On the Durability and Strength of Compacted Coal Fly Ash-Carbide Lime Blends

N.C. Consoli, R.B. Saldanha, J.F. Novaes, H.C. Scheuermann Filho

Abstract. Present investigation intends to examine the mechanical behaviour of compacted coal fly ash - carbide lime mixes to assess their potential use as a sub-base/base material for low volume roads. This study plans to compute the impact of carbide lime content and dry density on the properties (durability and strength) of compacted coal fly ash - carbide lime blends. Its main significant addition to knowledge is quantifying the accumulated loss of mass (*ALM*) after wetting/drying cycles, tensile (q_t) and compressive strength (q_u) as a function of the porosity/lime index. A specific q_t/q_u matching 0.13 was established, being autonomous of the porosity/lime index. In addition, it is empirically revealed the existence of an exclusive relation connecting accumulated loss of mass divided by the number of wetting/drying cycles and porosity/lime index. This broadens the applicability of such index by demonstrating it controls endurance performance of compacted coal fly ash - lime blends.
Keywords: durability, coal fly ash, carbide lime, strength, porosity/lime index.

1. Introduction

In the last years the development of new geomaterials with the use of industrial by-products has been of concern to researchers. This can be seen as a positive process in which the premises for progress are closely related to the issue of environmental sustainability, a concept that intends to assure the conservation of natural resources that enables meeting current needs without compromising future generations (World Commission on Environment and Development 1987). In this context, the construction industry is an important cause of environmental impacts, since it consumes large amounts of natural resources and generates considerable quantities of waste. Hence, it is crucial an increase in the development and use of new materials and techniques capable of reducing those impacts, like the utilization of recycled waste.

An important industrial residue, which is responsible for pozzolanic reactions and, therefore, capable of generating cementing materials when properly stabilized with an alkaline activator, is the coal fly ash (*FA*) derived from the coal combustion in thermal power plants. Annually, about 750 Mt of this waste are generated in the whole world, however the average reutilization in this global perspective is only around 25% (Blissett & Rowson, 2012). Moreover, the *FA* can be stabilized with carbide lime, a by-product in the production process of acetylene gas (*e.g.* Consoli *et al.*, 2014; Arulrajah *et al.*, 2016, Saldanha & Consoli, 2016). Therefore, the use of these industrial residues makes it possible to decrease the use of natural resources in civil construction and prevents the allocation of them to landfills.

The mixture, in a wet process, of coal fly ash and carbide lime provides minerals, such as calcium silicate hydrate (*CSH*) and calcium aluminate hydrate (*CAH*), that crystallize and constitute the cementing by forming interparticle bonds (Massazza, 1998). Nevertheless, there are many factors that are able to interfere in the pozzolanic reactions originated in the mixture and compaction of these residues and, consequently, influence their mechanical properties. Thereby, it is necessary to assess variables for the main parameters which govern the development of these reactions, such as: amount of lime, porosity, curing period and temperature, and correlate these with the mechanical response of the *FA*-lime blends (Haque *et al.*, 2014; Rocha *et al.*, 2014; Dash & Hussain, 2015; Islam *et al.*, 2015; Saldanha & Consoli, 2016).

Strength tests are usually employed as a way to examine the influence of diverse variables on cemented materials behaviour. A logical dose procedure for coal fly ash - lime blends was created by Consoli *et al.* (2014) taking into consideration the porosity/lime index as a proper parameter to assess strength (q_u) of fly ash-carbide lime mixes. Yet, so far, no research has examined the applicability of the porosity/lime index (η/L_v) for compacted coal fly ash-lime mixes in terms of loss of mass after dry/wet cycles to check durability and tensile strength (q_t), as well as q_t/q_u. The target of

Nilo Cesar Consoli, Ph.D., Full Professor, Departamento de Engenharia Civil, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. e-mail: consoli@ufrgs.br.
Rodrigo Beck Saldanha, Ph.D. Student, Departamento de Engenharia Civil, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. e-mail: becksaldanha@yahoo.com.br.
Jéssica Flesch Novaes, M.Sc., Departamento de Engenharia Civil, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. e-mail: jessicafleschn@gmail.com.
Hugo Carlos Scheuermann Filho, M.Sc. Student, Departamento de Engenharia Civil, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. e-mail: hugocsf@gmail.com.
Submitted on January 13, 2017; Final Acceptance on July 5, 2017; Discussion open until December 29, 2017.

this study is to determine straight relations between η/L_v and accumulated loss of mass after wetting/drying cycles (durability), q_t and q_t/q_u for compacted coal fly ash-carbide lime mixes.

2. Background

Durability can be stated as the capability of a material to maintain stability and integrity over large periods of exposure to detrimental weathering (Dempsey & Thompson, 1968). Such property, as well as strength, is one of the important engineering properties of cemented mixes.

Previous studies have been carried out to evaluate the durability of soil-cement mixtures, most of them (*e.g.*, Starcher *et al.*, 2016, Jamshidi *et al.*, 2016) centered on two ASTM standards: wetting and drying (ASTM, 2015a) and freezing and thawing (ASTM, 2013).

Shihata & Baghdadi (2001) immersed sets of silty sand-cement specimens in saline water for different durations prior to running 12 wetting-drying cycles followed by brushing strokes. The authors found that soils with larger amounts of fines presented higher weight loss values in such tests. They also observed a close relationship between percent mass loss and reduction of unconfined compressive strength after the cycles.

Zhang & Tao (2008) performed durability tests in low plastic silty clay stabilized with cement. The authors observed that the mass loss decreased with the increase in cement contents, but increased with the increase of water-cement ratio.

Kelley (1988) and Cuisinier *et al.* (2012) showed qualitatively that the efficiency of lime treatment could be damaged by the alternation of wet/dry cycles in the long term. Such behaviour was also observed by Cuisinier *et al.* (2014). The latter authors also observed significant irreversible shrinkage strains at the end of the first cycle for lime treated clays. A dramatic decrease in yield stress brought by a loss of the lime cementation bonding was also evidenced after the first cycle.

Theivakularatnam & Gnanendran (2015) observed that the accelerated reaction of binders due to increasing temperature masked the detrimental effect of the wet-dry cycles.

However, there were no studies looking for the understanding of the key parameters that control durability of coal fly ash - lime blends and the analysis of the effect of such factors (*e.g.* porosity/lime index).

3. Experimental Program

The materials and methods used in present research are discussed below.

3.1. Materials

The coal fly ash characterization tests are displayed in Table 1. The fly ashes [type F according to ASTM (2015b)] utilized in the testing were taken from a thermal power plant disposal site situated in southern Brazil, being classified (ASTM, 2006) as low plasticity silt (ML). Surface area using nitrogen adsorption - BET method (ASTM, 2012) is 3.20 m^2/g. As a result of X-Ray Fluorescence Spectrometry (XRF) it was possible to identify the main components of the fly ash, among which stand out SiO_2 (64.8%), Al_2O_3 (20.4%), Fe_2O_3 (4.8%), and CaO (3.1%).

Table 1 - Physical properties of the coal fly ash sample.

Liquid limit (%)	-
Plastic limit (%)	-
Plasticity index (%)	Non-plastic
Specific gravity	2.17
Medium sand (0.2 mm < diameter < 0.6 mm) (%)	1.5
Fine sand (0.06 mm < diameter < 0.2 mm) (%)	12.9
Silt (0.002 mm < diameter < 0.06 mm) (%)	82.4
Clay (diameter < 0.002 mm) (%)	3.2
Mean particle diameter, D_{50} (mm)	0.02
USCS class	ML (low plasticity silt)

Carbide lime, a by-product of the production of acetylene gas, is a hydrated lime and was used throughout this research as the activator agent. Moreover, the determination of calcium and magnesium oxides (on a non-volatile basis) using the wet chemical analysis (ASTM, 2011) established 96% of calcium oxide, being then a calcitic lime. To ensure the occurrence of the pozzolanic reactions, the minimum lime content in the mixture was determined through the Initial Consumption of Lime Method (*ICL*) (Rogers *et al.*, 1997). For this study, a minimum quantity of 4% of carbide lime (based on the mass of dry coal fly ash) was found to stabilize the blends. So, based on such result, carbide lime contents of 5%, 8% and 11% were chosen for the present research. Carbide lime grains specific gravity is 2.12.

Distilled water was employed for characterization tests and moulding specimens for the mechanical tests.

3.2. Methods

3.2.1. Moulding and curing of specimens

For strength tests, cylindrical specimens with 50 mm diameter and 100 mm from top to bottom were employed. For durability (wetting and drying) tests, cylindrical specimens with 100 mm diameter and 120 mm from top to bottom were utilized. A designed dry unit weight for a particular specimen was then established as a result of the dry mass of coal fly ash-carbide lime inserted in the cylindrical mould divided by the total volume of the specimen. As exhibited in Eq. 1 (Saldanha & Consoli, 2016), porosity (η) is a function of dry density (γ_d) of the mix and carbide lime content (L). Each substance (fly ash and carbide lime) has a unit weight of solids (γs_{FA} and γs_L), which also requires to be pondered for computing porosity.

$$\eta = 100 - 100\left\{\left[\frac{\gamma_d}{1+\frac{L}{100}}\right]\left[\frac{1}{\gamma s_{FA}} + \frac{\frac{L}{100}}{\gamma s_L}\right]\right\} \qquad (1)$$

Once the coal fly ash and carbide lime were weighed, they were blended till the mix attained uniformity. Moisture contents for the coal fly ash and carbide lime blends were then supplemented, remaining the mix procedure till a homogeneous paste was generated. Each specimen was then constructed in three layers, each layer being statically compacted inside a cylindrical split mold, so that each layer reached the prescribed dry unit weight. In the process, the top of each layer was slightly scarified. After the molding, the specimen was immediately extracted from the split mold and its weight, diameter and height measured with accuracies of about 0.01 g and 0.1 mm, respectively. The specimens were cured for 7 days in a moist chamber at 23 °C ± 2 °C and relative moisture of about 98%.

3.2.2. Unconfined compression and split tensile tests

Compression tests followed standard ASTM C 39 (ASTM, 2010) while tension tests obeyed standard ASTM C 496 (ASTM, 2011). Before testing, specimens were put underwater for 24 h to reduce suction (Consoli *et al.*, 2011). Compaction tests of coal fly ash - carbide lime blend (8% was the lime content used - based on the mass of dry coal fly ash) mix under standard, intermediate and modified energies (see Fig. 1) presented maximum dry unit weights and optimum moisture contents of 11.61 kN/m^3 and 31.5%, 11.96 kN/m^3 and 29.2% and 12.36 kN/m^3 and 27.6%, respectively. Specimens were moulded on top of the line formed by maximum dry unit weights and optimum moisture contents (at three distinct points) (see Fig. 1): 10.6 kN/m^3 and 36.6% (point 1), 11.6 kN/m^3 and 31.3% (point 2) and 12.6 kN/m^3 and 26.0% (point 3); carbide lime contents used were 5%, 8% and 11% and specimens were cured for 28 days. As for Portland cement, the amounts of water needed for lime-pozzolan reaction are minimum, and the Proctor optimum moisture content is more than enough to guarantee the necessary water amount.

3.2.3. Durability tests

Durability (wetting-drying cycles) tests of coal fly ash - carbide lime mixtures were completed according to standard ASTM D 559 (ASTM, 2015a). Specimens were moulded with the same variables as for strength tests. Test procedures determine mass losses produced by recurrent (12) wet-dry series. Every cycle begins by oven drying through 42 h at 71 °C ± 2 °C. Then, specimens are brushed a

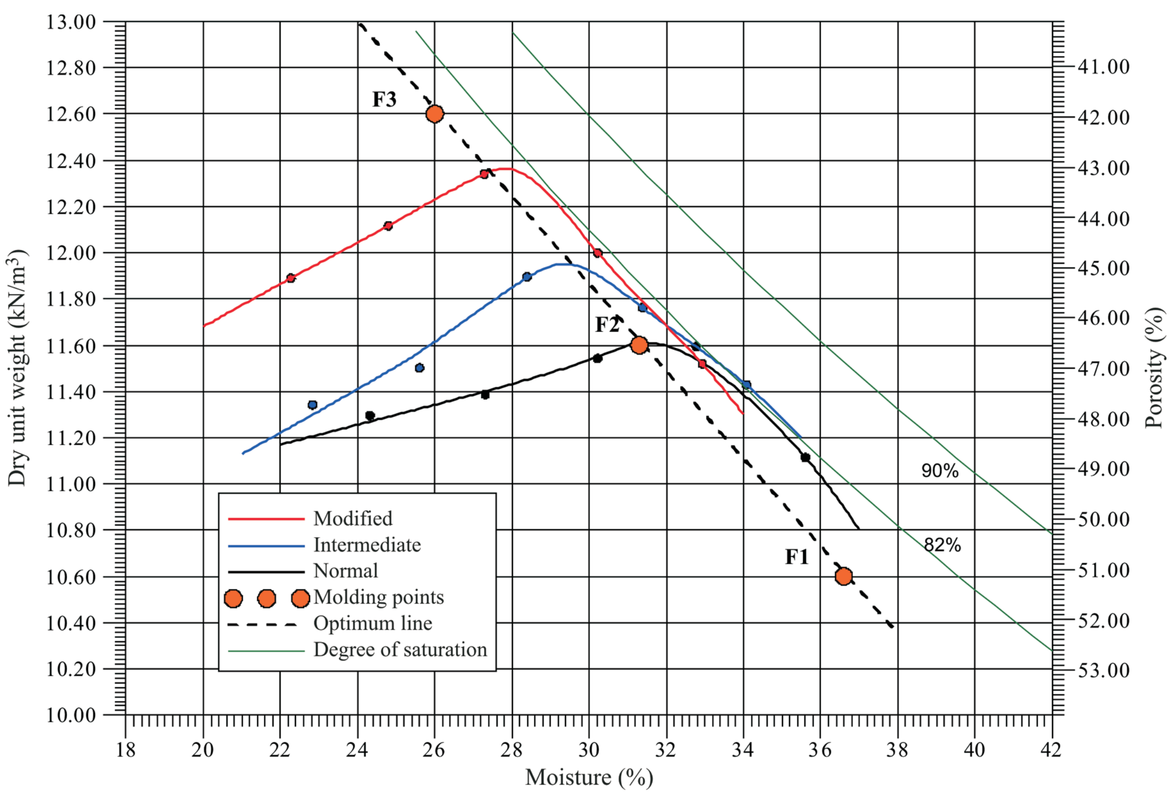

Figure 1 - Compaction test results, optimum compaction line and moulding points.

number of times using a force of approximately 15 N. Lastly, specimens are put underwater for 5 h at 23 °C ± 2 °C. It is important to point out that pozzolanic reactions are accelerated with temperature and so the 42 h at 71 °C during wetting and drying cycles can improve the material strength.

4. Results

4.1. Influence of the porosity/lime index on q_t and q_u

Figure 2 portrays q_t and q_u as a function of $\eta/(L_v)^{0.11}$ [stated as porosity (η) divided by the volumetric lime content (L_v), the latter expressed as a percentage of carbide lime volume to the total volume of the coal fly ash - carbide lime mixtures (Consoli *et al.*, 2014)] for the curing period studied (28 days). Fig. 2 indicates that the adjusted porosity/lime index is helpful in normalizing tensile and compressive strength results for coal fly ash - carbide lime mixtures. Fair correlations ($R^2 = 0.95$ and 0.91) can be perceived concerning q_t (Eq. 2) and q_u (Eq. 3) and $\eta/(L_v)^{0.11}$ for the coal fly ash - carbide lime mixtures studied.

$$q_t\ (\text{MPa}) = 0.30 \times 10^5 \left[\frac{\eta}{L_v^{0.11}}\right]^{-3.00} \quad (2)$$

$$q_u\ (\text{MPa}) = 2.32 \times 10^5 \left[\frac{\eta}{L_v^{0.11}}\right]^{-3.00} \quad (3)$$

The capability of the adjusted porosity/lime index to normalize strength of lime treated coal fly ash has been shown by Consoli *et al.* (2014, 2016). They have shown that rates of change of strength with porosity (η) and the inverse of the volumetric lime content ($1/L_v$) are as a rule not the same. Thus, the application of an exponent (as a directive around 0.11 - Consoli *et al.*, 2014, 2016; Saldanha & Consoli, 2016) to L_v is required for the rates of η and $1/L_v$ to be compatible.

By examining Fig. 2, as well as Eqs. 2 and 3, it can be seen that the tension and compression tests present rather similar trends. Plotting q_t *vs.* q_u of all tests carried out (see Fig. 3) it can be observed that q_t/q_u is a scalar (= 0.13) for the fly ash - carbide lime studied blend, being independent of porosity, carbide lime content, or porosity/lime index.

4.2. Influence of the carbide lime, porosity and porosity/lime index on durability (wetting and drying cycles) of compacted coal fly ash-carbide lime blends

Figure 4 shows compacted coal fly ash-carbide lime blends accumulated loss of mass (ALM) *vs.* adjusted porosity/lime index [$\eta/(L_v)^{0.11}$] after 3 [Eq. 4 - $R^2 = 0.91$], 6 [Eq. 5 - $R^2 = 0.92$], 9 [Eq. 6 - $R^2 = 0.92$] and 12 [Eq. 7 - $R^2 = 0.93$] wetting-drying cycles (during durability tests).

$$ALM(\%) = 1.26 \times 10^{-14} \left[\frac{\eta}{L_v^{0.11}}\right]^{8.30} \quad (4)$$

$$ALM(\%) = 2.48 \times 10^{-14} \left[\frac{\eta}{L_v^{0.11}}\right]^{8.30} \quad (5)$$

$$ALM(\%) = 3.20 \times 10^{-14} \left[\frac{\eta}{L_v^{0.11}}\right]^{8.30} \quad (6)$$

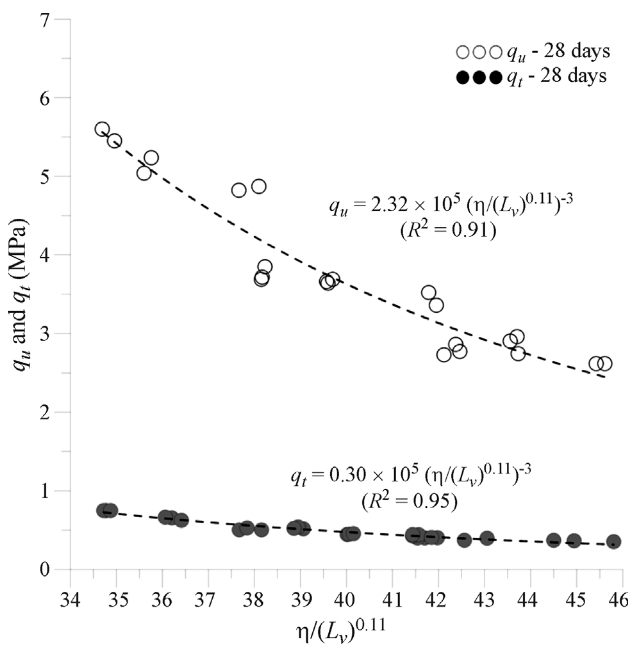

Figure 2 - Variation of split tensile strength (q_t) and unconfined compressive strength (q_u) with adjusted porosity/lime index for coal fly ash-carbide lime blends for 28 days of curing.

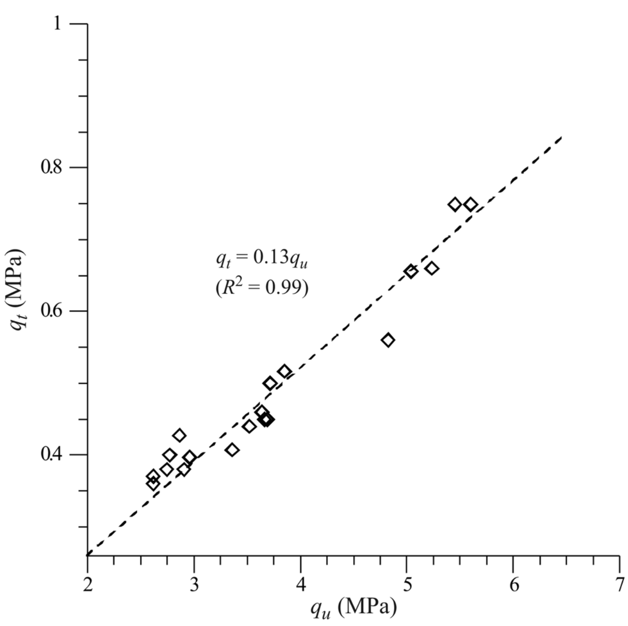

Figure 3 - Split tensile strength (q_t) *vs.* unconfined compressive strength (q_u) for 28 days of curing.

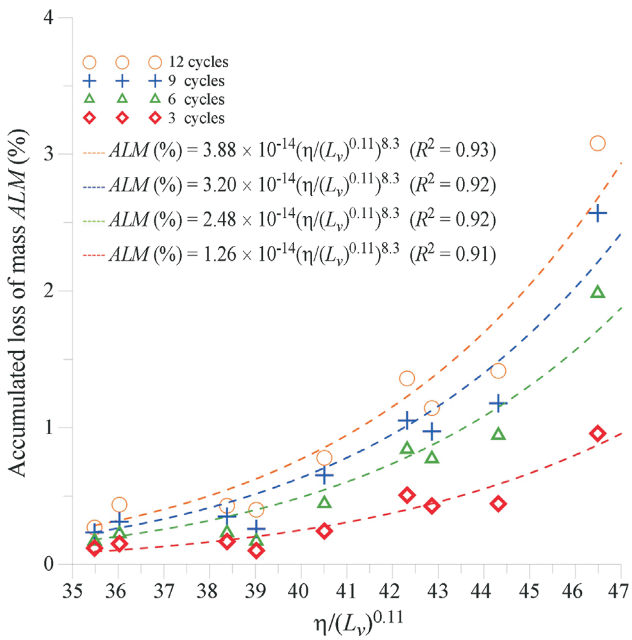

Figure 4 - Coal fly ash - carbide lime blends accumulated loss of mass *vs.* adjusted porosity/lime index after 3, 6, 9 and 12 wetting-drying cycles (during durability tests).

$$ALM(\%) = 3.88 \times 10^{-14} \left[\frac{\eta}{L_v^{0.11}} \right]^{8.30} \qquad (7)$$

In order to further normalize the presented durability results, compacted coal fly ash - carbide lime blends accumulated loss of mass values for 3, 6, 9 and 12 cycles are divided by the number of cycles and plotted *vs.* adjusted porosity/lime index (see Fig. 5). A unique relationship

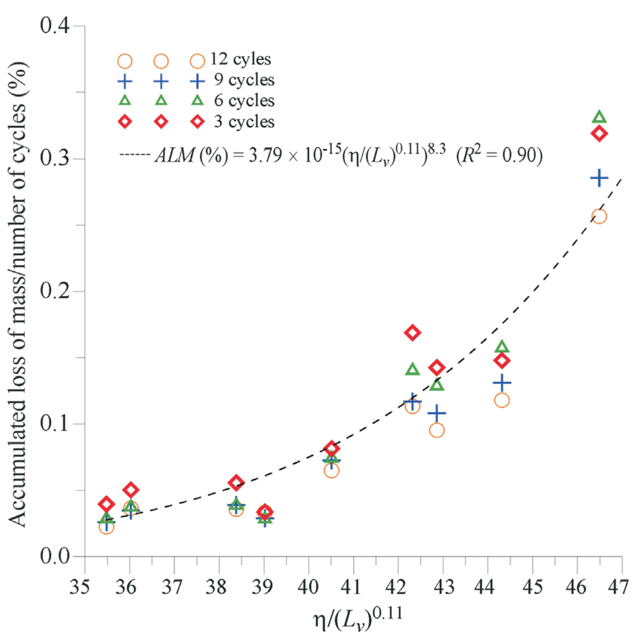

Figure 5 - Coal fly ash - carbide lime blends *ALM/NC vs.* adjusted porosity/lime index after wetting-drying cycles during durability tests.

(R^2 = 0.90) linking accumulated loss of mass divided by number of cycles (ALM/NC) and adjusted porosity/lime index $[\eta/(L_v)^{0.11}]$ after distinct wetting-drying cycles is found [see Eq. 8]. So, it can be seen, for the first time ever, that the porosity/lime index also controls the durability of compacted coal fly ash-carbide lime blends.

$$\frac{ALM}{NC}(\%) = 3.79 \times 10^{-15} \left[\frac{\eta}{L_v^{0.11}} \right]^{8.30} \qquad (8)$$

Therefore, the porosity/lime index controls strength and endurance performance of the compacted coal fly ash-carbide lime blends.

5. Concluding Remarks

- From the studies developed in this document the following conclusions can be sketched:
- The accumulated loss of mass (*ALM*) (durability quantification) of individual wetting/drying cycles of compacted coal fly ash-carbide lime mixes were originally perceived in the present research to be directly associated with the adjusted porosity/lime index;
- An unique relationship linking accumulated loss of mass divided by number of cycles (*ALM/NC*) and adjusted porosity/lime index $[\eta/(L_v)^{0.11}]$ after distinct wetting-drying cycles is presented for the first time;
- The q_t/q_u ratio is distinctive (= 0.13) for the compacted coal fly ash-carbide lime assessed in the current study, being independent of the porosity/lime index;
- The porosity/lime index controls tensile and compressive strength, as well as endurance performance of the compacted coal fly ash-carbide lime blends. So, according to the strength and durability requirements, the earthwork designer can establish the adjusted porosity/lime index that fulfills the design needs. Lastly, distinct dry unit weights and carbide lime amounts can fulfill the project requirements.

Acknowledgments

The authors wish to express their gratitude to Edital FAPERGS/CNPq 12/2014 - PRONEX (Project # 16/2551-0000469-2) for the financial support to the research group.

References

Arulrajah, A.; Mohammadinia, A.; Phummiphan, I.; Horpibulsuk, S. & Samingthong, W. (2016). Stabilization of recycled demolition aggregates by geopolymers comprising calcium carbide residue, fly ash and slag precursors. Construction and Building Materials, 114:864-873.

ASTM (2006). Standard Classification of Soils for Engineering Purposes. ASTM D 2487, West Conshohocken, Philadelphia.

ASTM (2010). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM C 39, West Conshohocken, Philadelphia.

ASTM (2011). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM C 496, West Conshohocken, Philadelphia.

ASTM (2012). Standard Test Methods for Precipitated Silica-Surface Area by Single Point B.E.T. Nitrogen Adsorption. ASTM D5604, West Conshohocken, Philadelphia.

ASTM (2013) Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures. ASTM D560, West Conshohocken, Philadelphia.

ASTM (2015a). Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures. ASTM D 559, West Conshohocken, Philadelphia.

ASTM (2015b). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM C 618, West Conshohocken, Philadelphia.

Blissett, R.S. & Rowson, N.A. (2012). A review of the multi-component utilisation of coal fly ash. Fuel, 97(1):1-23 .

Consoli, N.C.; Dalla Rosa, A. & Saldanha, R.B. (2011). Variables governing strength of compacted soil-fly ash-lime mixtures. Journal Materials in Civil Engineering, 23(4): 432-440.

Consoli, N.C.; Rocha, C.G. & Saldanha, R.B. (2014). Coal fly ash-carbide lime bricks: An environment friendly building product. Construction and Building Materials, 69:301-309.

Consoli, N.C.; Quiñónez Samaniego, R.A.; Marques, S.F.V.; Venson, G.I.; Pasche, E. & González Velázquez, L.E. (2016). A single model establishing strength of dispersive clay treated with distinct binders. Canadian Geotechnical Journal, 53(12):2072-2079.

Cuisinier, O.; Gandille, D.; Robinet, A.; Stoltz, G.; Mehenni, A. & Robin, V. (2012). Long term behaviour of treated soils - case study of a lime and cement stabilized backfill. Proc. 3rd Int. Seminar on Earthworks. Technische Universität München, Berlin, pp. 189-200.

Cuisinier, O.; Stoltz, G. & Masrouri, F. (2014). Long term behavior of lime-treated clayey soil exposed to successive drying and wetting. Geo-Congress 2014 Technical Papers, American Society of Civil Engineers, Atlanta, pp. 4146-4155.

Dash, S.K. & Hussain, M. (2015). Influence of lime on shrinkage behavior of soils. Journal Materials in Civil Engineering, 27(12):04015041.

Dempsey, B.J. & Thompson, M.R. (1968). Durability Properties of Lime-Soil Mixtures. Highway Research Record 235, Highway Research Board, Washington, D.C., pp. 61-75.

Haque, A.; Tang, C.K.; Islam, S.; Ranjith, P.G. & Bui, H.H. (2014). Biochar sequestration in lime-slag treated synthetic soil: A green approach to ground improvement. Journal Materials in Civil Engineering, 26(12):1-5.

Islam, S.; Haque, A.; Wilson, S. & Ranjith, P. (2016). Time-dependent strength and mineralogy of lime-GGBS treated naturally occurring acid sulfate soils. Journal Materials in Civil Engineering, 28(1):04015077.

Jamshidi, R.J.; Lake, C.B.; Gunning, P. & Hills, C.D. (2016). Effect of freeze/thaw cycles on the performance and microstructure of cement-treated soils. Journal Materials in Civil Engineering, 28(12): 04016162.

Kelley, M. (1988). A long range durability study of lime stabilized bases at military posts in the southwest. Bulletin 328, National Lime Association, WSA, pp. 1-20.

Massazza, F. (1998). Pozzolana and pozzolanic cements. 4th ed. In: Lea-s Chemistry of Cement and Concrete, Peter C. Hewlett, ed., Arnold, pp. 471-635.

Rocha, C.G.; Consoli, N.C. & Johann, A.D.R. (2014). Greening stabilized rammed earth: devising more sustainable dosages based on strength controlling equations. Journal of Cleaner Production, 66:19-26.

Rogers, C.D.F.; Glendinning, S. & Roff, T.E.J. (1997). Lime modification of clay soils for construction expediency. Proceedings Institution of Civil Engineering - Geotechnical Engineering, 125(4):242-249.

Saldanha, R.B. & Consoli, N.C. (2016). Accelerated mix design of lime stabilized materials. Journal of Materials in Civil Engineering, 28(3):06015012.

Shihata, S.A. & Baghdadi, Z.A. (2001). Long-term strength and durability of soil cement. Journal Materials in Civil Engineering, 13(3):161-165.

Starcher, R.D.; Gassman, S.L. & Pierce, C.E. (2016). The durability of chemically treated soils subjected to cycles of wetting and drying. Geo-Chicago 2016:728-737.

Theivakularatnam, M. & Gnanendran, C.T. (2015). Durability of lightly stabilized granular material subjected to freeze-thaw and wet-dry cycles. Proc. IFCEE 2015, American Society of Civil Engineers,. San Antonio, pp. 1410-1419.

World Commission on Environment and Development (1987). Our Common Future. Oxford University Press, Oxford,.

Zhang, Z. & Tao, M. (2008). Durability of cement stabilized low plasticity soils. Journal of Geotechnical and Geoenvironmental Engineering, 134(2):203-213.

List of symbols

ALM: accumulated loss of mass

D_{50}: mean particle diameter

FA: coal fly ash

L: lime content (expressed in relation to mass of dry coal fly ash)

L_v: volumetric lime content (expressed in relation to the total specimen volume)

NC: number of wetting/drying cycles
q_u: unconfined compressive strength
R^2: coefficient of determination
η: porosity
η/L_v: porosity/lime index
γ_d: dry unit weight
γ_s: unit weight of solids
w: moisture content