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Shrinkage and Strength Characteristics of Expansive Soil Amended with Bagasse Ash and Lime.

Características de contracción y resistencia del suelo expansivo modificado con ceniza de bagazo y cal.

Goutham, D.R. [*1] *A. J. Krishnaiah* [*]

*Department of Civil Engineering, Malnad College of Engineering, Hassan, INDIA.

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Abstract

Bagasse ash (BA) is a non-environmental waste product gathered from sugarcane manufacturing industries. As a result of the large accumulation and shortage of disposal yards, handling BA has become an immediate challenge. This paper presents studies on the Atterberg limit, shrinkage index, linear shrinkage after 7 days of curing, compaction, and unconfined compressive strength (UCS) tests (following 7 days of curing) of BA and lime-BA assorted expansive soil (ES) by differing BA content from 0 to 18% at an interval of 3% and adding 4% lime by dry weight of ES. The outcomes disclosed that the inclusion of BA and lime beneficially controls the shrinkage attribute. According to the research, changes in moisture-density correlations resulted in reduced maximum dry densities (MDD) and greater optimal moisture content (OMC). The volume change characteristic of ES can be mitigated by mixing BA and lime. In addition, test findings showed that both BA and lime-BA enhanced axial stress while reducing axial strain. As a result, a substance that was once thought to be a misery to the environment and society has become a benefit to the civil engineering industry.

Keywords: *Expansive soil; Atterberg limit; Shrinkage index; linear shrinkage; MDD & OMC; UCS.*

Resumen

La ceniza de bagazo (BA) es un producto de desecho no ambiental que se recolecta de las industrias manufactureras de caña de azúcar. Como resultado de la gran acumulación y escasez de patios de eliminación, el manejo de BA se ha convertido en un desafío inmediato. Este artículo presenta estudios sobre el límite de Atterberg, índice de contracción, contracción lineal después de 7 días de curado, compactación y pruebas de resistencia a la compresión libre (UCS) (después de 7 días de curado) de suelos expansivos (ES) variados BA y cal-BA diferenciándose el contenido de BA de 0 a 18% en un intervalo de 3% y agregando 4% de cal en peso seco de ES. Los resultados revelaron que la inclusión de BA y cal controla beneficiosamente la característica de contracción. Según la investigación, los cambios en las correlaciones humedad-densidad dieron como resultado una reducción de las densidades secas máximas (MDD) y un mayor contenido de humedad óptimo (OMC). El cambio de volumen característico de ES se puede mitigar mezclando BA y cal. Además, los resultados de las pruebas mostraron que tanto el BA como el BA con cal mejoraron la tensión axial y al mismo tiempo redujeron la tensión axial. Como resultado, una sustancia que alguna vez se pensó que era una miseria para el medio ambiente y la sociedad se ha convertido en un beneficio para la industria de la ingeniería civil.

Palabras clave: Suelo expansivo; Límite de Atterberg; Índice de contracción; contracción lineal; MDD & OMC; UCS.

[1] ***Corresponding author:***
Department of Civil Engineering, Malnad College of Engineering, Hassan, INDIA.
Corresponding author: goutham.dr03@gmail.com

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1. Introduction

Expansive soils are weak soils and possess low bearing strength. The reason for their weak behaviour is their swell and shrink characteristics. These soils are habitually regarded as problematic soils in the various construction activities. The foundation placed on these soils will react accordingly and drive differential settlement. Swell and shrink parameters yield due to the alteration in mass of the soil upon the ingress of moisture content, and this behaviour is measured by means of shrinkage characteristics. Particles in fine-grained soils promote shrinkage. Capillary menisci create pore water tensions, which cause motions. The gathering of soil particles to generate a stronger formation is a major mechanism intricate in structure formation during drying. Particle aggregation is fueled by the soil suction that develops as water is pulled out of the soil pores by the drying activity. At a given void ratio, the inclination is to create a more flocculated or arbitrary structure since this morphology is sturdier, notably when there is isotropic volume fluctuation. The particle triangle configuration is one of the most basic structural elements. To overcome the indicated issue, soil stabilization has been used to amend the engineering characteristics of the ES and to make them feasible for bearing heavy loads with the least settlements (Reddy et al., 2018).

Lime stabilization is one of the most widely used approaches for the stabilization of ES's, which have long been a source of concern for civil and geotechnical engineers worldwide. However, in recent years, the emphasis has shifted to the use of factory waste materials in conjunction with lime in order to attain better effectiveness and waste disposal (James and Pandian, 2018). The most used chemical stabilizer for treating expansive soils is lime. It has been recognized as an effective additive for clay (Baig and Elkady, 2013). Lime increases workability and strength while reducing the risk for swell in expansive soils (Parvathy and Anitha, 2016). Bagasse ash is a by-product of raw waste that is produced during bagasse burning in the sugar industry. As the BA is pozzolan due to its high silica concentration, this natural waste is mainly used in concrete and cement mortar (Jamsawang et al., 2017). BA inclusion will decrease the plasticity and shrink potential of expansive soils (Hasan et al., 2016).

Many previous efforts to study the geotechnical features of ES mixed with admixtures have been made. The dampness level of the clays, which is attributed to the quantity of clays with extraordinary cation exchange ability and the kind of interlayer cations, determines the elementary key properties of expansive soils, such as the plastic limit and liquid limit (Jayasree et al., 2015). According to (Wubshet and Tadesse, 2014), 15% BA combined with 3% lime by dry weight of the soil raised the California bearing ratio (CBR) value and reduced the optimum moisture level (OMC). (Osinubi et al., 2009) the study examined how up to 12% BA by weight of dry soil affected the geotechnical properties of poor lateritic soil. With increasing BA concentration, the MDD exhibits a general trend of decreasing value. (Ito and Azam, 2010) the goal of this study is to better understand the phenomenon of swelling and contraction in the surface deposit of expansive soils. The majority of the civil infrastructure suffering heave and settlement is located on the surface deposit of the clay, which is in close contact to the atmosphere due to seasonal fluctuations in climatic conditions. (Al-Swaidani et al., 2016) the effect of natural pozzolana on several geotechnical parameters of lime treated clayey soils has been investigated. The test findings demonstrate that adding natural pozzolana as a stabilising agent can significantly improve the examined properties of lime-treated clayey soils. (Jairaj et al., 2020) observed the influence of lime response and supplementary heat of hydration on coir fibre. After seven days of curing, both natural and treated coir fibres in lime-stabilized ES induce a drop in unconfined compressive strength (UCS) due to the heat of hydration of the lime reaction, which appears to impact fibre properties. (Sivapullaiah et al., 2006) observed the effect of sulphate content on two of the finest fine-grained soils, montmorillonite black cotton soil and kaolinite red earth stabilised with an optimal lime level of 6%, have been studied. Because the results of soil lime reactions changed to swelling ettringite type chemicals in the presence of sulphate, the strength of both lime-treated soils fell significantly. (Dang et.al 2016) using 0.5%, 1.0%, and 2.0% randomly dispersed bagasse fibres, they were added to ES, and hydrated lime-expansive soils combined with varying bagasse fibre proportions were also tested. The results of this study show that bagasse fibre reinforcement combined with hydrated lime enhanced the compressive strength of ES as curing time and additive concentration increased. The swelling behaviour of ES modified with fly ash and GGBS binder was studied by (Sharma and Sivapullaiah, 2017). The accumulation of 1% lime to the binder resulted in a more significant decrease in swelling. The compressibility of soil/binder combinations reduced slightly as the binder concentration increased, but it decreased considerably in the presence of lime. In an oedometer, (Darikandeh and Phanikumar, 2021) performed laboratory-scale swell-shrink experiments on an ES stabilised by calcium carbide residue-

fly ash (CCR-FA) columns. When CCR-FA columns were utilised at the CCR: FA, a substantial reduction of 62% in swell potential was detected.

Estimating the shrinkage aspects of a soil can aid to determine the clay mineralogical composition and shrink/swell ability of a geologic layer. In this study, with microstructural and chemical composition observations, an experimental study was designed to investigate the index properties, shrinkage index, linear shrinkage, compaction, and stress-strain behaviour of an ES treated with lime and BA. The current study compares the efficacy of BA and optimum lime with BA in the stabilisation of expanding soil.

2. Materials and experimental details

2.1. Materials

The ES used in the studies was collected at a depth of 1.5 m from the ground surface in Kadur town in the Chikkamagaluru district, India. In order to mix the BA uniformly, the soil was pulverised (to a size fewer than 4.75 mm) using a hammer and then desiccated to condense the dampness content to roughly 0%. (Table 1) summarises the engineering properties of air-dried ES as determined experimentally employing standard test procedures. Following grain size examination, it was discovered that 61.2% of the particles are clay size and 20.8% are silt size. According to the IS: 1498, the earth is classed as highly compressible clay, CH (IS:1498-2007). The lime used for the study was laboratory class hydrated lime factory-made by the Nandi brand. BA was procured from Mugulavalli Sugar Mills Pvt. Ltd. in the Chikkamagaluru area of Karnataka, India. (Table 2) lists the chemical composition of the materials employed in the study.

The morphology of the materials was studied employing scanning electron microscopy (SEM) images. SEM images of the materials used in the investigation are exhibited in (Figure 1). The cohesive nature of the clayey soil causes soil particles to collect into lumps, as shown in the micrograph. The platy clay mixture contains the soil aggregates are also visible. BA had well-defined burnt bagasse particles in its microstructure. BA, on the other hand, is made up of crystalline bulky grains and pyrolyzed organic components (James and Pandian, 2018).

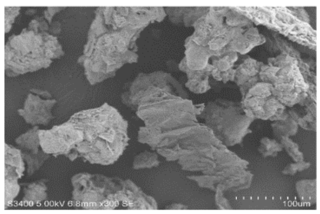
EDX analysis was also used in this experiment to investigate the stability of expanding soil as well as its chemical makeup and components, as indicated in (Table 2). The primary components are SiO_2, Al_2O_3, and Fe_2O_3, which together account for approximately 84% of expansive soil. As a result, it is possible to conclude the enrichment of quartz mineral in coarse mineral and the enrichment of aluminium silicate clay minerals in fine mineral. Natural pozzolans with a ratio of $SiO_2 + Al_2O_3 + Fe_2O_3$ to entire mass greater than 70% are classified as class-F pozzolans, according to ASTM D 653-03 2010). Therefore, the BA used in the current study belongs to class-F pozzolan.

Table 1. *Soil classification and properties of ES*

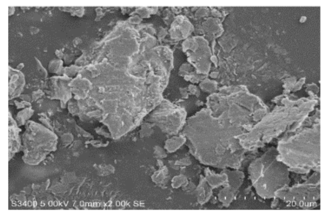
Property of soil	Values
Specific gravity	2.63
Fine sand particles	18.0 (%)
Silt particles (%)	20.8 (%)
Clay particles (%)	61.2 (%)
Liquid Limit (LL)	65 (%)
Plastic Limit (PL)	27 (%)
Plasticity index (PI)	38 (%)
Shrinkage Limit (SL)	13 (%)
Optimum Moisture Content	28 (%)
Dry Density	13.3 (kN/m^3)
Free swell index	97 (%)
Soil Classification	CH

Table 2. *Chemical composition of ES, lime, and BA*

Materials	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	Na_2O (%)	P_2O_5 (%)	TiO_2 (%)	SO_3 (%)
ES	64.71	17.12	2.40	7.89	2.15	1.68	0.03	1.53	0.03	0.99	0.30
Lime	0.22	0.06	72.09	0.05	0.004	15.30	0.003	0.06	0.005	0.004	0.03
BA	63.92	5.340	12.10	4.28	3.85	0.91	0.03	1.02	1.10	0.03	0.05



(a)



(b)

Figure 1. *SEM images of the materials: (a) ES, and (b) BA*

2.2 Experimental Programme

The soil's geotechnical properties, which included liquid and plastic limits (IS: 2720 Part 5, 1985), shrinkage limits (IS: 2720 Part 6, 1972), specific gravity (IS: 2720 Part 3, 1980), grain size distribution (IS: 2720 Part 4, 2006), linear shrinkage (IS: 2720 Part 20, 1992), compaction characteristics (IS: 2720 Part 7, 2011), and unconfined compressive strength test (IS: 2720 Part 10, 1991), were determined in the laboratory in conformity with BIS guidelines. By adjusting the BA concentration in the range of 3, 6, 9, 12, 15, and 18% to the dry weight of the soil, the Atterberg limits, shrinkage index, linear shrinkage, compaction, and UCS behaviour are found. Further, the experiments for the expansive soil are carried out by adding 4% lime and varying the BA content. The optimum dosage of lime used in the current study is obtained from the pH test and found to be 4% for the expansive soil.

2.2.1 Shrinkage index

Various codes describe the shrinkage index (SI) in diverse ways. The SI, conferring to (ASTM D 653-03, 2003), is the difference between the PL and the SL, whereas (IS: 2720 Part 6, 1972) defines it as the distinction between the PI and the SL. The SL is elucidated by Ranganatham and Satyanarayana, 1984) and (BS: 1377-1, 1990) as the distinction between LL and SL. In this study, the final definition is employed to compute the SI.

2.2.2 Linear shrinkage test

The linear shrinkage mould was initially cleaned and oiled. Greasing provides for simple soil placement and removal. About 300 g of soil sample passed through a 425 micron IS sieve, and the soil was combined with water equal to the soil sample's liquid limit. The soil was then properly combined into a homogenous consistency and poured into the mould. The length of the filled mould was then measured. The drying process should then be continued at 60 to 65°C until shrinking has virtually stopped, and then at 105 to 110°C to complete the drying process. The soil mixture-filled mould was maintained in the oven for 24 hours. The shrinking soil specimen was measured linearly after 24 hours. This procedure is in accordance prescribed in (IS 2720 Part 20, 1992). The linear shrinkage index (LSI) of the ES was calculated by (Equation 1)

$$LSI = 1 - L_{avg} / L_o \quad (1)$$

Where, L_0 is the initial length of brass mould and L_{avg} is the mean length of ES (mm).

2.2.3 Compaction Test

The compacting behaviour is determined using the standard proctor test. This test is used to determine the maximum dry density and optimum moisture content. To start, 3 kilogrammes of sampled soil were sieved across a 20 mm IS sieve, and a 1000 cc mould was greased and weighed. After that, the soil is mixed with water equivalent to 2% of the total dry soil mass. Following that, the water content was increased by 1% for each successive trial. The mixed soil was then positioned in the mould in three stages until every layer was compacted. The compaction was reached after 25 blows were delivered using a 2.6 kg hammer. A small portion of compacted soil was laid in small containers for the determination of water content by oven drying technique. This procedure is in accordance with (IS 2720 Part 7, 2011).

2.2.4 UCS Test

Cylindrical samples with a diameter of 38 mm and a height of 76 mm were formed at the optimal moisture content, compacted to the MDD, and tested according to (IS 2720 Part 10, 1991). The samples were cured in plastic bags and evaluated in the unconfined compression testing equipment at a strain level of 1.25 mm/min after 7 days of curing to prevent moisture loss. UCS was measured with a change in BA content and 4% lime-BA content after the stress-strain response was plotted.

3. Results and discussion

3.1Outcome of BA on consistency limits

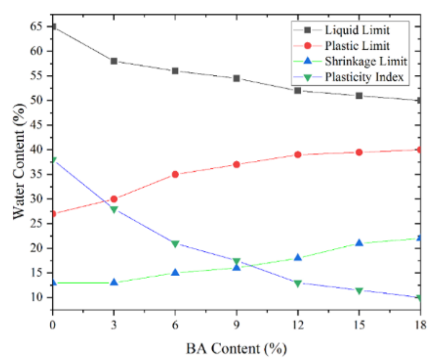


***Figure 2.** Atterberg limits and PI variations with BA treated ES on 7 days of curing*

The inclusion of BA altered the expansive soil's Atterberg limits. (Figure 2) depicts the fluctuation of Atterberg limits and plasticity index with BA content on 7 days of curing. The liquid limit decreased with the increase in the BA addition. This may be attributed to the lower liquid limit of BA. Due to the decrease in diffuse double layer thickness induced by the free lime content of BA imparted to soil, the PL and SL increased with the addition of BA, resulting in particle flocculation. The resistance of soil to volume change due to desiccation is shown by an increase in its shrinkage limit. As shown in (Figure 2), the plasticity index reduces with the insertion of BA. It can be used as an acceptable boundary to show how much soil expands. The lower the plasticity index, the less water that may be absorbed during expansion, and thus the soil's impending movement will be reduced. As a result, as the plasticity index decreases, the expansion of soil decreases as well.

3.2. Outcome of BA+4% lime on consistency limits

The inclusion of BA and 4% lime changed the Atterberg limits of the ES. (Figure 3) show the variation of Atterberg

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limits and plasticity index with BA and 4% lime content after 7 days of curing. The liquid limit decreased with an increase in BA content and the plastic limit was amplified with an increase in BA content. Much of the difference has not been notified compared to (Figure 2). The plastic limit and shrinkage limit increased, which could be attributed to an increase in cation concentration, increased viscosity, and flocculation of clay particles. (Figure 3) depicts a reduced plasticity index of soil caused by flocculation of soil particles in the presence of lime. At 18% of BA content and 4% lime, the plasticity index was reduced by 89%, which is a remarkable improvement. By lowering the plasticity index from 38% to 4%, it is clear that adding 4% lime to the soil was adequate to improve its workability. This is due to chemical processes between lime and ES, such as ion exchange and accompanying flocculation reactions. When lime is added to plastic soils, it triggers a colloidal response that involves the substitution of naturally conveyed cations on the clay surface by Ca^2+ cations, an upsurge in pH, and a decrease in twin layer water. This aids in the flocculation and agglomeration of colloidal clay particles, reducing their plasticity (Al-Swaidani et al., 2016).

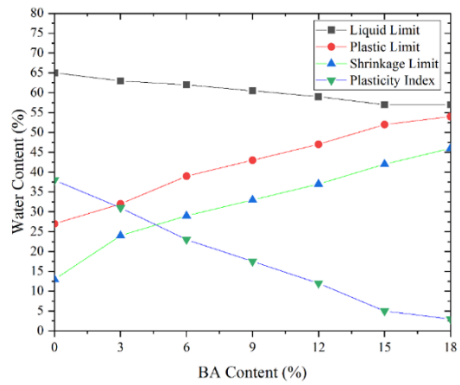

Figure 3. *Atterberg limits and PI variations with BA and 4% lime-BA treated ES on 7 days of curing*

3.3 Outcome of BA and lime on SI

The amount of enlargement of fine-grained soils is assorted by IS 1498 2007 established on the liquid limit, plasticity index, and shrinkage index, as shown in (Table 3). (Table 4) clearly show that the BA inclusion reduces plasticity and thus limits the volume modification behaviour of ES. When the values are compared to those in (Table 3), it is clear that adding BA to ES does not aid to control the degree of strictness of augmentation. As a result, the experiments were recurrent with the addition of 4% lime and BA to condense the degree of soil expansion. (Table 5) depicts the reduction in the degree of severity due to the inclusion of 4% lime and BA to the ES. At 9% BA and 4% lime, the severity level was reduced to marginal from critical. Non-critical severity level was observed when the clayey soil was mixed with 18% BA and 4% lime.

Table 3*. Degree of augmentation of fine grained soil (IS:1498 - 2007)*

LL (%)	PI (%)	SI (%)	Degree of augmentation (DOA)	Degree of severity (DOS) (IS:1498 - 2007)
20 to 35	Less than 12	Less than 15	Low	Non-critical
35 to 50	12 to 23	15 to 30	Medium	Marginal
50 to 70	23 to 32	30 to 60	High	Critical
70 to 90	Greater than 32	Greater than 60	Very high	Severe

Table 4*. Degree of augmentation of ES used in present study with BA*

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Soil blend	LL (%)	PI (%)	SI (%) (IS: 2720 Part 5 - 1985) (Ranganatham and Satyanarayana, 1984)	DOS (IS:1498-2007)
ES	65	38	52	Critical
ES + 3% BA	58	28	45	Critical
ES + 6% BA	56	21	41	Critical
ES + 9% BA	54.5	17.5	38.5	Critical
ES + 12% BA	52	13	34	Critical
ES + 15% BA	51	11.5	30	Marginal
ES + 18% BA	50	10	28	Marginal

Table 5. *Degree of augmentation of ES used in present study with 4% lime and BA*

Soil blend	LL (%)	PI (%)	SI (%) (IS: 2720 Part 5 - 1985) (Ranganatham and Satyanarayana, 1984)	DOS (IS:1498-2007)
ES	65	38	52	Critical
ES + 3% BA + 4% lime	63	31	39	Critical
ES + 6% BA + 4% lime	62	23	33	Critical
ES + 9% BA + 4% lime	60.5	17.5	27.5	Marginal
ES + 12% BA + 4% lime	59	12	22	Marginal
ES + 15% BA + 4% lime	57	5	15	Marginal
ES + 18% BA + 4% lime	57	3	11	Non-Critical

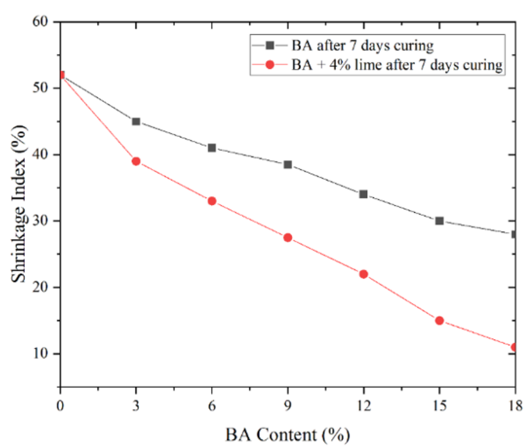

Figure 4. *Shrinkage index of BA and 4% lime-BA treated ES after 7 days of curing*

(Figure 4) show the shrinkage index of ES treated with BA after 7 days of curing. The addition of 18% BA to the expansive soil lowered the shrinkage index by 46%, but the severity of the shrinkage was only marginally less than critical. When expansive soil is mixed with BA and 4% lime content and tested after 7 days of curing, the shrinkage index findings show a significant decrease. The shrinkage index dropped by 79% from its original value when soil is mixed with BA and 4% lime, indicating a lower degree of expansion. As a result, using 4% lime and BA resulted in a reduction in the degree of severity.

3.4 Effects on Linear Shrinkage

(Figure 5) show a comparison of the linear shrinkage advancement of lime and BA admixtures in ES after a 7-day curing period. As shown in (Figure 5), increasing the BA content from 0% to 18% after the 7-day curing period significantly

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reduced the linear shrinkage. In comparison to virgin soil specimens, the linear shrinkage of BA mixed with ES was significantly reduced by 50%. The effects of 4% lime-BA on linear shrinkage of treated ES were stronger than the effects of BA mixed with ES. When compared to the original ES specimen, there was a remarkable depletion in linear shrinkage of approximately 77%. As a result, it is worth noting that the addition of lime-BA resulted in reduced linear shrinkage of ES even when only BA was used.

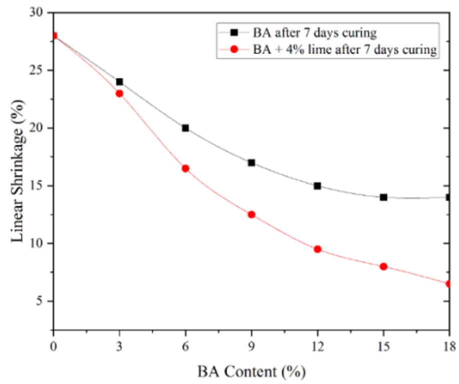

Figure 5. *Influence of BA and lime-BA combinations on linear shrinkage of ES soil after 7 days of curing*

3.5 Effects on MDD and OMC

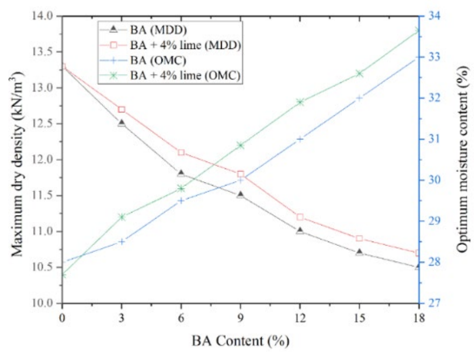

Figure 6. *MDD & OMC relationship of BA and lime-BA combinations mixed ES*

The MDD and OMC of soil stabilised with BA and lime-BA concentration were determined using standard proctor tests. (Figure 6) depicts the deviation in MDD and OMC for parent soil stabilised with BA and 4% lime-BA concentration, respectively. OMC and MDD were found to be 28% and 13.3 kN/m^3 for parent soil, respectively. OMC varies from 28 to 33% for soil stabilised with BA, and MDD changes from 13.3 kN/m^3 to 10.4 kN/m^3 as the percentage of BA concentration increases. Due to an increase in the percentage of BA, an upsurge in OMC and a reduction in MDD can be seen. The presence of BA, which has a low specific gravity, causes the density to decrease. The rise in OMC is caused by the absorption of water by BA. Because of its porous properties, BA has a high water absorption capacity. OMC ranges from 28 to 33.7% in ES soil stabilised with 4% lime-BA, while MDD changes from 13.3 to 10.8 kN/m3 as BA content increases. It has been discovered that when the BA content rises, so does the OMC. The value of MDD does not change much with the proportion of BA added to the soil, but there is a downward tendency. The addition of lime to the parent clay may explain the increase in OMC of the soil with increased BA content. In the case of lime-stabilized clayey soils, similar behaviour has been found in the literature (Al-Swaidani et al., 2016). The explanation for this behaviour is most likely due to the following factors: (1) the lime bases particle aggregation, which modifies the effective categorising of the soils; (2) the specific gravity of lime is substantially slighter than that of the ES soil assessed; and (3) The increase in the OMC is caused by the pozzolanic interaction between the lime and the clay in the ES soil (Al-Swaidani et al., 2016).

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3.6 Outcome of BA on UCS

(Figure 7) depicts the stress-strain relationship between ES and BA-stabilized soil after 7 days of curing with various mix proportions. The BA admixed soil outperformed the virgin ES in terms of resistivity. The UCS value for ES has been recorded as 58.8 kN/m^2 with 12% strain. The stress values for BA content of 3, 6 and 18% combined with ES soil are minimal. The weight bearing capability, on the other hand, has increased a little. At a BA concentration of 12%, the highest increment in stress occurred, which was roughly 225% greater than that of ES soil, resulting in a stress of 132 kN/m^2 with corresponding strain of 9.5%. (Figure 7) show that adding 12% BA to ES improved stress bearing ability more than any other concentration.

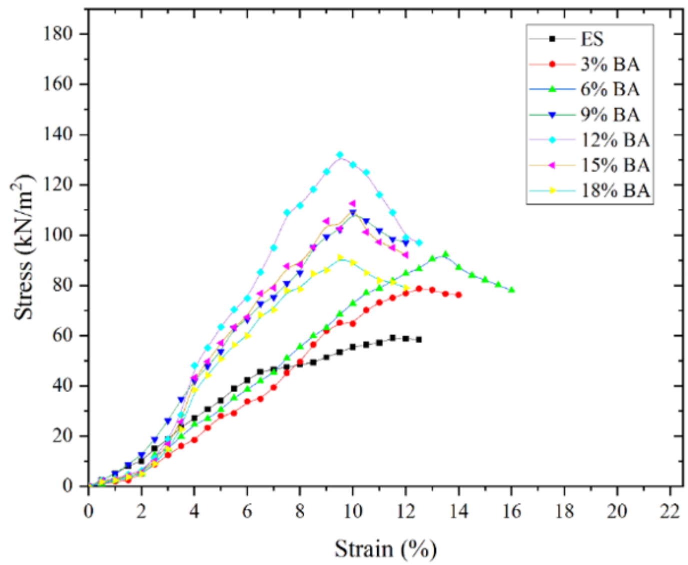

Figure 7. *Stress-strain relationship of ES and ES-BA mix*

3.7 Outcome of BA and lime on UCS

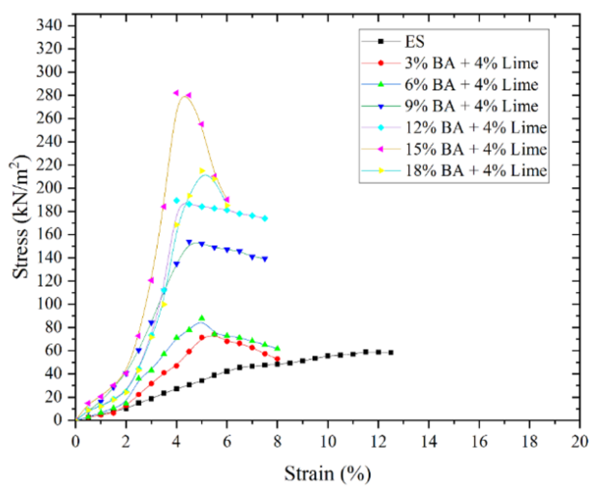

Figure 8. *Stress-strain relationship of ES and lime-BA mix to ES*

(Figure 8) illustrates the stress-strain relationship between ES and 4% lime-BA treated soil after 7 days of curing with various mix proportions. When the lime-BA level was increased, the peak stress increased considerably, and the treated ES also showed

a notable stiffness and comparative brittleness when associated to virgin soil. To be more exact, the failure stress and strain of treated ES rise to 282 kN/m² and 4.5%, respectively, with 15% BA + 4% lime addition. It was also shown that when the BA concentration was increased by 18%, the axial stress decreased but the axial strain increased. The interface and interlock mechanism among clay particles and fibres formed throughout the sample preparation activity by compactive energy and with age of curing might be linked to the improved strength of BA reinforced ES. Increases in fibre content of up to 15% enhance the surface area of fibre exposed to the soil matrix, allowing for higher resistance to applied loads.

Cation interchange between calcium ions in lime and metal ions on clay particle surfaces might explain the significant increase in compressive strength. As a result of these physical and chemical interactions, clay particles agglomerate and flocculate, becoming coarser, more brittle, and less flexible, facilitating the promotion of soil matrix friction resistance. The following are time-dependent pozzolanic reactions. Such pozzolanic processes are generally slow and are aided by high alkaline soil, pH approximately 12.4 created by lime-soil blend, which causes silica and alumina dissolution from the clay mineral lattice. Calcium accessible in the lime reacts with dissolved silica and alumina from the lattice of clay particles to form new cementitious compounds, calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). With time, these chemicals solidify, growing the compressive strength of treated ES.

4. Conclusion

The efficacy of BA and lime as stabilisers for volume change behaviour, compaction and stress-strain characteristics of an ES was investigated in the current study. The following outcomes can be described based on test results:

1. With an increase in BA and lime-BA concentration, the plasticity index of ES decreases dramatically. With a rise in BAand lime-BA concentration, the shrinkage limit of ES increases.

2. When BA and lime-BA were added to ES, the shrinkage properties improved. The amount of expansiveness of ES changed from "critical" to "non-critical" for a 4% lime-BA combination.

3. It is noticed that both the BA and lime-BA treatments had a decreasing shrinkage index value. The linear shrinkage strain decrease was 50% and 77% for BA and lime-BA treatments, respectively. The BA lowers the MDD while raising the ES's OMC. When ES is blended with 4% lime-BA content, a similar pattern emerges.

4. An increase in BA and the lime-BA content raised the UCS values of stabilized expansive soils. The 4% lime-BA addition results in a significantly larger improvement in strength than BA alone.

5. The use of 15% BA in combination with 4% lime to ES produced better results in terms of shrinkage, compaction, and strength. The findings of the tests suggest that BA admixed with lime can be used as a viable binder for expansive soils. The findings suggest that BA (Class-F) mixes can be used as stabilising materials with a small quantity of chemical additives, such as lime, typically essential for chemical activation. This will aid in the widespread use of industrial discarded products, thus saving natural resources.

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