Durability of reclaimed asphalt pavement-coal fly ash-carbide lime blends under severe environmental conditions

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ABSTRACT: The sustainable use of industrial residue in enhancing the long-term performance of reclaimed asphalt pavement (RAP) has been proven to be effective under freeze-thaw and wet-dry conditions. This study focuses on coal fly ash and carbide lime as the enhancing agents. It evaluates how the durability and long-term performance of compacted RAP-fly ash-carbide lime mixtures are impacted by dry unit weight and lime content. The tested mixture's specimens were moulded in three layers through static compaction inside a cylindrical mould. Several single-level variables were used in the stabilisation process. Among these were: fly ash content of 25 %, optimum water content of 9 % (modified effort) and seven days of curing. Additionally, three target dry unit weights (17, 18 and 19 kN/m^3 – the last of which was determined using the modified Proctor energy) and three percentages of lime content (3, 5 and 7%) were used for a comparative analysis. The tested specimens' accumulated loss of mass (after wetting-drying and freezing-thawing cycles) and splitting tensile strength were both evaluated as a function of the porosity/lime index. The experiments revealed that compacted RAP-coal fly ash-carbide lime mixtures performed noticeably worse when subjected to freezing-thawing cycles than when subjected to wetting-drying cycles. These results indicate an increase in the breadth of the porosity/lime index, as it is shown to control the long-term performance of compacted RAP-coal fly ash-carbide lime mixtures, in addition to controlling their mechanical response.

Keywords: reclaimed asphalt pavement; long-term performance; industrial by-products; soil stabilisation; and porosity/lime index.

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Introduction

Road infrastructure is a fundamental component of the production system of a country, since it promotes integration among the various regions within the country interconnecting its ports, railways, waterways and airports. Over time, various types of pavement distresses start to develop such as longitudinal and transverse cracking, potholes, as well as several other types of pavement surface irregularities. These factors can increase the probability of occurrence of road accidents. In addition, the quality of a road pavement is one of the main factors affecting road users' travels and transportation costs, particularly when roads with precarious functionality are available.

Several pavement rehabilitation methods can be used to correct pavement distresses, including overlaying, partial or complete removal of existing asphalt pavement layers, or their recomposition with new asphalt concrete. This reclamation process that involves cutting off the top asphalt concrete layer produces a great amount of waste during highway rehabilitation operations (FHWA 2011). Issues may arise if no project specifications are made either for the beneficial use or final proper disposal of this waste material. Such material may end up being improperly dumped in landfills or even along the highway, which can become an environmental liability as rainwater ends up carrying the material to nearby streams or rivers. An alternative approach for road maintenance and rehabilitation includes the use of reclaimed asphalt pavement (RAP) stabilised with Portland cement in base or subbase layers of a pavement (e.g. Puppala *et al.* 2011). Recently, Consoli *et al.* (2017) conducted research on the mechanical properties (unconfined compressive strength, q_u, and splitting tensile strength, q_t) and the viscoelastic behaviour (dynamic modulus, E*, and phase angle, δ) of mixtures of RAP, powdered rock and Portland cement. They found out that the porosity/cement index (η/C_{iv}) is a proper parameter to predict q_u, q_t, E* and δ of RAP-powdered rock-Portland cement mixtures. Their study was mainly based on the evaluation of the unconfined compressive strength, resilient modulus and dynamic modulus of the mixtures tested.

RAP improvement becomes more interesting when used in conjunction with other by-products (e.g. carbide lime and coal fly ash) in earthworks, reducing the consumption of natural resources and the possibility of improper disposal. Consoli *et al.* (2014) achieved high strength by adding lime to fly ash, due to the occurrence of pozzolanic reactions. The pozzolanic chemical reaction (Massazza 1993) between silica (SiO_2) and alumina (Al_2O_3) of coal fly ashes, lime [$Ca(OH)_2$] and water (H_2O) is presented in Equations (1) and (2).

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2.H_2O$$ - (known as C-S-H, calcium silicate hydrate) (1)

$$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO.Al_2O_3.H_2O$$ - (known as C-A-H, calcium aluminate hydrate) (2)

The wetting-drying cycles due to climate variation may result in tension and surface cracks on bases/subbases of pavements, both of which reduce the endurance of such materials (Horpibulsuk *et al*. 2015). On the other hand, in cold regions the main damage resulting from freezing–thawing cycles on bases/subbases of pavements are cracks and spalls (Yarbasi *et al*. 2007, Cruzda and Hohmann 1997).

However, the durability and long-term performance of compacted mixtures of RAP treated with industrial wastes has received reduced attention. One of the few studies on this topic was carried out by Avirneni *et al.* (2016), who assessed the mass loss of RAP materials mixed with fly ash and sodium hydroxide after wetting-drying cycles. Similar research is also being carried out in southern Brazil, where the seasons are well defined and temperature extremes can reach about -15^{o}C in the winter and exceed 40^{o}C in the summer (INPE 2017). However, there is an ongoing need to understand the effect of severe environmental conditions on the durability of such newly developed mixtures.

For this reason, the present study investigated the performance of a RAP material treated with coal fly ash and carbide lime under extreme wet-dry (cycles reaching 71^{o}C for 42 h followed by 23°C for 5 h) and freeze-thaw (cycles reaching -23^{o}C for 24 h followed by 21°C for 23 h) conditions. The study assessed the potential use of such mixtures as a road embankment material, as well as a sub-base material for low volume roads. Possible relationships between the porosity/lime index (η/L_{iv}) and the accumulated loss of mass (ALM) of compacted RAP-fly ash-lime mixtures were also established following wetting-drying and freezing-thawing cycles.

Experimental programme

Materials

The particle size distribution of the RAP material tested is shown in Figure 1 with some key parameters summarised in Table 1 along with its USCS classification. Such recycled aggregate was reclaimed from BR 290 highway, which connects the capital city of Porto Alegre to the seaside region and main towns along the coastline in southern Brazil. RAP samples were collected in sufficient amount to complete all tests. The asphalt binder content (SBS Modified - PG 70-22S) found in the RAP was about 5 %, having been determined according to ASTM D2172 (2011a). The specific gravity of the aggregate fraction of RAP was 2.51.

The fly ash (FA) used in this study is classified as type F according to ASTM C618 (2008). The results of the FA characterization tests are also summarised in Table 1. The FA is nonplastic and is classified as silt (ML) according to the Unified Soil Classification System (ASTM D2487 2006). Based on X-Ray fluorescence spectrometry (XRF) results, it was possible to identify the main FA components, which include SiO_2 (64.8%), Al_2O_3 (20.4%), Fe_2O_3 (4.8%) and CaO (3.1%). Thus, FA is a source of essential amorphous material for the occurrence of pozzolanic reactions (Lu *et al.* 2008).

The carbide lime, which is a by-product of the acetylene gas manufacturing process, was obtained from a single supplier and used throughout this investigation as the calcium-source for pozzolanic reactions (Lu *et al.* 2008). The amount of calcium oxide present in the carbide lime tested was equal to 96%.

Distilled water was employed for both characterization and moulding of the specimens tested in the mechanical testing programme.

The X-ray diffractometry of the coal fly ash-carbide lime mixture tested in this study is shown in Figure 2. Tobermorite [$Ca_5(OH)_2Si_6O_{16}.4H_2O$] and hillebrandite [$Ca_2(SiO_3)(OH)_2$] were the novel crystalline phases detected, acting as the binder in the mixture, and definitely increasing its strength and durability.

Methods

Specimen Preparation and Curing

Cylindrical specimens with diameter equal to 100 mm were used for all tests. The specimen height for split tensile tests and durability (wet-dry and freeze-thaw cycles) tests were equal to 60 and 127 mm, respectively. Specimen dry unit weight (γ_d) was simply determined as the ratio of the dry weight of compacted RAP-fly ash-lime mixture to the total specimen volume (ASTM D7263 2009). Porosity (η) is defined as the volume of the voids (V_v) over the total volume of the specimen (V). The amount of carbide lime used in each mixture was determined based on the mass of dry RAP-fly ash. As exhibited in Equation (3), the porosity (η) of the mixture is a function of the dry unit weight (γ_d) of the mix and the RAP, coal fly ash (FA) and carbide lime

(CL) contents of the mixture, expressed as a percentage, along with the unit weight of solids of RAP (γs_{RAP}), fly ash (γs_{FA}) and lime (γs_{CL}) (Consoli *et al.* 2017).

$$\eta\ (\%) = 100 - 100\left\{\left[\frac{\gamma_d}{1+\frac{CL}{100}}\right]\left[\frac{\frac{RAP}{100}}{\gamma s_{RAP}} + \frac{\frac{FA}{100}}{\gamma s_{FA}} + \frac{\frac{CL}{100}}{\gamma s_{CL}}\right]\right\} \quad (3)$$

Once the RAP, fly ash and carbide lime were weighed, they were blended for about 10 minutes, until mixture uniformity was attained. Then, water was added to the mixture to achieve the target water content (w) of 9%, which is the optimum water content obtained using the modified Proctor compaction effort as per ASTM D1557 (2012). Next, mixing resumed until a homogeneous paste was obtained and the specimens were statically compacted in 3 layers inside a cylindrical mould. After compaction, the specimens were removed from the moulds and their weights, diameters and heights measured with resolution of nearly 0.01 g, 0.1 mm and 0.1 mm, respectively. Specimens were cured for 7 days in a humid room at 23º±2ºC with relative humidity of about 95% (ASTM C511 2013).

Splitting Tensile Tests

Splitting tensile tests followed standard ASTM C496 (2011b). This type of strength test is commonly used in the design of pavements since it directly provides the resistance of bases and subbases in relation to the occurrence of tensile cracks. Before testing, specimens were submerged for 24 h to help reduce the matric suction in the specimen (Consoli *et al.* 2011). Specimens containing 25% of FA were compacted with water content of 9%, as described above. The target dry unit weights used during specimen compaction were equal to 19 kN/m^3 (i.e., maximum dry unit weight for the modified Proctor compaction effort), as well as two additional, lower values, namely 18 kN/m^3 and 17 kN/m^3. The adopted carbide lime contents of 3%, 5% and 7% were determined following international (Mitchell 1981) and Brazilian (Consoli *et al.* 2009, 2016a,b) experience with soil–lime mixtures. All of the splitting tensile test specimens were cured for 7 days. The dimensions of the specimens were 60 mm in height and 100 mm in diameter. The automatic loading machine used for the tests had a maximum capacity of 50 kN and a proving ring with a capacity of 10 kN and resolution of 0.005 kN. The rate of displacement adopted was of 1.14 mm per minute.

Durability Tests

Durability tests of compacted RAP-fly ash-carbide lime mixtures were carried out according to standards ASTM D559 (2015) for wetting-drying cycles and ASTM D560 (2016) for freezing-thawing cycles. Many authors [e.g. Horpibulsuk *et al.* 2015, Avirneni *et al.* (2016), Consoli *et al.* (2016a)] have already used durability tests to evaluate long term performance of cemented mixtures, simulating severe environmental conditions. In both types of durability tests carried out in the present research, the specimens measured 127 mm in height and 100 mm in diameter.

Wetting-Drying Cycles

The standard test method ASTM D559 (2015) was used to determine the mass losses produced by recurrent (12) wet-dry cycle series followed by brushing strokes. In summary, every cycle begins by oven drying the specimens for 42 h at 71°±2°C. The specimens are then brushed a number of times (the side of the specimen was brushed with 19 strokes and top and base with 4 strokes) using a force of approximately 13.3 N. After the brushing the specimens were weighed and subsequently submerged for 5 h at 23°±2°C.

Freezing-Thawing Cycles

Mass losses produced by repeated (12) freeze-thaw cycles followed by brushing strokes were determined according to ASTM D560 (2016). Every cycle begins by introducing specimens in a freezing cabinet having a constant temperature not warmer than -23°C for 24 h and after remove. Next, placing the assembly in the moist room to defrost at a temperature of 21°C and a relative humidity of 100 % for 23 h and remove. Following, specimens are brushed a number of times (the side of the specimen was brushed with 19 strokes and top and base with 4 strokes) using a force of approximately 13.3 N. The specimens were then weighed.

Results and analysis

Influence of Porosity/Lime Index on Splitting Tensile Strength

Figure 3 shows the variation of the splitting tensile strength with increasing porosity/lime index, $\eta/(L_{iv})^{0.11}$, which is defined as the ratio of porosity (η) to the volumetric lime content (L_{iv}) of the specimen. The parameter L_{iv} is expressed as the percentage of carbide lime volume to the total specimen volume (Consoli *et al.* 2014). Figure 3 indicates that the adjusted porosity/lime index is helpful in normalizing strength results for RAP-fly ash-carbide lime mixtures. A very high coefficient of determination (R^2=0.95) can be perceived concerning $\eta/(L_{iv})^{0.11}$ and q_t [see Equation (4)] for the RAP-fly ash-carbide lime mixtures studied. Values of the parameters *a*, *b* and *c*, which have been determined for the materials tested in this study, are summarised in Table 2.

$$q_t(kPa) = a\left[\frac{\eta}{(L_{iv})^b}\right]^c \tag{4}$$

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.

For the different moulding characteristics of RAP-coal fly ash-carbide lime mixtures (shown in Figure 3), it can be seen that for the same dry unit weight (17 kN/m^3), the increase of the carbide lime content (from 3% to 7%) provided a slight enhancement in the splitting tensile strength. However, considering the same carbide lime content (5%), an important increase in splitting tensile strength occurred when increasing dry unit weight (from 17 kN/m^3 to 19 kN/m^3), reaching values of q_t close to 120 kPa.

Influence of Carbide Lime Content, Porosity and Porosity/Lime Index on Durability (wetting-drying cycles and freezing-thawing cycles)

Figures 4(a) and 4(b) show the variation of the accumulated loss of mass (ALM) of the compacted RAP-coal fly ash-lime mixtures with the number of wetting-drying and freezing-thawing cycles, respectively. Results shown in Figures 4(a) and 4(b) relate to the single curing period of 7 days and the various levels of dry unit weight (17, 18 and 19 kN/m^3) and carbide lime content (3, 5 and 7%) used in this study. The accumulated loss of mass of the mixtures tested decreases with increasing carbide lime content and increasing dry unit weight. Similar specimens submitted to either wetting-drying or freezing-thawing show distinct ALM values. ALM values observed for the specimens submitted to freezing-thawing were always larger than those subjected to wetting-drying cycles. The reason for such different losses is due to the distinct effect of temperature variations 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 temperatures below -23°C. Conversely, under dry-wet conditions and following the curing period of 7 days under a normal temperature of about 23°C, the pozzolanic reactions are accelerated during the drying stage at a temperature of 71°C (Consoli *et al.* 2014). As a result, specimens submitted to wetting-drying cycles develop stronger bonds, which leads to smaller loss of mass during brushing.

Figure 5(a) shows the variation of the accumulated loss of mass of the compacted RAP-coal fly ash-carbide lime mixtures tested with increasing adjusted porosity/lime index [$\eta/(L_{iv})^{0.11}$] after 1, 3, 6, 9 and 12 wetting-drying cycles. A relationship describing this variation, which is similar to that developed in Equation (4) for the splitting tensile strength, is expressed in Equation (5), with a minimum coefficient of determination of 0.93. Values of the parameters *d*, *b* and *c*, as well as R^2 are summarised in Table 2 for all wetting-drying cycles mentioned above.

$$ALM(\%) = d\left[\frac{\eta}{(L_{iv})^{b}}\right]^{c} \quad (5)$$

Similarly, Figure 5(b) displays the variation of the accumulated loss of mass with an increase in the adjusted porosity/lime index [$\eta/(L_{iv})^{0.11}$] for the same mixtures tested and identical numbers of cycles as discussed above. However, these curves were obtained following freezing-thawing cycles instead. Table 2 also summarises the relevant parameters associated with the fitting of Equation (5) for these freezing-thawing durability tests, which had a minimum coefficient of determination of 0.97.

Figures 5(a) and 5(b) suggest that the accumulated loss of mass is controlled by $\eta/(L_{iv})^{0.11}$ for all cycles in both wetting-drying and freezing-thawing durability tests. This original data shows that the existence of such relationships also applies for compacted RAP-coal fly ash-carbide lime mixtures. For specimens with $\eta/(L_{iv})^{0.11}$~15 (smallest value studied here) the ALM under wetting-drying conditions varies from about 0.5% to 1.0% as the number of cycles varies from one to twelve cycles, whereas the ALM varies from about 0.1% to 3.2% under freezing-thawing conditions for a ratio of $\eta/(L_{iv})^{0.11}$~17.5. For specimens $\eta/(L_{iv})^{0.11}$~23 (largest value studied here) the ALM under wetting-drying conditions varies from about 1.4% to 2.3% after one and twelve cycles, respectively, whereas it increases from about 8% to 25% under freezing-thawing conditions for similar changes in number of cycles. These results illustrate that the long-term performance of compacted RAP-fly ash-carbide lime mixtures is also dependent on

$\eta/(L_{iv})^{0.11}$ and that such mixtures are more durable under wetting-drying cycles than under freezing-thawing cycling conditions.

So, according to the requirements of the compacted RAP-fly ash-carbide lime mixtures' wet-dry and/or freeze-thaw durability conditions, the pavement designer can establish the porosity/lime index that fulfils the design needs. The capability of the porosity/lime index to normalize compacted RAP-fly ash-carbide lime mixtures durability conditions (under both wet-dry and freeze-thaw) allows the use of distinct dry unit weights and lime amounts to fulfil the project requirements.

Finally, relationships between the accumulated loss of mass after 12 cycles under both wetting-drying and freezing-thawing conditions and the splitting tensile strength of the compacted RAP-coal fly ash-carbide lime mixtures tested are presented in Figure 6. Distinct non-linear relations between ALM_{WD} and q_t as well as between ALM_{FT} and q_t are presented in Equations (6) and (7), respectively. Both have high coefficients of determination (R^2=0.97).

$$ALM_{WD}(\%) = 22\ {q_t}^{-0.6} \quad (6)$$

$$ALM_{FT}(\%) = 9493\ {q_t}^{-1.7} \quad (7)$$

Further research is still necessary, extending the study to other binders. But, in the future, these types of relationships may enable researchers to reduce time in assessing the durability of RAP-binder mixtures, as wetting-drying and freezing-thawing durability tests require long periods of time to be properly carried out.

Concluding remarks

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

- The porosity/lime index [$\eta/(L_{iv})^{0.11}$] controls the mechanical response (strength) and long-term performance (durability) of the compacted RAP-coal fly ash-carbide lime mixtures tested, which substantially broadens the applicability of the index. Therefore, according to appropriate strength and durability requirements, geotechnical engineers may define the adjusted porosity/lime index that fulfils their design needs;

- The accumulated loss of mass of the mixtures tested decreases with higher carbide lime content and higher dry unit weight;
- The compacted RAP-coal fly ash-carbide lime mixtures are more durable under wetting-drying than freezing-thawing conditions, e.g. for specimens with $\eta/(L_{iv})^{0.11}$~23 the ALM under wetting-drying conditions varies from about 1.4% to 2.3% after one and twelve cycles, respectively, whereas it increases from about 8% to 25% under freezing-thawing cycles; and
- This research obtained distinct non-linear relations between ALM_{WD} and q_t [$ALM_{WD}(\%) = 22\ {q_t}^{-0.6}$] as well as between ALM_{FT} and q_t [$ALM_{FT}(\%) = 9493\ {q_t}^{-1.7}$] for the analysed mixtures.

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References

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. (2009). *Standard test methods for laboratory determination of density (unit weight) of soil specimens*. ASTM D 7263, 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/*m^3*).* 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. (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.

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 Eng*ineering, 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 Eng*ineering*,* 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 Eng*ineering*,* 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*, doi: 10.1080/14680629.2017.1345779.

Cruzda K. A.; & Hohmann M. (1997). Freezing effect on strength of clayey soils. *Applied Clay Science*. 12, 165–87.

Horpibulsuk, S.; Suksiripattanapong, C.; Samingthong, W.; Rachan, R.; & Arulrajah, A. (2015). Durability against wetting–drying cycles of water treatment sludge-fly ash geopolymer and water treatment sludge-cement and silty clay-cement systems. *Journal of Materials in Civil Engineering*, 28(1), 04015078.

INPE (2017). “http://www.inpe.br/”. Brazilian Institute of Spatial Research, Brasília, Brazil.

Lu, P.; Li, Q.; & Zhaiw, J. (2008). Mineralogical characterizations and reaction path modeling of the pozzolanic reaction of fly ash–lime systems. *Journal of the American Ceramic Society,* 91(3), 955–964.

Mitchell, J. K. (1981). Soil improvement—state-of-the-art report. *Proceedings 10th Int. Conf. on Soil Mechanics and Foundation Engineering*. International Society of Soil Mechanics and Foundation Engineering, Stockholm, 509–565.

Massazza, F. (1993). Pozzolanic cements. *Cement & Concrete Composites*, 15, 185-214.

Puppala, A. J.; Hoyos, L. R. and 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.

Yarbasi, N.; Kalkan E.; & Akbulut S. (2007). Modification of the geotechnical properties, as influenced by freeze–thaw, of granular soils. *Cold Regions Science and Technology*, 48(1), 44–54.

Notation

ALM	*accumulated loss of mass*
CL	*carbide lime content (expressed in relation to mass of RAP+fly ash)*
FA	*fly ash*
L_{iv}	*volumetric lime content (expressed in relation to the total specimen volume)*
q_u	*unconfined compressive strength*
q_t	*splitting tensile strength*
R^2	*coefficient of determination*
RAP	*reclaimed asphalt pavement*
V	*total volume of the specimen*
V_v	*volume of voids*
η	*porosity*
η/C_{iv}	*porosity/cement index*
η/L_{iv}	*porosity/lime index*
γ_d	*dry unit weight*
γ_s	*unit weight of solids*
w	*water content (ratio of mass of water to mass of solids)*

TABLES

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

Properties	RAP	Coal fly ash
Plasticity index (%)	Nonplastic	Nonplastic
Specific gravity (kN/m^3)	25.1	21.8
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, D_{50} (mm)	5.0	0.022
USCS class	GW (well-graded gravel)	ML (silt)

TABLE 2. Fitting parameters for Equations (2) and (3) for the RAP-fly ash-carbide lime mixtures tested.

Test type	Cycle	*a*	*b*	*c*	*d*	R^2
		[kPa]	-	-	-	-
Splitting tensile strength	-	44×10^4		-3.0	-	0.95
Durability (wet-dry)	1				1.5×10^{-3}	0.93
	3				1.8×10^{-3}	0.94
	6			2.20	2.1×10^{-3}	0.94
	9				2.3×10^{-3}	0.93
	12		0.11		2.4×10^{-3}	0.93
Durability (freeze-thaw)	1				1.0×10^{-12}	0.98
	3				2.0×10^{-12}	0.98
	6			9.50	2.6×10^{-12}	0.99
	9				3.0×10^{-12}	0.99
	12				3.5×10^{-12}	0.97

FIGURES

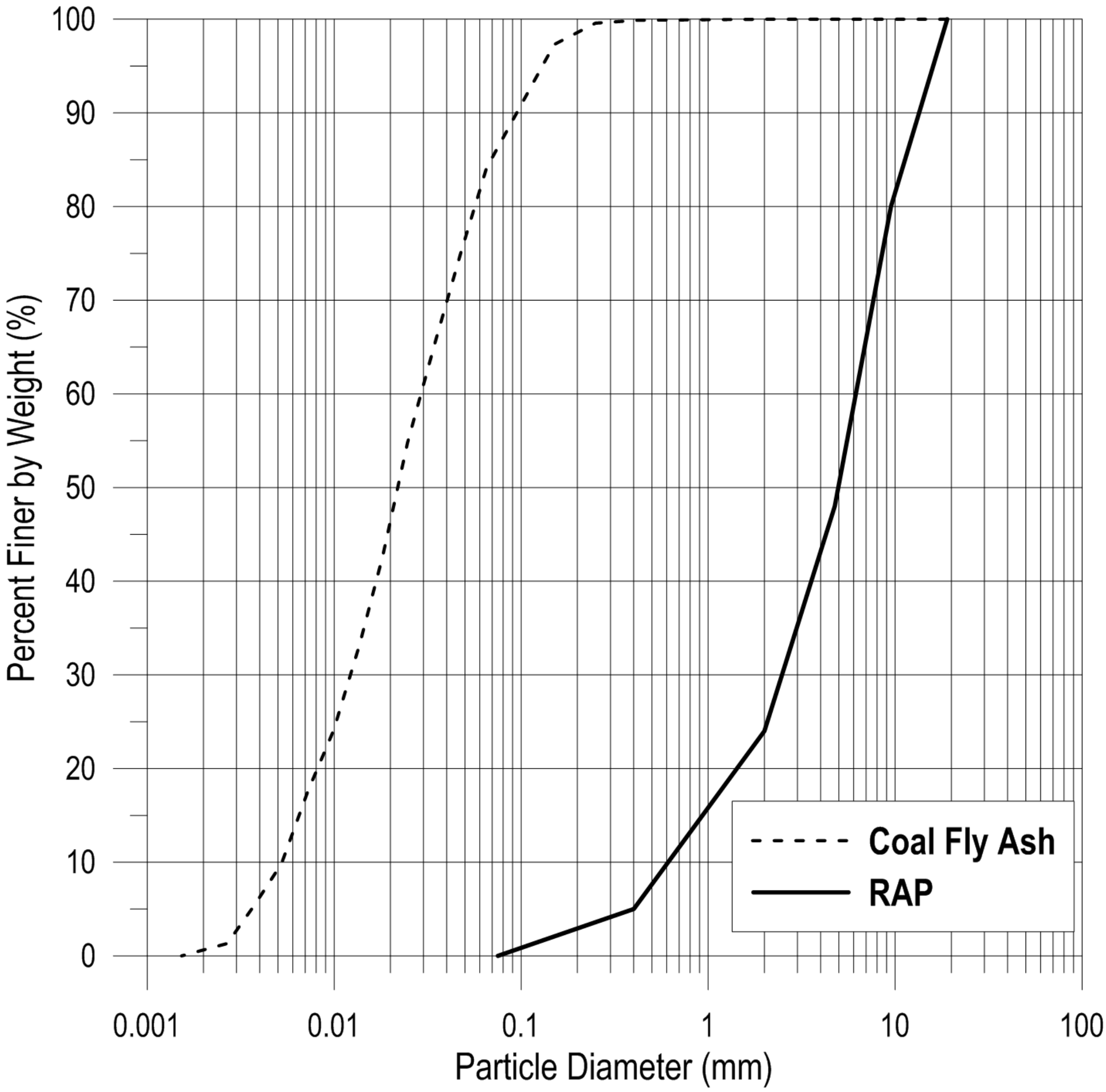


FIGURE 1. Particle size distribution of the RAP and coal fly ash materials tested.

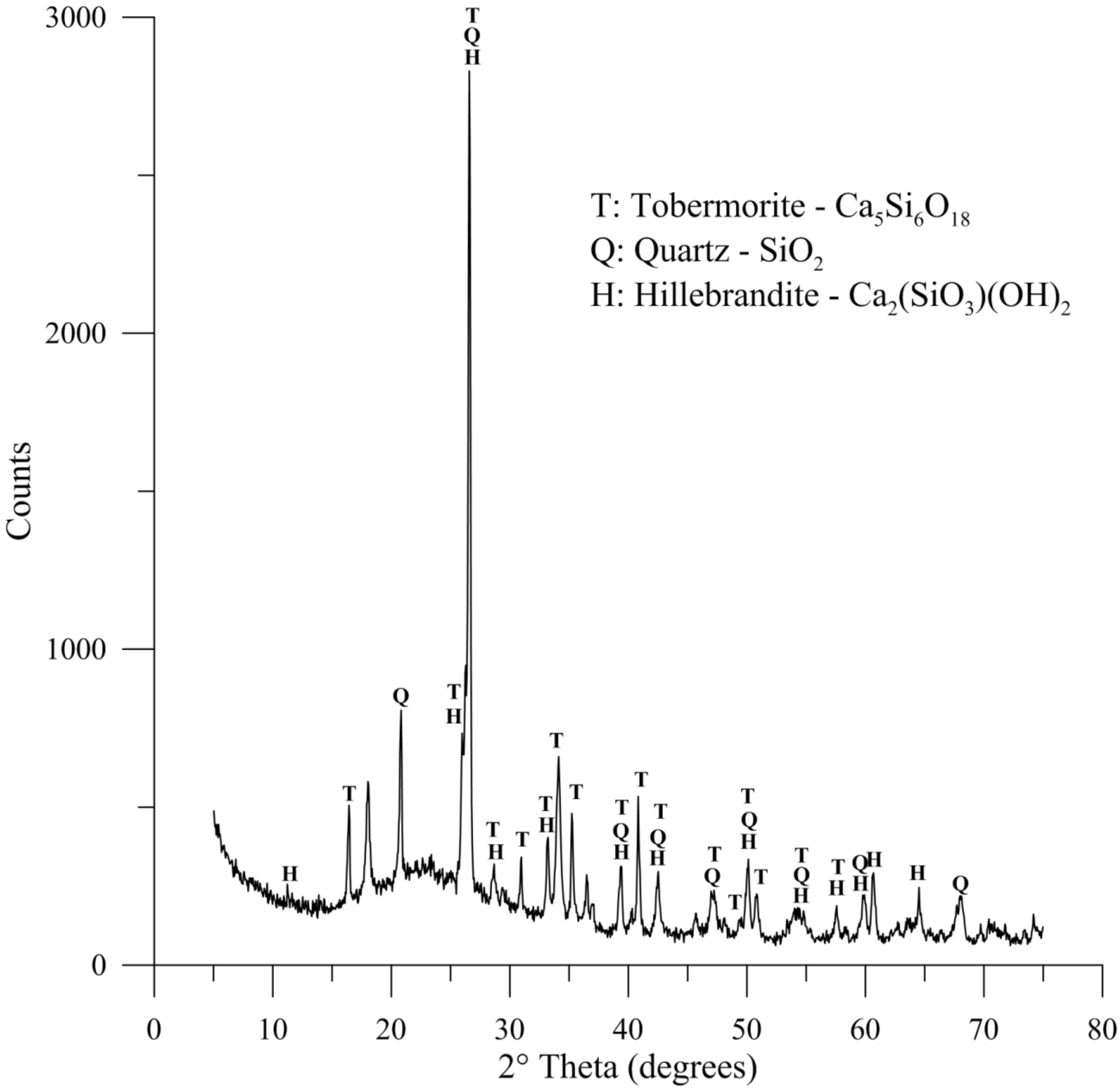


FIGURE 2. X-Ray diffractometry of the coal fly ash-carbide lime mixture tested.

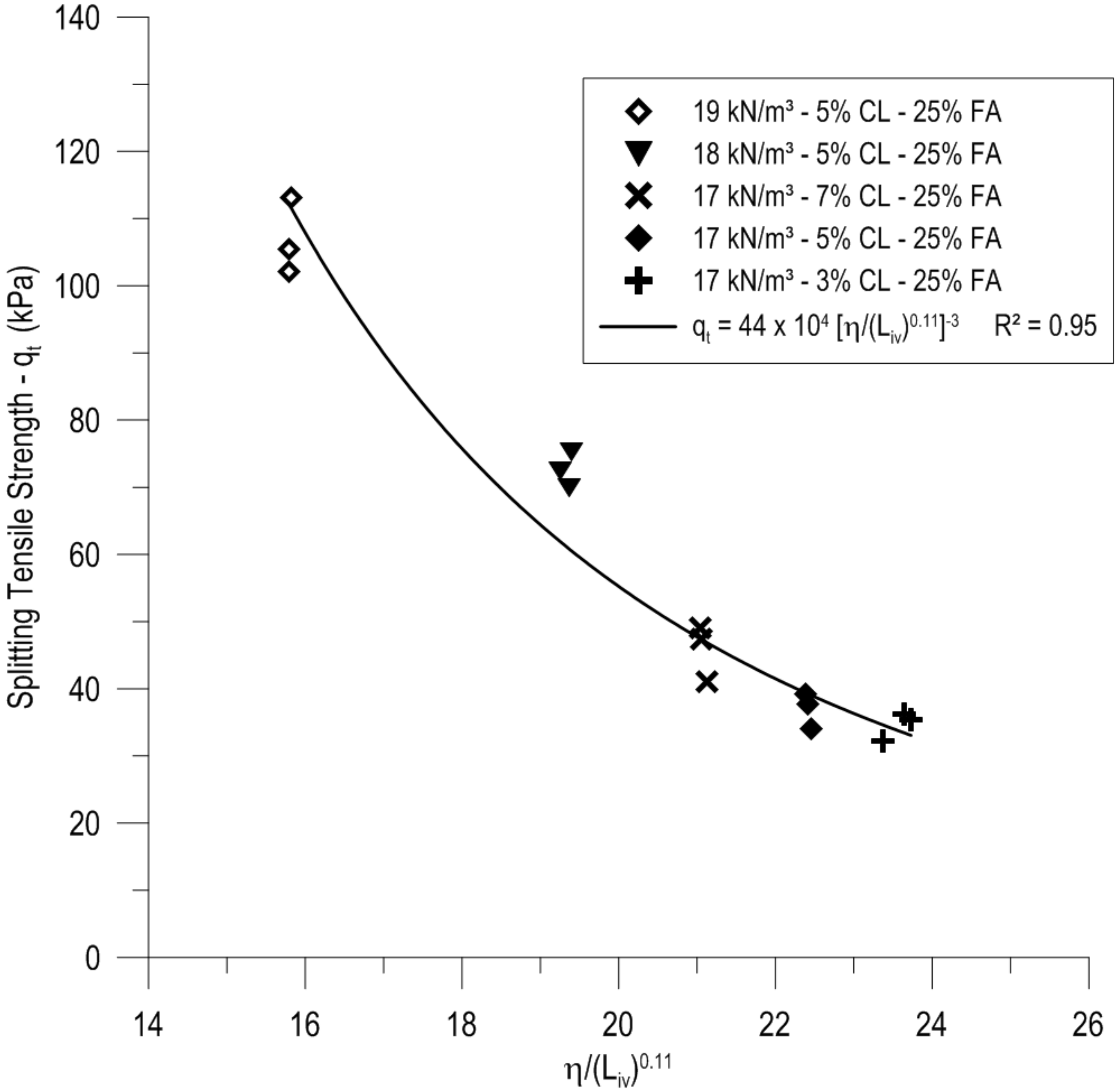
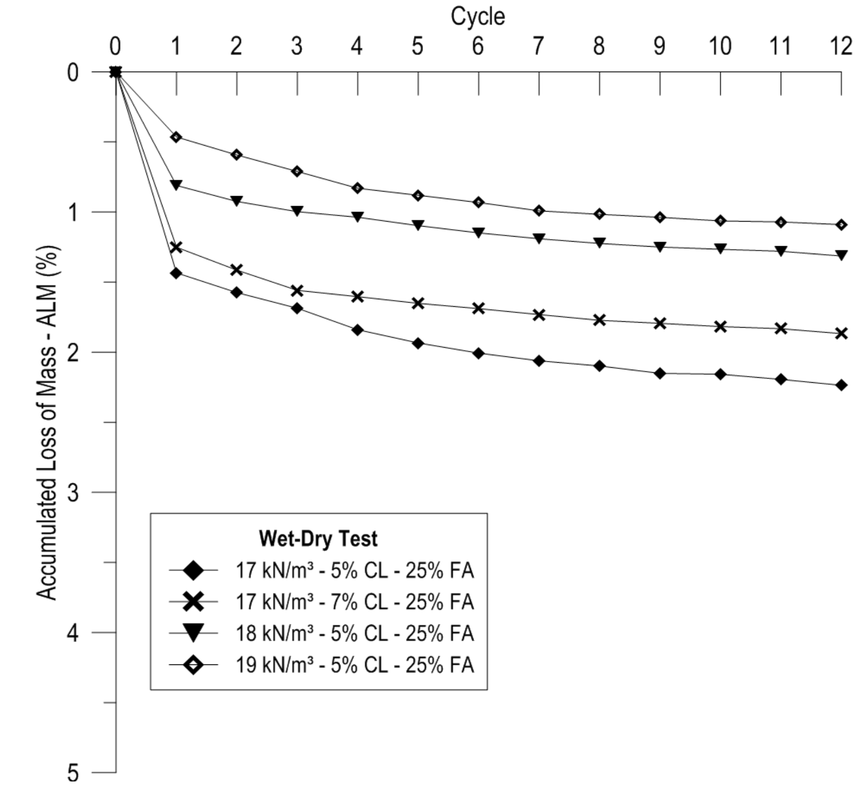
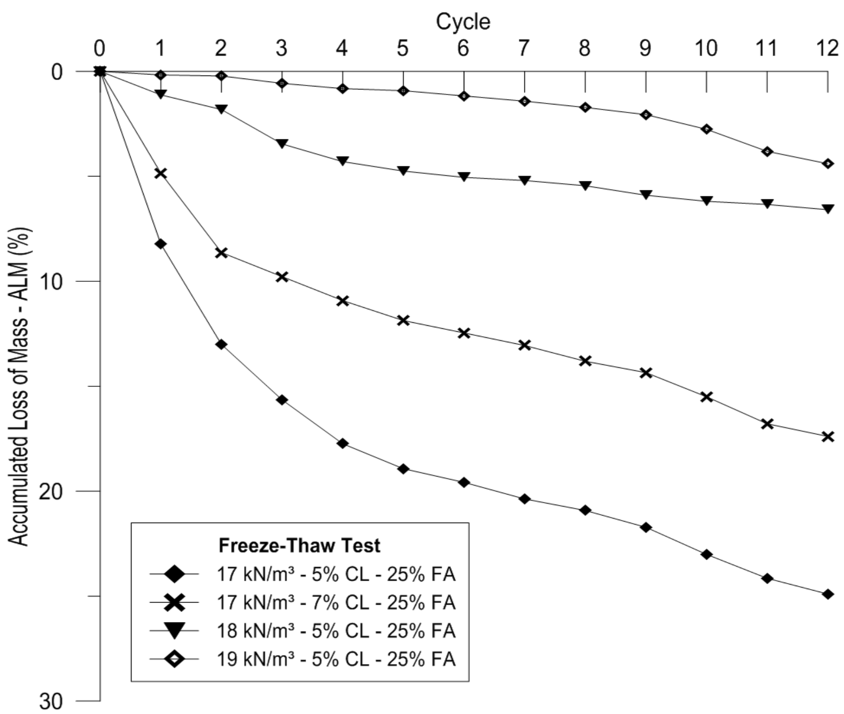


FIGURE 3. Variation of splitting tensile strength (q_t) with porosity/lime index for RAP-fly ash-carbide lime mixtures for 7 days of curing.

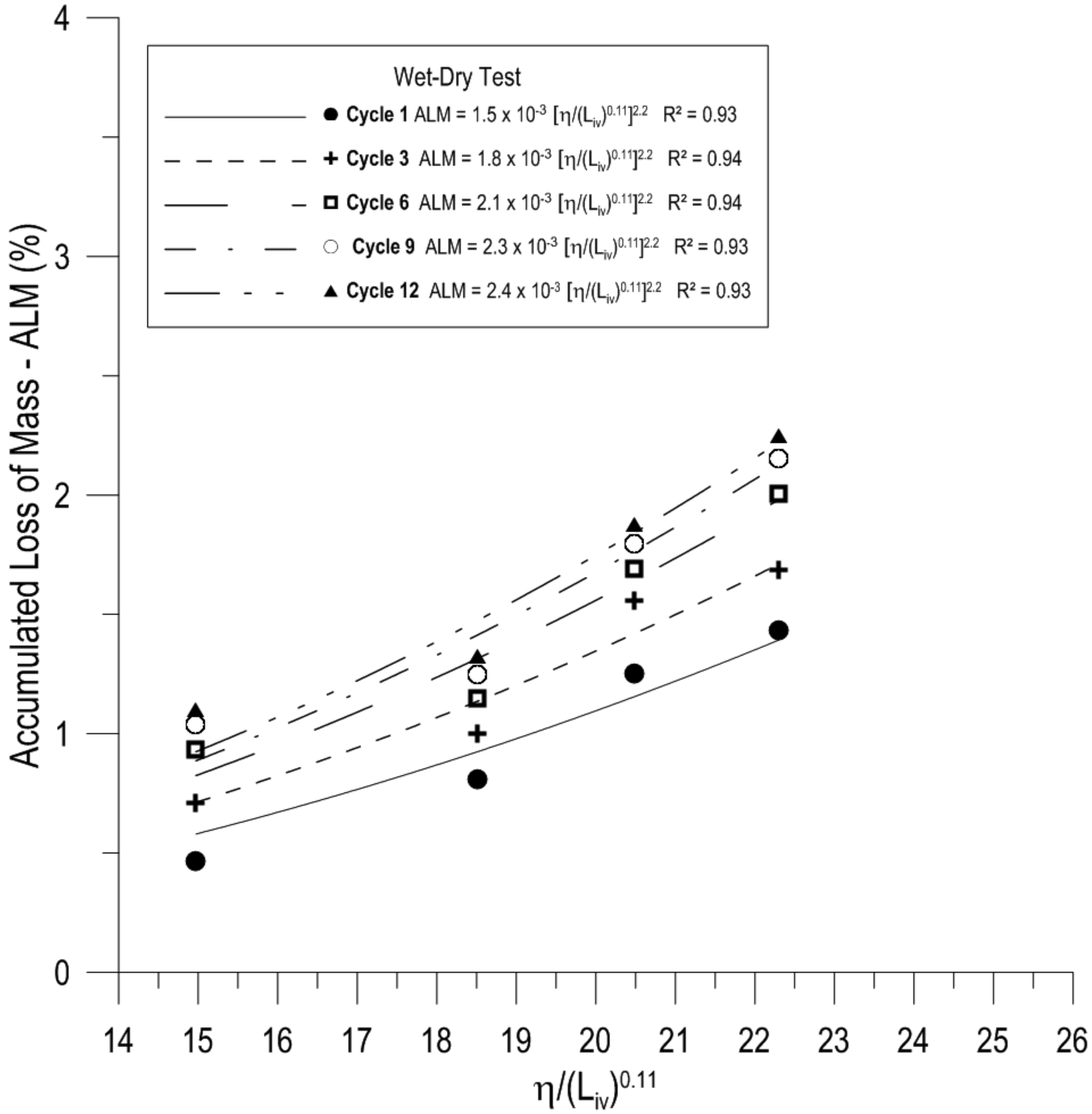


(a)



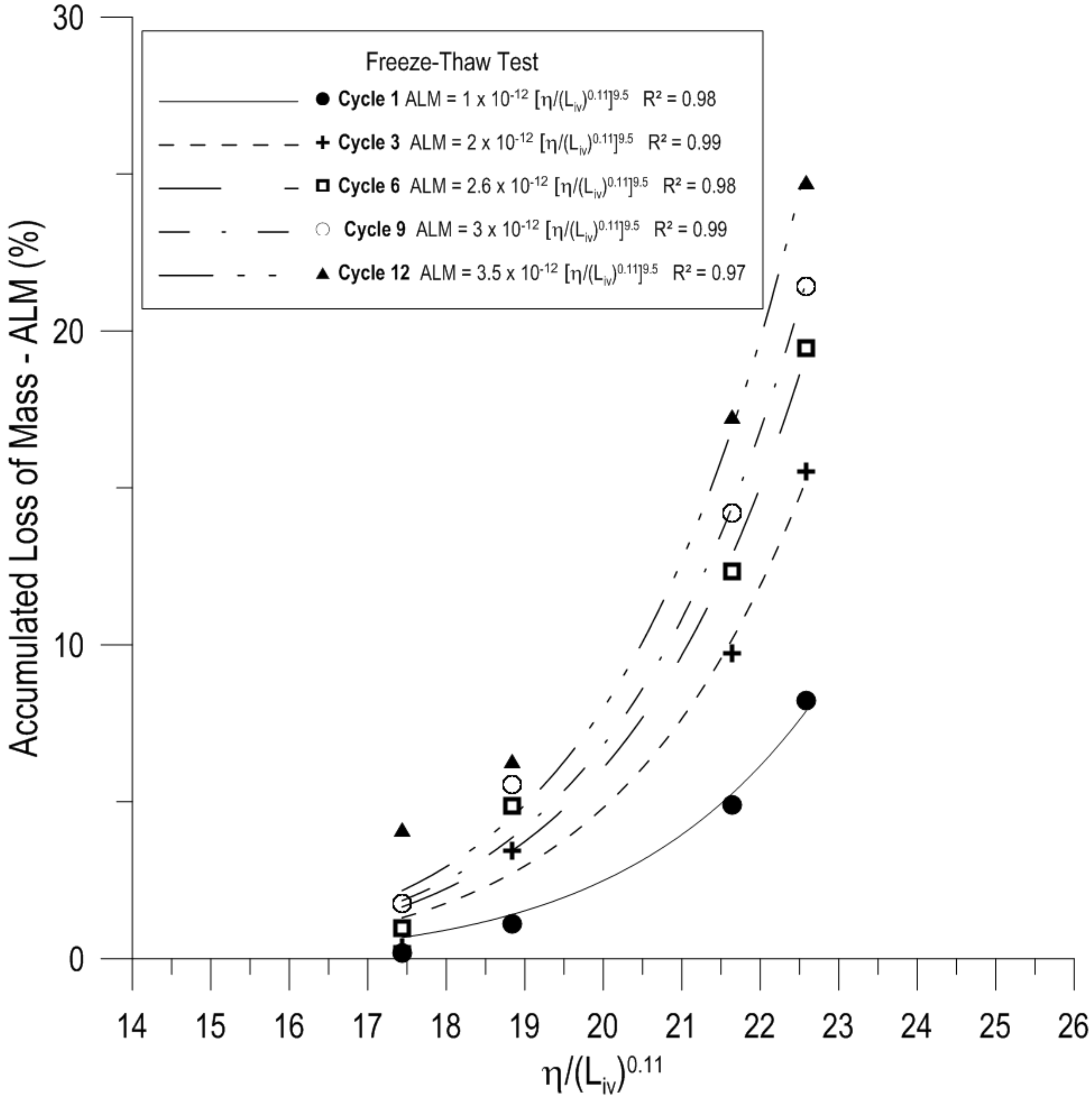
(b)

FIGURE 4. Accumulated loss of mass after (a) wet-dry and (b) freeze-thaw cycles considering RAP-fly ash-carbide lime specimens compacted with dry unit weights of 17, 18 and 19 kN/m^3, carbide lime contents of 3%, 5% and 7% specimens and 7 days as the curing period.



Wet-Dry Test
Cycle 1 ALM = 1.5 x 10-3 [η/(Liv)0.11]2.2 R² = 0.93
Cycle 3 ALM = 1.8 x 10-3 [η/(Liv)0.11]2.2 R² = 0.94
Cycle 6 ALM = 2.1 x 10-3 [η/(Liv)0.11]2.2 R² = 0.94
Cycle 9 ALM = 2.3 x 10-3 [η/(Liv)0.11]2.2 R² = 0.93
Cycle 12 ALM = 2.4 x 10-3 [η/(Liv)0.11]2.2 R² = 0.93
Accumulated Loss of Mass - ALM (%)
η/(Liv)0.11
0
1
2
3
4
14
15
16
17
18
19
20
21
22
23
24
25
26

(a)



(b)

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

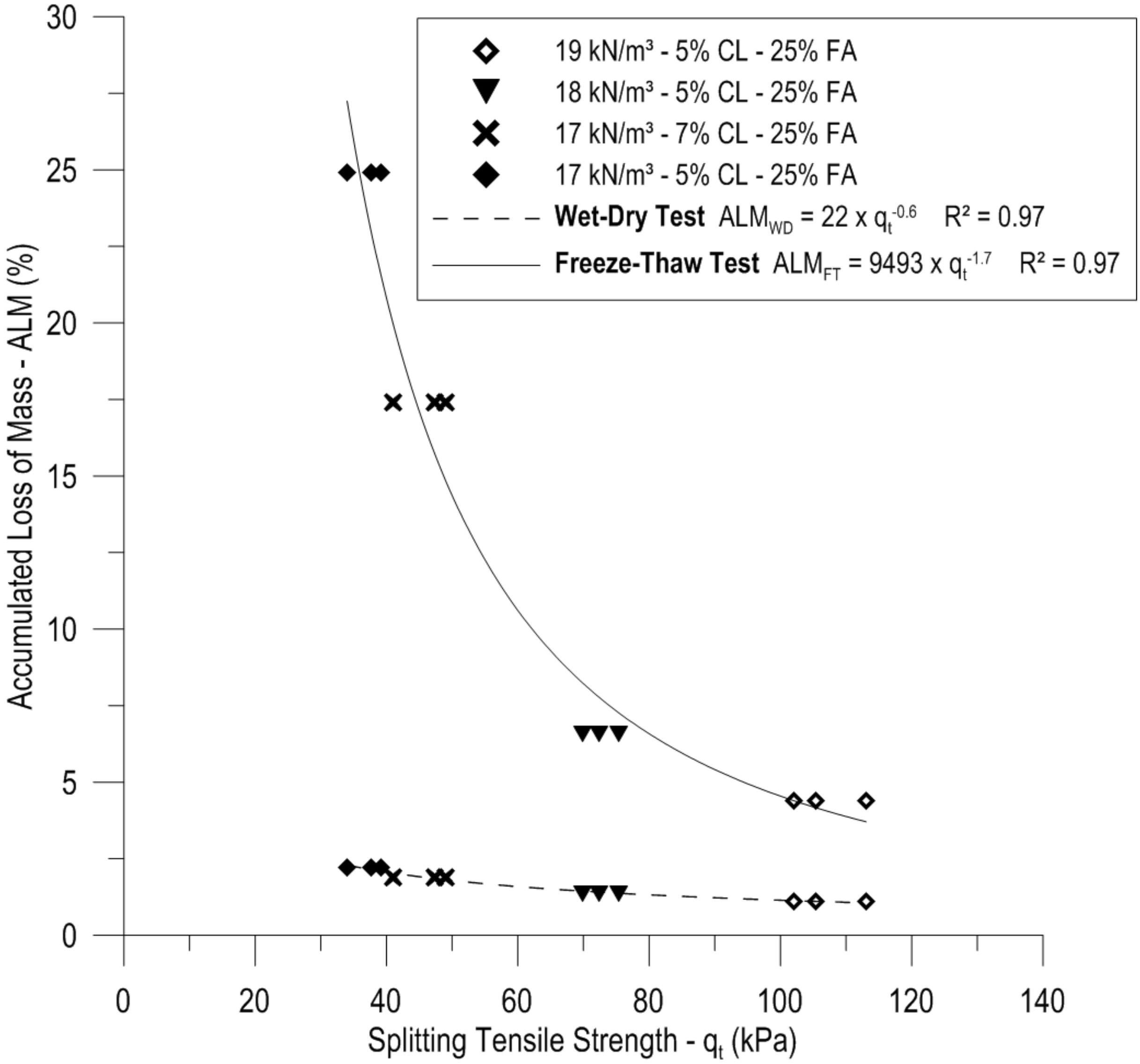


FIGURE 6: Accumulated loss of mass considering twelve (12) wetting-drying (or freezing-thawing) cycles versus q_t for the RAP-coal fly ash-carbide lime mixtures tested – results from all specimens tested are shown including various levels of dry unit weight (17, 18 and 19 kN/m^3), carbide lime content (3, 5 and 7%) specimens and 7 days used as the curing period.