

Durability of RAP-Industrial Waste Mixtures Under Severe Climate Conditions

N.C. Consoli, H.C. Scheuermann Filho, V.B. Godoy, C.M.D.C. Rosenbach, J.A.H. Carraro

Abstract. The sustainable use of industrial wastes such as coal fly ash and carbide lime is an effective procedure to enhance the long-term performance of reclaimed asphalt pavement (RAP) under extreme freeze-thaw and wet-dry conditions. This study evaluates the impact of lime content (L) and dry unit weight (γ_d) on the durability and long-term performance of compacted RAP-fly ash-carbide lime mixes. For all mixtures tested, specimens were statically compacted inside a cylindrical mould to their target dry unit weights. Single-level variables used in the stabilisation process included: fly ash (FA) content of 25% (in relation to the RAP), optimum water content of 9% (modified compaction effort) and seven days of curing. Three target dry unit weights equal to 17, 18 and 19 kN/m³ (the last one determined using the modified Proctor energy) as well as three different lime contents (3, 5 and 7%) were also used in the analysis. Both the accumulated loss of mass (ALM) after wetting-drying and freezing-thawing cycles and the splitting tensile strength (q_t) of the specimens tested were evaluated as a function of the porosity/lime ratio index (η/L_n). Compacted RAP-fly ash-carbide lime mixtures performed better when subjected to wetting-drying cycles than to freezing-thawing cycles. The results indicate that the porosity/lime ratio index controls not only the mechanical response but also the long-term performance of compacted RAP-fly ash-carbide lime mixes, which substantially broadens the applicability of the index.

Keywords: durability, industrial wastes, porosity/lime index, reclaimed asphalt pavement, soil stabilisation.

1. Introduction

The road network is a fundamental element for the supply and distribution chains, since it promotes the integration of regions, states, ports, railways, waterways and airports. With time, pavements start to present defects, such as irregularities in pavement surface, holes, interconnected, longitudinal and transverse cracks, landslides, absence of shoulder, among others. These factors may increase the risk of road accidents. Moreover, the quality of the pavement is one of the main determinants of the users' performance during their travels and in addition to the increase of the road costs when one has roads with precarious functionality.

One of the ways currently used to correct defects in pavements is the restoration of the cutting off of the old asphalt pavement and recomposition with a new asphalt coating. This operation (cutting off the asphalt coating) produces a great amount of residue in the works of restoration of highways (FHWA, 2011). The problem arises since there is no specification in the project for using this waste, which ends up generating problems in its final disposal, and is usually deposited in inappropriate places, such as along the highways, in landfills or mistakenly used as a primary coating, when its use can become an environmental liability,

as the rains end up carrying this residue to streams and rivers. One viable alternative to road maintenance and rehabilitation is the use of cement stabilised reclaimed asphalt pavement (RAP) in the base or sub-base layers of a pavement (e.g., Puppala *et al.*, 2011). Recently, Consoli *et al.* (2017) carried out research on the mechanical properties (unconfined compressive strength - q_u and splitting tensile strength - q_t) and the viscoelastic behavior (dynamic modulus - E^* and phase angle - δ) of RAP - powdered rock - Portland cement blends. These authors found out that the porosity/cement index (η/C_n) is a proper parameter to predict q_u , q_t , E^* and δ of RAP - powdered rock - Portland cement mixes. Such studies were based mainly in the mechanical behaviour (unconfined compressive strength, resilient and dynamic modulus) of such blends. However, the durability and long-term performance of compacted RAP treated industrial wastes has received reduced attention. One of the few investigations on this topic was carried out by Avirneni *et al.* (2016), who assessed the loss of mass after wetting-drying cycles on reclaimed asphalt pavements mixed with fly ash and sodium hydroxide. As present research is being developed in southern Brazil, where seasons are quite well defined, with temperatures reaching extremes of about -15 °C in winter and over 40 °C in summer (INPE, 2017),

Nilo Cesar Consoli, Ph.D., Full Professor, PPGEC, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. e-mail: consoli@ufrgs.br.

Hugo Carlos Scheuermann Filho, M.Sc. Student, PPGEC, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. e-mail: hugocsf@gmail.com.

Vinicius B. Godoy, Ph.D. Student, PPGEC, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. e-mail: vinigodoy@msn.com.

Caroline M. De Carli Rosenbach, M.Sc. Student, PPGEC, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. e-mail: carolmomoli@gmail.com.

J. Antonio H. Carraro, Ph.D., Associate Professor, Department of Civil and Environmental Engineering, Imperial College London, UK.

e-mail: antonio.carraro@imperial.ac.uk.

Submitted on November 22, 2017; Final Acceptance on May 16, 2018; Discussion open until December 31, 2018.

DOI: 10.28927/SR.412149

there is a need to search for the endurance of newly developed blends under severe climate conditions.

This research aims to investigate the performance under extreme wet-dry (cycles reaching 71 °C for 42 h followed by 23 °C for 5 h) and freeze-thaw (cycles reaching -23 °C for 24 h followed by 21 °C for 23 h) conditions of a RAP treated with coal fly ash and carbide lime to assess its potential use as road embankment, as well as sub-base material for low volume road. Besides, this study seeks to establish possible relationships between the porosity/lime index (η/L_v) and accumulated loss of mass (ALM) after wet-dry and freeze-thaw cycles for compacted RAP-fly ash-lime blends. Such index has already been correlated to strength and durability performance of lime treated clayey soils, lime-fly ash improved sands and in the stabilization of fly ash through the use of carbide lime (Consoli *et al.*, 2011, 2014, 2016a).

Consoli *et al.* (2018) performed an initial analysis of the effect of sodium chloride addition on blends with RAP, only indicating the accumulated loss of mass for wet-dry cycles, without relating such loss with the index $\eta/(L_v)^{0.11}$. The present article does not analyze the addition of salt, but the increase of compaction effort and lime content in relation to the splitting tensile strength (q_t). This enabled to establish a direct relationship for the accumulated loss of mass of both types of cycle (wet-dry and freeze-thaw cycles) with the index $\eta/(L_v)^{0.11}$, which demonstrated that such index controls the long-term behavior (durability) of the analyzed mixtures.

2. Experimental Program

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

2.1. Materials

RAP grain size distribution is presented in Table 1 and in Fig. 1. Such recycled aggregate was reclaimed from the BR 290 highway, which connects the city of Porto Alegre (located in southern Brazil) to the seashore. RAP samples were collected in sufficient amount to complete all tests. The bitumen content (SBS Modified - PG 70-22S) found in the RAP was about 5.0%, having been determined according to ASTM D 2172 (ASTM, 2011a). Specific gravity of RAP for coarse aggregate was determined according to NBR NM 53 (ABNT, 2009b), for the fine aggregate was determined according to NBR NM 52 (ABNT, 2009a) and the relationship between them results in (γ_{RAP}) of 2.505. It is important to notice that the RAP grain size distribution is influenced, amongst other factors, by the milling machine process, so it can spatially vary, being therefore essential to particularly characterize the granulometry for each case. It is possible to adopt a control of the grain size of the selected milling, as was done in this research: 70% of the material retained in the 4' (4.75 mm opening) sawmill and 30% of the material passed through this same sieve.

The type F fly ash (FA) selected, according to ASTM C 618 (ASTM, 2008), is a residue of coal burning from a thermal power station. The results of the FA characterization tests are also presented in Table 1. The material is nonplastic and its specific gravity (γ_{FA}) was determined according to ASTM D 854 (ASTM, 2014), being equal to 2.18. Due to its granulometry, the FA is classified as silt (ML) according to the Unified Soil Classification System, presented in ASTM D 2487 (ASTM, 2006). As a result of X-Ray fluorescence spectrometry (XRF), it was possible to identify the main components of the FA, among which stand out SiO₂ (64.8%), Al₂O₃ (20.4%), Fe₂O₃ (4.8%) and CaO (3.1%).

Table 1 - Physical properties of the RAP and coal fly ash samples.

Properties	RAP	Coal fly ash
Liquid limit (%)	-	-
Plastic limit (%)	-	-
Plasticity index (%)	Nonplastic	Nonplastic
Specific gravity	2.505	2.180
Fine gravel (4.75 mm < diameter < 20 mm) (%)	52.0	-
Coarse sand (2.00 mm < diameter < 4.75mm) (%)	24.0	-
Medium sand (0.425 < diameter < 2.00 mm) (%)	19.0	0.1
Fine sand (0.075 mm < diameter < 0.425 mm) (%)	5.0	13.5
Silt (0.002 mm < diameter < 0.075 mm) (%)	-	84.1
Clay (diameter < 0.002 mm) (%)	-	2.3
Mean particle diameter (mm)	5.0	0.022
USCS class	GW (well-graded gravel)	ML (silt)

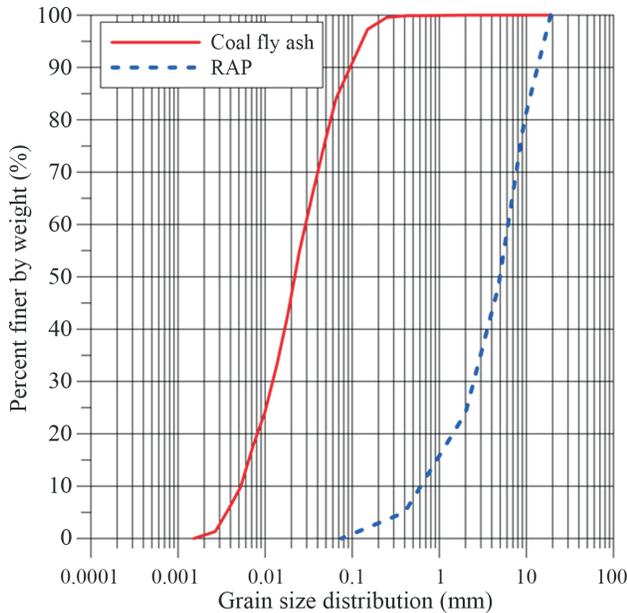


Figure 1 - Grain size distribution of studied RAP and coal fly ash.

The carbide lime (L), a by-product of the manufacture of acetylene gas, obtained from one source, was used throughout this investigation as the alkaline activator agent. The determination of calcium oxide established a value of 96%. In addition, its specific gravity ($\gamma_{s_{cl}}$) was, likewise, measured in accordance to ASTM D 854 (ASTM, 2014) and is 2.12.

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

2.2. Methods

2.2.1. Moulding and curing of specimens

For (split tensile) strength tests, cylindrical specimens 100 mm diameter and 60 mm from top to bottom were employed. For durability (wet-dry and freeze-thaw) tests, cylindrical specimens 100 mm diameter and 127.3 mm from top to bottom were utilized. A target dry unit weight for a particular specimen was then instituted as a result of the dry compacted RAP-fly ash-lime mix divided by the total volume of the specimen. As exhibited in Eq. 1 (Consoli *et al.*, 2017), porosity (η) is a function of dry unit weight (γ_d) of the mix, fly ash (FA) and carbide lime contents (L). The volumetric lime content (L_v), on the other hand, is defined as the ratio between the volume of lime and the total volume of the specimen, where the volume of lime was obtained through the ratio between added mass of lime and specific gravity of carbide lime.

Each substance (RAP, fly ash and lime) has a unit weight of solids ($\gamma_{s_{RAP}}$, $\gamma_{s_{FA}}$ and γ_{s_L}), which also requires to be pondered for computing porosity.

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

Once the RAP, fly ash and carbide lime were weighed, they were blended for about 10 min, until the mix visually attained uniformity. Moisture content (w) of 9% [optimum moisture content for modified Proctor compaction effort (ASTM, 2012)] for the blends was then supplemented, and mixing was resumed until a homogeneous paste in appearance was generated. The amount of fly ash (25%) was referenced to the dry mass of RAP + FA, based on previous research (Consoli *et al.*, 2018). Dry unit weights of 19 kN/m³ [maximum dry unit weight for modified Proctor compaction effort (ASTM, 2012)], and two other lower values below (18 kN/m³ and 17 kN/m³) were employed. The lime content applied to the mixtures was based on the ICL (Initial Consumption of Lime), method proposed by Rogers *et al.* (1997). Such method performs pH measurements of the blend with different lime contents. The minimum value indicated for use in the mixture is the percentage at which the pH reaches a maximum and constant value. Thus obtaining the values of 3%, 5% and 7% in this research [same values as those adopted for soil-cement mixtures (Consoli *et al.*, 2009, 2016a, 2016b; Mitchell, 1981)]. Specimens were statically compacted in the interior of a cylindrical mould in 3 strata, for the durability tests, and in 1 stratum for the split tensile strength tests. Subsequently to moulding, specimens were removed from the moulds and their weights, diameters and heights measured with precisions of nearly 0.01 g and 0.1 mm, respectively. The specimens were then sealed in plastic bags and cured in a humid room at 23° ± 2 °C with relative moisture of about 95%, in consonance with ASTM C 511 (ASTM, 2013), for a period of 7 days, which is the minimum time required by ASTM D 7762 (ASTM, 2018). Before all tests, specimens were put underwater for 24 h to reduce suction (Consoli *et al.*, 2011).

2.2.2. Splitting tensile tests

Splitting tensile tests were performed with a rate of loading equal to 1.14 mm/min, in agreement with the standard ASTM C496 (ASTM, 2011b). The split tensile strength was determined through the following relation, which is a function of the specimen diameter (D), height (H) and applied load (P).

$$q_t = \frac{2P}{\pi DH} \quad (2)$$

2.2.3. Durability tests

Durability tests of compacted RAP-fly ash-carbide lime blends were carried out according to standards ASTM D 559 (ASTM, 2015) for wet-dry cycles and ASTM D 560 (ASTM, 2016) for freeze-thaw cycles.

2.2.3.1. Wet-dry (ASTM D 559)

Test procedures determine mass losses produced by twelve recurrent wet-dry series followed by brushing strokes. Every cycle begins by full immersion of the specimens in water for 5 h at 23° ± 2 °C followed by oven drying during 42 h at 71° ± 2 °C. Lastly, specimens are brushed a number of times using a force of approximately 13.3 N.

2.2.3.2. Freeze-thaw (ASTM D 560)

Test procedures determine mass losses produced by twelve repeated freeze-thaw series followed by brushing strokes. Every cycle begins by introducing specimens in a freezing cabinet having a constant temperature not higher than -23 °C for 24 h and after removing. Next, placing the assembly in the moist room under a temperature of 21 °C and a relative humidity of 100% for 23 h and removing. Finally, specimens are brushed a number of times using a force of approximately 13.3 N.

3. Results and Analysis

3.1. Influence of the porosity/lime index on splitting tensile strength (q_t)

Figure 2 presents the splitting tensile strength (q_t) as a function of $\eta/(L_{iv})^{0.11}$ [quantified as porosity (η) divided by the volumetric lime content (L_{iv}), the latter expressed as a percentage of carbide lime volume to the total volume of the specimen (Consoli *et al.*, 2014). Fig. 2 indicates that the adjusted porosity/lime index is helpful in normalizing strength results for RAP-fly ash-carbide lime mixtures. A very good correlation ($R^2 = 0.95$) can be perceived concern-

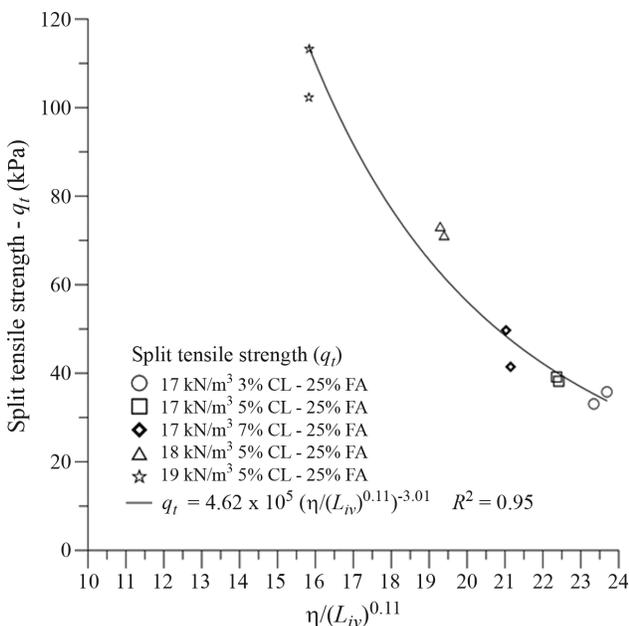


Figure 2 - Variation of splitting tensile strength (q_t) with porosity/lime index for RAP-fly ash-carbide lime blends for 7 days of curing.

ing $\eta/(L_{iv})^{0.11}$ and q_t [see Eq. 3] of the RAP-fly ash-carbide lime mixtures studied.

$$q_t \text{ (kPa)} = 4.62 \times 10^5 \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{-3.0} \quad (3)$$

The capability of the adjusted porosity/lime index to normalize strength of lime treated soils has been shown by Consoli *et al.* (2014, 2016a,b). They have shown that rates of change of strength with porosity (η) and the inverse of the volumetric lime content ($1/L_{iv}$) are as a rule not the same. Thus, the application of a power (as a rule 0.11 - Consoli *et al.*, 2014) to L_{iv} is required for the rates of η and $1/L_{iv}$ to be compatible.

3.2. Influence of the carbide lime content, porosity and porosity/lime index on durability (wetting-drying cycles and freezing-thawing cycles) of RAP-coal fly ash-carbide lime blends

Figure 3 presents relations of accumulated loss of mass (*ALM*) vs. number of wetting-drying and freezing-thawing cycles for compacted RAP-coal fly ash-lime blends (for a curing period of 7 days) in view of distinctive dry unit weights (17, 18 and 19 kN/m³) and carbide lime contents (5 and 7%). It can be seen in Fig. 3 that the *ALM* of each specimen is reduced with the increase of carbide lime content and with increase in dry unit weight. Similar specimens submitted to wetting-drying and freezing-thawing show distinct accumulated loss of mass (*ALM*), always occurring larger values of *ALM* brushing specimens submitted to freezing-thawing. The reason for different losses is due to distinct effects of temperature during wetting-drying and freezing-thawing cycles. For freezing-thawing testing conditions, after curing for 7 days at a standard temperature of about 23 °C the pozzolanic reactions are periodically stopped during freezing at temperature below -23 °C. On the contrary, under dry-wet conditions, after curing for 7 days at a normal temperature of about 23 °C the pozzolanic reactions are accelerated during drying at temperature 71 °C (Consoli *et al.*, 2014). As a consequence, specimens submitted to wetting-drying cycles have stronger bonds and so, smaller loss of mass during brushing.

Figure 4a exhibits compacted RAP-coal fly ash-carbide lime blends accumulated loss of mass (*ALM*) vs. adjusted porosity/lime index [$\eta/(L_{iv})^{0.11}$] after 1 [$R^2 = 0.93$ - see Eq. 4], 3 [$R^2 = 0.94$ - see Eq. 5], 6 [$R^2 = 0.94$ - see Eq. 6], 9 [$R^2 = 0.93$ - see Eq. 7] and 12 [$R^2 = 0.93$ - see Eq. 8] wetting-drying cycles (during durability tests).

$$ALM(\%) = 150 \times 10^{-3} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{2.20} \quad (4)$$

$$ALM(\%) = 184 \times 10^{-3} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{2.20} \quad (5)$$

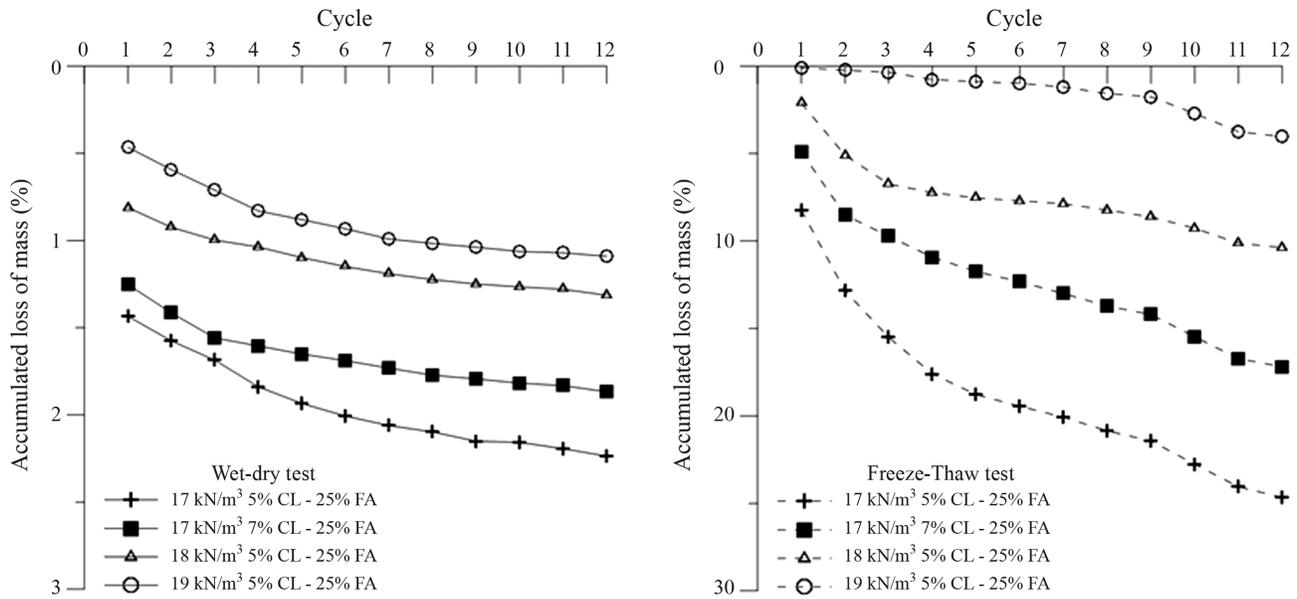


Figure 3 - Accumulated loss of mass after (a) wet-dry and (b) freeze-thaw cycles considering RAP-fly ash-carbide lime specimens moulded with dry unit weights of 17, 18 and 19 kN/m³, carbide lime contents of 5% and 7% specimens and 7 days as curing period.

$$ALM(\%) = 2.14 \times 10^{-3} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{2.20} \quad (6)$$

$$ALM(\%) = 2.30 \times 10^{-3} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{2.20} \quad (7)$$

$$ALM(\%) = 2.40 \times 10^{-3} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{2.20} \quad (8)$$

Similarly, Fig. 4b exhibits compacted RAP-coal fly ash-carbide lime blends accumulated loss of mass (*ALM*) vs. adjusted porosity/lime index [$\eta/(L_{iv})^{0.11}$] after 1 [$R^2 = 0.98$ - see Eq. 9], 3 [$R^2 = 0.98$ - see Eq. 10], 6 [$R^2 = 0.99$ - see Eq. 11], 9 [$R^2 = 0.99$ - see Eq. 12] and 12 [$R^2 = 0.97$ - see Eq. 13] freezing-thawing cycles.

$$ALM(\%) = 1.08 \times 10^{-12} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{9.50} \quad (9)$$

$$ALM(\%) = 2.10 \times 10^{-12} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{9.50} \quad (10)$$

$$ALM(\%) = 2.66 \times 10^{-12} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{9.50} \quad (11)$$

$$ALM(\%) = 2.97 \times 10^{-12} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{9.50} \quad (12)$$

$$ALM(\%) = 3.49 \times 10^{-12} \left[\frac{\eta}{(L_{iv})^{0.11}} \right]^{9.50} \quad (13)$$

It is clear in Figs. 4a and 4b that the accumulated loss of mass (*ALM*) is controlled by $\eta/(L_{iv})^{0.11}$ for all cycles in both wetting-drying and freezing-thawing tests. The existence of such relationships is shown for the first time ever for compacted RAP-coal fly ash-carbide lime blends. Looking at such figures, it might be observed that for the specimens with $\eta/(L_{iv})^{0.11} \sim 15$ (smaller studied value) the *ALM* under wetting-drying conditions varies from about 0.5% to 1.0% after one and twelve cycles while it varies only from about 0.4% to 4.0% under freezing-thawing conditions. For specimens in which $\eta/(L_{iv})^{0.11} \sim 22.5$ (larger studied value) the *ALM* under wetting-drying conditions varies from about 1.2% to 2.4% after one and twelve cycles while it varies only from about 8% to 25% under freezing-thawing conditions. These results also show that the long-term performance of compacted RAP-fly ash-lime blends is a function of $\eta/(L_{iv})^{0.11}$ and that such material is more durable under wetting-drying than freezing-thawing conditions.

It was expected that the dry unit weight vary along the test, particularly for the freeze-thaw tests. Nonetheless, it was also expected that the specimens with lower initial $\eta/(L_{iv})^{0.11}$ values perform better than those with higher values, which is one of the explanations for the correlation between the porosity/lime index and the accumulated loss of mass (in each cycle). The change in the porosity along the cycles can be one of the reasons for the not so good fitting observed in Fig. 4b (even with high values of R^2), although further studies, such as micro structural, combined with a

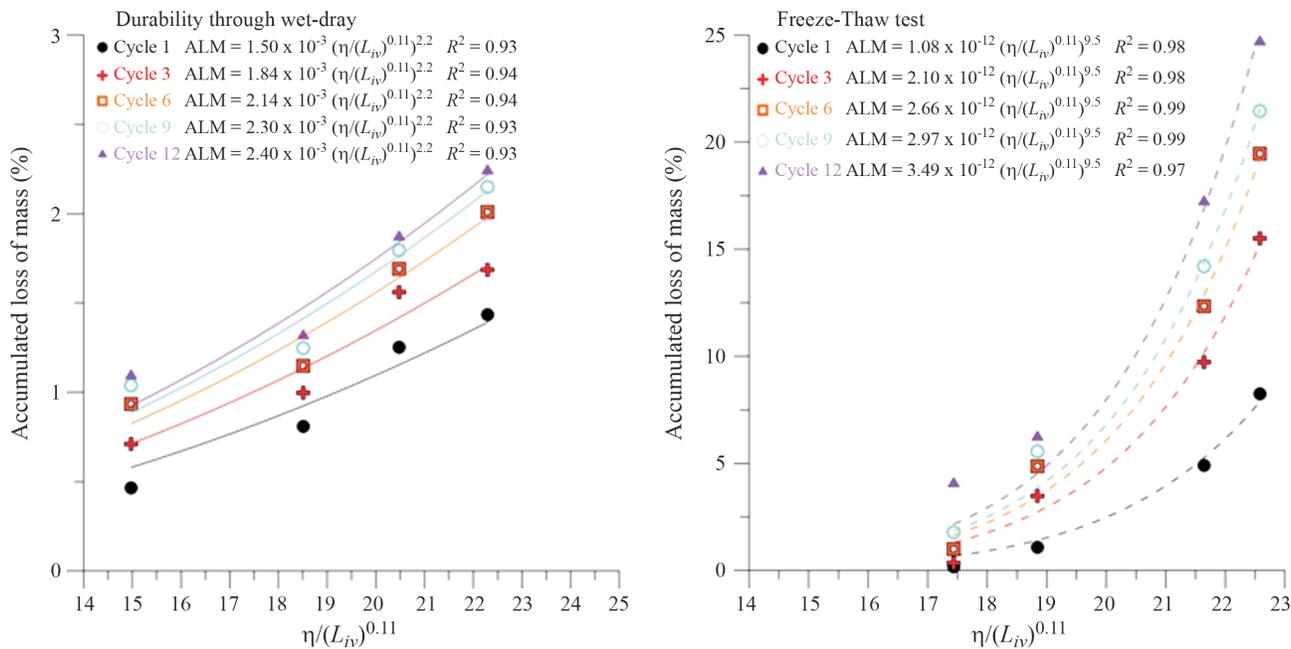


Figure 4 - Accumulated loss of mass for (a) wet-dry and (b) freeze-thaw for 1, 3, 6, 9 and 12 cycles vs. $\eta/(L_{iv})^{0.11}$ of RAP-fly ash-carbide lime blends considering distinct dry unit weight (17, 18 and 19 kN/m³) and carbide lime content (5 and 7%) specimens and 7 days curing period.

statistical analysis, should be performed to reach up definitive conclusions.

Finally, relationships of accumulated loss of mass (*ALM*) (after twelve cycles under wetting-drying and freezing-thawing conditions) vs. splitting tensile strength (q_t) for compacted RAP-coal fly ash-carbide lime blends are presented in Fig. 5. Unique non-linear relations ALM_{WD} vs. q_t and ALM_{FT} vs. q_t are presented in Eq. 14 and Eq. 15, respectively. Both have high correlations ($R^2 \geq 0.96$).

$$ALM_{WD} (\%) = 1.47 \times 10^4 \times q_t^{-1.77} \quad (14)$$

$$ALM_{FT} (\%) = 25.92 \times q_t^{-0.68} \quad (15)$$

Further research is still necessary to enhance the understanding of such materials, specially in what concerns the microstructural level and the effect of addition of other binders. Even so, in the future, this kind of relationships might enable researchers to reduce time in assessing durability of RAP-binder blends, as wetting-drying and freezing-thawing durability are time and effort consuming tests.

4. Concluding Remarks

From the studies described in this manuscript the following conclusions can be drawn:

- The accumulated loss of mass (*ALM*) (long term performance) of individual wetting-drying and freezing-thawing cycles of compacted RAP-coal fly ash-carbide lime blends was observed in the present research to be directly associated with the adjusted porosity/lime index;

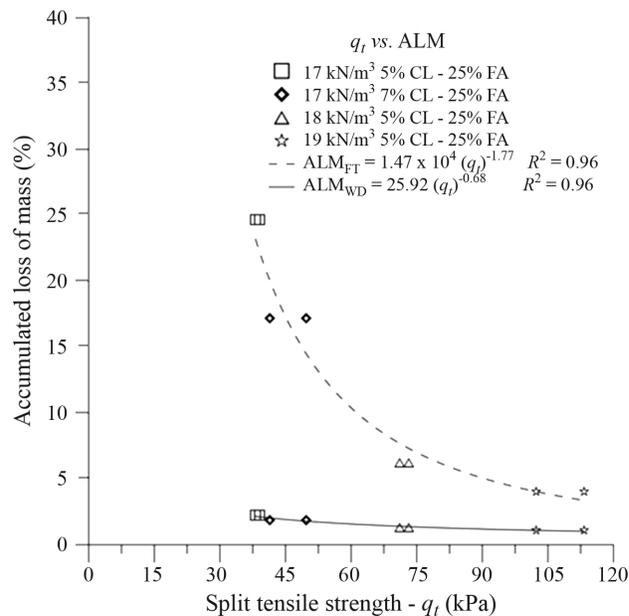


Figure 5 - Accumulated loss of mass considering twelve wetting-drying (and freezing-thawing) vs. q_t for RAP-coal fly ash-carbide lime blends in view of distinct dry unit weight (17, 18 and 19 kN/m³) and carbide lime content (3, 5 and 7%) specimens and 7 days curing period.

- Long term performance of compacted RAP-fly ash-lime blends is a function of $\eta/(L_{iv})^{0.11}$. Such material is more durable under wetting-drying than freezing-thawing conditions;

- The porosity/lime index controls strength and endurance of the compacted RAP-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 fulfils the design needs.

Acknowledgments

The authors desire to express their gratitude to Edital 12/2014 FAPERGS/CNPq - PRONEX (project # 16/2551-0000469-2) and CNPq (INCT-REAGEO and Produtividade em Pesquisa) for funding the research group.

References

- ABNT (2009a). Fine Aggregate - Determination of the Bulk Specific Gravity and Apparent Specific Gravity. NBR NM 52, Rio de Janeiro, Brazil (in Portuguese).
- ABNT (2009b). Coarse Aggregate - Determination of the Bulk Specific Gravity, Apparent Specific Gravity and Water Absorption. NBR NM 53, Rio de Janeiro, Brazil (in Portuguese).
- ASTM (2006). Standard Classification of Soils for Engineering Purposes. ASTM D 2487, West Conshohocken, Philadelphia.
- ASTM (2008). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM C 618, West Conshohocken, Philadelphia.
- ASTM (2011a). Standard Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures. ASTM D 2172, West Conshohocken, Philadelphia.
- ASTM (2011b). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM C 496, West Conshohocken, Philadelphia.
- ASTM (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (2,700 kN-m/m³). ASTM D 1557, West Conshohocken, Philadelphia.
- ASTM (2013). Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes. ASTM C 511, West Conshohocken, Philadelphia.
- ASTM (2014). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM D 854, West Conshohocken, Philadelphia.
- ASTM (2015). Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures. ASTM D 559, West Conshohocken, Philadelphia.
- ASTM (2016). Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures. ASTM D 560, West Conshohocken, Philadelphia.
- ASTM (2018). Standard Practice for Design of Stabilization of Soil and Soil-Like Materials with Self-Cementing Fly Ash. ASTM D 7762, West Conshohocken, Philadelphia.
- Avirneni, D.; Peddinti, P.R.T. & Saride, S. (2016). Durability and long-term performance of geopolymer stabilized reclaimed asphalt pavement base courses. *Construction and Building Materials*, 121:198-209.
- Consoli, N.C.; Lopes Jr., L.S. & Heineck, K.S. (2009). Key parameters for the strength control of lime stabilized soils. *Journal of Materials in Civil Engineering*, 21(5):210-216.
- Consoli, N.C.; Dalla Rosa, A. & Saldanha, R.B. (2011). Variables governing strength of compacted soil-fly ash-lime mixtures. *Journal of 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. & Kanazawa Villalba, N.M. (2016a). Durability, strength and stiffness of dispersive clay-lime blends. *Journal of Materials in Civil Engineering*, 28(11):04016124.
- Consoli, N.C.; Quiñónez Samaniego, R.A.; Marques, S.F.V.; Venson, G.I.; Pasche, E. & González Velázquez, L.E. (2016b). A single model establishing strength of dispersive clay treated with distinct binders. *Canadian Geotechnical Journal*, 53(12):2072-2079.
- Consoli, N.C.; Pasche, E.; Specht, L.P. & Tanski, M. (2017). Key parameters controlling dynamic modulus of crushed reclaimed asphalt paving-powdered rock-Portland cement blends. *Road Materials and Pavement Design*, (published online) DOI: 10.1080/14680629.2017.1345779.
- Consoli, N.C.; Giese, D.N.; Leon, H.B.; Mocelin, D.M.; Wetzel, R. & Marques, S.F.V. (2018). Sodium chloride as a catalyser for crushed reclaimed asphalt pavement - fly ash - carbide lime blends. *Transportation Geotechnics* 15:13-19.
- Federal Highway Administration (FHWA) (2011). Publication No. FHWA-PL-11-028, U.S. Department of Transportation, Washington, DC.
- INPE (2017). <http://www.inpe.br/>. Brazilian Institute of Spatial Research, Brasília, Brazil.
- Mitchell, J.K. (1981). Soil improvement - State-of-the-art report. Proc. 10th Int. Conf. on Soil Mechanics and Foundation Engineering. International Society of Soil Mechanics and Foundation Engineering, Stockholm, pp. 509-565.
- Puppala, A.J.; Hoyos, L.R. & Potturi, A.K. (2011). Resilient moduli response of moderately cement treated reclaimed asphalt pavement aggregates. *Journal of Materials in Civil Engineering*, 23(7):990-998.
- Rogers, C.D.F.; Glendinning, S. & Roff, T.E.J. (1997). Lime modification of clay soils for construction expediency. *Proc. Inst. Civil Eng., Geotech. Eng.*, 125(3):242-249.

List of Symbols

ALM: accumulated loss of mass

D: specimen diameter

*E**: dynamic modulus

FA: fly ash

H: specimen height

L: lime content (expressed in relation to mass of RAP + fly ash)

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

P: applied load

q_u : unconfined compressive strength

q_t : splitting tensile strength

R^2 : coefficient of determination

RAP: reclaimed asphalt pavement

η : porosity

η/C_w : porosity/cement index

η/L_w : porosity/lime index

γ_d : dry unit weight

γ_s : unit weight of solids

δ : phase angle

w: moisture content (ratio of mass of water to mass of solids)