Construction and Building Materials 55 (2014) 238–245

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Devising dosages for soil–fly ash–lime blends based on tensile strength controlling equations

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HIGHLIGHTS

- Equations that govern the tensile strength of soil–fly ash–lime blends are proposed.
- All equations involve a unique ratio between porosity and volumetric lime content.
- These equations can be used to devise dosages that allow a more rational use of resources.
- Dosages devised using these equations and their environmental implications are discussed.

ARTICLE INFO

Article history:
Received 30 April 2013
Received in revised form 27 September 2013
Accepted 12 January 2014
Available online 8 February 2014

Keywords:
Curing temperature
Splitting tensile strength
Porosity/lime ratio and resource consumption

ABSTRACT

Compaction of layers of soil–fly ash–lime blends is often used to improve soil conditions for infrastructure projects. As system failures usually start up under tensile stresses at the base of such layers, splitting tensile strength can be used as a direct measure of the mechanical strength. In spite of that, there is not yet an understanding of the effect of distinct variables on the splitting tensile strength. Such understanding is the starting point to develop more rational dosages that allow for a more efficient use of resources (i.e. energy and raw materials). A series of splitting tensile tests were carried out. An equation linking the effect of porosity and lime content to the tensile strength was found for each curing temperature studied (20 °C, 27.5 °C, 35 °C and 50 °C). For all equations, it was found that a unique ratio between porosity and volumetric lime content controls the tensile strength. These equations could be further generalized into a single equation (linking the effect of curing temperature, porosity, and volumetric lime content to the tensile strength) that is valid for the studied blends and curing temperatures between 20 °C and 35 °C. An example showing how the proposed equations can be used to devise more rational dosages is also presented and highlights the practical application of this study.

1. Introduction

Improvement of local soils is usually necessary to meet the mechanical requirements of infrastructure projects such as foundations and subgrades of roads and railways platforms. Soil–fly ash–lime blends are often used for such improvement (e.g. [8,5,20], particularly as compacted layers over low bearing capacity soils. In such cases, Thomé et al. [21] and Consoli et al. [10] have shown that the system failure mechanism usually start up under tensile stresses at the base of the improved layer. This indicates that the tensile strength (q_t) can be used as a direct measure of the mechanical strength of soil–fly ash–lime blends when used as compacted layers.

In spite of that, there is not yet an understanding of the effect of distinct variables (e.g. lime content, porosity, curing period, curing temperature) on the splitting tensile strength of such blends. More specifically, no equations linking the effect of these variables to the tensile strength have been proposed. From a theoretical viewpoint, these equations would elicit the relationship among variables and also their effect on the tensile strength. From a practical viewpoint, these equations would provide the basis to devise more rational dosages. Once these equations are defined, the variables embedded in them can be manipulated to meet project specific requirements (including environmental ones) and thus, enable dosages that allow for a more efficient use of resources (e.g. energy, raw materials) to be created.

Equations linking the effect of variables to strength for soil–fly ash–lime blends were first developed by Consoli et al. [12]. In that study, it was found that the unconfined compressive strength (q_u) is governed by a ratio (η/L_{iv}) between two variables: porosity of the

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http://dx.doi.org/10.1016/j.conbuildmat.2014.01.044
0950-0618/

Nomenclature

D_{50}	mean particle diameter	V_L	volume of lime
G_o	initial elastic shear modulus	V_{total}	total volume of specimen
L	lime content (expressed in relation to mass of dry soil)	V_v	volume of voids
L_{iv}	volumetric lime content (expressed in relation to the total specimen volume)	γ_d	dry density
q_t	splitting tensile strength	η	porosity
q_u	unconfined compressive strength	η/L_{iv}	porosity/lime ratio
T	temperature		

compacted blend (η and volumetric lime content (L_{iv}). However, it is still unknown if this porosity/lime ratio (η/L_{iv}) also governs the splitting tensile strength (q_t) of soil–fly ash–lime blends.

This paper seeks to fulfill this gap by investigating the effect of lime content and porosity on the splitting tensile strength of soil–fly ash–lime blends, as well as to evaluate the use of a porosity/lime ratio as a variable that controls the splitting tensile strength (q_t). In addition to the two variables (i.e. porosity and lime content) investigated in the study carried out by Consoli et al. [12], curing temperature is also examined here. As already recognized by previous investigations (e.g., [16–19,9,2,3], the strength of soil–fly ash–lime blends (based on pozzolanic reactions of soil and coal fly ash with lime) is dependable of curing temperature and curing period. Thus, this study aims to determine the effect of curing temperature on the tensile strength of these blends.

2. Experimental program

The experimental program was carried out in two parts. First, the properties of the studied soil and fly ash were characterized. Then a series of splitting tensile tests for soil–fly ash–lime blend specimens cured at temperatures varying from 20 to 50 °C were carried out as discussed below.

2.1. Materials

The soil used in this study was a rounded wind transported 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 C 618 [4]] was a residue of burning coal in a thermal power station, located nearby 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. A chemical analysis has shown that the fly ash is 65.2% SiO_2, 23.3% Al_2O_3 and 6.1% Fe_2O_3. 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 throughout the whole study. The specific gravity of the lime grains is 2.49. According to Transportation Research Board [22] and Brown [6], it is important to point out that the fine portion of sandy soil is formed predominantly by crystalline minerals while FA is formed basically of amorphous minerals (without definable crystalline structure). Chemically both materials are mainly formed of silica and alumina. After several days of curing, time and temperature dependent chemical reactions between lime and soil/fly ash particles, namely pozzolanic reactions, have occurred. Such reactions occurs because silica and alumina within the soil/fly ash structure react with water and lime to form calcium silicate hydrate and calcium aluminate hydrate gels, which subsequently crystallize to bind the structure together. Insertion of fly ash in the mixture increases availability of alumina and silica from amorphous minerals (which promptly solubilize under high pH due to lime addition), growing reactions with lime and consequently increasing strength.

Distilled water was used both for molding specimens for the tensile 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	2.64	2.28
Medium sand (0.2 mm < diameter < 0.6 mm)	–	1.0%
Fine sand (0.06 mm < diameter < 0.2 mm)	100.0%	13.6%
Silt (0.002 mm < diameter < 0.06 mm)	–	84.9%
Clay (diameter < 0.002 mm)	–	0.5%
Effective diameter (D_{50})	0.16 mm	0.018 mm

Table 2
Values used for each variable.

Variables	Values used
Dry unit weight (and related porosity)	14 kN/m^3 (porosity of about 38%) 15 kN/m^3 (porosity of about 42%) 16 kN/m^3 (porosity of about 46%)
Lime content	3%, 5% and 7%
Curing temperature	20 °C, 27.5 °C, 35 °C and 50 °C
Curing time	28 days
Fly ash content	25%

Table 3
Effect of variables on the splitting tensile strength.

Variable	Effect on splitting tensile strength
Curing time period	Increasing curing time period increases splitting tensile strength
Curing temperature	Increasing curing temperature increases the gains of splitting tensile strength
Porosity	Reducing porosity increases splitting tensile strength
Lime content	Increasing lime content increases the splitting tensile strength
Porosity–lime ratio	Reducing porosity–lime ratio increases splitting tensile strength

2.2. Specimen preparation

Cylindrical specimens, 50 mm in diameter and 100 mm high, were prepared by hand-mixing dry Osorio sand, fly ash, lime and water (moisture content of all specimens molded was about 14%). The amount of fly ash (fixed in 25%) 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. As the specific gravity of the sand grains (Gs_s = 2.63) is greater than the specific gravity of the lime (Gs_L = 2.49) which is greater than the specific gravity of the fly ash grains (Gs_{FA} = 2.28), the porosity of a soil–fly ash–lime specimen is a function of the specific gravity of sand grains (Gs_s), as well as of the fly ash grains (Gs_{FA}) and the lime (Gs_L), and can be calculated according to Eq. (1)

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

where η is the porosity of the soil–fly ash–lime specimen, FA is fly ash content (percentage of dry weight of sand), L is lime content (percentage of dry weight of soil plus fly ash), γ_d is dry unit weight of the specimen and V_s is volume of specimen.