaction behaviour of lime treated black cotton soil and reported a decrease in optimum moisture content and an increase in maximum dry unit weight with the addition of sisal fibers.

They further reported that addition of sisal fibers to lime treated black cotton soil increased the unconfined compressive strength and changed the behaviour from brittle to ductile. Hejazi et al. (2012) reviewed the use of natural and synthetic fibers as a construction and building material. They reported that fiber reinforcement improves the strength and stiffness of the composite soil. Addition of fibers to expansive soils improves the strength. Further, hardly any literature is available to study the effect of sisal fibers on the unconfined compressive strength of Bentonite-lime phosphogypsum mixture. The present study tries to fill this gap. In the present work, the effect of sisal fibers on the unconfined compressive strength of Bentonite lime-phosphogypsum mixture is studied. The load deformation response in various cases is plotted, compared and discussed for possible use in ground improvement.

LITERATURE REVIEW

Expansive soils pose serious problems to structures constructed over them in terms of differential settlements, poor strength and high compressibility especially during rainy season. The current approach adopted to deal with such soils is to modify the properties with admixture like lime and gypsum to make them suitable for the construction of overlying structures. To further improve the mechanical properties of these stabilized soils, coir fibres holds promise. The chapter briefly reviews the literature on Bentonite lime mixes, Bentonite-lime-gypsum mixes and Bentonite-lime-gypsum mixes reinforced coir fibres.

Studies on Expansive Soil-Lime Mixes

Bentonite soil is a highly expansive as it exhibits high swelling, shrinkage, compressibility and poor strength in contact with water. The current approach adopted to deal with such soils is to modify the properties with admixture like lime and gypsum to make them suitable for the construction of overlying structures. Bell (1996) studied the lime stabilization of clay minerals and soils. They stabilized the most frequently occurring minerals in clay deposits, namely, kaolinite, montmorillonite and quartz and treated two other soils, namely, till and laminated clay. The author mentioned that the clay soil can be stabilized by addition of small percentages, by weight, of lime, to improve the engineering properties of the soil and producing an efficient construction material. The author reported that the expansive clay minerals such as montmorillonite exhibited a high cation exchange capacity. The cation exchange capacity of montmorillonite was reduced when lime was added but at 6 % addition, by weight, it began to increase.

He observed an increase in optimum moisture content and a decrease in their maximum dry unit weight of montmorillonite with the addition of varying percentages of lime. Samples of montmorillonite were mixed with 2, 4, 6, 8 and 10 % lime at their optimum moisture content and dry unit weight. They were sealed in plastic containers and kept for curing for one year, these samples were later analyzed using an electron microscope. The author observed the presence of silicon and aluminium in the montmorillonite-lime mixes. The author noticed the formation of calcium aluminium hydrates of the form CAH, C4AH13 or CAH10 along with the calcium silicate hydrates of the form CSH in the montmorillonite-lime mixes. The amount of strength increase in the clay soil with the addition of lime was dependent on the pozzolans present.

The improvement of strength was due to the reaction of the desirable pozzolans in the montmorillonite-lime mix. The author also mentioned that the absolute amount of silica or alumina required to sustain pozzolanic reaction in soils is relatively small. Hence clays generally show a significant increase in strength when lime is used for stabilization. Expansive clays respond more quickly to strength increase. For instance, montmorillonite showed a rapid initial increase in unconfined compressive strength with small additions of lime in less time than one to which a higher content of lime was added. However, the increase in the strength of expansive soil with the addition of lime was not linear, but reduced with excessive addition of lime.

The author studied the effect of curing on the strength improvement of clay soils, mentioning a rapid increase in strength during first 7 days of curing, and thereafter a slow or constant rate of increase in the strength. The author mentions the importance of achieving a homogenous soil-lime mixture to avoid deviations. The montmorillonite underwent an initial increase in Young's modulus with up to 4% addition of lime, after which there was a general decline. The maximum value of Young's modulus of montmorillonite appeared to be reached after 14 days, after which a gradual decline occurred. The strength was greatly influenced by the length of time curing and temperature. They also reported that montmorillonite clays respond much more rapidly to lime stabilization, and so exhibit earlier gains in strength than kaolinite clays. Kumar et al. (2007) studied the influence of fly ash, lime, and polyester fibres on compaction and strength properties of expansive soil and reported a decrease in maximum dry unit weight and increase in optimum moisture content with the increase in lime content. The fall in density was more significant at lower percentages of lime than at higher percentages of lime.

Studies on Expansive Soil-Lime-Gypsum Mixes

The effect of stabilization of expansive soil with lime and gypsum has been individually reviewed in the previous sections. Researchers (Abdi and Wild, 1993; Wild et al., 1993; Kinuthia et al., 1999) reported studies on clay-lime-gypsum mixes. They have reported the improvement in the behavior of the clay with the addition of lime and gypsum. Studies of Kinuthia et al. (1999) shows the effect of sulphates on lime stabilized kaolin clay. They reported that complicating effects with regard to the modified cation exchange processes and/or the pozzolanic reactions with the influence of presence of sulphates either in the parent stabilization material, or in the water used in the mixing and/ or in the ground water. The changes were reported to vary with, among other factors, the sulphates concentration, the metal cation type, the amount of available calcia and alumina and hence the amount of lime added and the type, the amount and the particle size distribution of the clay.

The presence of gypsum in lime-stabilized clay soil provides further Ca^2+ cations in addition to those donated by the lime, as well as the introduction of SO^2- anions. The extra Ca^2+ cations lead to an increase in the overall number of cations attracted to the clay particle surfaces. In the absence of sulphates, formation of following compounds was reported: calcium silicate hydrates (CSH) gel, crystalline or semicrystalline calcium aluminate hydrates (C_4AH_{13}), calcium alumino silicate hydrates (C_2ASH_8) and carbo-aluminate hydrates depending on the availability of CO2 or carbonates. They reported that the presence of gypsum leads to the formation of a colloidal product consisting of a complex calcium-sulpho-aluminate-silicate hydrate (CASSH) on the surface of kaolinite clay plates. This surface product, a compound of higher crystallinity, commonly known as ettringite ($C_3A_3CSH_{32}$) was said to nucleate.

The increase in the dry unit weight at higher sulphates content was due to the reduction of flocculation effect by the renewed repulsive forces. The optimum moisture content of the clay-lime mix increased with the increase in the sulphates content. The authors reported that the clay-lime-sulphates mixes would consume more water during mixing operations. Wild et al. (1993) reported the mineralogical and morphological study on the kaolin clay + 6 % lime+ gypsum mixes. They observed formation of small poorly defined ettringite needles on the surface of the clay plates after moist curing of one week.

The boundaries of the needles are diffuse and ill-defined and tend to form a continuum with the clay particle surface. Further increase in the concentration of ettringite was observed with increase in the gypsum content. They also reported formation of larger more clearly defined rods with the increase in the curing period, which grew outwards in to the pore spaces between the clay particles. This resulted in the formation of a dense interconnected network of ettringite rods leading to a dense mat like structure. They reported the difficulty in analyses of ettringite due to decomposition in the microscope and used the EDAX of standard ettringite sample for comparative purposes. The EDAX of the standard ettrinigite of geological origin, consisted of well-formed hexagonal rods up to 2 mm in length as shown in the

Table 1. Table 2.2 EDAX analysis of natural ettringite crystals (after Wild et al., 1993)

Compound	Al	Si	S	Ca
Theoretical ettringite composition	18.2	-	27.3	54.4
	18.2	-	27.7	54.1
	15.1	-	27.0	57.9
	19.5	-	27.3	53.1

Study of the elemental composition of ettringite shows that the predominance of the elements like aluminium, sulphur and calcium. They also reported an increase in the concentration of S and decrease in the concentration of Si with the increase in the gypsum content.

UNCONFINED COMPRESSIVE STRENGTH

The axial stress-strain curve of the bentonite with varying percentages of lime and cured for 3, 7, 14 and 28 days, respectively is shown in Fig. 1 (a). Fig. 1 (b) also contains the axial stress-strain curves for the bentonite cured for 3, 7, 14 and 28 days, respectively. Study of Fig. 1 (a) 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. 1 (a) 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 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. 1(a) reveals that the axial stress at failure increased with the increase in lime content up to

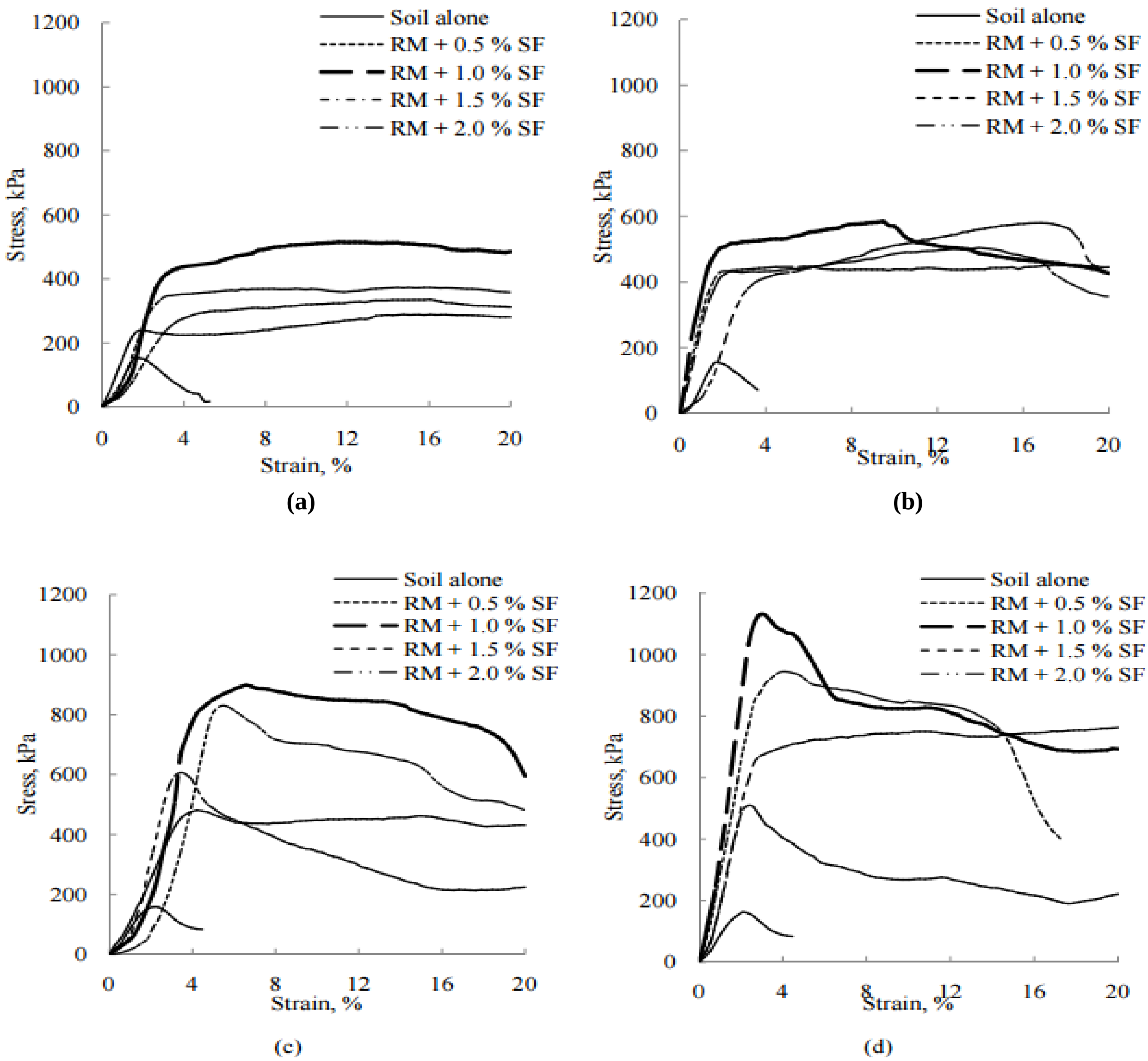

Figure (1): Variation of unconfined compressive strength for reference mix mixed with varying percentages of sisal fibers at (a) 3 days (b) 7 days (c) 14 days (d) 28 days

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 Kumar et al. (2007) where the effect of lime on the unconfined compressive strength of black cotton soil was reported. 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.1 (a).

The axial stress-strain curve of the bentonite + 8% lime mixture with varying percentages of phosphogypsum and cured for 3, 7, 14 and 28 days, respectively is shown in Fig. 1(b). Fig. 1(b) 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. 1(b) reveals that the axial stress at failure increased with the increase in curing period up to 14 days of curing. 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 an increase in axial stress at failure up to 14 days of curing. Beyond 14 days of curing, the formation of ettringite perhaps decreased the unconfined compressive strength.

However, this needs to be verified through SEM study. 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. 1 (b) reveals that the axial stress at failure increased with the increase in phosphogypsum content up to a content of 8%, it further decreased with the phosphogypsum content of 10%. 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 at phosphogypsum content of 1, 2, 4 and 8%, respectively and decreased to 357.65 kPa with the addition of phosphogypsum content of 10%. 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. 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. 1 (b). Since the unconfined compressive strength of the reference mix decreased beyond a curing period of 14 days, it was decided to improve its strength with the addition of sisal fibers. The axial stress-strain behavior of the reference mix reinforced with varying percentages of sisal fibers is shown in Fig. 1 (c). A close examination of Fig. 1 (c) reveals that the axial stress increases with the curing period.

For example, the axial stress of reference mix reinforced with 0.5 % sisal fibers and cured for 3 days was 373.902 kPa which increased to 433.22 kPa, 830.53 kPa and 944.31 kPa, respectively after 7, 14 and 28 days. Similar trend of increase in axial stress at failure was observed for a fiber content of 1, 1.5 and 2%. A close examination of Fig. 1 (c) reveals that the axial stress at failure increased with the increase in fiber content up to a content of 1%. For example, for the reference mix + 0.5% sisal fiber mix cured for 3 days, the axial stress at failure was 373.91 kPa which increased to 515.48 kPa for reference mix + 1% sisal fiber and decreased to 335.90 kPa and 289.20 kPa with the increase in fiber content to 1.5 and 2%, respectively. 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. 1 (c).

The increase in unconfined compressive strength with the addition of sisal fibers up to a fiber content of 1% is attributed to the fact that the cementing gel formed due to the reaction of Bentonite with lime binds the sisal fibers with the Bentonite particles leading to an enhancement in the unconfined compressive strength. Sabat (2012) made similar observations where the effect of polypropylene fiber on the engineering properties of rice husk ash–lime stabilized expansive soil was reported. The unconfined compressive strength decreased beyond a fiber content of 1%. This is attributed to the fact that the formation of lump of fibers due to excessive adhesion and poor contact of fibers with Bentonite particles results in a decrease in unconfined compressive strength. Similar observations were made by Sabat (2012) where the effect polypropylene fiber on the unconfined compressive strength of rice husk ash–lime stabilized expansive soil was reported.

CONCLUSION

A comprehensive review is carried out to study the compaction and unconfined compressive strength of Bentonite stabilized with lime-phosphogypsum and random inclusion of sisal fibers. The study brings forth the following conclusions.

1. The dry unit weight and optimum moisture of Bentonite- lime mix increased with the addition of phosphogypsum.

2. The dry unit weight of the reference mix decreased and the optimum moisture content increased with the addition of sisal fibres.

3. The unconfined compressive strength of the Bentonite increased with the addition of 8% lime. Beyond 8 %, the unconfined compressive strength decreased.

4. The unconfined compressive strength of the Bentonite + 8% lime increased up to 8% phosphogypsum. Beyond 8%, the unconfined compressive strength decreased.

5. The unconfined compressive strength of the reference mix increased with the addition of sisal fibers up to 1%. The trend was reversed after that.

6. The unconfined compressive strength of Bentonite lime-phosphogypsum increased with the addition of sisal fibers and with the increase in curing period.

7. The improvement in post peak region was better for the reinforced sisal fibers as compared to the unreinforced soil.

8. The optimum value of lime content, phosphogypsum content and sisal fiber content in Bentonite- lime phosphogypsum-sisal fiber mixtures may be taken as 8%, 8 % and 1%, respectively.

On the whole, this study has attempted to provide an insight into the compaction and unconfined compressive strength of Bentonite stabilized with lime and phosphogypsum reinforced with sisal fibres. The improved behavior of the Bentonite-lime phosphogypsum-sisal fiber mixture will boost the construction of temporary roads on such problematic soils. Further, its use will also provide environmental motivation for providing a means of consuming large quantities of phosphogypsum and sisal fibers.

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