Mechanical properties of stabilized deflocculated residual semi-arid soil

Propriétés mécaniques du sol semi-aride résiduel défloculé stabilisé

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ABSTRACT: The effect of mixed carbonate and phosphate oxalates on the shear strength and tensile properties of lime stabilized residual soil was investigated. Addition of low salt dosage resulted in increase in both average brittleness index and Exchangeable sodium percentage (ESP) and maximum value of average brittleness index was mobilized by soil composites with ESP of 4.02, beyond which a decrease in brittleness index was evident. The reduction is also associated with the synthesis of 1:2 plate clay minerals, with increased moisture affinity. The pozzolanic index is a better correlator of changes in the mobilized tensile strength and splitting modulus than the cation exchange capacity (CEC). The mobilized strength and modulus of lime stabilized soil was dependent on physical properties especially porosity at low salt dosage and heavily contaminated lime stabilized soil was more dependent on the relative proportions of cementitious compound especially silica, calcium silicates and 1:2 clay minerals.

RÉSUMÉ : L'effet des oxalates mixtes de carbonate et de phosphate sur la résistance au cisaillement et les propriétés de traction du sol résiduel stabilisé à la chaux a été étudié. L'ajout d'un faible dosage de sel a entraîné une augmentation de l'indice de fragilité moyen et du pourcentage de sodium échangeable (ESP) et la valeur maximale de l'indice de fragilité moyen a été mobilisée par les composites de sol avec un ESP de 4,02, au-delà de laquelle une diminution de l'indice de fragilité était évidente. La réduction est également associée à la synthèse de minéraux d'argile en plaques 1: 2, avec une affinité accrue pour l'humidité. L'indice pouzzolanique est un meilleur corrélateur des changements de la résistance à la traction mobilisée et du module de division que la capacité d'échange cationique (CEC). La résistance et le module mobilisés du sol stabilisé à la chaux dépendaient des propriétés physiques, en particulier de la porosité à faible dosage de sel et le sol stabilisé à la chaux fortement contaminé dépendait davantage des proportions relatives de composé cimentaire, en particulier de silice, de silicates de calcium et de minéraux argileux 1: 2

KEYWORDS: cation exchange capacity, shear strength, tensile strength, porosity, exchangeable sodium percentage.

1 INTRODUCTION

The contamination of soils by complex industrial effluent can lead to significant modification of the pore fluids, soil properties and associated stability problems of geotechnical infrastructures and these are well documented. Goodarzi and Salimi (2015) investigated potential stabilization of soil which was treated with sodium nitrate, on samples of GGBS and BOF Slag. They reported no dispersive activity when the electrical Conductivity is higher than 5ms/cm and increased dispersivity can be decreased by >50% of BOF Slag and > 15% of GGBS. Gidday and Mittal (2020) investigated absorption Ratio (SAR), Percent Sodium (PS) and strength properties in soils from Ethiopia and reported that addition of up to 9% Lime reduced the SAR from percentage sodium. Vakili et al (2012) stabilized naturally occurring silty clay with high electrical conductivity and percentage sodium with natural pozzolan and reported significant increase in UCS and the electrical conductivity. Sunil et al. (2009) reported that increased dosage of the municipal leachate associated with high degree of contamination, resulted in increase in pH and cohesion of residual soil and decrease in friction angle. Abbaslou et al. (2020) investigated the effect of sodium hexamethaphosphate induced dispersion and stabilization on the shear strength properties of sepiolites, montmorillonites and kaolintes. They observed that the difference between strength parameters was not very significant between dispersive and non-dispersive soils. Fang et al (2009) investigated the effect of pore fluid concentration of of sodium chloride on the mobilized shear strength of fine expansive soil. They reported that the mobilized shear strength slightly decreased with increase in NaCl solution concentration at low vertical stress. Wahid et al (2011) investigated the chemical and mechanical effect of pore salt concentrations in kaolinite clays and found that the shear strength parameter is not affected by the salinity of the pore fluids. Unique to old mining cities like Johannesburg, Rastenberg and Mpumalanga coal field is the contamination of low cost paved and unpaved roads and potential backfill material sources by leachates and industrial chemical effluent. Prediction of the potential effect of the leachates is difficult in part because of the complex chemical natural of the effluents and thus laboratory study of the effect of standard chemical compounds on the shear strength properties of residual subgrades presents a standard reference for the assessment of the potential geotechnical effect of complex leachates. The relationship between modified chemical properties and shear strength parameters facilitated the evaluation of the stability of contaminated dispersive backfill materials as potential candidates for municipal and provincial road construction.

2 MATERIALS AND METHODS

2.1 *Materials*

The residual formations underlying the Auckland Park area of Johannesburg are the transported product of Parktown shale and the Brixton quartzite (Brink, 2008 and Blight, 2008). The materials that were excavated from depths of 2m – 3m from public works storm water drainage construction sites were put into bags and were air-dried in the laboratory and sieved through the 4.75mm mesh. The properties of the residual soil are presented in Table 1. Commercially available hydrated lime normally used by the Johannesburg Road Agency for road construction and repairs was used. Leachates in industrial part of Johannesburg is generally rich in sodium phosphates and carbonates. These chemicals especially in form of sodium hexametaphosphate and sodium carbonate are commonly used as a dispersing agents in different combinations. BS 1377 Part 2 (BS 1990) specified a mix of with 7 grams of sodium carbonate and 33 grams of sodium hexametaphosphate. A mixture of 33 grams of sodium hexametaphosphate , 7 grams of sodium carbonate was mixed and diluted in 1 litre of water to produce

1 dosage (D) of salt solution. Commercially available hydrated lime was used for soil stabilization. The minimum Lime demand for the residual soil is approximately 6% . The effect of Lime content of 8% was investigated. It is also the minimum value recommended locally for road construction backfills stabilization.

2.2 *Test Methods*

2.2.1 *Physical Properties of Residual Soils*

Residual soils often contain compounds with crystalline water like allophane and meta and tetra halloysites that are sensitive to drying temperature and thus all the samples were dried in a materials chamber at 50^oC, bagged and sealed. The wet particle size distribution test is applicable to residual soils because of their weakly bonded fabric of clays on silica sand. Wet sieve tests were conducted to ASTM D 422. The major atterberg Limit tests i.e. Liquid Limit, and Plastic Limit tests were conducted on air-dried soils (ASTM D 4318). Specific Gravity of soil solids passing through the No. 4 sieve (4.75 mm) was conducted in accordance with ASTM D 854-02. Compaction Test was conducted in accordance to ASTM D1557 , using modified effort on 5 layers in AASHTO mould.

2.2.2 *Direct Shear Test*

The shear strength parameters were determined in accordance with (ASTM D 3080). Soil samples were mixed with 5% lime , different percentages of oxalate salt and 20% moisture content. The blended soil was transferred into a concrete mixer and mixed for 20 minutes and then oven dried for 5 days at 40C. The stabilized materials were broken down in a concrete mixer. Dry mass of the crushed stabilized soils equal to 90% MDD were mixed stepwise with salt water and compacted in three layers into the direct shear box to a depth of 36mm in a 100mm x 100mm device, and then soaked with the same salt water at normal stress of 5kPa. Two samples each were subjected to applied normal stresses of 50kPa, 100kPa, 150kPa, 200kPa and 250kPa and tested at a shear rate of 0.05mm/min. The following groups of samples were tested (a) Natural residual soil (b) Lime stabilized residual soils (c) Lime stabilized samples that were treated with different salt concentrations. The samples are thus represented as Soil (S), lime stabilized soil (SL) and lime stabilized soil containing 1 , 2 and 3 dosage of oxalate salt as SL4Na, SL8Na and SL12Na respectively.

2.2.3 *Indirect Tensile Strength Test.*

Soil samples containing lime and different percentages of oxalate salt were mixed with 20% moulding water content and compacted into rings of 120mm diameter and 60mm thickness to 0.90 MDD. They were demolded after 24 hours and cured at temperature of 40 C for 5 days.

3 RESULTS

3.1 *Physical and Chemical Properties*

The physical properties of the residual soil was presented in Table 1 , the soil is a well graded clayey sand of medium plasticity. The specific gravity and colour is due to the presence of iron oxide. The grading and atterberg limits meet the ASSTHO requirement for A24 materials which are suitable for road construction. The result of the XRD tests revealed the predominance of quartz, 1:1 plate clay minerals kaolinites, hylosites (K,Na) $Al_2S_{i2}O_5(OH)_4$, and aluminosilicates. The addition of lime to the residual subgrade soil resulted in increase in silica , and reduction in 1:1 clay minerals . The treatment of lime stabilized soil with small quantities of oxalate salt i.e. SL4Na resulted in further increase in silica and conversion of 1:1 clay minerals Kaolintes to 1:2 clay minerals illitic muscovites. Illitic clay minerals are unstable transitional platy minerals between stable 1:1 kaolinites and 1:2 plate minerals montmorillonites. The synthesis of haematite FeO_2 due to cation exchange capacity was also evident. Large increase in salt dosage ie SL12Na resulted in significant reduction in silica and the synthesis of Anothite Sodian from calcium silicate nitrate. The result of the XRF tests reveal that the dominate oxides in the residual soil are alumina and silica. Treatment with lime, SL, resulted in decrease in alumina oxide and increase in silica and calcium oxide, while salt treated SL , resulted in reduction in Silica, aluminum oxide , calcium and iron oxide and increase in sodium and phosphoric oxide.

Table 1: Geotechnical properties of the semi arid residual soil .

Physical Properties	Residual Clayey Sand
Colour	Reddish brown
% < 0.075mm /0.425mm	37/55
D_{10} /D_{30}/D_{60}	0.166/0.557/1.85
Cu	14
Cc	0.36
Liquid Limit	40
Plasticity Index	27
MDD (kg/m^3)	1701
OMC (%)	17
Gs	2.73

3.2 *Shear stress – displacement of lime stabilized residual soil.*

The shear stress displacement curves of naturally occurring residual backfill soil presented in Fig 1(a) exhibited a mild strain hardening behavior at low applied normal stress i.e. 50kPa , which was associated with mild shear induced dilatant volume change. With further increase in applied normal stress, strain softening and ductile behavior was evident and specimen volume change was associated with shear induced contractive behavior. The shear stress displacement curves of lime modified residual soil presented in Figure 1(b) is characterized by shear induced strain softening behavior, and while the mobilized peak stress decreased with applied normal stress, the degree of strain softening ie the ratio of difference between peak stress and shear stress at large strain to the peak stress , decreased with applied stress. The direct shear induced volume change of the lime stabilized soil was predominantly dilative and the angle of dilation ie dy/ dx , or ψ , decreased with applied normal stress. From table 2 and XRF data , the increase in mobilized shear stress due to lime stabilization is associated with increase in CaO and SiO_2 and the synthesis of Calcium silicate nitrate.

3.3 *Effect of salt on shear strength parameters of lime stabilized soil*

Lime stabilized soil that was treated with 1 dosage of sodium oxalate concertation, SL4Na, shown in Fig 2(a) exhibited strain softening and shear induced dilatant behavior for the range of normal stress up to 250kPa. However, increase in the salt concentration resulted in reduction in maximum mobilized shear stress. Thus increase in salt concentration to 3D or SL12Na shown in Fig 2(b) resulted in reduction in the brittle behavior, significant reduction in the mobilized shear stress. The shear induced volume change is dilatant at applied normal stress up to 100 kPa and contractive volume change at greater applied normal stress. From Table 2 and Table 3, the reduction in brittle response with increase in oxalate dosage is associated with reduction in silica and increase in synthesized 1:1 and 1:2 plate clay minerals especially Illitic clay minerals with high water affinity associated with increased diffuse double layer. Fang et al (2009) observed that changes in mobilized shear strength of kaolin – bentonite mixture were due to electric double-layer repulsion between bentonite particles.

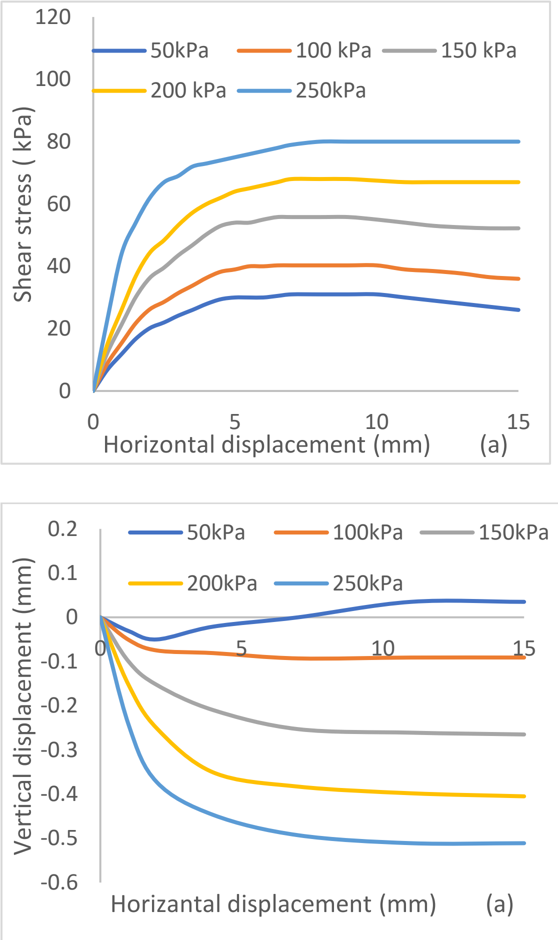

Figure 1. (a, b) Shear stress – displacement behavior of residual soil (S) .

3.4 *Effect of salt content on strength parameters of lime stabilized soil*

The direct shear strength envelopes of residual soil and lime stabilized and oxalate treated residual soil backfill is presented in Figure 3. Lime treatment increased the mobilized friction angle and cohesion from 15 and 16kPa to 19 and 26kPa which is associated with the synthesis of cementitious compound dominated by CaO and SiO_2 and the synthesis of Calcium silicate nitrate. Subsequent treatment with oxalate salt resulted in a decrease in strength parameters, the friction angle decreased to 11 while the cohesion decreased to 20 kPa due to 12% increase in oxalate salt. It is however noted that the initial increase in salt dosage from SL to SL4Na resulted only in marginal decrease in strength parameters, however further increase resulted in stepwise significant decrease in strength parameters. The effect of exchangeable sodium percentage , ESP, and pozzolanic index on mobilized friction angle and cohesion was presented in Figure 4 and Figure 5. Figure 4 show that ESP decreased with addition of Lime from 0.46 to 0.30 , the reduction is associated with the abundance of exchangeable calcium ions in the lime, however subsequent addition of oxalate salt in SL4Na to SL12Na increased the ESP. Fig 4 also revealed that friction angle is inversely related to the ESP. The significant decrease in mobilized friction angle is associated with the synthesis of 1:2 clay minerals, illite and anothite sodian and is better reflected by ESP than the pozzolanic index. In particular the pozzolanic index was more sensitive to the addition of lime to the residual soil, 1.93 – 7.3 , but only marginal change in pozzolanic index, 7.3 – 6.7, was evident due to incremental addition of oxalate salt. The pozzolanic index, reflects the ratio of the Calcium oxide supplied by the lime to the pozzolanas i.e. oxides of aluminum, iron and silica in the soil. Fang et al (2019) observed reduction in friction angle with high salt dosage. The changes in cohesion shown in Fig 5, was also more strongly correlated to changes in ESP and less correlated with changes in pozzolanic index. It is noted initial increase in oxalate salt from ESP of 0.3 to 2.31 only resulted in marginal increase in cohesion. The marginal reduction was best reflected by the marginal change in SiO_2 in Table 2. Subsequent increase in oxalate salt resulted in proportional decrease in SiO_2. (Carey and Simo 1984). Abbaslou et al. (2020) also observed that the effect of salt concentration on cohesion of low plastic soils is only marginal.

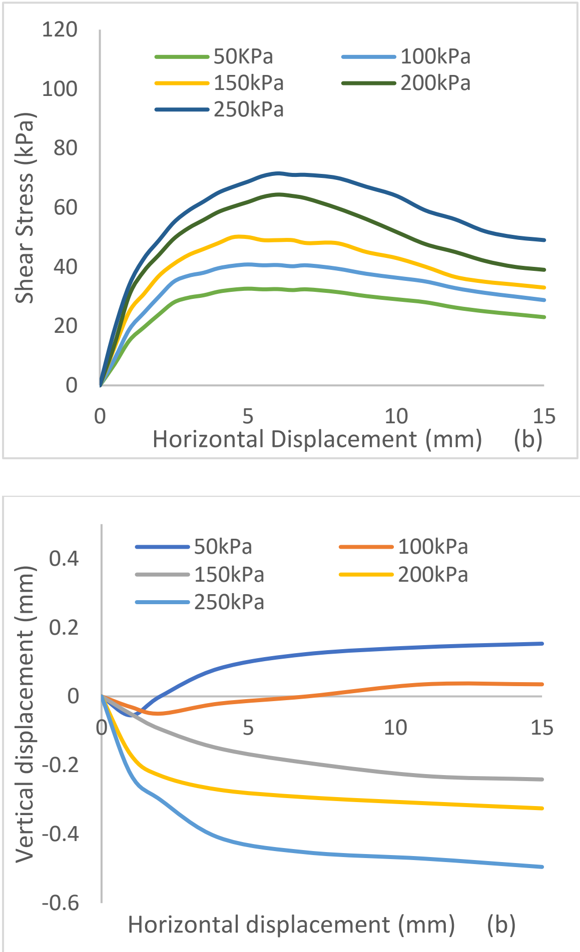

Figure 2. (a,b) The stress – displacement curves of SL8Na soil composites.

Exchangeable Sodium Percentage ESP (meq $100g^{-1}$). ESP is calculated as the portion of the proportion of the Cation Exchange capacity occupied by the Sodium ions, and expressed as Equation 2

$$ESP = \frac{100ENa}{CEC} \tag{2}$$

An ESP or SAR of 15 or 13 is generally taken as the threshold above which the soil are dispersive and unstable in water (Marchuck 2013).

Cation Exchange capacity CEC (meq $100g^{-1}$) of Exchangeable Sodium, Aluminum, Calcium, Potassium and Magnesium is presented as Equation 3.

$$CEC = \frac{XRF\ (\%)}{\left(\frac{Atm}{Valency}\right)} \quad (3)$$

Pozzolanic Index (PR):

$$PR = \frac{CaO_{XRF}}{(AlO+MgO+FeO)_{XRF}} \quad (4)$$

The minimum standard chemical composition of Silicon dioxide content is 25 % by mass and the minimum combined percentage of Silicon dioxide, Iron oxide and Aluminum oxide (SiO_2 + Fe_2 O_3 + Al_2O_3) content is 70 %. That is the specification for the standardized pozzolans (ASTM 618-12) (Table 1).

Pozzolanic Index (PI):

$$PR = \frac{CaO_{XRF}}{(AlO+MgO+FeO)_{XRF}} (100) \quad (4)$$

Based on the specification for the standardized pozzolans (ASTM 618-12) (Table 1), the minimum standard chemical composition of Silicon dioxide content is 25 % by mass and the minimum combined percentage of Silicon dioxide, Iron oxide and Aluminum oxide (SiO_2 + Fe_2 O_3 + Al_2O_3) content is 70 %.

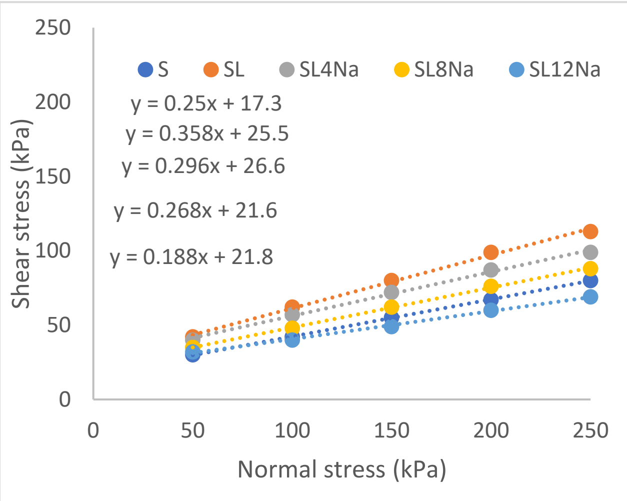

Figure 3. Direct shear strength envelope of residual soil and Lime stabilized and salt treated residual soil.

3.5 *Brittleness Index and Pozzolanic Index*

The brittleness index (I_B) proposed by Consoli et al. (1998) was introduced to quantitatively analyze the brittleness and ductility of cement-stabilized sand reinforced with waste polyester fiber blocks. Brittleness index expressed as Equation (5) relates the mobilized shear strength (q_{max}) to the residual shear strength (q_{res}). Negative values indicate strain hardening ductile behaviour.

$$I_B = \frac{q_{max}}{q_{res}} - 1 \quad (5)$$

The brittleness indices of Lime and salt treated soil was presented in Figure 6. For the untreated soil at low applied normal stress of 50KPa, the brittleness index of 0,07 was due to natural salt content of soil as reflected by the ESP of 0.46 and the dilatancy of the granular material that are easily expressed at low applied normal stress. Lime stabilization ie SL, resulted in increase in average brittleness index to 0.27, and a reduction in ESP to 0.3. Addition of low salt dosage resulted in increase in both average brittleness index and ESP and maximum value of average brittleness index was mobilized by SL8Na at ESP of 4.02, beyond which a decrease in brittleness index was evident. The reduction is also associated with the synthesis of 2:1 plate clay minerals, with increased moisture affinity. The effect of salt dosage on the average brittleness of Lime stabilized soil at different applied normal stress from 50kPa to 250kPa was also presented in Fig 6. At low salt dosage, the brittleness index decreased with increase in applied normal stress, due to progressive degradation of the weakly pozzolanic cementation bond. However, the rate of increase in brittleness with salt dosage was greater for soil specimen subject to high applied normal stress and maximum brittleness index was mobilized by specimens subjected to applied normal stress of 200kPa. Fig 7 show the effect of salt dosage on average brittleness and pozzolanic index and CEC of soil. The pozzalanic index increased significantly with the addition of lime and then decreased stepwise but marginally with increased in salt content , while the CEC increased significantly with addition of lime and then marginally with increase in salt content.

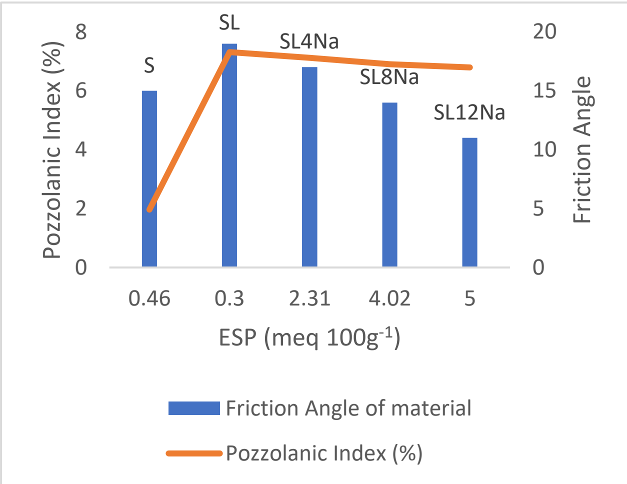

Figure 4. The friction angle of residual soil and lime stabilized – sodium salt treated soil

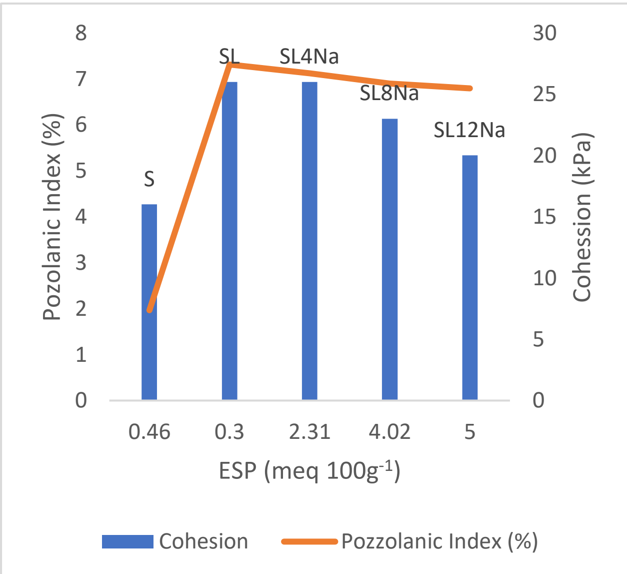

Figure 5. The friction angle of residual soil and lime stabilized – sodium salt treated soil

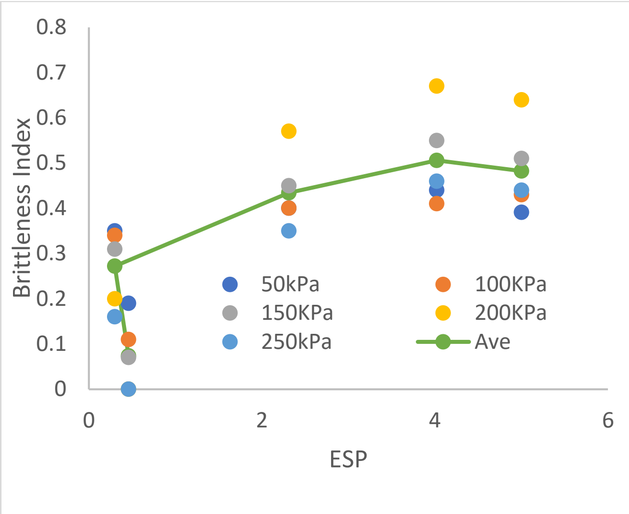

Figure 6. Effect of Salt dosage on brittleness index of lime stabilized soil

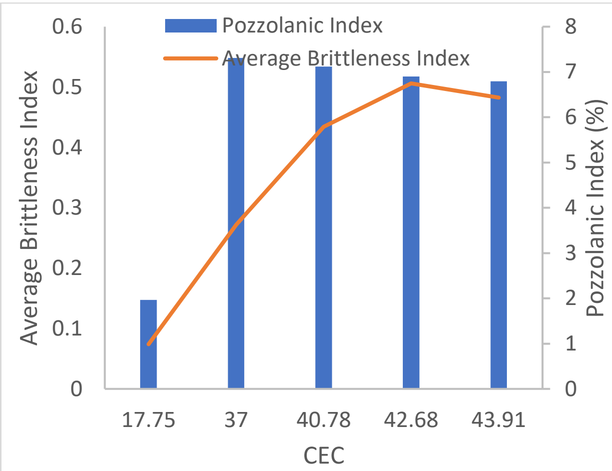

Figure 7. Effect of Salt dosage on Brittleness and pozzolanic index and CEC of soil

3.6 *Indirect Tensile Strength*

The tensile strength (σ_t) and splitting modulus derived by the indirect tensile test of a soil disc is conventionally computed in relation to the ultimate load imposed in diametral axis on the sample is expressed by Equation 3 and Equation 4.

$$\sigma_t = \frac{2P_{ult}}{\pi dt} \qquad (3)$$

$$E_{sp} = \frac{0.5P_{ult}}{\pi dt} * \frac{1}{\varepsilon_v} \qquad (4)$$

Pult is the maximum force (kN)

ε_v is the vertical, diametral strain per specimen diameter, at Pult.

The effect of lime and oxalate on the tensile strength splitting elastic modulus of residual soils is presented in Table 1. Lime stabilization resulted in increased by approximately two-fold increase in tensile strength and splitting elastic modulus and salt inclusions resulted in stepwise decrease increase in both tensile strength and modulus. Also increase in salt content increased the brittleness of the composites. The effect of lime and salt dosage on brittleness and pozzolanic index and CEC of residual soil was presented in figure 8. The pozzolanic index is a better correlator of changes in the splitting modulus than CEC as the CEC did not reflect the observed reduction in modulus with increase in salt dosage. The effect of divalent and trivalent pozzolanic cations in the development of cementitious bond was reported by Absolou et al (2020). Moreira et al. (2019) proposed a model presented as Equation 3, for the determination of initial porosity (η) of stabilized specimen based on relative specific gravities of soil and binders. The specific gravities of sodium oxalate, sodium carbonate and hydrated lime are 2.34 , 2.54 and 2.3 respectively. The effect of lime and salt dosage on the porosity and modulus of residual soil was presented in Fig 9. Addition of lime and incremental dosages of salt resulted in stepwise decrease in specimen porosity. The decrease in porosity resulted in increased modulus of SL and SL4Na and decrease in splitting modulus was evident for salt dosage greater than SL4Na.

Thus the mobilized strength of lime stabilized soil at high salt dosage was dependent on strength of cementitious chemical bond and less on physical properties or porosity.

$$\sigma_t = \frac{2P}{\pi Dt} \ \text{N/mm}^2$$

where, D = Diameter of Sample = 120mm
t = Thickness of the Sample = 60mm
P = Applied Load

Table 2: Indirect tensile parameters of the semi-arid residual soil.

Sample	ITS(N/mm^2)	Displ(mm)	Splitting Modulus
Soil	0.10	1.56	7.69MPa
S7L	0.24	2.20	13.09MPa
S7L 4Na	0.19	1.71	12.63
S7L 8Na	0.11	1.62	8.14
S7L 12Na	0.06	1.23	5.85

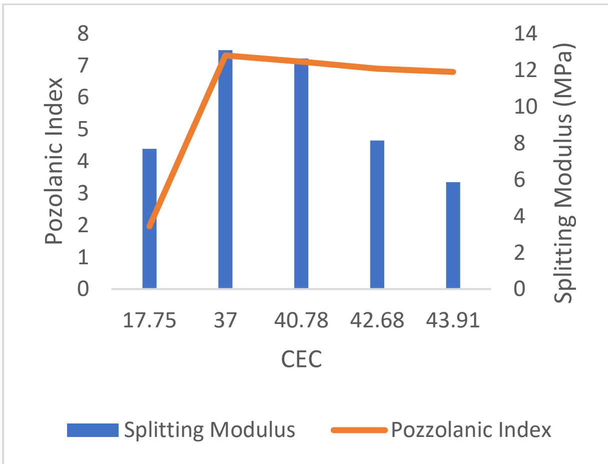

Figure 8. Effect of Lime and salt dosage on Brittleness and pozzolanic index and CEC of residual soil

Department of Texas specification for construction and maintenance of highway, Tex 117- E , (2004) prescribed the transfer of the failure envelope to the chart for the classification of subgrade and flexible base materials and to classify the material to the nearest one tenth of a class. Based on the superposition of strength envelopes of the soil lime salt composites, The saturated residual soil is classified as class 5 i.e. weak subgrade , however the addition of lime , SL and subsequent addition of salt , while SL4Na and SL8Na are classified as weak subgrade. Further increase in salt dosage to SL12Na resulted in degradation of the stabilized soil to class

According to TRH4 (1996) road backfill and cement stabilized materials are classified as C1 to C4 depending on their physical and mechanical properties. classified as a cemented natural gravel (code C4). The TRH4 (1996) states in table13 that a C4 material has a minimum ITS =200kPa at 90-95% Mod. AASHTO compaction. Thus only SL met the criteria, however the difference in splitting modulus of SL and SL4Na is marginal.

4 CONCLUSION

The residual semi arid backfill soil is constituted of quartz, 1:1 plate clay minerals kaolinites, hylosites (K,Na) $Al_2Si_2O_5(OH)_4$, and aluminosilicates. The addition of lime resulted in increase in silica , and reduction in 1:1 clay minerals and addition of lage dosage of oxalate salt resulted in synthesis of unstable illitic clay minerals and anothite salts.

Lime treatment increased the mobilized friction angle and cohesion from 15 and 16kPa to 19 and 26kPa which is associated with the synthesis of cementitious compound dominated by CaO and SiO_2 and the synthesis of Calcium silicate nitrate. Subsequent treatment with oxalate salt resulted in a decrease in strength parameters, the friction angle decreased to 11 while the cohesion decreased to 20 kPa due to 12% increase in oxalate salt.

Addition of low salt dosage resulted in increase in both average brittleness index and ESP and maximum value of average brittleness index was mobilized by SL8Na at ESP of 4.02, beyond which a decrease in brittleness index was evident. The reduction is also associated with the synthesis of 2:1 plate clay minerals, with increased moisture affinity.

Low salt concentration resulted in more brittle direct shear displacement response due to synthesis of silica, and higher salt concentration resulted in significant reduction in friction angle due to the presence of 1:2 clay minerals.

The pozzolanic index is a better correlator of changes in the splitting modulus than CEC as the CEC did not reflect the observed reduction in modulus with increase in salt dosage. Addition of lime and incremental dosages of salt resulted in stepwise decrease in specimen porosity. The decrease in porosity resulted in increased modulus of SL and SL4Na and decrease in splitting modulus was evident for salt dosage greater than SL4Na.

The mobilized strength and modulus of soil and lime stabilized soil with low salt dosage was more dependent on physical properties ie porosity, while the mechanical behavior of heavily contaminated lime stabilized soil was more dependent on the chemical properties ie relative proportions of cementitious compound especial silica, calcium silicates and 1:2 clay minerals.

5 ACKNOWLEDGEMENT

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