Maximum Tensile Strength of Sand - Coal Fly Ash - Lime Blends for Varying Curing Period and Temperature

C. Silvani, M. Benetti, N.C. Consoli

Abstract. The pozzolanic reactions, responsible for the resistance of soil-lime blends, are endothermic. As such, increasing the curing temperature in turn increases the strength of lime-stabilized soil. Recent research has shown that there is a maximum limit to the resistance of a specimen, based on its curing time. This study aims to predict the maximum tensile strength of sand-coal fly ash-lime blends for several curing times. To achieve that, a series of splitting tensile tests were carried out using cylindrical specimens with diameter and length equal to 50 mm and 100 mm, respectively. Lime content varied from 3% to 7%, dry unit weight ranged from 14 kN/m$^3$ to 16 kN/m$^3$, curing temperatures were 20, 35, 50, 65, 80 and 90 °C, curing periods were 1, 3 and 7 days and fly ash content was established as 25%. Results show that the increase in curing temperature boosts the tensile strength of sand-coal fly ash-lime blends up to a limit that varies with curing time. The porosity/lime index, defined as the ratio of the compacted mixture’s porosity and volumetric lime content adjusted by an exponent, proves to be an appropriate parameter to estimate the splitting tensile strength of the soil-fly ash-lime studied for all curing times and temperatures studied. Using this index, curves were obtained for the calculation of the maximum temperature that influences the resistance of the studied mixture for each curing time. An equation capable of determining the maximum resistance that can be reached in each curing time, independent of curing temperature, was also obtained through the index.

Keywords: coal fly ash, curing temperature, curing time, lime, maximum splitting tensile strength, sand, soil stabilization.

1. Introduction

Lime stabilization in quartzitic soil, like Osório sand, is not possible since lime needs to react with amorphous silica or alumina to become a water-resistant cementitious material. Quartz is a crystalline material, so it does not react with lime. To be able to stabilize Osório sand with lime, adding a source of amorphous material, such as the coal fly ash used in this research, is necessary.

The development of alternatives for Portland cement, such as using industrial by-products (e.g. coal fly ash, carbide lime) as a cementitious material, brings environmental and economical benefits. In southern Brazil, materials such as coal fly ash (by-product of coal combustion in thermal power plants) and carbide lime (by-product of acetylene gas manufacture) are profusely produced. From an environmental perspective, the use of by-products and wastes instead of Portland cement is a more sustainable solution, since it reduces the use of Portland cement, whose manufacture is the origin of about 8% of the world’s CO$_2$ pollutant emissions (Zhang et al., 2014). From an economical viewpoint, the use of coal fly ash plus carbide lime, instead of Portland cement, comes from the fact that such industrial by-products have a very reduced cost at their place of production. The commercial feasibility of using such by-products is related to the distance from the production sites to the place where they are going to be used (the main cost is linked to transportation), the shorter the distance, the lower the cost and the higher the economic feasibility of using them. Soil-coal fly ash-carbide lime blends have been successfully used to enhance the bearing capacity of footings leaning on improved layers above weak foundation soil (e.g. Pedreira, 2000; Pedreira et al., 2002; Consoli et al., 2009a), as well as the base/sub-base of pavements (e.g. Kampala et al., 2014). Other procedures have focused on assessing the use of wastes to produce building materials such as bricks (e.g. Consoli et al., 2014a) and new products from reclaimed asphalt pavement, coal fly ash and carbide lime blends (Consoli et al., 2018).

The porosity/lime index (n/Lc) has been shown to be useful to design lime-stabilized soil (Consoli et al., 2009b, 2011, 2015). One problem in lime stabilization is that the reaction between lime and the amorphous materials is slow. That can be accelerated with the increase of curing temper-
ature (Thompson, 1966, Toohey et al., 2013, Saldanha & Consoli, 2016). However, according to Consoli et al. (2014a, 2014b, 2014c), the maximum strength of coal fly ash-lime and soil-coal fly ash-lime blends is limited by curing time.

Thomé et al. (2005) and Consoli et al. (2008, 2009a) have shown that the failure in stabilized layers usually starts with fissures at the bottom of the layer once tensile strength ($q_t$) is reached. For this reason, tensile strength is a good parameter to evaluate failure of lime-stabilized soils. This research looks for a way to predict the maximum tensile strength for each curing time. The temperature at which that maximum strength can be reached for sand-coal fly ash-lime blends is also investigated.

2. Experimental Program

The experimental program was carried out in two parts. First, soil and fly ash had their geotechnical properties established. The second part was a series of splitting tensile tests for sand-coal fly ash-lime specimens cured for 1, 3 and 7 days at temperatures of 20, 35, 50, 65, 80 and 90 °C. Temperature variation was chosen in a way that the maximum strength for each curing time could be reached. Since temperature works as a catalyzer, it is expected that there will be no need of a curing period longer than a few days to develop the full cementation for higher curing temperatures.

2.1. Materials

Quartzitic rounded wind sand (Osório Sand) was used in this study. The samples were collected in a disturbed state, through manual excavation, in the region of Osório, southern Brazil. According to the Unified Soil Classification System (ASTM D2487, 2006), Osório sand is classified as poorly graded sand (SP).

The coal fly ash (FA) used was obtained from a coal-fired power plant and such residue is composed predominantly by amorphous minerals (SiO$_2$ and Al$_2$O$_3$) according to X-ray diffraction tests. The FA used has only 0.8% of lime, so it is classified as Class F fly ash, according to ASTM C618 (ASTM 1998) and it has the granulometry of a sandy silt. The results of the characterization tests of Osório sand and the FA are shown in Table 1.

Carbide lime was used throughout this investigation; such lime is a by-product of the manufacture of acetylene gas. In ambient temperature (about 20 °C) the gain of strength due to chemical reactions between Ca$^{2+}$ [from Ca(OH)$_2$], SiO$_2$ and Al$_2$O$_3$ (from coal fly ash) is relatively slow, when compared to other binders (such as Portland cement) at equal curing temperatures. The specific gravity of the lime grains is 2.49.

Distilled water was used for both the characterization tests and molding of the specimens for the splitting tensile tests. The use of distilled water in all testing is due to the necessity of guaranteeing that no impurities (e.g., minerals) that might exist in the tap water will affect the results.

2.2. Initial consumption of lime

The minimum amount of lime required for full stabilization, based on the initial consumption of lime (ICL) (Rogers et al., 1997), was established on the basis of the interpretation of pH tests carried out on soil-coal fly ash with lime added - water (proportions of 1:3) mixtures. Tests carried out in the present study have shown that the variation of pH due to lime addition presented an asymptotic pH result with varying lime amount starting at 3% lime content. So, according to such methodology, 3% lime content is the minimum amount that will guarantee full stabilization of the studied blends.

2.3. Methods

2.3.1. Molding and curing of specimens

All the tests in this study used cylindrical specimens, 50 mm in diameter and 100 mm in length. The first step in the preparation of the specimens was the weighing of dry Osório sand, coal fly ash and lime. The second step was the hand mixing of the dry materials until they reached a uniform consistency. The third step was the addition of water and subsequently hand-mixing the blend for 5 min. It is important to say that the amount of FA (25%) was calculated based on the mass of the dry sand, while the amount of lime (3% to 7%) was calculated based on the mass of the dry sand plus the mass of the fly ash. Eq. 1 was used in the cal-

| Properties                      | Osório sand | Coal fly ash |
|--------------------------------|-------------|--------------|
| Specific gravity                | 2.63        | 2.28         |
| Medium sand size particles (0.2 mm < diameter < 0.6 mm) | -           | 1.0%         |
| Fine sand size particles (0.06 mm < diameter < 0.2 mm) | 100.0%      | 13.6%        |
| Silt size particles (0.002 mm < diameter < 0.06 mm) | -           | 84.9%        |
| Clay size particles (diameter < 0.002 mm) | -           | 0.5%         |
| Mean particle diameter ($D_{pm}$) | 0.16 mm     | 0.018 mm     |
culation of the porosity of a sand-fly ash-lime specimen (Consoli et al., 2011).

\[
\eta = 100 - \frac{\left( \frac{\gamma_d V_s}{1 + \frac{\gamma_d}{100}} 100 \right) + \left( \frac{\gamma_d V_{FA}}{1 + \frac{\gamma_d}{100}} \frac{FA}{100} \right) + \left( \frac{\gamma_d V_L}{1 + \frac{\gamma_d}{100}} \frac{L}{100} \right)}{V_s} \]

where: \( \eta \) = porosity of the sand-coal fly ash-lime specimen, \( FA \) = coal fly ash content (percentage of dry weight of sand), \( L \) = lime content (percentage of dry weight of soil plus fly ash), \( \gamma_d \) = dry unit weight of the specimen and \( V_s \) = volume of specimen. \( G_s \) = specific gravity of the sand grains, \( G_{s,FA} \) = specific gravity of the fly ash grains and \( G_s \) = specific gravity of the lime grains.

During the confection of the specimens, the sand-coal fly ash-lime mixture was kept in a covered container to avoid moisture loss. The water content was obtained through two small portions retrieved from the mixture.

The static compaction of the specimens was carried out in three layers inside a lubricated cylindrical split mold. To ensure sample integrity the top of the first and the second layers were scarified. When the three layers were done the specimen was removed from the mold. The specimen was then measured and weighed with accuracies of about 0.01 g and 0.1 mm. The specimens were cured inside plastic bags in a humid room at distinct temperatures and relative humidity above 95% for 1, 3 or 7 days.

The samples were accepted for testing if they met the following tolerances: **Dry Unit Weight** (\( \gamma_d \)): degree of compaction between 99% and 101% (the degree of compaction being defined as the value obtained in the molding process divided by the target value of \( \gamma_d \)); **Moisture Content** (\( \omega \)): within ±0.5% of the target value and **Dimensions**: diameter to within ±0.5 mm and height ± 1 mm.

### 2.3.2. Splitting tensile tests

Carneiro & Barcellos (1953) developed a simple test able to measure the tensile strength of brittle materials: the splitting tensile test. ASTM C496 (ASTM 2011) follows the concepts established by Carneiro & Barcellos (1953). After curing, the specimens were soaked in water at 20 °C for 24 h to minimize suction (Consoli et al., 2011). After these 24 h period immersed in water, all specimens had a degree of saturation above 85%, irrespective of the initial porosity or cementitious material content. All specimens have had their matric suction measured using the filter paper technique (Marinho, 1995). Such tests were carried out with pieces of artificially cemented material collected from the center of the specimens just after they have been taken to failure. The values of suction measured were low, ranging from about zero up to 10 kPa, allowing suction to be eliminated as a variable in the analysis. For the test, the samples were removed from water and placed horizontally between two stainless steel plates in an automatic loading machine with a maximum capacity of 50 kN and a proving ring with a capacity of 10 kN and a resolution of 0.005 kN. The tests were carried out by compressing the samples along two opposite generatrices leading to failure in tension along the diameter contained in the plane formed by these two generatrices. Tests in which the average strength deviated by more than 10% were disregarded.

#### 2.3.3. Program of splitting tensile tests

In the program of splitting tensile tests, the molding points were positioned in a vertical line (Points A1, A2, and A3), with the same moisture content and three different dry unit weights (16 kN/m³, 15 kN/m³ and 14 kN/m³). Such values were chosen after standard Proctor compaction test results carried out by Silvani (2013) on a sand-coal fly ash-lime blend (containing 25% of coal fly ash and 7% lime) presented maximum dry unit weight (\( \gamma_{d, max} \)) of about 16.0 kN/m³ at optimum moisture content (\( \omega_{d, opt} \)) of 14% (Fig. 1). It is important to state that standard Proctor compaction tests were also carried out on sand-coal fly ash-lime blends containing 3% and 5% lime, which resulted in about the same \( \gamma_{d, max} = 16.0 \text{ kN/m}^3 \) and \( \omega_{d, opt} = 14\% \) as the mixture containing 7% lime. Three different lime percentages (calculated based on the mass of dry soil plus coal fly ash) were
chosen starting with 3% [minimum amount to guarantee full stabilization of the studied blends according to Initial Consumption of Lime (ICL) proposed by Rogers et al. (1997)], plus two other values above it, 5% and 7% (Mitchell, 1981). Consoli et al. (2014b) studied the same sand-coal fly ash-lime blends studied here in (considering the same compaction conditions - same molding points, curing method, and curing temperatures of 20, 35 and 50 °C), but only contemplating 28 days of curing time. Since temperature can be a catalyzer in lime-fly ash reactions, this research focused on shorter curing times (1, 3 and 7 days) and considered the following range of curing temperatures: 20, 35, 50, 65, 80 and 90 °C. All specimens had 25% FA content. This agrees with Brazilian practice (Consoli et al., 2001). Three specimens were tested for each molding point so as to account for the typical scatter of data from the strength tests.

3. Results and Analysis

3.1. Effect of porosity/lime index

Consoli et al. (2014b) showed that the tensile strength of sand-fly ash-lime blends, cured for 28 days, can be evaluated by the porosity/lime index ($\eta/L_v$), defined by the porosity ($\eta$) of the compacted blend divided by the volumetric lime content ($L_v$) (defined as the volume of lime in relation to the total specimen volume) adjusted by an exponent (0.30). Figures 2, 3 and 4 show that $\eta(L_v)^{0.3}$ can also be used to evaluate the tensile strength of the studied mixture when the curing time is 1, 3 and 7 days. All fits were based in the whole raw experimental data.

It can be observed in Figs. 2, 3 and 4 that for the lower curing temperatures, $q_t$ does not change much with increasing values of $\eta(L_v)^{0.3}$, and consequently the coefficient of determination ($R^2$) is low. In the extreme, if $q_t$ was constant with increasing values of $\eta(L_v)^{0.3}$ the coefficient of determination would be close to zero.

Consoli et al. (2014b) found that for 28 days of curing the $q_t$ increased with temperature up to 35 °C, after which it stabilized. Figure 2 presents that for 7 days of curing, $q_t$ increases with the temperature up to 50 °C. According to Figs. 3 and 4, the temperature of 80 °C seems to be the limit temperature for 1 and 3 days of curing time. For any temp-

Figure 2 - Variation of splitting tensile strength with adjusted porosity/lime index considering 7 days of curing time.

Figure 3 - Variation of splitting tensile strength with adjusted porosity/lime index considering 3 days of curing time.

Figure 4 - Variation of splitting tensile strength with adjusted porosity/lime index considering 1 day of curing time.
perature beyond 50 °C for 7 days of curing time and 80 °C for 1 and 3 days of curing time, the $q_t$ remains constant. The data of Figs. 2 to 4 plus the result of Consoli et al. (2014b) can be summarized in Fig. 5. Figure 5 presents the variation of normalized splitting tensile strength $q_t/[\left(n/(L_p)^{0.3}\right)]^{-3}$ with curing temperatures (T). Figure 5 shows that for each curing time $q_t/[\left(n/(L_p)^{0.3}\right)]^{-3}$ increases linearly with rising temperatures up to a threshold and after that it becomes an asymptote. The strength gain leveled off for each specific curing time period because there is a maximum velocity for the chemical reactions between silica and alumina in amorphous phase (from the coal fly ash) and Ca$^{++}$ from the Ca(OH)$_2$ that can occur. As such, increasing temperature expedites pozzolanic reactions up to a certain temperature (until the kinematic of the reactions reach a maximum) and increasing temperature beyond that will not cause any strength increase. Figure 5 also shows that $q_t/[\left(n/(L_p)^{0.3}\right)]^{-3}$ depends on the time and temperature of curing. Thus in order to optimize the tensile strength, it is necessary to know the maximum temperature capable of effectively increasing $q_t$ for each curing time and the maximum tensile strength that can be reached in each curing time. Figure 6 presents the maximum temperature that is effective in growing $q_t$. That temperature decreases with the rise of curing time according with a power function [Eq. 2]. So, Eq. 2 is useful to optimize the expenditure of energy in the form of heat to increase $q_t$.

$$T_i = 88.89(t_{curing})^{-0.27}$$  \hspace{1cm} (2)

The space $q_t/[\left(n/(L_p)^{0.3}\right)]^{-3}$ vs. curing time ($t_{curing}$) can be divided in two areas (see Fig. 7): one possible (below the curve represented in Fig. 7) and one impossible (above the curve represented in Fig. 7). These areas are divided by a power equation [Eq. 3]. Equation 3 enables the calculation of the maximum tensile strength that can be reached for each curing time.

$$q_t = [6.22(t_{curing})^{0.22}] \left[\frac{n}{(L_p)^{0.3}}\right]^{-3}$$ \hspace{1cm} (3)

where $T_i$ = temperature of stabilization (maximum) of the increase in tensile strength, and $t_{curing}$ = curing time.

Figure 5 - Variation of normalized splitting tensile strength with curing temperatures (for 1, 3, 7 and 28 days curing).

Figure 6 - Relationship between the temperature of tensile strength stabilization ($T_i$) and the curing time ($t_{curing}$).
4. Concluding Remarks

From the data presented in this manuscript the following concluding remarks can be drawn:

- Increase in temperature boosts tensile strength of sand-coal fly ash-lime blends up to a limit. This limit varies with curing time. To optimize the dosage of sand-coal fly ash-lime mixtures, it is necessary to know the maximum temperature ($T$) capable of effectively increasing $q_t$ [see Eq. 2]. The maximum tensile strength, for each curing time ($t_{curing}$), is also a restraining value. This information can be calculated from Eq. 3. Equations 2 and 3 are valid for the sand, coal fly ash and lime used in the present study and further studies are necessary to check if analogous equations are found for other soils, ashes and limes. Additionally, subsequent investigation shall be carried out to assess if similar trends are also observed regarding initial shear stiffness ($G_0$);

- The porosity/lime index, defined by the porosity of the compacted mixture divided by the volumetric lime content, adjusted by an exponent, $[\eta/(L_c)^{0.3}]$ has been shown to be an appropriate parameter for evaluating the splitting tensile strength of several combinations of curing temperatures and curing times for the sand-coal fly ash-lime blends studied. Further studies are being carried out by the authors considering the efficiency of the porosity/lime index to detect the impact of distinct curing temperatures and curing times on similar blends considering clayey soils;

- Curing temperature only works as a catalyst, meaning that increasing temperature only expedites strength gain but does not increase it (final strength depends only on dosage and time to reach such strength is the only aspect affected by temperature). However, given the possibility of encountering temperatures above 40 °C in the field during certain times of year (mainly in summer), it is important to know that in such situations shorter curing periods will be required in order to develop the full cementation using coal fly ash - lime blends. Finally, the development of strength of sand-coal fly ash-lime blends due to field temperatures above the ambient temperature commonly considered for design (about 20 °C) is key to soil stabilization and ground improvement, since the faster the final target strength is reached in the field, the sooner the earthwork can be used for the purpose for which it has been built.

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### List of Symbols

- $L$: lime content (expressed in relation to mass of dry soil)
- $L_v$: volumetric lime content (expressed in relation to the total specimen volume)
- $D_{50}$: mean particle diameter
- $q_s$: splitting tensile strength
- $T$: curing temperature
- $T_c$: temperature of stabilization (maximum) of the increase in tensile strength
- $t_{curing}$: curing time
- $V$: volume of specimen
- $V_v$: volume of voids
- $\gamma$: dry unit weight
- $\gamma_{max}$: maximum dry unit weight
- $\eta$: porosity
- $\eta/L_v$: porosity/lime index
- $\omega$: moisture content
- $\omega_{opt}$: optimum moisture content