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Effect of Curing Temperature on the Compressive Strength of Sand, Fly Ash, and Lime Blends

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SUMMARY:
Soil is the base of most civil engineering constructions, and when it cannot support the construction loads, such problem can be solved through the use of soil stabilization technique. Lime stabilization is a classical technique, but the first rational dosage methodology for soil-fly ash-lime was developed by Consoli et al. (2011). That methodology consider the porosity/lime ratio (η/L_{iv}), defined by the porosity of the compacted mixture divided by the volumetric lime content, as an appropriate parameter to evaluate the unconfined compressive strength (q_u) of soil-fly ash-lime mixtures. On the other hand, even though it is already recognized by previous studies (e.g., Rojas and Cabrera 2000, 2001; Consoli et al. 2001; Al-Mukhtar et al. 2010a, b) that strength of soil-fly ash-lime mixes (based on pozzolanic reactions) is dependent on temperature (T), which acts as a catalyzer of pozzolanic reactions, it is still unknown if the effect of curing temperature should be inserted in a rational methodology. So the present research aims to quantify the influence of curing temperature (T), amount of lime (L), porosity (η), and porosity/lime ratio (η/L_{iv}) on the assessment of unconfined compressive strength (q_u) of sand–fly ash–lime blends. A series of unconfined compression tests were carried out in cylindrical specimens with diameter and height equal to 50 and 100mm, respectively, with lime contents varying from 3% to 7%, dry unit weight ranging from 14kN/m³ to 16kN/m³, curing temperature 20º, 35º and 50ºC, time curing period of 28 days and fly ash content of 25%. A power function fits well as the relation between q_u with η, and a linear function fits well the relation between q_u with L for all curing temperatures of the specimens. It was also shown that the porosity/lime ratio (η/L_{iv}) is a good parameter in the evaluation of q_u of the studied blends for the whole range of lime, porosities and temperature studied, at specific amount of fly ash (25%) and curing time period (28 days). The volumetric cementitious material content (L_{iv}) is adjusted by an exponent (0.30 for all curing temperatures blends) to end in unique correlations for each temperature. For a given curing time period (28 days), the relation q_u-η/L_{iv} versus T is shown to vary linearly up to a threshold, when asymptotes occur.

KEYWORDS: Lime, fly ash, sand, lime stabilization, curing temperature.

1 INTRODUCTION

Lime-coal fly ash is used worldwide in the improvement of local soils, particularly blended in compacted layers over low bearing capacity soils (e.g. Thomé et al. 2005 and Consoli et al. 2008) and as pavement layers (e.g. Crockford et al. 1993). Although, there are no dosage methodologies based on rational criteria considering the effect of different variables (e.g. amount of lime, porosity) on the blends compressive strength.

The first rational dosage methodology for soil-fly ash-lime was developed by Consoli et al. (2011) considering the porosity/lime ratio (η/L_{iv}), defined by the porosity of the compacted mixture divided by the volumetric lime content, as an appropriate parameter to evaluate the unconfined compressive strength (q_u) of soil-fly ash-lime mixtures. On the other hand, even though it is already recognized by previous studies (e.g., Rojas and Cabrera, 2000, 2001, Consoli et al. 2001, Al-Mukhtar et al. 2010a, b) that strength of soil-fly ash-lime mixes (based on pozzolanic reactions) is dependable of temperature (T), which acts as a catalyzer of pozzolanic reactions, it is still unknown if the effect of curing temperature should be inserted in a rational methodology. So, this study aims at approaching this issue by quantifying the influence of T, L, η and adjusted η/Liv on q_u of a sand-fly ash-lime blend.

2 EXPERIMENTAL PROGRAM

The experimental program was carried out in two parts. First, the geotechnical properties of the studied soil and fly ash were characterized. Then a series unconfined compression tests for sand-fly ash-lime blend specimens cured at temperatures 20^o, 35^o and 50^{o}C were carried out as discussed below. Temperature variation all over Brazil is between 20^o and 50^{o}C, which is the reason for choosing inferior and superior temperatures of present research, besides of intermediate values.

2.1 Program of Unconfined Compression Tests

The unconfined compression tests carried out under distinct curing temperatures constituted the main part of this research. The program was conceived in such a way as to evaluate, separately, the influences of the curing temperature, lime content, porosity and porosity/lime ratio on the mechanical strength of the soil – coal fly ash – lime blends. Three different dry densities (14 kN/m^3, 15 kN/m^3 and 16 kN/m^3) were chosen after standard Proctor compaction test results carried out by Silvani (2013) presenting maximum dry density (γ_{dmax}) of 16 kN/m^3 at optimum moisture content (ω_{opt}) of 14%. Such results are in accordance with Brazilian practice on compacted sandy soils-fly ash-lime blends using standard Proctor energy (Consoli et al. 2001, 2011); three different lime percentages (calculated based on the mass of dry soil): 3%, 5% and 7% were chosen following international and Brazilian experience (Mitchell 1981, Consoli et al. 2001, 2011) and 28 days of curing (minimum curing time for such blends when used as base of roads in Brazil – Consoli et al. 2001, 2011) at temperatures of 20^{o}C, 35^{o}C and 50^{o}C.

Because of the typical scatter of data for the strength tests, a minimum of three specimens were tested for each point.

2.2. Materials

The soil used in this study was a rounded wind transported quartzitic sand (named Osorio sand) and was obtained from a borrow site in the region of Osorio, southern Brazil. The sample was collected in a disturbed state, by manual excavation, in sufficient quantity to complete all the tests. The results of the characterization tests are shown in Table 1. This soil is classified as uniform fine sand (SP) according to the Unified Soil Classification System.

The fly ash (FA) selected [type F according to ASTM C618 (ASTM 1998)] was a residue of burning coal in a thermal power station, located near Porto Alegre. The main characteristic of Class F fly ash is the amount of calcium oxide (CaO) in the ash, which is typically less than 12% (in the present case CaO percentage is

0.8%). The results of the FA characterization tests are presented in Table 1. The FA is classified sandy silt (ML) according to the Unified Soil Classification System. X-ray diffraction showed that the material is composed predominantly by amorphous minerals. The fly ash pH is about 8.3.

Dry hydrated lime [$Ca(OH)_2$] was used as the cementing agent. The specific gravity of the lime grains is 2.49.

Distilled water was used both for molding specimens for the tests and for the characterization tests.

Table 1 Physical properties of Osorio sand and coal fly ash samples

PROPERTIES	Osorio sand	Fly Ash
Specific Gravity	2.63	2.28
Medium Sand (0.2 mm < diameter < 0.6 mm)	-	1.00%
Fine Sand (0.06 mm < diameter < 0.2 mm)	100.00%	13.60%
Silt (0.002 mm < diameter < 0.06 mm)	-	84.90%
Clay (diameter < 0.002 mm)	-	0.50%
Effective Diameter (D50)	0.16 mm	0.018 mm

2.1 Methods

2.1.1 Molding and Curing of Specimens

For unconfined compression tests, cylindrical specimens, 50 mm in diameter and 100 mm high, were used. The compacted sand-fly ash-lime specimens used in the tests were prepared by weighing dry Osorio sand, fly ash and lime, followed by hand-mixing the materials for about 5 minutes to a uniform consistency. The water [moisture content of all specimens molded was about 14%, which is in accordance with optimum moisture content after standard Proctor compaction test results carried out by Silvani (2013)] was then added continuing the mixing process for another 5 minutes until a homogeneous paste was created.

The amount of fly ash used in this work (25%), was selected according to Brazilian practice (Consoli et al. 2001) and taking into account compaction difficulties found using higher amounts of fly ash. The 25% of fly ash for each mixture was calculated based on the mass of dry soil. The amount of lime for each mixture (varying from 3 to 7%) was calculated based on the mass of dry sand plus the mass of fly ash. The specific gravity of the sand grains (G_{ss}=2.63) is greater than the specific gravity of the lime (G_{sL}=2.49) which is greater than the specific gravity of the fly ash grains (G_{sFA}=2.28). The porosity of a sand-fly ash-lime specimen is a function of the specific gravity of sand grains (G_{ss}), as well as of the fly ash grains (G_{sFA}) and the lime (G_{sL}), and can be calculated according to Eq. (1) [Consoli et al. 2011],

$$\eta = 100 - \frac{100\left(\left(\frac{\left(\frac{\gamma_d V_s}{\left[1+\left(\frac{L}{100}\right)\right]}\right)\left(\frac{S}{100}\right)}{Gs_S}\right)+\left(\frac{\left(\frac{\gamma_d V_s}{\left[1+\left(\frac{L}{100}\right)\right]}\right)\left(\frac{FA}{100}\right)}{Gs_{FA}}\right)+\left(\frac{\left(\frac{\gamma_d V_s}{\left[1+\left(\frac{L}{100}\right)\right]}\right)\left(\frac{L}{100}\right)}{Gs_L}\right)\right)}{V_s} \quad (1)$$

where: η = porosity of the sand-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), γ_d = dry density of the specimen and V_s = volume of specimen.

After mixing sufficient material for one specimen, the mixture was stored in a covered container to avoid moisture losses before subsequent compaction. Two small portions of the mixture were also taken for moisture content determination.

The specimen was then statically compacted in three layers inside a cylindrical split mold, which was lubricated, so that each layer reached the specified dry density. The top of the first and the second layers was scarified. After the molding process, the specimen was immediately extracted from the split mold, and its weight, diameter and height determined measured with accuracies of about 0.01g and 0.1mm. The samples were then placed within plastic bags to avoid significant variations of moisture content. They were cured in a humid room at four distinct temperatures and relative humidity above 95% for 28 days of curing days.

The samples were considered suitable for testing if they met the following tolerances: Dry Density (γ_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 γ_d); Moisture Content (ω): within ± 0.5% of the target value and Dimensions: diameter to within ±0.5mm and height ±1mm.

2.1.2 Unconfined Compression Tests

Unconfined compression tests have been systematically used in most experimental programs reported in the literature in order to verify the effectiveness of the stabilization with cement or to assess the importance of influencing factors on the strength of cemented soils. One of the reasons for this is the accumulated experience with this kind of test for concrete. The tests usually followed Brazilian standard NBR 5739 (ABNT 1980), which is in accordance with standard ASTM C39 (ASTM 2012), being simple and fast, while reliable and cheap.

Unconfined compressive tests were done with an automatic loading machine with maximum capacity of 50kN and a proving ring with capacity of 10kN and 50kN and resolutions of 0.005kN and 0.023kN.

After curing in the humid room for 28 days, the specimens were submerged in a water tank for 24 hours for saturation to minimize suction (Consoli et al. 2011). The water temperature was controlled and maintained at about 20ºC. Immediately before the test, the specimens were removed from the tank and dried superficially with an absorbent cloth. As acceptance criteria, it was stipulated that the individual strengths of three specimens, molded with the same characteristics, should not deviate by more than 10% from the mean strength.

3 RESULTS

3.1 Effect of the Porosity and Lime Content

Figures 1 show, for a curing time period of 28 days, how lime amount affect unconfined compressive strength of the sand-fly ash-lime mixtures at curing temperature of 35ºC. Figures 2 show, for the same curing time and curing temperature, how porosity affects unconfined compressive strength of the sand-fly ash-lime mixtures. A linear function and a power function fit well the relations between strength and lime content and strength and porosity (η) for all lime contents, porosities and temperatures studied. Compressive strengths increase with increasing amount of lime and with reduction in porosity. An interesting feature that can be seen in Fig. 1 is the increase in the rate of strength gain with lime content, represented by the gradient of the fitted line, with the increase of the dry density. In present study, a reduction of porosity from about 46% to about 38% conduces to an increase of about 100% on compressive strengths. The mechanism by which the reduction in porosity influences the sand-fly ash-lime strength is related to the existence of a larger number of contacts.

Regarding temperature increase, current results have presented similar trends as obtained by Al-Mukhtar et al. (2010a, 2010b) in lime – clay blends, which presented a considerable higher rate of strength increase for specimens cured at higher temperatures, confirming that temperature acts as a catalyzer of pozzolanic reactions. Al-Mukhtar et al. (2010b) have also observed that increasing temperature conduces to higher strengths at short curing time periods and that at very long curing periods blends with same porosity and amount of lime will have similar strengths, indistinctly of the curing temperature being 20ºC or 50ºC.

3.2 Effect of the Porosity and Lime Content

Considering all range of lime contents, porosities and curing temperature studied, unconfined compressive strength is dependent of both the porosity and the lime content of the mixture. Rising values of porosity cause reduction of q_u while increasing values of lime content ends up in larger values of q_u. Consoli et al. (2012) has proposed, specifically for soil-lime blends, the existence of explicit relations between q_u with η/L_{iv} [expressed as porosity (η) divided by the volumetric lime content (L_{iv}), the first stated as the volume of voids divided by total volume of specimen and the latter expressed as volume of lime regarding total volume of specimen], as defined by Eq. (2)

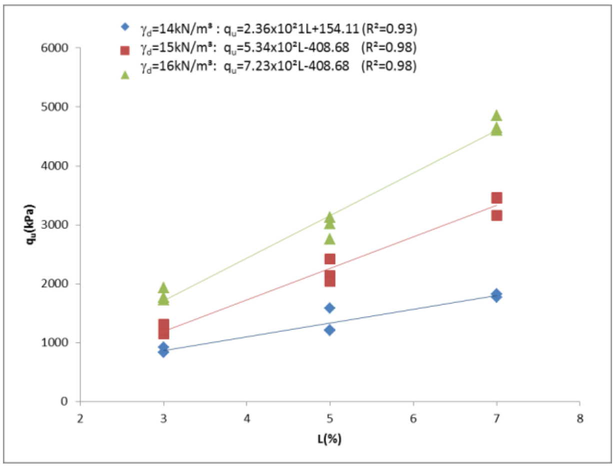

Figure 1-Variation of unconfined compressive strength (q_u) with lime content (L) for curing temperature of 35°C.

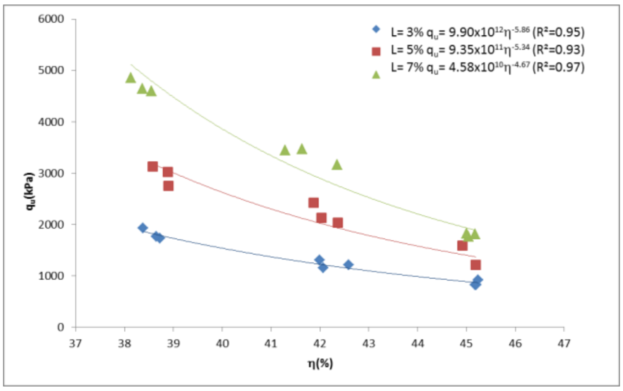

Figure 2-Variation of unconfined compressive strength (q_u) with porosity (η) for curing temperature of 35°C.

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$$\frac{\eta}{L_{iv}} = \frac{\left(\frac{V_v}{V_{total}}\right)}{\left(\frac{V_L}{V_{total}}\right)} = \frac{V_v}{V_L} \qquad (2)$$

where V_v is the volume of voids (water + air) of the specimen, V_L is the volume of lime of the specimen and V_{total} is the total volume of the specimen.

The reason for using porosity/lime ratio (η/L_{iv}) in present research is based on the concept that water/lime ratio (defined as the water mass divided by the lime mass) was a useful parameter in the analysis of the strength development of cemented soils in which pores of the samples were predominantly water-filled, so that the water content would reflect the amount of voids. In the present study, the voids are only partially filled by water, and there is not a unique relationship between the voids and the amount of water. Therefore for the soil lime in the unsaturated state, as is usual in geotechnical engineering practice, a relationship between porosity and volumetric lime content should be more appropriate in the analysis and control of its mechanical strength.

The relation q_u versus η/L_{iv} suggests that η/L_{iv} joins the distinct effects of both variables (η and L_{iv}) in a unique factor controlling q_u. From a mechanical standpoint, it means that although η and L_{iv} affect separately q_u, the negative effect on q_u of increasing values of porosities might be counteracted by increasing the volumetric lime content (for a given change in the porosity, a variation in the volumetric lime content would be enough to balance the strength gain or loss).

Figures 3 present unconfined compressive strength as a function of the porosity/lime ratio (η/L_{iv}), for specimens cured at temperature of 35°C and 28 days of curing, distinguishing the plotted points by their lime contents. Points with similar η/L_{iv}, but obtained by different combinations of lime content and porosity, show distinct strengths for each lime content (similar results are obtained for other curing temperatures). It is supposed to be due to substantial differences in rates of change of q_u with porosity (η) and with the inverse of the volumetric lime content ($1/L_{iv}$). A way to make the variation rates of η and $1/L_{iv}$ compatible is through the application of a power to one of them (in the present work the application of a power is suggested to be on L_{iv} - the optimum fit was found to be applying a power equal to 0.30 to the sand-fly ash-lime blends studied herein) as shown in Figs. 4 considering a curing temperature of 35°C. Similar results are obtained for other curing temperatures, as can be seen in Fig. 5.

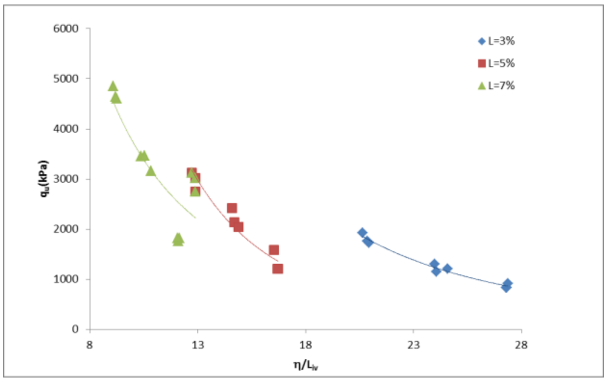

Figure 3- Variation of porosity/lime ratio (η/L_{iv}) with unconfined compressive strength (q_u) for curing temperature of 35°C.

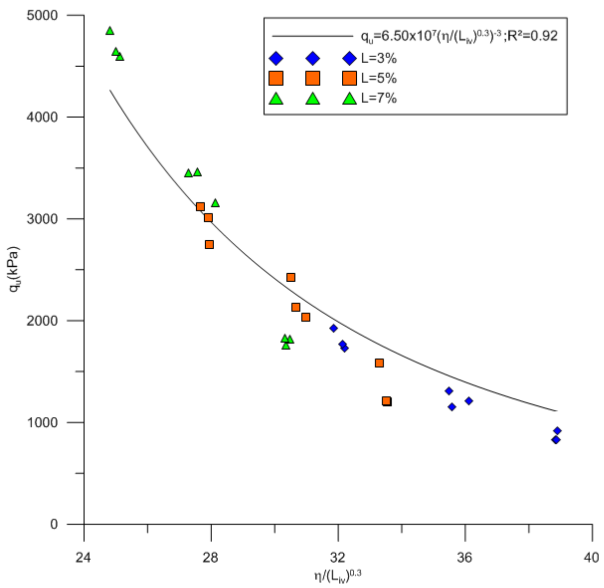

Figure 4-Variation of adjusted porosity/lime ratio $[\eta/(L_{iv})^{0.3}]$ with unconfined compressive strength for curing temperature of 35°C.

Coefficients of determination (R^2) of 0.75, 0.92 and 0.94, respectively for curing temperatures of 20°C – Eq. (3), 35°C – Eq. (4), and 50°C – Eq. (5), can be observed in Fig. 5 between $\eta/(L_{iv})^{0.30}$ and the unconfined compressive strength (q_u).

$$q_u(kPa) = 3.14x10^7 \left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad (3)$$

$$q_u(kPa) = 6.50x10^7 \left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad (4)$$

$$q_u(kPa) = 7.03x10^7 \left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad (5)$$

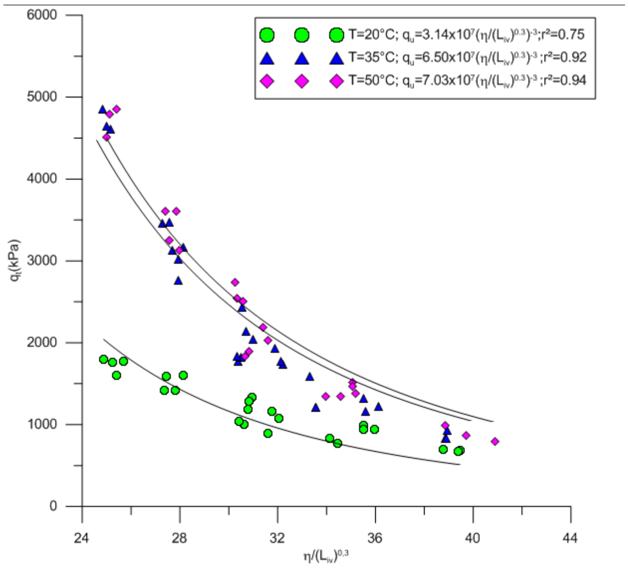

Figure 5-Relationships of adjusted porosity/lime ratio $[\eta/(L_{iv})^{0.3}]$ with unconfined compressive strength (q_u) considering distinct curing temperatures (T) of 20°C, 35°C and 50°C.

Further considerations can be made drawing the variation of normalized unconfined compressive strength $\dfrac{q_u}{\left[\dfrac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0}}$ with curing temperatures (T). The normalized compressive strengths increase linearly with increasing temperature up to 35°C, when it reach an asymptote, meaning that for a curing period of 28 days, temperatures above 35°C do not cause further increase in strength (meaning that all pozzolanic reactions have finished, at 28 days of curing, under a temperature of 35°C). Besides, between 20°C and 35°C unique relationships can be achieved linking the q_u with η, L_{iv} and T, as presented in Figs. 6 and in Eqs. (6) - (R^2=0.99):

$$q_u(kPa) = \left[0.22x10^7(T) - 1.3x10^7\right]\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad (6)$$

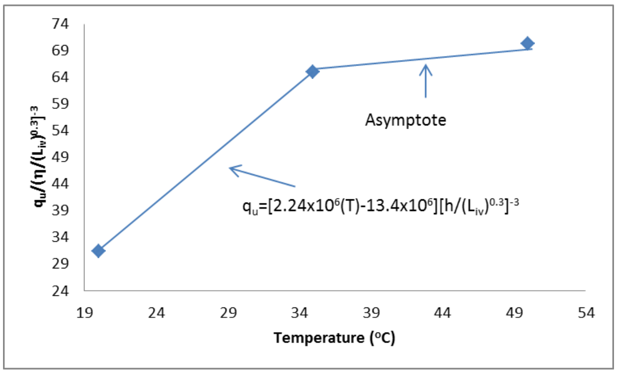

Figure 6-Variation of normalized unconfined compressive strength with temperature (T).

So, Eq. (6) can be used as dosage relationships for the soil, fly ash and lime studied, taking into consideration the curing time period of 28 days, fly ash contents of 25%, lime contents varying from 3% to 7% and dry densities ranging from 14 kN/m^3 (related to a porosity of about 38%) to 16 kN/m^3 (related to a porosity of about 46%) and curing temperature from 20ºC to 35ºC. There are several technical ways of reaching a target strength value for a given project: carrying out the earthwork in a hot season, reducing porosity through heavy compaction equipment and/or increasing lime content.

4 CONCLUSIONS

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

- For the sand-fly ash-lime mixtures cured for 28 days at distinct temperatures varying between 20^{o}C and 35^{o}C, unique relationships were achieved linking q_u to T, η and L_{iv}. For the studied curing time period, the relation $\frac{q_u}{\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0}}$ versus T is shown to vary linearly up threshold, when become asymptotes, meaning that larger temperatures do not further enhance strength due to extinction of soil-lime-fly ash reactions. So, temperature is seen as an efficient catalyzer for sand-fly ash-lime mixtures up to the threshold.
- The porosity/lime ratio, defined by the porosity of the compacted mixture divided by the volumetric lime content, adjusted by an exponent $[\eta/(L_{iv})^{0.30}]$ has been shown to be, at distinct curing temperatures, an appropriate parameter to evaluate the unconfined compressive strength of sand-coal fly ash-lime blends studied.

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