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Engineering Properties of Bentonite-Lime-Phosphogypsum Composite Reinforced with Treated Sisal Fibers

Sujeet Kumar[1*], Vidya Tilak B.[2], Rakesh Kumar Dutta[2]

RESEARCH ARTICLE

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Abstract

The present work primarily investigates the unconfined compressive strength, the tensile load-diametral strain, the toughness characteristics and the shear strengths of bentonite-lime-phosphogypsum-treated sisal fibre composite. The unconfined compressive strengths and tensile strengths were obtained using the unconfined compressive test and indirect tensile test respectively. The results revealed that the unconfined compressive stress, the deviator stress and the tensile load at failure of bentonite-lime-phosphogypsum composite with untreated sisal fibres could be improved by the successive chemical treatment with sodium periodate, p-aminophenol and sodium hydroxide. The brittleness index and deformability index indicated a change from the brittle to ductile behavior of the bentonite-lime-phosphogypsum-untreated sisal fiber composite, with the chemical treatment.

Keywords

bentonite-lime-phosphogypsum, compressive strength, tensile strength, treated sisal fiber

[1] Department of Civil Engineering, Indian Institute of Technology (BHU), Varanasi – 221005, Uttar Pradesh, India,

[2] Department of Civil Engineering, National Institute of Technology, Hamirpur – 177005, Himachal Pradesh, India,

[*] Corresponding author email: sujeetkumar.ce@gmail.com

1 Introduction

Bentonite is an absorbent aluminium phyllosilicate clay consisting mostly of montmorillonite. It is formed by the weathering of volcanic ash. USA, Greece, Australia, India, Russia and Ukraine have bentonite spreads. These expansive soils pose serious problems to structures constructed over them in terms of differential settlements, poor strength and high compressibility especially during rainy season. Thus, it is treated with additives like lime and phosphogypsum and analysed in detail in our earlier study [1]. The bentonite-lime-phosphogypsum composite, however, posed low tensile strength. One of the possible efforts to improve the tensile strength was that of reinforcing the soil composite. Synthetic fibres, natural fibers, metallic elements and geo-synthetics are a few among them. Owing to the environmental damages, global warming and constant rise in the climate changes caused due to the synthetics manufacturing, the authors have considered to drive a study on natural fibres and their consequent application in construction industry. Natural fibres like banana, sisal, hemp and flax, jute, coconut, bamboo, sponges, wood dusts and oil palm [2] have attracted scientists. Sisal is one such plant fibre produced abundantly in eastern part of India and is used to make ropes and twine. Sisal fiber is fairly coarse and inflexible. It possesses moderately high specific strength and stiffness, durability, ability to stretch, and resistance to deterioration in saltwater [3]. The main disadvantages of natural fibers in composites have been the poor compatibility between fiber and matrix and the relative high moisture sorption. Therefore, chemical treatments are considered in modifying the fiber surface properties.

Various researchers [2–12] have studied the effect of different chemicals and reported improvement in the properties of sisal fibers. Sisal fibers inherently facilitate characteristic surface modification and the hollow helical microstructure of sisal fibers being responsible for the very distinctive failure mechanism reasons the choice of the fiber among many other available natural fiber [13]. The presence of waxy particles on the surface of sisal fibers leads to reduction in the mechanical properties [14]. This motivated the researchers [15–16] to experiment different surface modification techniques such as alkali treatment,

dewaxing, vinyl grafting, etc. A significant reduction in the moisture absorption and improved wettability of Brazilian variety of sisal fibers was observed after surface treatment with NaOH or N-isopropyl-acrylamide solutions [17]. It was further reported that surface alteration, improved thermal and mechanical resistance, improved interfacial adhesion, increased tensile strength of sisal fibers with the treatment. Investigator [18] studied the effect of 5 % NaOH on the sisal fibers and reported an increase of 21 % in flexural strength. The effect of sisal fibers on the compaction and unconfined compressive strength of lime treated black cotton soil was further analysed and was reported that addition of sisal fibers to lime treated black cotton soil increased maximum dry unit weight and the unconfined compressive strength and changed the behaviour from brittle to ductile [19]. Researcher [20] studied the effect of random inclusion of sisal fibers on strength behaviour 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. A decrease in the unconfined compressive strength and increase in the optimum moisture content of bentonite-lime-phosphogypsum with the addition of sisal fibers was reported by [21]. From the literature presented above, it is evident that the engineering properties like compaction, unconfined compressive strength, strength parameters and tensile strength of bentonite-lime-phosphogypsum mix reinforced with sodium periodate, p-aminophenol and sodium hydroxide treated sisal fibers has not been reported so far. The present study attempts to fill this gap.

2 Materials Used and Experimental Procedure

Commercially available bentonite of specific gravity (according to IS 2809:1972 [22] and IS 2720:1980-Part III-sec I [23]), liquid limit, plastic limit, dry unit weight and optimum moisture content of 2.30, 220 % and 39.74 %, 13.95 kN/m^3 and 27.98 % respectively was used. As per Universal Soil Classification System, the clay was classified as clay of high compressibility. Hydrated lime and phosphogypsum were brought from the retailers. The specific gravity of lime and phosphogypsum used was 2.37 and 2.20 respectively. The content of lime and phosphogypsum was varied from 0 to 10 % and 0 to 10 % respectively. The sisal fibers were brought from a local supplier in Bihar, India and were cut into 15 mm in length with scissors. The specific gravity, diameter and tensile strength of the sisal fibers used in this study were 1.40, 0.25 mm and 405.2 N/mm^2 respectively. To remove the surface impurities (wax, natural oils, cellulose, lignin, hemicelluloses, lumen etc.) present on the surface of natural sisal fibers, these fibers were given a prewash with tap water followed by washing in distilled water. The washed sisal fibers were then dried. The chemicals used to treat the sisal fiber were sodium periodate, p-aminophenol and sodium hydroxide and their chemical composition is shown in Table 1.

Table 1 Chemical composition and properties of the chemicals used

Chemical name		
p-Aminophenol	Sodium Periodate ($NaIO_4$)	Sodium Hydroxide (NaOH)
M. W. 109.13 Minimum assay 96.0% (Non-aqueous; Potentiometric) Melting Point about 184^{0}C (decom.) Sulphated ash Max. 2.0 %	M.W. 213.89 Minimum assay - 98.0 % Maximum limits of impurities: Bromate, bromide, chlorate and chloride (*Cl*) – 0.01 % Sulphate (SO_4) – 0.005 % Manganese (*Mn*) – 0.0005 %	M.W. 40.00 Assay – 97 % min Sulphate (SO_4) – 0.05 % max Potassium (*K*) - 0.1 % max Zinc (*Zn*) – 0.02 % max Lead (*Pb*) – 0.001 % max Chloride (*Cl*) – 0.01 % max Carbonate (Na_2CO_3) –2 % max Silicates (SiO_2) – 0.05 % max 10 % Aqueous solution – clear & colourlesses Iron (*Fe*) – 0.001 % max

The dried sisal fibers were first oxidized with 20 % w/v aqueous solution of $NaIO_4$ to produce cellulose aldehyde. After the oxidation, sisal fibers were washed with tap water to remove the excess of $NaIO_4$ (Designated as *SFT1*). This is designated as first stage of treatment. The first stage treated sisal fibers were then immersed in a solution of 5 % p-aminophenol for about 4 h at 70 °C (Designated as *SFT2*). This is designated as second stage of treatment. After the second stage of treatment, sisal fibers were taken out of the beaker and washed first with 1 % solution of sodium hydroxide followed by distilled water (Designated as *SFT3*). This is designated as third stage of treatment. The treated sisal fibers (*SFT1, SFT2, SFT3*) were then dried in open air and finally in an oven at 85 °C. The dried sisal fibers were kept in a sealed container for further use. The standard proctor compaction tests [24] were conducted on bentonite-lime and bentonite-lime- phosphogypsum and bentonite-lime phosphogypsum with and without treated sisal fibers and water was added as needed to facilitate the mixing and compaction process. The unconfined compressive strength, unconsolidated undrained triaxial and tensile strength tests [25-27] were subsequently conducted. For the preparation of specimens for these tests, required quantities of bentonite, lime, phosphogypsum and sisal fibers were mixed in dry state. The sisal fibers have a tendency to lump together. Therefore, a considerable care and time was spent to separate them to get an even distribution of the fibers in the mixture. The dry bentonite-lime-phosphogypsum–sisal fiber mixture was then mixed with the required amount of water corresponding to optimum moisture content. All the mixing was done manually and proper care was taken to prepare homogeneous mixtures at each stage of mixing. The mix was then 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 an air tight polythene bags which were placed inside the desiccator for curing for 3, 7, 14 and 28 days. The specimen was taken out of the desiccator and polythene bag after the desired period of curing and tested for unconfined compressive strength, unconsolidated undrained triaxial and tensile strength. Failed specimens of unconfined compression tests were powdered and sieved through a 45 μm sieve and gold-coated prior to scanning electron micrographs (*SEM*) tests. Energy Dispersive X-ray Analysis (*EDAX*) was simultaneously performed with *SEM*. For easy reference and identification of specimen, specific codification was used. Specimens containing only bentonite and lime (without sisal fiber) were designated by four letter codification. The first letter of codification indicates bentonite; the next three digits indicate percent lime. For example, code *B08L* will indicate bentonite mixed with 8 % lime. For specimens containing bentonite-lime-phosphogypsum (without sisal fiber) was designated by nine letter codification. The first letter of codification indicates bentonite, the next three digits and next to next five digits indicates the percent lime and percent phosphogypsum respectively. For example, code *B08L005PG* will indicate bentonite mixed with 8 % lime and 0.5 % phosphogypsum. For specimens containing sisal fibers, a fifteen letter codification scheme was used. The first letter of codification indicates bentonite; the second three digits and third five digits indicate percent lime and phosphogypsum content respectively. The next four digits indicate the percent sisal fibers. The remaining two digits indicate the chemical treatment. For example, code *B08L005PG05SFT1* will indicate bentonite mixed with 8 % lime, 0.5 % phosphogypsum, 0.5 % sisal fibers and treated with *T1* process.

3 Testing Results and Analyses

3.1 Optimum mix of bentonite-lime-phosphogypsum-sisal fibers

In order to fix the reference mix for the bentonite-lime-phosphogypsum-sisal fiber, a multi-variable approach is used. For this, compaction, unconfined compressive strength and unconsolidated undrained triaxial tests were conducted. The results of compaction for the different proportions of bentonite-lime-phosphogypsum-sisal fiber mixture are shown in Table 2. Study of Table 2 reveals a decrease in the maximum dry unit weight and increase in the optimum moisture content of bentonite with the increase in the lime content. Decrease in the maximum dry unit weight is attributed to the quick reaction of lime with bentonite resulting Base Exchange aggregation and flocculation leading to increase in void ratio of the mixture resulting decrease in the dry unit weight of the mix. The increase in optimum moisture content with the addition of lime to the bentonite is due to additional water held within the flocs resulting from flocculation due to lime reaction. Further from Table 2, it is observed that the maximum dry unit weight and the optimum moisture content increases with the addition of phosphogypsum to the bentonite-lime mix. This increase in the dry unit weight and the optimum moisture content 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. Similar observations were reported on lime-stabilized kaolinite in the presence of sulphates by [28]. A close examination of Table 2 further reveals that the decrease in the dry unit weight and increase in the optimum moisture content with the addition of sisal fiber to the bentonite-lime-phosphogypsum mix is observed. Decrease in dry unit weight and increase in optimum moisture content due to sisal fiber addition is attributed to lower specific gravity and water absorbing tendency of the sisal fibers respectively. Similar observations were observed where the effect of sisal fibers on the black cotton soil and lime treated black cotton soil was analysed by [29]. Thus, from the above discussion, it is observed that there is no clear trend as evident from Table 2 to fix the optimum content of sisal fibers. In order to decide the optimum mix of bentonite-lime-phosphogypsum-sisal fibers composite, it was decided to conduct unconfined compressive strength tests. The results of the unconfined compressive strength of bentonite–lime–phosphogypsum-sisal fiber composite cured for 3, 7, 14 and 28 days respectively are shown in Table 3.

Table 2 Compaction characteristics of bentonite–lime–phosphogypsum with and without treated sisal fiber composite.

Mixes	MDD (kN/m^3)	OMC (%)
B	13.95	27.98
B02L	13.72	29.88
B04L	13.45	31.71
B06L	13.37	31.90
B08L	13.34	32.40
B10L	13.29	33.20
B08L005PG	13.25	32.98
B08L010PG	13.49	33.05
B08L020PG	13.59	33.38
B08L040PG	13.73	33.65
B08L080PG	13.89	33.89
B08L100PG	14.01	34.05
B08L080PG05SF	13.18	31.00
B08L080PG10SF	13.02	33.00
B08L080PG15SF	13.44	36.50
B08L080PG20SF	12.20	38.00
B08L080PG10SFT1	13.17	31.50
B08L080PG10SFT2	13.25	30.60
B08L080PG10SFT3	13.39	29.00

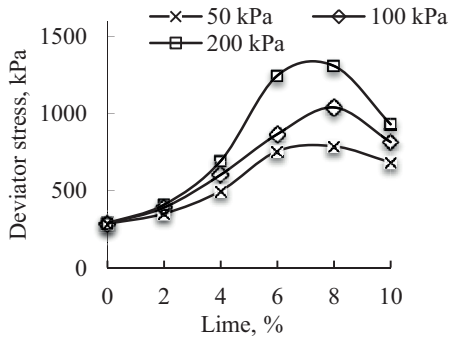
Table 3 Unconfined compressive strength of bentonite–lime–phosphogypsum-sisal fiber composite

Mixes	Unconfined compressive strength (kPa)			
	Curing period (days)			
	3	7	14	28
B	154.25	154.26	158.89	162.03
B02L	248.24	287.51	303.60	311.01
B04L	325.25	345.93	347.04	371.29
B06L	387.47	404.06	535.82	1057.87
B08L	442.77	1378.89	1395.02	1446.11
B10L	306.54	910.85	931.06	950.14
B08L005PG	225.15	467.33	810.00	584.01
B08L010PG	321.67	496.38	817.00	620.36
B08L020PG	363.53	592.26	831.00	661.91
B08L040PG	429.49	652.10	921.00	761.09
B08L080PG	450.24	726.24	1122.30	843.20
B08L100PG	357.65	473.00	635.67	531.52
B08L080PG05SF	373.90	433.21	830.52	944.30
B08L080PG10SF	515.47	584.12	898.63	1129.63
B08L080PG15SF	335.90	580.27	606.54	703.11
B08L080PG20SF	289.20	446.86	481.01	509.66
B08L080PG10SFT1	535.06	640.78	906.73	1138.49
B08L080PG10SFT2	795.53	843.99	934.12	1185.19
B08L080PG10SFT3	416.91	554.30	906.23	954.22

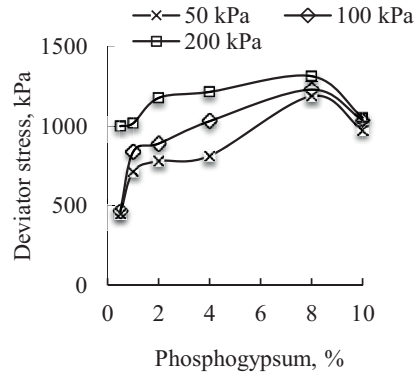
Study of Table 3 reveals that at a curing period of 3 days, the unconfined compressive strength of the bentonite increased with the increase in lime content up to 8 %. Beyond a content of 8 %, the unconfined compressive strength decreased. Similar trend was observed for other curing periods of 7, 14 and 28 days respectively. The increase in unconfined compressive strength with the curing period is attributed to the pozzolanic reactions of lime with the bentonite leading to increase in strength. The decrease in strength beyond a lime content of 8 % is attributed to the platy shapes of the unreacted lime particles in bentonite. Therefore a mix *B08L* was chosen for studying the unconfined compressive strength by varying the content of phosphogypsum. Table 3 reveals that the increase in the unconfined compressive strength was up to a phosphogypsum content of 8 % and a curing period of 14 days and beyond this the trend was reverse. The increase in compressive strength 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 unconfined compressive strength up to 14 days of curing. Beyond 14 days of curing, the formation of ettringite perhaps decreased the unconfined compressive strength. Therefore, a mix *B08L080PG* was chosen for studying the unconfined compressive strength by varying the content of sisal fibers. Table 3 further reveals that the unconfined compressive strength increased with the addition of sisal fibers up to a fiber content of 1 %. This is attributed to the fact that the cementing gel formed due to the reaction bentonite with lime, binds the sisal fibers with the bentonite particles leading to an enhancement in the unconfined compressive strength. The unconfined compressive strength decreased beyond a fiber content of 1 %. This may be due to formation of lump of fibers due to excessive adhesion and poor contact of fibers with bentonite particles resulting decrease in unconfined compressive strength. The above discussion reveals that the mix *B08L080PG10SF* is the optimum one.

In order to validate that the mix *B08L080PG10SF* was really the optimum mix, it was decided to conduct unconsolidated undrained triaxial tests. The results of the deviator stress obtained from the triaxial tests with varying percentage of lime, phosphogypsum, sisal fibers and chemically treated sisal fibers and cured for 28 days are shown in Fig. 1(a) to (d) respectively. The strength parameters are shown in Table 4. Study of Fig. 1(a) reveals that the deviator stress at failure increased with the increase in lime content up to a content of 8 %. Beyond a lime content of 8 %, the deviator stress decreased. The trend was consistent at other confining pressure also as evident from Fig. 1(a). The improvement in deviator stress at failure up to lime content of 8 % is attributed to that formation of cementing compound due to pozzolanic reaction. The decrease in deviator stress beyond a lime content of 8 % is attributed to decrease in cohesion of mix as evident from Table 4. Therefore, on the basis of the results of the compaction, unconfined compressive strength and triaxial tests, the mix *B08L* was chosen for studying the variation in deviator stress at failure by varying the content of phosphogypsum. The results of the deviator stress at failure of the mix *B08L* with varying percentage of phosphogypsum and at a confining pressure 50, 100 and 200 kPa respectively is shown in Fig. 1(b). This figure reveals that the deviator stress at failure increased up to a phosphogypsum content of 8 % and the trend was reverse after this. Decrease in the deviator stress beyond 8 % phosphogypsum perhaps is attributed to the possible effect of sulphates which reduce the formation of the pozzolanic compounds leading to a decrease in the cohesion of the mix as evident from Table 4. Figure 1(b) further reveals that the deviator stress of the mix *B08L005PG* is less than that of *B08L*. This may be due to the effect of impurities and sulphates present in the phosphogypsum. Therefore, on the basis of the results shown in Figs. 1(a) and 1(b), a mix of *B08L080PG* was chosen for studying the variation in deviator stress by varying the sisal fibers. The results are shown in Fig. 1(c). This figure reveals that the deviator pressures too. The increase in deviator stress at failure is due to the reinforcing action of the sisal fibers leading to increase in the deviator stress at failure. The decrease in deviator stress beyond a fiber content of 1 % is attributed to the formation of lump of fibers

due to poor contact with bentonite particles. Therefore, on the basis of the multi-variable approach stated in earlier section, a mix of *B08L080PG10SF* is conclusively the optimum mix which has been used for further study.



(a)



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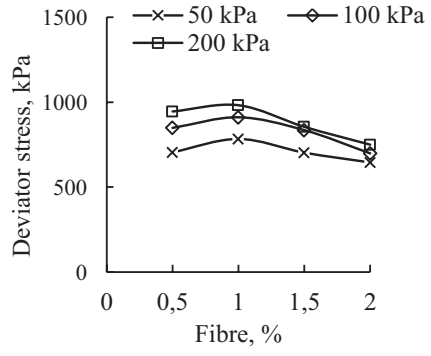

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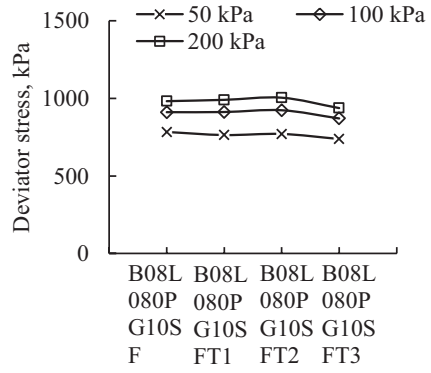

(d)

Fig. 1 Deviator stress with varying percentage of (a) lime (b) phosphogypsum (c) sisal fibre (d) treated sisal fibre

Table 4 Strength parameter of various mixes from unconsolidated undrained triaxial test

Mixes	Cohesion, kPa	Friction angle, degrees
B	139.96	0.78
B08L	144.16	39.71
B10L	143.34	35.03
B08L080PG	421.24	17.42
B08L100PG	382.63	12.22
B08L080PG10SF	234.04	23.75
B08L080PG10SFT1	215.71	25.81
B08L080PG10SFT2	214.08	26.48
B08L080PG10SFT3	218.90	23.81

3.2 Effect of chemical treatment of sisal fibers on compaction

The untreated sisal fibres and the treated sisal fibres were successively added to *B08L080PG* for studying the compaction behaviour. The results of the compaction are also shown in Table 2. Study of this table reveals that the optimum moisture content of the optimum mix *B08L080PG10SF* decreased with the chemical treatment. For example, the optimum moisture content of the mix *B08L080PG10SF* was 33.00 %. The optimum moisture content decreased to31.50 %, 30.60 % and 29.00 % for the mixes *B08L080PG10SFT1*, *B08L080PG10SFT2* and *B08L080PG10SFT3* respectively. This decrease in the optimum moisture content of the optimum mix B08L080PG10SF can be attributed to the decrease in the moisture absorption tendency of the sisal fibers due to the chemical treatment. It is further evident from Table 2 that a mix *B08L080PG10SFT3* absorbs less water in comparison to other mixes *B08L080PG10SFT1, B08L080PG10SFT2*. This is perhaps due to the fact that the third stage of treatment decreases the tendency of sisal fibers to absorb water better in comparison to second and first stage of treatment. Table 2 further reveals that the maximum dry unit weight of the optimum mix *B08L080PG10SF* increased with the chemical treatment. For example, maximum dry unit weight of the optimum mix B08L080PG10SF was 13.02 kN/m³. This increased to 13.17 kN/m³, 13.25 kN/m³ and 13.39 kN/m³ for the mixes *B08L080PG10SFT1*, *B08L080PG10SFT2* and *B08L080PG10SFT3* respectively. This increase in the dry unit weight of the optimum mix *B08L080PG10SF* with the addition of chemically treated fibers is attributed to the removal of surface impurities (wax, natural oils, cellulose, lignin, hemicelluloses, and lumen) from the surface of sisal fibers due to chemical treatment. It should be noted that for the mix *B08L080PG10SFT3*, the dry unit weight is higher in comparison to other mixes *B08L080PG10SFT1, B08L080PG10SFT2* owing to the surface deposition of heavier chemicals on the sisal fibres.

3.3 Effect of chemical treatment of sisal fibers on unconfined compressive strength

The untreated sisal fibres and the treated sisal fibres were successively added to *B08L080PG* for studying the unconfined compressive strength. The results of the unconfined compressive strength are also shown in Table 3. Study of this table reveals that for a curing period of 3 days, the unconfined compressive strength of the mix *B08L080PG10SF* was 515.47 kPa which increased to 535.06 kPa and 795.53 kPa for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* respectively. The improvement in unconfined compressive strength of the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* is attributed to the conversion of hydroxyl groups present in the cellulose of sisal fiber to C=O group due to oxidation reaction which is further converted to C=N with the coupling reaction of amino group of p-aminophenol. This chemical process leads to the removal of impurities like wax, oil and reduction in size and diameter of the loose materials deposited on the surface of the sisal fibers. Removal of impurities makes the surface cleaner and surface irregularities become clear leading to improved interaction of fibers with the bentonite-lime-phosphogypsum mix. The unconfined compressive strength for the mix *B08L080PG10SFT3* decreased to 416.91 kPa. This reduction in the unconfined compressive strength for the mix *B08L080PG10SFT3* is due to the delignification and the smoothening of fiber surface. Study of Table 3 further reveals that the unconfined compressive strength of the mixes *B08L080PG10SFT1*, *B08L080PG10SFT2* and *B08L080PG10SFT3* increased with the increase in curing period. This increase in unconfined compressive strength with the increase in curing period is attributed to the time dependent pozzolanic reaction between soil silica and lime leading to the formation of cementing gel which improves the adhesion in composite.

3.4 Effect of chemical treatment of sisal fibers on deviator stress

The untreated sisal fibres and the treated sisal fibres were successively added to *B08L080PG* for studying the variation of deviator stress. The results are shown in Figure 1(d) and Table 5, study of which reveals that for a curing period of 28 days, the deviator stress at failure of the mix *B08L080PG10SF* was 783.58 kPa which changed to 763.59 kPa, 770.59 kPa and decreased to 738.21 kPa for the mixes *B08L080PG10SFT1, B08L080PG10SFT2* and *B08L080PG10SFT3* respectively. Similar trend was observed at other confining pressures also. The increase in deviator stress at failure of the mixes *B08L080PG10SFT1, B08L080PG10SFT2* and the decrease in deviator stress at failure for the mix *B08L080PG10SFT3* is attributed to the removal of surface impurities and the smoothening of fiber surface respectively. The strength parameters for the mixes *B08L080PG10SFT1*, *B08L080PG10SFT2* and *B08L080PG10SFT3* are shown in Table 4.

Table 5 Summary of triaxial test results of optimum mix reinforced with treated sisal fibers

Mixes		B08L080 PG10SF	B08L080 PG10SFT1	B08L080 PG10SFT2	B08L080 PG10SFT3
Confining pressure, kPa					
Dev. Stress, kPa	50	783.58	763.59	770.59	738.21
	100	911.08	912.10	923.52	870.72
	200	982.09	990.57	1004.53	937.51

Study of Table 4 reveals that the friction angle of the optimum mix *B08L080PG10SF* increased with the chemical treatment up to second stage of treatment. The friction angle decreased beyond second stage of chemical treatment. For example the friction angle of the optimum mix *B08L080PG10SF* was 23.75^0 which increased to 25.81^0 and 26.48^0 for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* respectively and decreased to 23.81^0 for the mix *B08L080PG10SFT3*. Table 4 further reveals that the cohesion of the optimum mix B08L080PG10SF was 234.04 kPa which decreased to 215.71 kPa and 214.08 kPa for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* respectively and increased to 218.90 kPa for the mix *B08L080PG10SFT3*.

3.5 Effect of chemical treatment of sisal fibers on tensile load-diametral strain behaviour

The untreated sisal fibres and the treated sisal fibres were successively added to *B08L080PG* for studying the variation of tensile load and diametral strain at failure. The specimen prepared was cured for 3, 7, 14 and 28 days. The results are shown in Table 6. Study of this table reveals that for a curing period of 3 days, the tensile load at failure of the mix *B08L080PG10SF* was 0.06 kN which increased to 0.07 kN and 0.09 kN for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* respectively. The improvement in tensile load at failure for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* is attributed to the removal of impurities from the surface of the fibers leading to improved interaction with the bentonite-lime-phosphogypsum mix. The tensile load at failure for the mix *B08L080PG10SFT3* decreased to 0.08 kN. This reduction in the tensile load at failure for the mix *B08L080PG10SFT3* is perhaps attributed to the delignification and the smoothening of fiber surface. Study of Table 6 further reveals that the tensile load at failure of the mixes *B08L080PG10SFT1*, *B08L080PG10SFT2* and *B08L080PG10SFT3* increased with the increase in curing period.

This increase in tensile load at failure with the increase in curing period is due to the time dependent pozzolanic reaction between the soil silica and the lime leading to the formation of cementing gel which improves the adhesion in composite. Study of Table 6 further reveals that for a curing period of 7 days, the diametral strain at failure of the mix *B08L080PG10SF*

was 6.4 % which increased to 6.8 %, 7.2 % and decreased to 5.6 % for the mixes *B08L080PG10SFT1*, *B08L080PG10SFT2* and *B08L080PG10SFT3* respectively. The improvement in the diametral strain at failure for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* is attributed to the fact that the improved bond of chemically treated sisal fibers with the bentonite-lime-phosphogypsum mix delays the propagation of crack which results in the increased diametral strain at failure of the specimen. The decrease in diametral strain at failure for the mix B08L080PG10SFT3 is due to reduction in the bond of chemically treated sisal fiber with the bentonite-lime-phosphogypsum mix due to the smoothening of the sisal fiber surface.

Table 6 Tensile load at failure for the optimum mix reinforced with treated sisal fibers and cured for 3, 7, 14 and 28 days

Mixes / Curing period, days		B08L080 PG10SF	B08L080 PG10SFT1	B08L080 PG10SFT2	B08L080 PG10SFT3
3	Tensile Load, kN	0.06	0.07	0.09	0.08
	Diametral strain, %	4	5.2	5.2	5.2
7	Tensile Load, kN	0.07	0.13	0.14	0.14
	Diametral strain, %	6.4	6.8	7.2	5.6
14	Tensile Load, kN	0.12	0.14	0.17	0.14
	Diametral strain, %	6.8	7.2	8.0	8.0
28	Tensile Load, kN	0.19	0.21	0.22	0.18
	Diametral strain, %	7.2	7.6	8.4	6.0

3.5.1 Toughness Characteristics

To better understand the toughening characteristics of the untreated and the treated sisal fibers in the post peak region, the tensile load (P) on the load axis and the deformation (d) on deformation axis were normalized with the peak tensile load (P_p) and the deformation at peak load (d_p) as shown in Figure 2. The variation of normalized load-deformation curve for the mixes B08L080PG10SF, *B08L080PG10SFT1*, *B08L080PG10SFT2* and *B08L080PG10SFT3* cured for 3, 7, 14 and 28 are shown in Figures 2 (a) to (d). An examination of Figures 2 (a) to (d) reveals the improved post peak behaviour for the mixes *B08L080PG10SFT1, B08L080PG10SFT2* whereas no such improvement is visible for the mix *B08L080PG10SFT3* as evident from Figure 2(d). It is further observed from Figures 2 (a) to (d) that addition of the treated sisal fiber to the mix *B08L080PG10SF* changes the behaviour from ductile to more ductile for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* whereas reverse change in the behaviour is observed for the mix *B08L080PG10SFT3*.

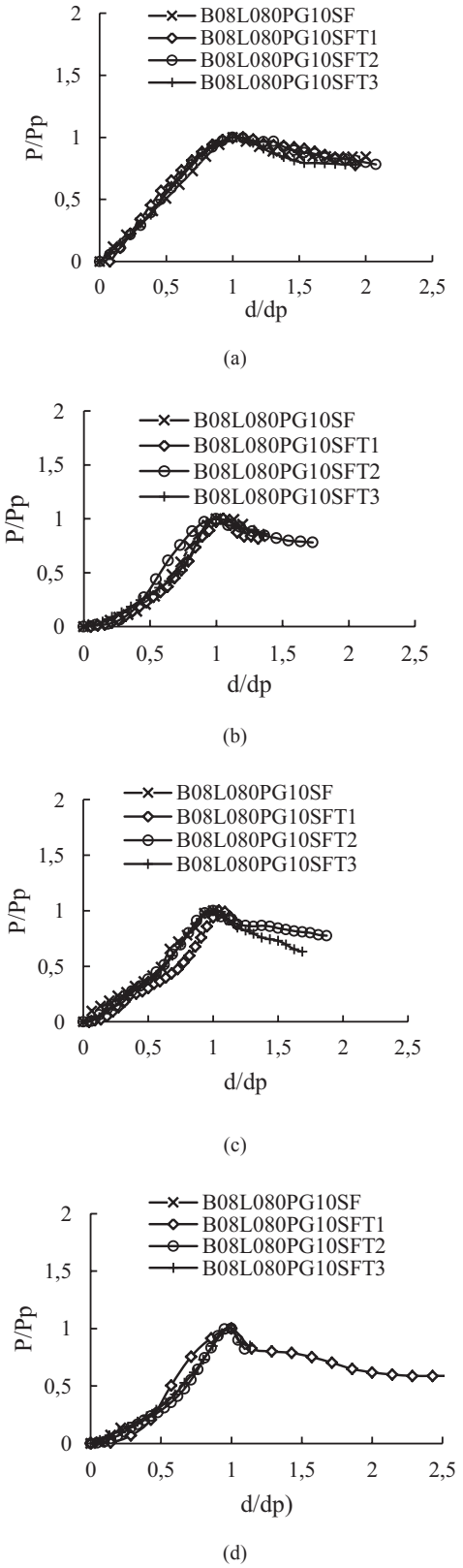

Fig. 2 Normalized tensile load-diametral deformation behaviour of various mix at (a) 3 days (b) 7 days (c) 14 days (d) 28 days

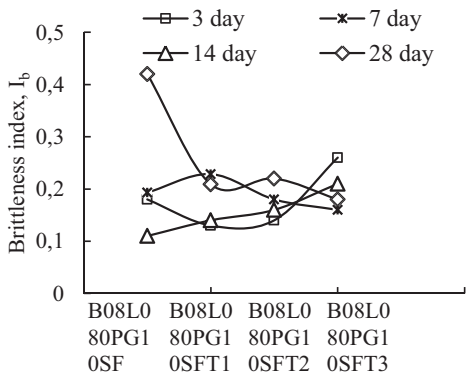

Fig. 3 Variations of brittleness index of various mixes with curing period

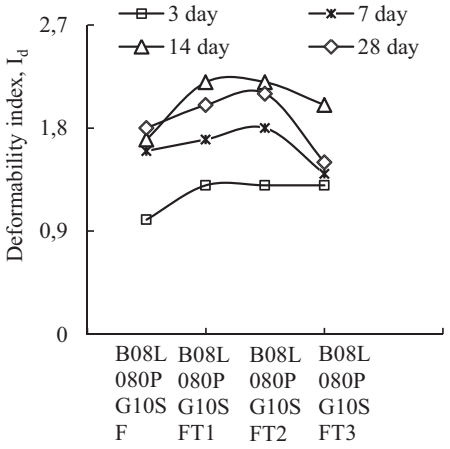

Fig. 4 Variations of deformability index of various mixes with curing period

To verify this, a dimensionless parameter called brittleness index (ratio of peak strength to ultimate strength, I_b) [30] and deformability index (ratio of diametral strain at failure of the mix *B08L080PG10SFT1* or *B08L080PG10SFT2* or *B08L080PG10SFT3* to the diametral strain at failure of the mix *B08L080PG10SF*, I_d) [31] were calculated using Eqs. (1) and (2) and the results are shown in Figures 3 and 4 respectively. The indices present the ductility behaviour of the chemically treated sisal fibres added to bentonite-lime-phosphogypsum with the increase in the curing period.

$$I_b = \left(\frac{q_f}{q_{ult}}\right) - 1 \tag{1}$$

$$I_d = \frac{\Delta_{\text{B08L080PG10SFT1 or B08L080PG10SFT2 or B08L080PG10SFT3}}}{\Delta_{\text{B08L080PG10SF}}} 2 \tag{2}$$

In Eq. (1), q_f is the peak tensile strength and q_{ult} is the ultimate tensile strength of the mixes whereas in Eq. (2), is the diametral strain at failure of the mixes *B08L080PG10SFT1, B08L080PG10SFT2 and B08L080PG10SFT3* and is the diametral strain at failure of the mix *B08L080PG10SF.*

Study of Figure 3 reveals that the brittleness index at a curing period of 3 days was 0.18 for the mix *B08L080PG10SF*, which changed to 0.13 and 0.14 for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* respectively. The brittleness index increased to 0.26 for the mix *B08L080PG10SFT3*. The increase in the brittleness index indicates brittle behaviour whereas decrease in the brittleness index indicates ductile behaviour. The chemical treatment was effective in reducing the brittleness of the bentonite-lime-phosphogypsum-untreated sisal fibre composite. Study of Figure 4 reveals that the deformability index at 7 days of curing for the mix *B08L080PG10SF* was 1.6, which increased to 1.7 and 1.8 for the mixes *B08L080PG10SFT1* and *B08L080PG10SFT2* respectively. The deformability index decreased to 1.4 for the mix *B08L080PG10SFT3* at the same curing period. This trend was consistent with all curing periods as evident from Figure 4. It can be further observed from Figure 4 that the deformability index for the mixes increased with the increase in curing period. The increase in the deformability index indicates ductile behaviour whereas the decrease in the deformability index indicates brittle behaviour. Further from the Figure 4, it can be observed that the change in the behaviour from brittle to ductile is higher for shorter curing periods whereas the rate of increase in the deformability index is lesser for longer curing period. This may be due to the pozzolanic reaction.

4 *SEM* and *EDAX* Studies

Scanning electron micrographs of the mixes bentonite, *B08L, B08L080PG*, the untreated sisal fiber and the treated sisal fibres are shown in Figure 5(a) to (g).

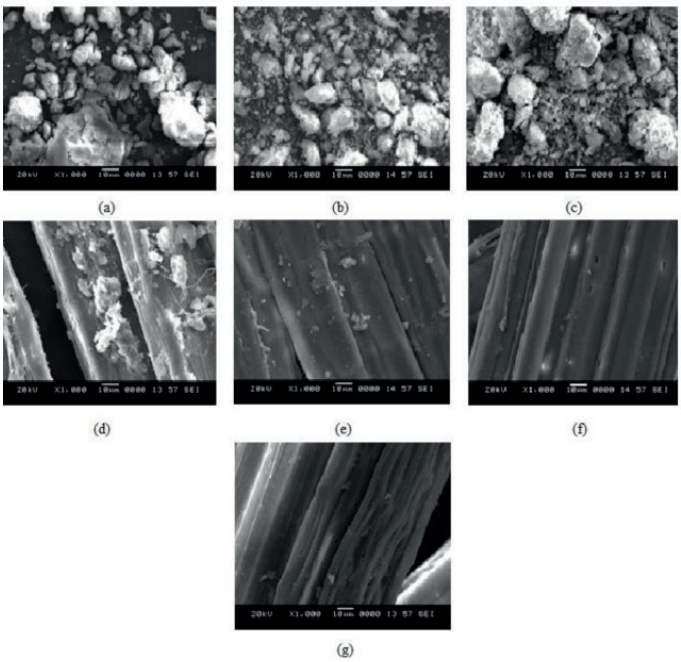

Fig. 5 Scanning Electron Micrograph of (a) bentonite (b) *B08L* (c) *B08L080PG* (d) sisal fibre (e) *SFT1* (f) *SFT2* (g) *SFT3*

A summary of *EDAX* analysis is presented in Table 7 . Study of Figure 5(a) reveals the particles of bentonite whereas Figure 5(b) shows the formation of compact matrix (cementing gel) in bentonite due to the time dependent pozzolanic reaction between the soil silica and the lime leading to an increase in the compressive strength as discussed in Section 4.1. This is evidently substantiated by the increase in the *Ca:Si* ratio of bentonite with the addition of lime proving the *C-S-H* formations. An observation of the *Ca:Si* ratios of B08L and *B10L* parallels the decrease in the effect of lime on the strength behaviour of the mix. Study of Figure 5(c) reveals the possible formation of ettringite due to sulphates and is responsible for the reduction in the unconfined compressive strength of *B08L080PG* mix beyond a curing period of 14 days. The *EDAX* provides a deep understanding of the morphological changes with the further addition of phosphogypsum. This leads to an increase in the Aluminium content and reduces the strength as shown in the decreasing *Si:Al* ratios in Table 7 . Figures 5(d) to (g) show a node-like structure on the surface of sisal fiber. This node-like structure gets reduced in the first stage and the second stage of chemical treatment resulting in the removal of materials such as lignin, oil and waxes and improving the surface characteristics of sisal fiber which in turn results in improving the bonding of treated sisal fibers with the bentonite-lime-phosphogypsum mix.

Table 7 Summary of *EDAX* analysis

MIXES	Curing period, days	Ca/Si	Si/Al
Bentonite	-	0.0002	2.2696
B08L	7	0.1727	2.1556
	28	0.2577	1.8765
B10L	28	0.2198	1.9766
B08L080PG	7	0.2351	2.0000
	14	0.4000	1.9557
	28	0.2706	1.8300
B08L100PG	28	0.3026	2.0242

5 Conclusions

An experimental study is carried out to investigate the effect of treated sisal fiber on the engineering properties of bentonite-lime-phosphogypsum mix using a multi variable approach. On the basis of the results of the experimental investigation and the discussions made in the earlier sections, the following conclusions can be drawn.

1. The dry unit weight of the optimum mix increased and the optimum moisture content decreased with the chemical treatment. The high moisture sorption of the untreated sisal fibres was thus decreased with the surface modification of fibres by the chemicals.
2. The unconfined compressive strength, the deviator stress, the tensile load and the diametral strain at failure of the optimum mix increased up to the second stage of chemical treatment. Beyond the second stage of treatment, the unconfined compressive strength, deviator stress and the tensile load decreased. Thus, the successive surface modifications with the use of sodium periodate and p-aminophenol produced maximum change in the engineering properties. This also makes way for further extensive research in the field of geosynthetics.
3. The unconfined compressive strength, the tensile load and the diametral strain at failure increased with the increase in the curing period for all the mixes studied.
4. The post peak behaviour of the untreated sisal fibres mixed with bentonite-lime-phosphogypsum increased/improved with the chemical treatment. The brittleness index and the deformability index reveals the effect of ductility brought in with the chemical modification.

Notation

B	Bentonite
d	Deformation
d_p	Deformation at peak load
I_d	Deformability index
EDAX	Energy Dispersive X-ray Analysis
I_b	Brittleness index
L	Lime
MDD	Maximum dry unit weight, kN/m^3
OMC	Optimum moisture content, %
P	Tensile load, kN
P_p	Peak tensile load, kN
PG	Phosphogypsum
q_u	Unconfined Compressive Strength, kN/m^2
SEM	Scanning Electron Micrograph
SF	Sisal Fiber

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