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Brackish water in swelling soil stabilization with lime and sugarcane bagasse ash (SCBA)

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Article

Keywords
Unconfined compressive strength
Chemical stabilization
Tap water saving

Abstract

This research shows that brackish water increases the unconfined compressive strength of swelling soil/sugarcane bagasse ash (SCBA)/lime blends. Therefore, brackish water may substitute tap water in soil stabilization. Sodium chloride (NaCl) has been used in lime-ashes-soil treatments. In northeast Brazil, swelling soils are usual and artesian wells sometimes provide brackish water containing NaCl. Northeast Brazil also has a strong sugar and ethanol industry producing sugarcane bagasse ash (SCBA) as a byproduct. Therefore, brackish water can be used in soil-SCBA-lime stabilization. Hence, this work aims to evaluate the use of brackish water as a substitute for tap water in swelling soil-SCBA-lime blends stabilization. Two series of unconfined compression tests were carried out: one with tap water and the other with brackish water. In each group, the lime content varied from 4% to 8%, and the dry density from 13 kN/m^3 to 15 kN/m^3. All tests were carried out with a swelling soil-SCBA proportion of 75/25 and a water content of 22%. Results have shown that increasing lime content or dry density or using brackish water allowed to increase unconfined compression strength of swelling soil-SCBA-lime blends. The porosity/volumetric content of lime index (η/L_{iv}) was suitable to predict the unconfined compressive strength of swelling soil-SCBA-lime blends, no matter if tap or brackish water was used in the molding process. Thus, brackish can be a feasible substitute for tap water in swelling soil-SCBA-lime stabilization, increasing blends unconfined compression strength, and preserving tap water, a scarce asset in Northeast Brazil.

1. Introduction

Expansive soils undergo volumetric changes by moisture variation. They expand when they are wetted and shrink when dried. (Khazaei & Moayedi, 2017; Pei et al., 2020). Such soils can exert enough pressure to crack floors, pipelines, foundations, and roadways, and usually have low bearing capacity. (Consoli et al., 2010; Taher et al., 2020; Tiwari et al., 2021). This kind of soil is common in several countries such as the United States of America, China, India, and Australia (Phanikumar & Singla, 2016; Pooni et al., 2019; Ito & Azam, 2020). The arid and semi-arid areas, such as northeast Brazil, Canadian Prairies, and the state of Texas-USA, have appropriate environmental factors for expansive soil existence (Puppala et al., 2013; Ferreira et al., 2017; Consoli et al., 2019a).

Chemical stabilization can improve these problematic soils (Mirzababaei et al., 2018). Therefore, some studies have been carried out to stabilize expansive soils with chemical additives, such as cement, blast furnace slag, rice husk ash, recycled ash, and natural fibers (Celik & Nalbantoglu, 2013; Liu et al., 2019; Consoli et al., 2021; Tiwari et al., 2021). However, lime stabilization is widely used in swelling soil improvement (Belchior et al., 2017; Silvani et al., 2020).

Lime can improve soils through the exchange of sodium or potassium cations present in soils for calcium cations. Lime can also react with silica or alumina in the amorphous phase (found in the soil or pozzolanic material) by pozzolanic reaction and produce cementitious material capable of immobilizing soil particles and increasing mechanical strength (Ingles & Metcalf, 1972). Nevertheless, the rate of development of those reactions can be considerably slower, so many materials (e.g., sodium chloride, sodium silicate, and sodium hydroxide) have been studied as reaction catalyzers.

Drake & Haliburton (1972) were the first to analyze sodium chloride (NaCl) use in lime-treated cohesive soils. Recently, several authors (Saldanha et al., 2016; Consoli et al., 2017, 2019b, c; Saldanha et al., 2017) investigated the

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addition of NaCl in soil-fly ash-lime blends. These authors found out that the NaCl catalyzed the pozzolanic reaction between lime and fly ash.

In Brazilian Northeast, artesian wells sometimes provide brackish water containing NaCl, unsuitable for human consumption (Lopes, 2004). Therefore, the NaCl in brackish water can act as a potential catalyst in soil-fly ash-lime stabilization, reducing consumption of tap water, a scarce asset in this region.

Although expansive soil areas in Northeast Brazil have a low offer of fly ash, the sugar and alcohol industry produces great amounts of sugarcane bagasse ash (SCBA) as a by-product. Its disposal usually is not appropriate and needs extra attention regarding potassium and heavy metals used in sugarcane's maturation control that can contaminate the soil and the groundwater table (Fernandes Filho et al., 2012; Cordeiro et al., 2019). The use of SCBA as a pozzolanic material has been demonstrated by different authors (i.e., Martirena Hernández et al., 1998; Ganesan et al., 2007; Cordeiro et al., 2009; Alavéz-Ramírez et al., 2012; Zareei et al., 2018).

Consoli et al. (2007) developed the porosity/cement index (η/C_{iv}) to predict unconfined compressive strength (q_u) for a clayey sand soil stabilized with cement. This index is a rational criterion like the water/cement ratio for concretes. Two years later Consoli et al. (2009) used the porosity/lime index (η/L_{iv}) to predict q_u for sandy lean clay stabilized with lime. Silvani et al. (2020) and Consoli et al. (2021) applied this index to predict the swelling behavior of chemical stabilized expansive soil. But there is no research using this index in expansive soil stabilized with brackish water, SCBA, and lime.

Therefore, this research aims to fill this gap in the literature and evaluate the use of brackish water as a substitute for tap water in expansive soil-SCBA-lime blends stabilization and assess the feasibility of this index as an alternative to predict or control q_u of expansive soil/ SCBA/lime blends.

2. Experimental program

The experimental procedure was divided in two parts. The materials were characterized by geotechnical and chemical methods, in the first part. Then, unconfined compressive strength tests (UCS) were carried out to assess the strength of the blends. Two groups of specimens for unconfined compressive strength were done differing only in molding water: the first group was done with tap water and the second group was done with brackish water. Inside each group, amounts of lime were 4%, 6%, and 8% and the dry unit weights were 13, 14, and 15 kN/m^3 with a water content of 22% (w) for the dry mass of swelling soil/SCBA/lime blend. Lime contents were established based on the initial consumption of lime (ICL) proposed by Rogers et al. (1997) and γ_d and w based on the compaction curve using Standard effort according to ASTM D698 (ASTM, 2012) (Figure 1).

2.1 Materials

The expansive soil was collected in Paulista-PE in northeastern Brazil. The soil was classified by USCS (Unified Soil Classification System) as low compressibility plastic clay (CL) (ASTM, 2017a). The SCBA was obtained in Paraiba (PB) state, north-eastern Brazil, from a cachaça (Brazilian drink made from sugarcane) factory and was classified by USCS as low compressibility silt (ML) (ASTM, 2017a). Table 1 presents detailed properties of SCBA and swelling soil. The high value of the soil plastic index is typical in swelling soils.

In addition, Figure 2 and Figure 3 present X-ray diffractograms of soil and SCBA. Swelling soil showed peaks of quartz, muscovite, and smectites (expansive clay mineral). SCBA showed peaks of quartz, aluminum, and calcium, supporting XRF results, and the diffractogram indicates amorphous material.

Calcitic hydrated lime with specific gravity of 2.41 was used as a stabilizer agent (ASTM, 2018a). Distilled water

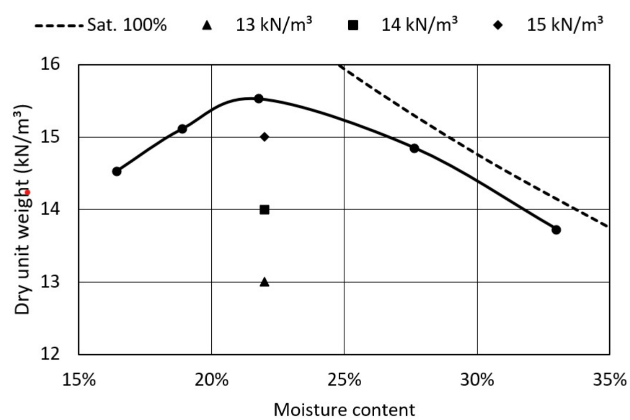

Figure 1. Proctor compaction curve of swelling soil.

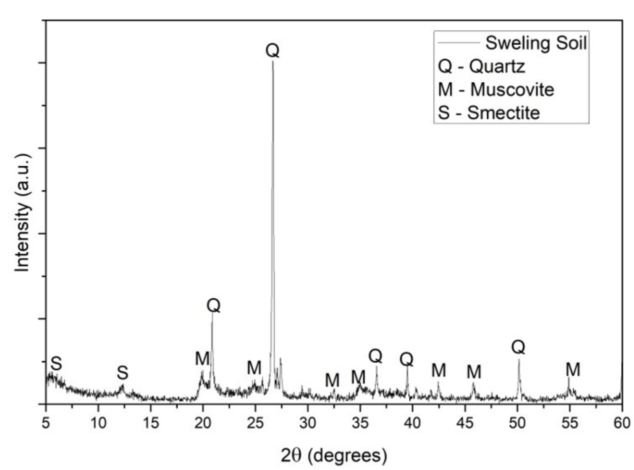

Figure 2. Expansive soil X-ray diffraction.

Table 1. Soil and SCBA characterization.

Properties	Soil	SCBA	Standard
Sand (%)	10.58	29.97	ASTM D6913/2017 (ASTM, 2017b)
Silt (%)	43.96	65.24	
Clay (%)	45.46	4.79	
Liquid limit (%)	49	-	ASTM D4318/2018 (ASTM, 2018b)
Plastic limit (%)	21	-	
Plastic index	28	Non plastic	
Specific gravity	2.65	2.38	ASTM D5550/2014 (ASTM, 2014)
Cation Exchange Capacity (meq/100g)	59.20	18.76	ASTM C837/2019 (ASTM, 2019)
Specific surface area (m^2/g)	462.01	146.41	
SiO_2 (%)	55	53.8	ASTM E1621/2021 (ASTM, 2021)
Al_2O_3 (%)	25	11.4	
CaO (%)	-	12.7	

Table 2. Chemical characterization of tap water and brackish water.

Parameters	Tap clean water	Brackish water	Parameters	Tap water	Brackish water
pH 25 °C	7.1	7.2	Chloride (mg/L)	28	2340
Electric conductivity 25 °C (Ms/cm)	0.238	7.8	Calcium (mg/L)	14	142
Turbidity (UNT)	2.0	1.7	Magnesium (mg/L)	9.2	187
Total hardness ($mgCaCO_3/L$)	73.2	1124	Total alkalinity ($CaCO_3/L$)	36	421
TDS* 103-105 °C (mg/L)	120	5396	Salinity (‰)	0.10	4.2
TDS* 180 °C (mg/L)	118	4792	Bicarbonate (mg/L)	44	421

Note: TDS*: Total dissolved solids.

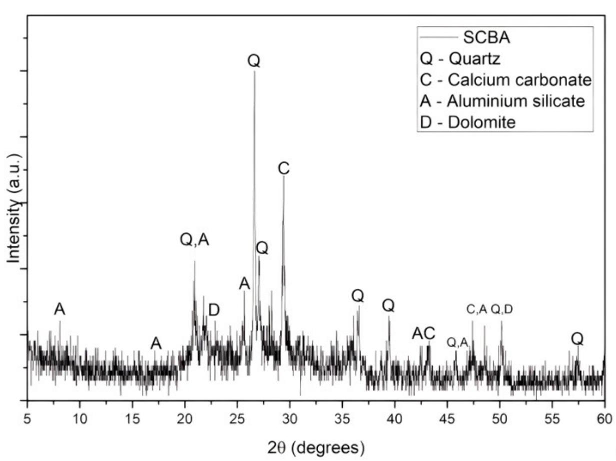

Figure 3. SCBA X-ray diffraction.

was used for the characterization of materials. Tap water from the public supply system and brackish water from an artesian well located in Campina Grande-PB were used for molding specimens. Table 2 presents the results of water characterization tests.

The nº 357 resolution of the Brazilian Environmental National Council (CONAMA) establishes that tap water has salinity lower than 0.5‰ and brackish water salinity can range from 0.5‰ to 30.0‰ (Brasil, 2005). Therefore, the data presented in Table 2 indicates the water from the artesian well is classified as brackish water because of its salinity of 4.2‰, so is inappropriate for human consumption. Tap water has a salinity of 0.10‰.

2.2 Molding and curing of specimens

Cylindrical specimens 50 mm in diameter and 100 mm in height were used. The soil, lime, and SCBA were mixed with water until acquired a homogeneous aspect and statically compacted in 3 layers. Between each layer, the top was scarified. The curing period was fixed at 28 days in a humid room at 23 °C. The specimens were submerged in water for 24 hours to minimize suction (Saldanha & Consoli, 2016) twenty-seven days after the molding, bringing the total curing time to 28 days. The specimens were molded in duplicate.

The cure timing was set to allow pozzolanic reactions to occur. The SCBA content was based on international and Brazilian practices with industrial byproducts (ashes) (Consoli et al., 2001, 2019d).

2.3 Porosity/lime index (η/L_{iv})

The initial porosity (η) can be calculated as the ratio of the volume of voids over the total volume of the specimen (Equation 1). It is a function of dry unit weight (γ_d) of the mixture, lime content (L), soil content (S), SCBA content (SCBA), total volume of the specimen (Vs), and the unit weight of solids of soil (γ_{sS} = 26.5 kN/m³), SCBA (γ_{sSCBA} = 23.8 kN/m) and lime (γ_{sL} = 24.1 kN/m³). Volumetric lime content is obtained from Equation 2 considering the volume of lime (lime mass divided by lime specific gravity) and total volume of blends.

$$\eta = 100 - \frac{100\left\{\frac{\frac{\gamma_d Vs}{1+\frac{L}{100}}\left(\frac{S}{100}\right)}{\gamma_{sS}} + \frac{\frac{\gamma_d Vs}{1+\frac{L}{100}}\left(\frac{SCBA}{100}\right)}{\gamma_{sSCBA}} + \frac{\frac{\gamma_d Vs}{1+\frac{L}{100}}\left(\frac{L}{100}\right)}{\gamma_{sL}}\right\}}{Vs} \quad (1)$$

$$L_{iv} = \frac{V_L}{V} = \frac{m_{L/\gamma sL}}{V} \quad (2)$$

2.4 Unconfined compression tests

Unconfined compression tests were carried out with an automated hydraulic press with a displacement rate of 1.14 mm/min.

3. Results

3.1 Lime content effect

Figures 4a and 4b show the relation between lime content and unconfined compressive strength (q_u) for swelling soil/SCBA/Lime molded with tap water and brackish water, respectively. q_u increases linearly when the lime content grows, in both situations, probably because SCBA is rich in amorphous silica and alumina (Figure 2) which allows pozzolanic reactions with lime. In addition, for the same lime content, the higher the dry density, the higher the inclination (slope) of the fitting line. This behavior indicates a bigger unconfined compressive strength growth rate. Especially for specimens with brackish water, the slope and the y-intercept of the fitting lines tend to increase as the dry unit weight also increases. Therefore, the lime effect is greater in more compacted blends as stated by Consoli et al. (2009).

3.2 Porosity effect

The influence of porosity in unconfined compressive strength is shown in Figure 5a for blends molded with tap water and (b) for mixtures done with brackish water. Each curve in Figure 5 is adjusted for specimens molded with the same amount of lime. The unconfined compressive strength decreases when the porosity increases, thus both variables are inversely proportional, no matter if tap or brackish water was used in the molding process. According to Consoli et al. (2007, 2009), when porosity reduces, the contact between lime and soil particles intensifies, improving the cementitious process and, hence, q_u.

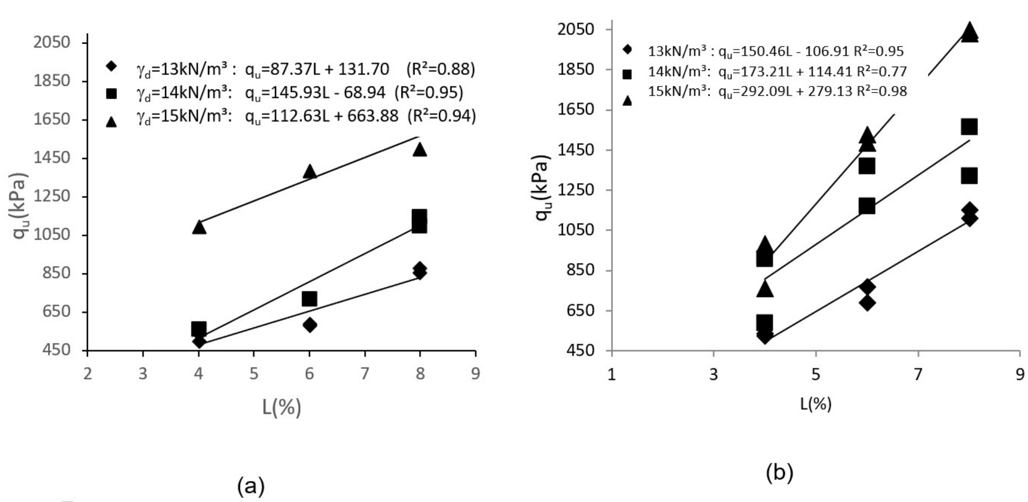

Figure 4. Unconfined compressive strength as a function of lime content of stabilized soil with (a) tap water and (b) brackish water.

3.3 Porosity/lime content index effect

The combination of variable porosity and lime content is presented in Figure 6a for blends done with tap water and (b) for mixtures molded with brackish water. Figure 6 shows that there is no unique relationship between strength and porosity/volumetric lime (η/L_{iv}) content. This behavior was also observed by Tenório (2019) when the author stabilized the same expansive soil using lime only. To obtain a unique dosage curve, it is necessary to make the two variables (η and L_{iv}) compatible setting an exponent (a) on the denominator (L_{iv}). According to Consoli et al. (2007, 2009, 2011) and Consoli & Foppa (2014), this exponent makes it possible to match the different growth rates of q_u with η and L_{iv} and hence, optimize the q_u x η/L_{iv} relation.

Figure 7 shows the relationship between the unconfined compressive strength and η/L_{iv}^{a} index for stabilized swelling soil with tap water and brackish water with an exponent of 0.26. This same exponent value was used by Silvani et al., (2020) relating the vertical swelling with porosity/lime content (η/L_{iv}), and by Guedes et al. (2022) correlating its q_u with porosity/cement content (η/C_{iv}), for the same soil. The authors found that 0.26 would be the best value to make the parameters and the variation rate compatible to better adjust porosity/cementing agent relation. Diambra et al. (2017) demonstrated through theoretical derivation that the coefficient a is highly dependent on the soil matrix (granular matrix) and is directly related to the external exponent $(3.97 \cong 1 / 0,26)$.

The analysis of Figure 7 indicates that q_u can be forecasted by the η/Liv^{a} index using a unique dosage curve as occurs with concrete strength while using the water/cement (w/c) ratio. The function to predict q_u with $\eta/L_{iv}^{0.26}$ index for blends molded with tap water is presented in Equation 3 and for blends done with brackish water is presented in Equation 4. The coefficient of determination is satisfactory ($R^2 > 0.85$) for both water molding tested. Comparing Equations 3 and 4 can be seen that the only difference between them is the scalar.

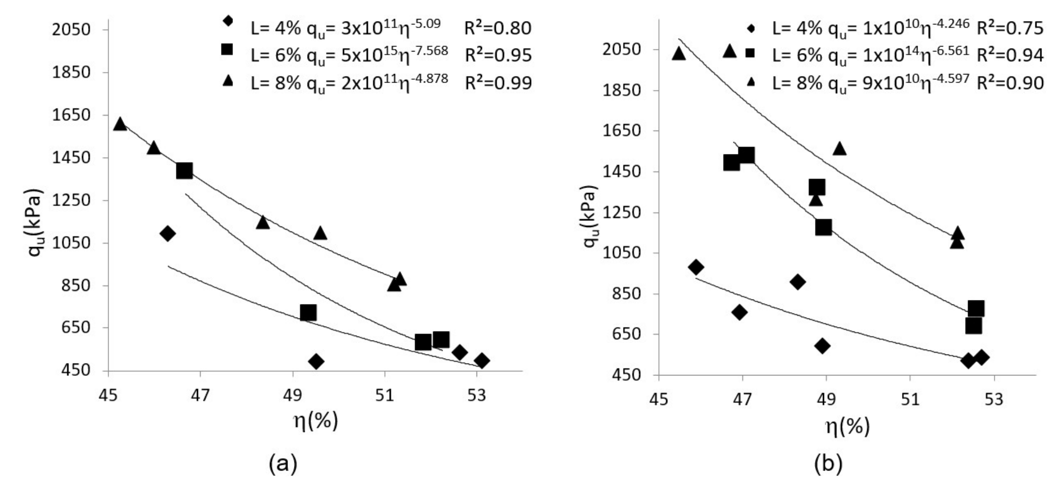

Figure 5. Unconfined compressive strength as a function of porosity of stabilized soil with (a) tap water and (b) brackish water.

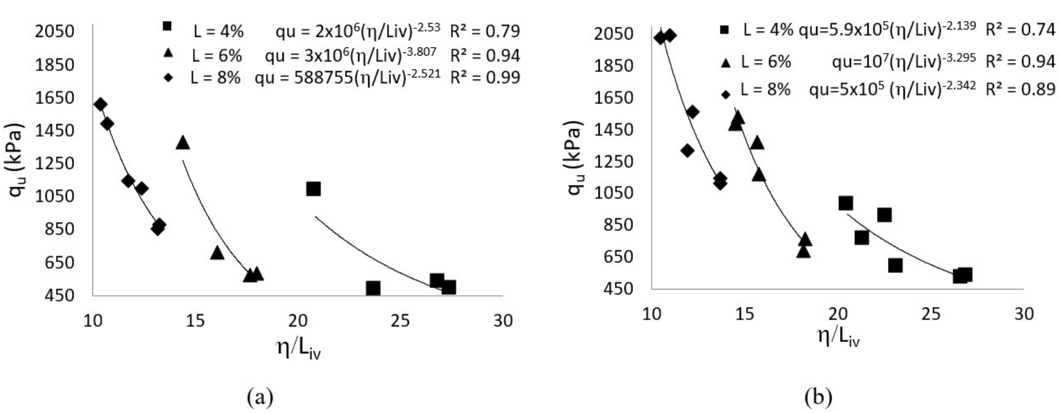

Figure 6. Unconfined compressive strength as a function of η/Liv index for the stabilized soil with (a) tap water and (b) brackish water.

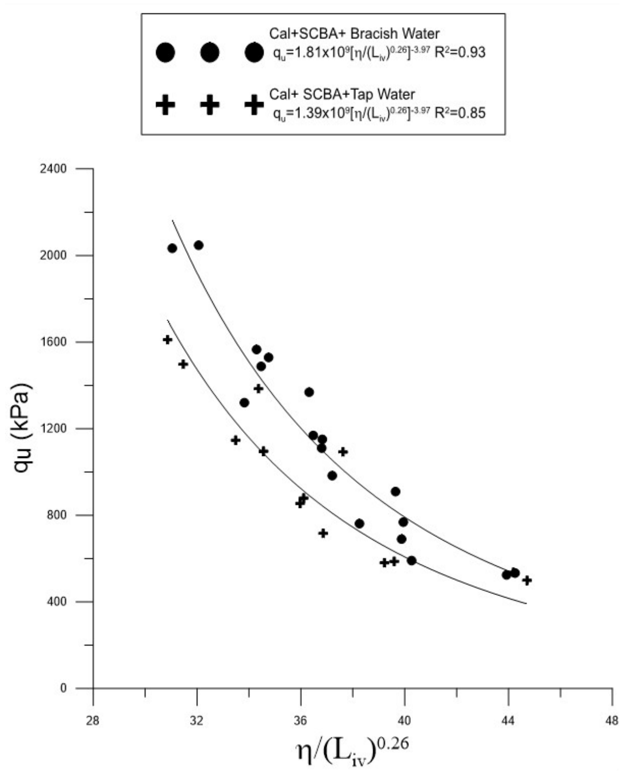

Figure 7. Unconfined compressive strength as a function of η/ Liv[a] index.

The scalar for mixtures done with brackish water is bigger than the scalar for blends molded with tap water. It shows that blends molded with brackish water have bigger q_u than mixtures done with tap water. The increase in q_u for specimens molded with brackish water came probably from the formation of calcium aluminum chlorohydrate ($Ca_2Al(OH)_6Cl{\bullet}2H_2O$). This mineral is formed due to the reaction of alumina (from SCBA) in conjunction with calcium (from lime) and chlorine (from brackish water) (Talero et al., 2011). Consoli et al. (2019e) studied coal fly ash/lime/NaCl blend and found out the formation of calcium aluminum chlorohydrate, through DRX and thermogravimetric results. SCBA and coal Fly ash are pozzolanic materials with similar compositions.

$$q_u = 1.81 \times 10^9 \left[\frac{\eta}{\left(L_{iv}\right)^{0.26}} \right]^{-3.97} \quad (3)$$

$$q_u = 1.39 \times 10^9 \left[\frac{\eta}{\left(L_{iv}\right)^{0.26}} \right]^{-3.97} \quad (4)$$

4. Conclusions

Based on the findings presented in this research, the following conclusions can be drawn:

- Swelling soil stabilized with lime and SCBA presented unconfined compression strength growth when the lime content was increasing, no matter if tap or brackish water was used in the molding process. This growth is probably due to the soil and SCBA chemical constitution, with high content of amorphous silica and alumina. However, the increase in porosity decays the blend's unconfined compression strength, probably due to the contact between particles reduction;
- The analyzed data showed that the applicability of porosity/Lime content (η/L_{iv}) index, adjusted by an exponent of 0.26 for the studied soil, allowed to forecast the unconfined compressive strength of expansive soil-SCBA-lime blends for both kinds of molding water through a unique dosage curve. However, blends molded with brackish water presented higher unconfined compression strength, probably because of NaCl present in its composition;
- The evaluation of using brackish water in soil stabilization was extremely worthwhile since it can be a feasible substitute for tap water regarding mechanical strength, a scarce asset in the world, especially in Northeast Brazil.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Carina Silvani: conceptualization, supervision, funding acquisition, project administration, writing – review & editing. João Pedro Camelo Guedes: conceptualization, data curation, methodology, formal analysis, writing – original draft. Jucimara Cardoso da Silva: conceptualization, methodology, formal analysis. Eduardo Antônio Guimarães Tenório: conceptualization, writing – review & editing. Renan Carlos de Melo Nascimento: conceptualization, methodology.

Data availability

The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols

q_u unconfined compressive strength;
w moisture content;
L_{iv} volumetric lime content;
L amount of lime;

R^2 coefficient of determination;
S soil content;
SCBA sugarcane bagasse ash;
Vs specimen total volume;
γ_d dry unit weight;
γ_{sS} unit weight of solids of soil;
γ_{sSCBA} unit weight of solids of SCBA;
γ_{sL} unit weight of solids of lime; and
η porosity
η/C_{iv} porosity/cement index.
η/L_{iv} porosity/lime index.

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