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Effect of wetting-drying cycles on physical and mechanical behavior of soil-aggregate-cement mixtures

Efeito dos ciclos de molhagem e secagem no comportamento físico e mecânico de misturas solo-agregado-cimento

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ABSTRACT
Soil-aggregate-cement (SAC) mixtures have been used in Brazil as base and/or subbase in pavements of heavy and very heavy volume roads, however, still lacks standardized protocols concerning material dosage and assessment of its performance and durability. Then, this study aims to understand the durability of the SAC mixtures by investigating their physical and mechanical behavior after wetting and drying cycles (ASTM D 559), and to contribute to creating reference data and constitutive models of this mixture. For this, four SAC mixtures composed of lateritic sandy soil and basaltic aggregate, in two different soil-aggregate proportions (20:80 and 30:70) and using 5% of two types of cement (PC-HE and PCC-S) were produced. Analyses were based on results of volume changes, weight loss, unconfined compression strength (UCS), indirect tensile strength (ITS) and resilient modulus (Mr) by repeated load triaxial test, at 0, 6 and 12 cycles. Findings show that SAC mixtures had small volume changes (±1.3%) and weight loss (from 4.8 to 5.5%) and their strength and stiffness properties were preserved or increased after W-D cycles. The stiffness of 20:80 mixtures was equivalent to the cement treated crushed rock (CTCR) ones, and 30:70 mixtures, to the soil-cement ones. The cycling effect on increasing mechanical properties warns against potential distresses in very high strengthen and stiff materials that can contribute to reduce fatigue performance of the mixture.

RESUMO
As misturas de solo-agregado e cimento (SAC) têm sido utilizadas no Brasil como base e/ou sub-base em pavimentos de rodovias de volumes pesados e muito pesados, porém, ainda carecem de protocolos padronizados quanto à dosagem do material e à avaliação de seu desempenho e durabilidade. Assim, este estudo tem como objetivo compreender a durabilidade das misturas de SAC, investigando seu comportamento físico e mecânico após ciclos de molhagem e secagem (ASTM D 559), e contribuir para a criação de dados de referência e modelos constitutivos dessa mistura. Para isso, foram produzidas quatro misturas SAC compostas de solo arenoso laterítico e agregado basáltico, em duas proporções diferentes de solo e agregado (20:80 e 30:70), usando 5% de dois tipos de cimento (PC-HE e PCC-S). As análises foram baseadas nos resultados de variação de volume, perda de peso, resistência à compressão simples (RTS), resistência à tração por compressão indireta (RTCD) e módulo de resiliência (Mr) por meio de teste triaxial de carga repetida, a 0, 6 e 12 ciclos. Os resultados mostram que as misturas SAC tiveram pequenas alterações de volume (±1.3%) e perda de peso (de 4.8 a 5.5%) e suas propriedades de resistência e rigidez foram preservadas ou aumentadas após os ciclos W-D. A rigidez das misturas 20:80 foi equivalente a misturas brita graduada tratada com cimento (BGTC), e as misturas 30:70 a misturas solo-cimento. O efeito da ciclagem no aumento das propriedades mecânicas adverte contra possíveis defeitos em materiais de alta resistência e rigidez que podem contribuir para reduzir o desempenho de fadiga da mistura.

1. INTRODUCTION

Material stability and integrity after seasonal fluctuations and long-term residual resistance are the basis of the durability concept. Environmental features such as repetition of prolonged wetting and drying (W-D) cycles might affect negatively the performance of pavement materials. It implies changes in engineering properties and premature degradation processes of pavements, evolving into fatigue and/or rutting. (Dempsey and Thompson, 1968; Khoury and Zaman, 2007; Sobhan and Das, 2007; Kasu, Manupati and Muppireddy, 2020).

In mixtures and composites, as cemented mixtures, durability tests may disclose whether the original material characteristics are effectively stabilized and whether the improved mixture properties are retained against the action of external agents. A durability study should combine the evaluation of material stabilization and the changes in mixture properties to simultaneously observe the material's ability to withstand traffic loading and climatic conditions.

Investigations on weather effect on the durability of chemically stabilized materials indicate that the W-D cycle test is the most appropriate alternative to simulate the seasonal moisture fluctuations and to induce damage to the materials (Khoury and Zaman, 2007; Chittoori, Puppala and Pedarla, 2018; Donrak et al., 2020). The ASTM D559 (ASTM, 2004) protocol is a reference for W-D cycles for soil-cement and their results are based on measurements of volume changes and weight loss. It has been used in combination with strength test results to predict if a given mixture will be damaged when subjected to W-D cycles, and to improve the dosage of the chemically stabilized mixture.

Biswal, Sahoo and Dash (2019) evaluated the durability of lateritic soils stabilized at different cement contents and observed that 4% was the minimum cement content to the mixture meets the permissible weight loss (PWL) of 10%, according to Portland Cement Association (PCA, 1992). Buritatum et al. (2021) investigated the weight loss after W-D cycles of mixtures composed of lateritic soils, natural rubber latex and cement at different contents. The weight loss was significant in the first W-D cycles and, thereafter it stabilized. Weight loss was lower than 14%, that is the PWL of American Concrete Institute (ACI, 2009).

Mechanical properties may change due to W-D cycles. Hoy et al. (2017) studied the effect of W-D cycles on strength of RAP-fly ash mixtures and identified a strength gain in the initial cycles, followed by strength reduction after the sixth cycle. The authors explained that wetting cycles can stimulate the formation of cementitious compounds from anhydrous cement, and drying cycles induce the development of external macro- and micro-cracks, evolving to some fragmentation and reduction of mixture strength.

Variations in cycling conditions, for instance the number and length of cycles, and testing temperature lead to different material responses. Rasul, Ghataora and Burrow (2018) compared the effect of a higher number of W-D cycles to the number recommended by ASTM D 559. The study highlighted cycling effects on the maintenance of the resilient modulus (Mr) and on the development of permanent deformation in these mixtures. Chittoori, Puppala and Pedarla (2018) analyzed UCS after 21 W-D cycles of soil-lime (3-8% of lime content) and soil-cement (3-6% of cement content) and observed that the property reduced; however, soil-cement mixtures withstood a greater number of cycles than the soil-lime ones. Khoury and Zaman (2002) evaluated UCS, Mr and elastic modulus of aggregate-10% fly ash mixtures after 30 cycles. The cycles consisted of 24h of oven-drying (71ºC), then 24h submerged in water at room temperature. Results showed that mixtures cured for 28 days were more damaged than those cured for 3 days. Interestingly, UCS, Mr and elastic modulus increased after the first cycles. As can be seen, results of W-D cycles studies differ considerably, this is due to variables influencing the material behavior, especially regarding to soil/stabilizer types and contents, test methods and curing conditions.

The adapted use of ASTM D 559 protocol for mixtures other than soil-cement and the modification of W-D cycles to simulate climatic fluctuations accentuates the variation in test results. In addition, different types of mixtures respond differently to W-D cycles, especially when factors related to the type and content of cement and the curing time are changed. Accordingly, the use of alternative materials, such as secondary soils, wastes and binders, in the mixtures also interferes in their durability because some of them might hinder the cementation reactions.

It is important to highlight that satisfactory durability results may not be aligned with other perspectives such as pavement design and service life prediction. Integrating the design approach with durability testing is fundamental to ensuring an adequate long-term pavement performance. For this, it is necessary to consider measurements of properties other than UCS. In the absence of fatigue models, this research takes a first step towards complementing ITS and Mr from triaxial repeated load (TRL) tests in the durability assessment of SAC mixtures. It contributes to creating reference data and constitutive models and understanding the effects of W-D cycles on their physical and mechanical properties.

2. EXPERIMENTAL PROGRAM

The experimental program focused on the durability study of predesigned SAC mixtures based on physical and mechanical parameters. Physical parameters were measured by means of volume changes and weight loss of SAC mixtures after W-D cycles, according to the ASTM D559 standard. Mechanical properties were measured by means of UCS, ITS, and Mr tests after specific W-D cycles.

2.1. Materials

In this study, the soil used is a typical Brazilian lateritic sandy soil, classified as A-2-6, according to HRB system. The aggregate was a basaltic mineral aggregate, which was used in different gradations, namely: coarse aggregate, with material retained on sieve nº 4 (4.8 mm), and fine aggregate with stone dust, composed of material passing through sieve nº 4. The main properties of the lateritic soil and natural aggregate are presented in Figure 1a. All properties and characteristics of the materials comply with the recommendations of the National Department of Transportation (NDOT).

Two types of cement were selected as stabilizing agent: a Portland composite cement with addition of slag, PCC-S (Brazilian type CP II-E-32) and a high early-strength cement, PC-HE (Brazilian type CP V-ARI). PCC-S is a widely used material in road construction due to durability and high final strength. PC-HE provides high strength at early curing days as a main property and is used on pavement repairs because it enables a quicker traffic opening (Porras, Jones and Schmiedeke, 2020). In this study, the same cement content of 5% was adopted for both types of cement, as recommended in previous studies of SAC research group (Simoni, 2019; Valoura, 2021), in which the selection of minimum cement content was based on the comparison of mechanical strengths with acting stresses on hypothetical pavements, to balance mixture dosage and pavement design requirements. Hypothetical pavements were designed according to the CBR method (Souza, 1981), considering two levels of traffic, heavy traffic ($N = 5x10^7$) and very heavy traffic ($N = 3x10^8$), for two types of subgrades, sandy or clayey soils. Structures were composed of hot mix asphalt (HMA) surface course, SAC base course and a soil subbase course for the clayey subgrade. Poisson's ratio, resilient modulus, structural coefficients and minimum layer thicknesses were adopted according to Sao Paulo-DOT guideline (2006).

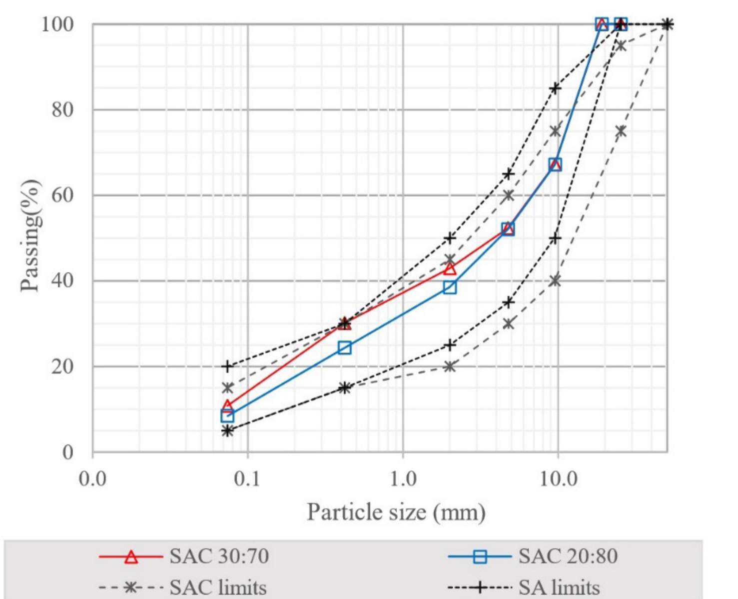
2.2. Soil-aggregate-cement mixture dosage and design

Mixture compositions were fitted into two Sao Paulo-DOT specifications related to the design of soil-aggregate (SA) and of SAC mixtures (DER, 2006b; 2006c), respectively. The quantity of each material was established to comply with both specification criteria, resulting in two material proportions: one composed of 30% of soil and 70% of aggregates (30:70), and another with 20% of soil and 80% of aggregates (20:80). These ranges were chosen to avoid detrimental effects of very low or very high amounts of soil in SAC mixtures. For example, a large amount of soil might improve the workability of the mix; however, it can worsen its arrangement and reduce its stability, due to the poor contact between the aggregate particles (Yoder and Witczak, 1991).

Figure 1b shows the particle size distributions of 30:70 and 20:80 mixtures and the envelope of the specifications. Note that particle size curves of mixtures differed from the 4.76 mm sieve. This occurs because the amounts of soil (20 and 30%) replaced the finest portion of fine aggregate, enabling tests on 10-cm diameter specimens (d_{spec}), since maximum aggregate diameter (D_{max}) at 19.1 mm and the ratio $d_{spec} \leq 5.D_{max}$ were maintained.

Lateritic sandy soil	
Properties	**Values**
Sand content (%)	66
Silt content (%)	13
Clay content (%)	21
Passing # 0.074mm (%)	34
Liquid limit (%)	34
Plasticity limit (%)	21
Plasticity index	13
Specific gravity (g/cm³)	2.663
Basaltic aggregates	
Properties	**Values**
Shape index - Flaky (%)	8
Los Angeles Abrasion (%)	17
Water Absorption (%)	2.2
Specific Gravity (g/cm³)	2.780

(a)



(b)

Figure 1. (a) Material properties; (b) particle size distributions of SAC mixtures.

2.3. Compaction test and specimen molding

Firstly, Proctor tests (ABNT, 2016) at modified energy were performed to determine the maximum dry unit weight (MDUW) and the optimum moisture content (OMC). The specimens for mechanical tests used optimum Proctor parameters as a target. To ensure homogeneous samples, a quality control of specimen compaction considered degree of compaction in the range of 100 ±1% and the moisture deviation of ±0.5%. Specimens of two sizes were produced: (a) the large specimens (10 cm in diameter and 20 cm in height) were compacted by static compression, using a hydraulic press, and (b) the small specimens (10 cm in diameter and 6.7 cm in height) which were compacted by impact, using a Marshall compactor. After compaction, specimens were cured for 7 days in a climatic chamber, wrapped in plastic film to prevent moisture variations, as recommended by ASTM D 559.

2.4. Durability studies

ASTM D 559 protocol was used to simulate moisture fluctuations. The test consists of subjecting the specimens cured for 7 days to 12 wetting and drying cycles (W-D) or until specimens are crumbled, fragmented or splintered. In the wetting cycle, the specimen is submerged in water at room temperature for 5h, and, in the drying cycle, the specimen is oven-dried at 72ºC for 42h. Durability results are expressed by the percentage of volume change and weight loss. Three specimens were tested for each experimental condition. Two of them were used to assess volume changes, and one for weight loss. Physical and mechanical properties were taken after a given W-D cycle to monitor the changes in the following conditions: initial (0 cycles), intermediate (6 cycles) and final (12 cycles).

Volume change (ΔV/V) is the ratio between the difference of volume after a cycle and its initial volume. Specimen height and diameter were measured on three different directions and the volume was computed using the average of measurements.

Weight loss is the ratio between the specimen mass at the end of a W-D cycle and its initial mass. Before weighing, a brushing is performed, consisting of 30 strokes of a wire brush distributed over all specimen surface with a force of ~13.3 N.

2.5. Mechanical tests

2.5.1. Unconfined Compressive Strength (UCS)

UCS test was performed according to AASHTO T22 standard (AASHTO, 2014). Large cylindrical specimens, compacted in five layers and cured for 7 days, were tested after 0, 6 and 12 W-D cycles. Tests were carried out using an automatic loading machine at a load rate of 0.30 MPa/s. Three specimens were compacted for the tests after 0 cycles, and 2 specimens for tests after 6 and 12 cycles, resulting in 7 specimens per experimental condition.

2.5.2. Indirect Tensile Strength (ITS)

ITS test was performed according to the DNIT 136 Brazilian standard (DNIT, 2018a). Small cylindrical specimens, compacted by impact, were tested after 0, 6 and 12 W-D cycles. Tests were carried out using an automatic loading machine at a displacement rate of 1.27 mm/s. Seven specimens were prepared for each per experimental condition (3 for tests at 0 cycles, and 2 for tests after 6 and 12 cycles).

2.5.3. Triaxial resilient modulus (Tx Mr)

The resilient modulus was evaluated using a repeated loaded triaxial test according to Brazilian Standard of National Department of Transportation DNIT 181 (DNIT, 2018b) indicated for chemically stabilized materials. In this test, specimen is subject to five different levels of deviator stress (σ_d), 100 to 500 KPa, without confining stress (σ_3). Frequency of load was 1 Hz (0.1 s of loading period and 0.9 s of resting period). Two LVDTs recorded vertical displacements. The Poisson's ratio adopted was 0.20, and the resilient behavior was fitted to the deviator stress model (Equation 1). Seven specimens were prepared for each per experimental condition (3 for tests at 0 cycles, and 2 for tests after 6 and 12 cycles).

$$M_r = k_1 \times \sigma_d^{k_2} \quad (1)$$

In which: M_R is the resilient modulus, σ_d is deviator stress and k_1 e k_2 are regression coefficients.

3. RESULTS AND DISCUSSION

3.1. Proctor parameters and UCS of SAC mixtures

Table 1 shows Proctor parameters and the UCS of the mixtures. Mixtures are represented by a code, where the first term represents the soil-aggregate proportion, and the second term represents cement type. All mixtures were stabilized using the same cement content (5%). Regarding Proctors parameter, one may observe that:

- PC-HE mixtures had higher MDUW than the PCC-S mixtures. This tendency is explained by the grain size distribution of the cements, since PC-HE is finer than the PCC-S and can envelope soil clusters and partially fill the voids in the mixture (Simoni, Valoura and Furlan, 2019);
- 20:80 mixtures had a higher MDUW, i.e. they are in a denser state. This may occur because 20:80 mixtures have more voids or space for accommodating materials, leading to a better arrangement between the soil particles and the aggregates;
- the variation of OMC was quite low and showed no dependence on either the type of cement or the proportion of material. However, it can be inferred that increasing the amount of water may have improved the lubrication and densification of the mixtures, since the greater the OMC, the higher the MDUW.

Table 1: Proctor parameters and mixture properties.

Mixture Code	MDUW (kN/m^3)	OMC (%)	$UCS_{immediate}$ (MPa)	UCS_{7days} (MPa)	UCS gain (MPa/day)
30:70_PC-HE	24.17	5.90	0.22	6.53	0.90
20:80_PC-HE	24.22	6.05	0.32	6.21	0.84
30:70_PCC-S	23.60	5.60	0.29	4.07	0.54
20:80_PCC-S	23.95	6.10	0.20	4.83	0.66

Regarding immediate UCS and after 7 days of curing of the mixtures, it is noted that UCSimmediate are, on average, 0.25 and 0.26 MPa, for the 30:70 and 20:80 mixtures, respectively. UCSimmediate seems to correlate with MDUW values; generally, the higher the MDUW, the higher the UCSimmediate. As expected, the curing led to significant strength gains. After 7 days of curing, UCS increased 28 times in the 30:70_PC-HE mixture and 18 times in the 20:80_PC-HE, and 13 times in the 30:70_PCC-S and 23 times in the 20:80_PCC-S. The UCS gain per day of curing (MPa/day) was, on average, 0.87 MPa/day for PC-HE mixtures, and 0.60 MPa/day for PCC-S mixtures. These data are consistent with previous studies that demonstrate that PC-HE leads the mixtures to achieve higher strength at early stages of curing (Valoura, Silva and Furlan, 2022). By contrast, the effect of material proportion on cured mixtures is barely noticeable, since the variation in UCS might be included in the test deviation (Valoura, 2021).

3.2. Durability studies as per ASTM D559

To analyze the durability of SAC mixtures, Figure 2 presents (a) the mass and (b) volume changes after W-D cycles. In Figure 2a, it is included, in blue, the curve of the original mass of the specimens in the optimum Proctor conditions (OMC and MDUW). In this test, one specimen was tested for 6 W-D cycles, and another for 12 cycles, per experimental condition.

Figure 2a reveals that (a) the greater mass of specimens was a consequence from the 1st wetting cycle, (b) the 1st drying cycle resulted in the greater mass amplitude, and (c) the mass changes become constant as W-D cycles repeat. The behavior of the W-D curves is quite similar, regardless of the number of cycles, suggesting that the quality control resulted in a homogeneous set of specimens. Moreover, PC-HE mixtures absorbed a greater amount of water, still small, though. For instance, 30:70_PC-HE specimens weighed ~90 g more after 1st wetting cycle and ~220 g less after the 1st drying cycle; while 20:80_PCC-S specimens weighed ~25 g more after 1st wetting cycle and ~187 g less after the 1st drying cycle (the minor mass variation in the 1st W-D cycle).

Mass change evaluation is a preponderant for the volume change ($\Delta V/V$), because the amount of residual water into the specimen helps to understand expansion or shrinkage of the specimens. Since SAC specimens preserved their shapes at the end of cycles (Figure 2b); it is reasonable to consider that the mass change is exclusively due to the water in/out movement. This finding is important because the reduction of water content caused by drying cycles may lead to microcracking and degradation on the specimen surface. When microcracking is substantial, it can propagate inward the specimen and reduce mixture strength, leading to stiffness reduction and premature fatigue (Aldaood, Bouasker and Al-Mukhtar, 2014; Hoy et al., 2017).

To verify whether the residual moisture content affects the specimen expansion or shrinkage, the water content in the 6th and 12th drying cycle was computed and it was observed that:

- at 6th drying cycle, the residual moisture content of PC-HE and PCC-S mixtures were, on average, 31% of OMC and 38% of OMC, respectively;
- at 12th drying cycle, the residual moisture content of PC-HE and PCC-S were, on average, 24% of OMC and 38% of OMC, respectively.

Although some moisture is preserved in the specimens, Figure 2b shows that there were no significant volume changes (less than ±1.5%). The largest expansion measurement was +1.3% for the 30:70_PC-HE mixture in the 2nd drying cycle, and the highest shrinkage was -1.2% for the mixture 20:80_PCC-S in the 1st drying cycle. The low volume changes were attributed to the use of stable materials and a robust aggregate skeleton mixed to high-quality soil, with low expansion. In short, the predominance of aggregate favors the strength and stability of SAC mixtures, unlike soil-rich mixtures, which are strongly impacted by water action (Yoder and Witczak, 1991).

Figure 3 presents (a) the mass change and (b) the weight loss by brushing over W-D cycles. In the graphs of Figure 3a, again, it is included, in blue, the curve of the original mass of the specimens for OMC and MDUW conditions. All mixtures completed 12 W-D cycles and brushing recommended by ASTM D 559. In Figure 3a, curves demonstrate that mass gain after wetting cycles and weight loss after drying cycles tended to a slight decreasing. As seen by the distance between curves, the mass gain and loss stabilized and remained constant already in the 2nd cycle for PCC-S mixtures, and from 6th for PC-HE mixtures.

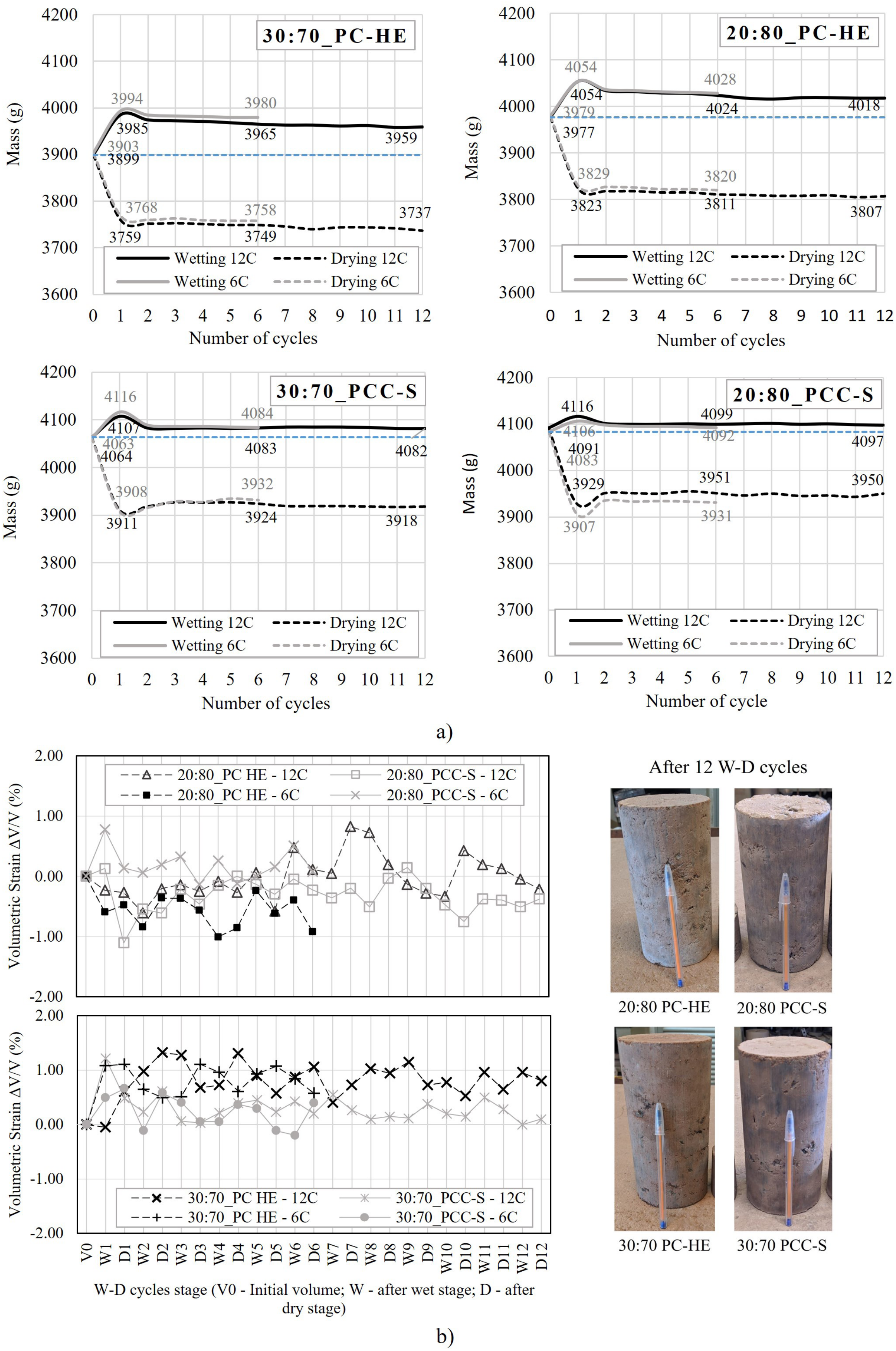


Figure 2. Mass variation (a) and volume changes (b) of specimens after W-D cycles.

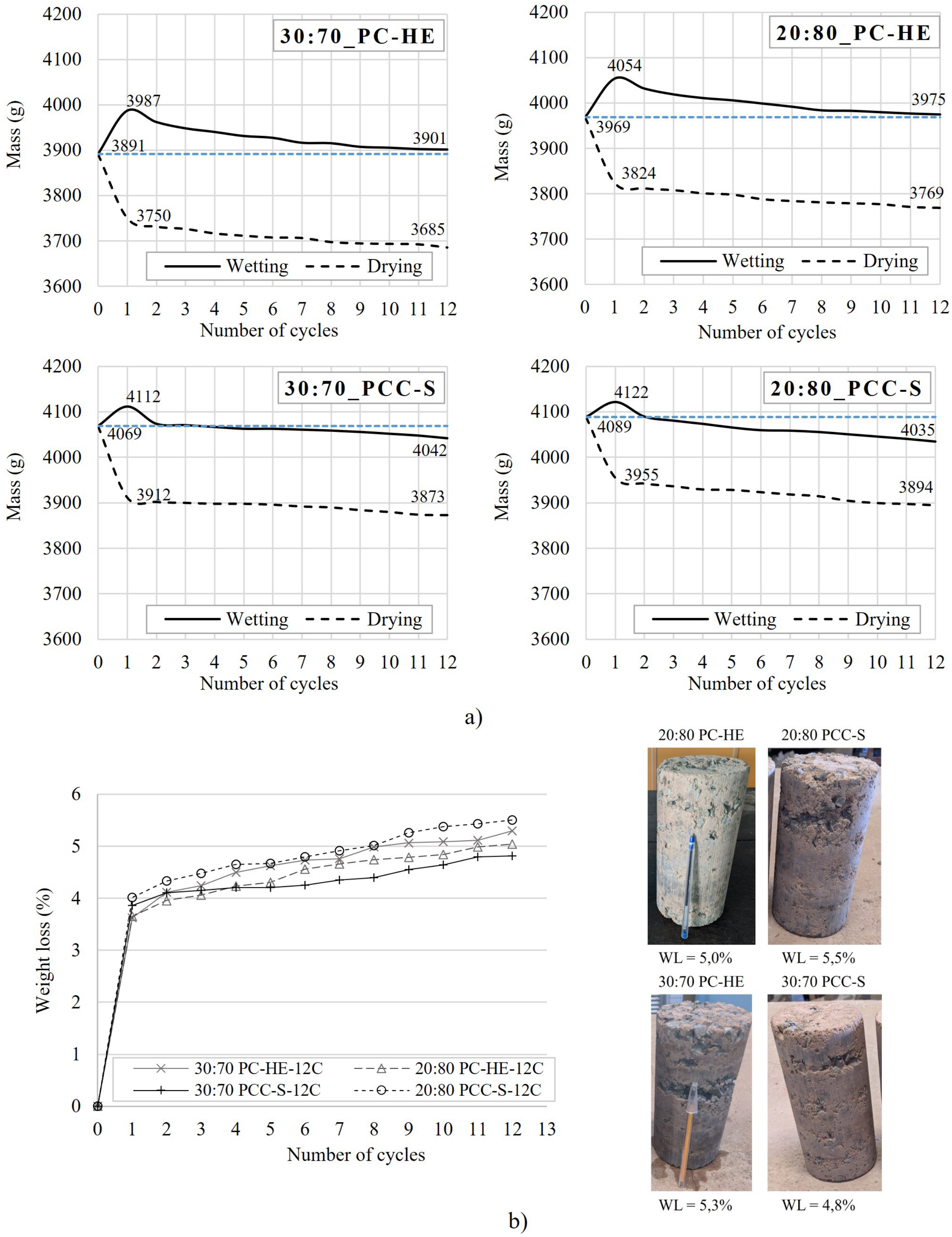


Figure 3. Mass variation (a) and weight loss (b) of specimens after W-D cycles.

PC-HE mixtures absorbed an amount of water (~90 g) greater than the PCC-S ones (~40 g), as observed in the peaks of the 1st wetting cycle, which represents 2.30 and 0.93% of mass gain, respectively. For PC-HE mixtures, final mass at the 12th wetting cycle met values quite close to the initial mass. Nevertheless, for PCC-S mixtures, final masses at the 12th wetting cycle are slightly lower than the initial ones. In this case, the mass changes were slightly higher than those observed in Figure 2a, this is due to the brushing process, which can modify the surface characteristics of the specimens by removing small portions of fines, consequently increasing the voids and leading to a higher water movement.

Regarding the weight loss, in Figure 3b, it is observed that the 20:80_PCC-S mixture had the highest weight loss (5.5%) whereas the 30:70_PCC-S mixture had the lowest one (4.8%). Therefore, all tested mixtures complied with permissible weight loss (PWL) of 10% and 8% specified by PCA (1992) and Corps of Engineer (1994), respectively.

SAC weight losses were lower when compared with results of lateritic soil-cement mixtures of Biswal, Sahoo and Dash (2019), which observed WL<10% with 4% minimum cement content. Buritatum et al. (2021) observed a WL<10% with a 5% cement content on mixtures of lateritic soil-cement with addition of natural rubber latex after 12 W-D cycles. Chindaprasirt et al. (2023) studied lateritic soil-cement mixtures and the results pointed out a WL<12% with a 6% minimum cement content. The presence of natural aggregate seems to improve SAC mixtures durability compared with soil-cement mixtures in terms of weight loss, since, mechanically, the predominance of aggregates in the SAC mixture contributes to improved stability due to greater contact between particles, while the soil portion contributes to increased shear strength (Yoder and Witczak, 1991).

Figure 3b also shows images of the specimens that underwent the 12 W-D cycles and the brushing procedures, and the weight losses of each one. Data reported here seem to support the following assumptions: (a) material selection and mixture dosage furthered a satisfactory durability for SAC mixtures; (b) the amount of water entering the specimens was low and (c) W-D cycles according to ASTM D 559 (for soil-cement) may not induce damage to SAC mixtures.

3.3. Mechanical properties after W-D cycles

3.3.1. Unconfined Compressive Strength (UCS)

Figure 4 shows the average results of UCS after W-D cycles. UCS varied from 4.07 to 11.65 MPa depending on the type of mixture, and reference mixtures ($UCS_{0cycles}$) had the lowest UCS. DOT-SP guidelines state UCS ranges to be used for pavement design purposes. The range $2.1<UCS_{7days}\leq 4.5$ MPa is indicated for soil-cement mixtures, and $4.0<UCS_{28days}\leq 6.0$ MPa, for cement-treated crushed rock (CTCR) mixtures. Accordingly, UCS_{7days} of SAC mixtures after 6 and/or 12 W-D cycles were remarkably higher than those recommended for pavement design.

The effect of the cement type on the property prevailed, making two set of curves (black and grey lines), where PC-HE mixtures presented UCS approximately 50% higher than PCC-S mixtures. Curves reveal that UCS increased throughout the cycling and curve slopes demonstrate that the property gain after 6 W-D cycles had a similar tendency. The absolute increase of UCS after 6 cycles (UCS6cycles) was found to be equals to ~3.5 MPa in relation to the initial ones, representing 52% for 30:70_PC-HE, 58% for 20:80_PC-HE, 83% for 30:70_PCC-S and 68% for 20:80_PCC-S. UCS12cycles show decelerations of the property gain in relation to the UCS6cycles. In relation to UCS_{0days}, the gain represents 78% for 30:70_PC-HE, 71% for 20:80_PC-HE, 88% for 30:70_PCC-S and 83% for 20:80_PCC-S.

PC-HE mixtures reached higher absolute strength after W-D cycles and PCC-S presented higher strength improvement in comparison with the initial results. This is due to the properties of the cements: in PC-HE chemical reactions occur faster at early ages while PCC-S has a slower cementitious compound formation (Valoura, Silva and Furlan, 2022). Otherwise, the effect of soil-aggregate proportion was not clear. The difficulty in assessing material proportion effect might be related to the type of applied effort, because the axial compression effort mobilizes both portions of the strength of the SAC mixtures: the bound and the unbounded contact zones.

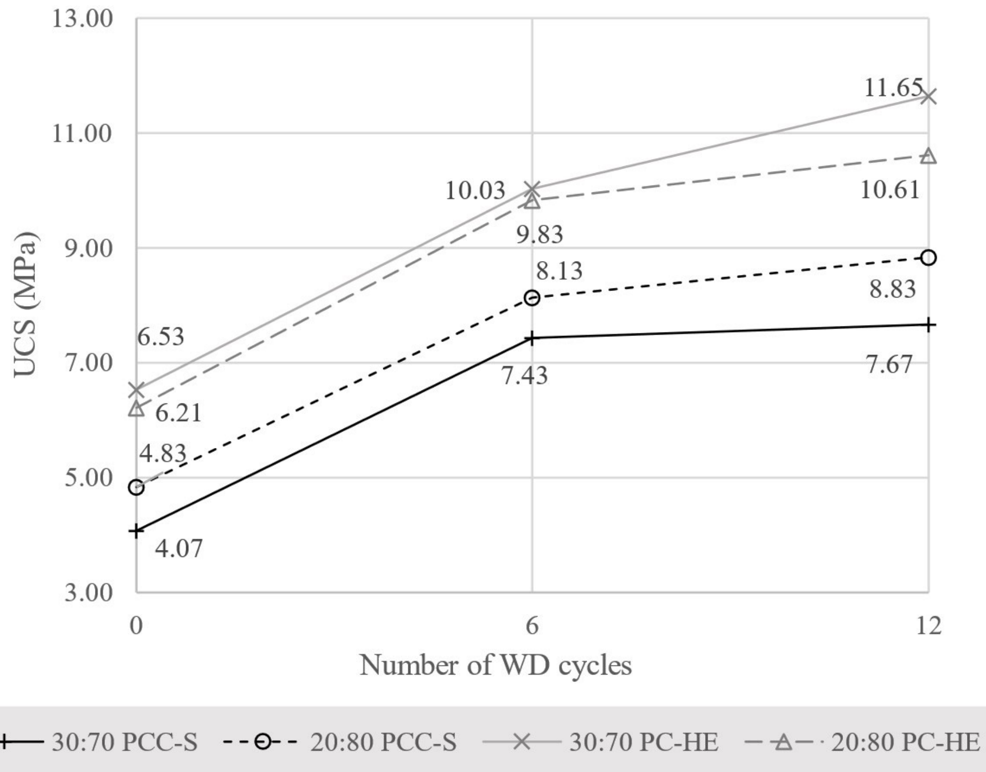


Figure 4. UCS after W-D cycles.

UCS test combined to durability protocol assess mechanical changes caused by W-D cycles. Strength loss has been observed in soil-cement or in secondary materials and alternative additives (Buritatum et al., 2021; Chindaprasirt et al., 2023; Hoy et al., 2023). Donrak et al. (2020) observed UCS gain during initial W-D cycles (3rd and 4th), with a subsequent UCS reduction. In this case, initial strength gain is attributed to the development of cementitious compounds from anhydrous cement; however, the formation of micro and macro-cracks over cycling decreased the mixture strength. The design and dosage of SAC mixtures seem to have contributed to a more reinforced soil-aggregate matrix, since the specimens still exhibited a well-preserved shape after 12 W-D cycles (Figure 2b).

3.3.2. Indirect Tensile Strength (ITS)

Figure 5 presents average ITS values after W-D cycles. ITS varied from 0.65 to 1.44 MPa depending on the type of mixtures; again, the reference mixtures ($ITS_{0cycles}$) had the lowest ITS, except for 20:80_PC-HE mixture. The effect of the soil-aggregate proportion prevailed on ITS, making two set of curves (full and dashed lines), where 20:80 mixtures are strengthener than 30:70 mixtures. The shape of the curves indicates that the type of cement also affected ITS behavior against W-D cycles.

ITS gain after 6 W-D cycles is observed for PCC-S mixtures, where the absolute increase of $ITS_{6cycles}$ was equal to 0.38 MPa (~50%) in relation to the $ITS_{0cycles}$. For PC-HE, the variation of ITS is small, increasing 0.12 MPa (~14%) in the 30:70_PC-HE mixture, and decreasing 0.11MPa (-8%) in the 20:80_PC-HE one. The small variation of $ITS_{6cycles}$ of PC-HE mixtures might be included in deviation of test results. The gain of $UCS_{12cycles}$ represents, on average, 60% of $ITS_{0cycles}$ for PCC-S mixtures and 4% for PC-HE mixtures. Then, it can be stated that W-D cycles increased ITS of PCC-S mixtures and did not change ITS for PC-HE mixtures.

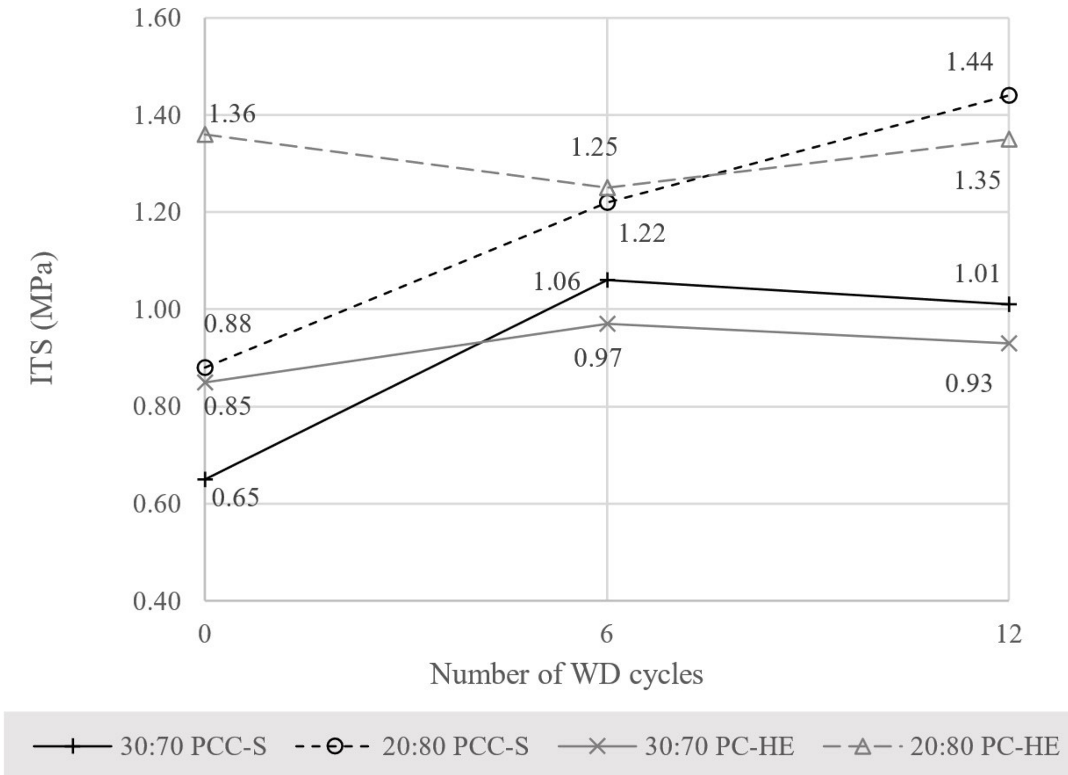


Figure 5. ITS after W-D cycles.

In SAC mixtures, aggregates contribute to a strong skeleton, soil densifies the mixture and partially restricts the particle sliding and cementitious compounds, at some level, lock the mixture matrix. Although ITS test is not part of durability protocols, it measures cohesion or bonding strength of geomaterials and mixtures, making the test suitable for pavement materials experiencing tensile stresses. Accordingly, soil-aggregate proportion affected this property, as observed by the distinction of behavior, where the denser mixtures composed of higher amount of soil (30:70) improved less than the mixtures with lower amount of soil (20:80). The strength gain of cemented mixtures is attributed to cement hydration and the formation of cementitious compounds. By analogy, the greater amount of soil hinders the effects of cementation on the strength gain.

The type of cement also helps to differentiate tensile behavior of the mixtures, that is, initial ITS of PC-HE mixtures is preserved after cycling while it increased in PCC-S mixtures. This occurs because PC-HE cement reacts quickly during the curing, leaving a small amount of anhydrous cement to hydrate during the W-D cycles. Otherwise, PCC-S mixtures can benefit from the extra hydration of anhydrous cement during wetting cycles, without significant strength gain, though (Simoni, Valoura and Furlan, 2019).

3.3.3. Triaxial resilient modulus (Tx Mr) according to Brazilian standard

Figure 6a shows the models of Mr in function of σ_d for SAC mixtures at different cycling conditions. Models presented high coefficients of determination (from 0.80 to 0.95) validating the good quality of adjustment. As recommended by the Brazilian standard, data were treated so that they fit in the tolerance interval of 10%. The curves represent the average model of resilient behavior of the mixtures.

Regarding the behavior of curves, one may identify that:

- *M_r decreases as σ_d increases.* The sensitivity of Mr to σ_d is not a typical resilient behavior for cemented materials. However, it is worth considering that SAC mixtures do not have enough cement for locking all soil and aggregates particles. Moreover, the lack of confining stress of Brazilian triaxial test method might have furthered displacements in the material as a response at load applications. Other studies on cemented mixtures indicated a Mr increase with the increase of σ_d under confining stress (Puppala, Hoyos and Potturi, 2011; Fedrigo et al., 2018; Rasul, Ghataora and Burrow, 2018);
- *W-D cycles do not change the resilient behavior of mixtures in relation to the initial condition*. For a given mixture, curves shifted in response to the cycling. Each mixture had a specific range of k_2, depending on the materials that make it up. Significant changes of Mr occurred at low tensions; from 0.2 MPa onwards, curves showed a certain parallelism;
- *30:70 mixture would perform better in pavements.* The structural responses of semi-rigid pavement demonstrate that very stiff cemented materials absorb more stress and would be susceptible to premature fatigue. Generally, 30:70 mixtures exhibited lower Mr values, with emphasis on 30:70_PC-HE mixture that was more stable and exhibited smaller property variations, as depicted by their flatter curves.

To demonstrate the effect of W-D cycles on the property, the values of Mr were computed based on the constitutive models (Figure 6b) for a σ_d equals to 0.2 MPa. This σ_d was adopted to avoid overestimating values that could contain experimental errors of the initial test phase. Figure 6b shows Mr after W-D cycles. Mr values varied from 4282 to 11702 MPa, depending on the type of mixtures. The effect of the soil-aggregate proportion prevailed in Mr, distinguishing two sets of curves (full and dashed lines), in which 30:70 mixtures presented lower Mr than 20:80 mixtures. In addition, curves had different behaviors after cycling:

- For the 20:80 mixtures, MR varied from 8000 to 12000 MPa, and W-D cycles tend to reduce the property after 6 cycles, or to maintain it after 12 cycles in relation to $Mr_{initial}$.
- For the 30:70 mixtures, Mr varied from 4000 to 8000 MPa, with different response to W-D cycles, namely, mixture using PC-HE was quite stable and keeping the $Mr_{initial}$ values for all conditions of cycling whereas mixtures using PCC-S had a noticeable increase in $Mr_{initial}$ over cycling.

These results show that the Mr of 20:80 mixtures are higher than those observed in other studies on SAC mixtures; generally, these values vary from 3000 to 9000 (Simoni, 2019; Valoura, 2021; Bessa et al., 2016). According to IP-DE-P00/001 (DER, 2006a), the recommended Mr of soil-cement mixtures varies from 5000 to 10000 MPa, and for CTCR, from 7000 to 18000 MPa. In this context, the stiffness of 20:80 mixtures would be compatible with CTCR, and 30:70-SAC mixtures compatible with soil-cement.

It is important to bear in mind that in service cemented base layers exhibit properties that differ from those measured in laboratory conditions. Balbo (2006) reported back-calculated elasticity modulus of CTCR mixtures. When the mixtures are undamaged, the modulus is around 15000 MPa. In mixtures that have already entered the cracking phase, this value drops to below 10000 MPa, and in those deteriorated by fatigue, the modulus is lower than 2000 MPa. Therefore, there will always be an adjustment factor between field and laboratory results.

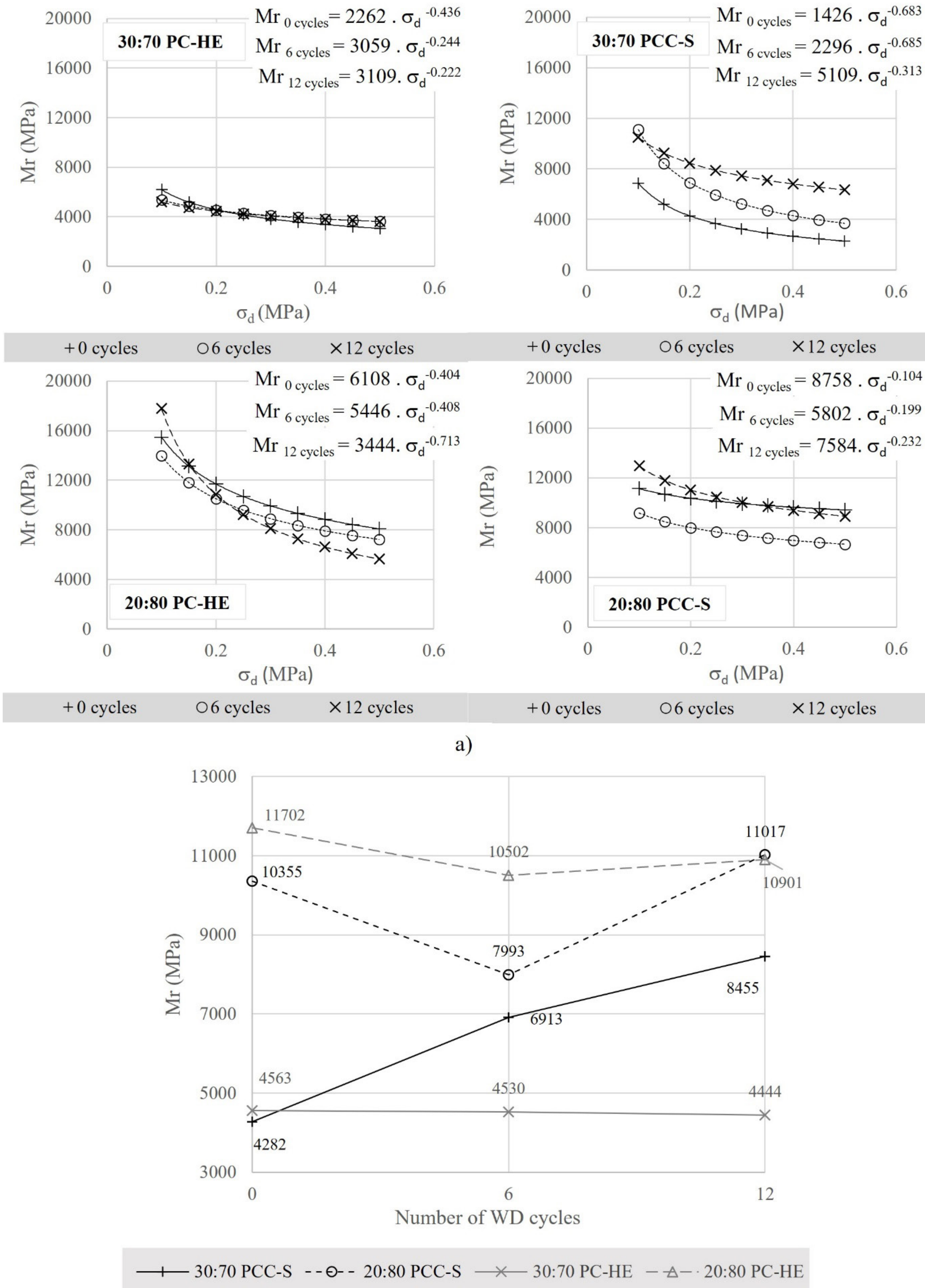


Figure 6. Resilient behavior (a) and Mr values (b) after W-D cycles.

4. RELATIONSHIP BETWEEN STRENGTH AND STIFFNESS PROPERTIES

Regarding strength and stiffness, one may conclude that tested SAC mixtures are promising in terms of durability, because they did not suffer the detrimental effects of W-D cycles. However, the increasing of the properties may be concerning from a pavement design perspective, since it is not embodied into the prediction of the material performance and service life of pavements with cemented layers.

It is important to highlight that the greater the stiffness of the cemented layer, the more stress it absorbs. Additionally, the brittle behavior and the tendency to shrinkage cracking of cemented materials make this layer susceptible to typical distresses. Thus, it is crucial to balance the goals of pavement design and mixture dosage to reduce fatigue potential (Chen, Hong and Zhou, 2011; Fedrigo et al., 2018).

Whilst fatigue models of SAC mixtures are not available, it is needed to understand its mechanical behavior by means of interrelated fatigue properties. The relationships ITS versus UCS and Mr versus ITS may indicate the performance of cemented bases, because these properties correlate to the design variable and service life of the pavement (Buritatum et al., 2021). ITSxUCS have been proposed as a way of estimating ITS without testing and to simultaneously observe tensile and compression behaviors. Figure 7a presents ITS in function of UCS of tested mixtures. Opportunely, other relationships (Fedrigo et al., 2018; Buritatum et al., 2021) of these properties are presented to observe whether SAC mixtures would fall within any range. Note that each relationship was proposed for specific sets of mixtures, aiming at mixture design, not durability. The relationship ITS = 0.10 UCS was added to complement the range.

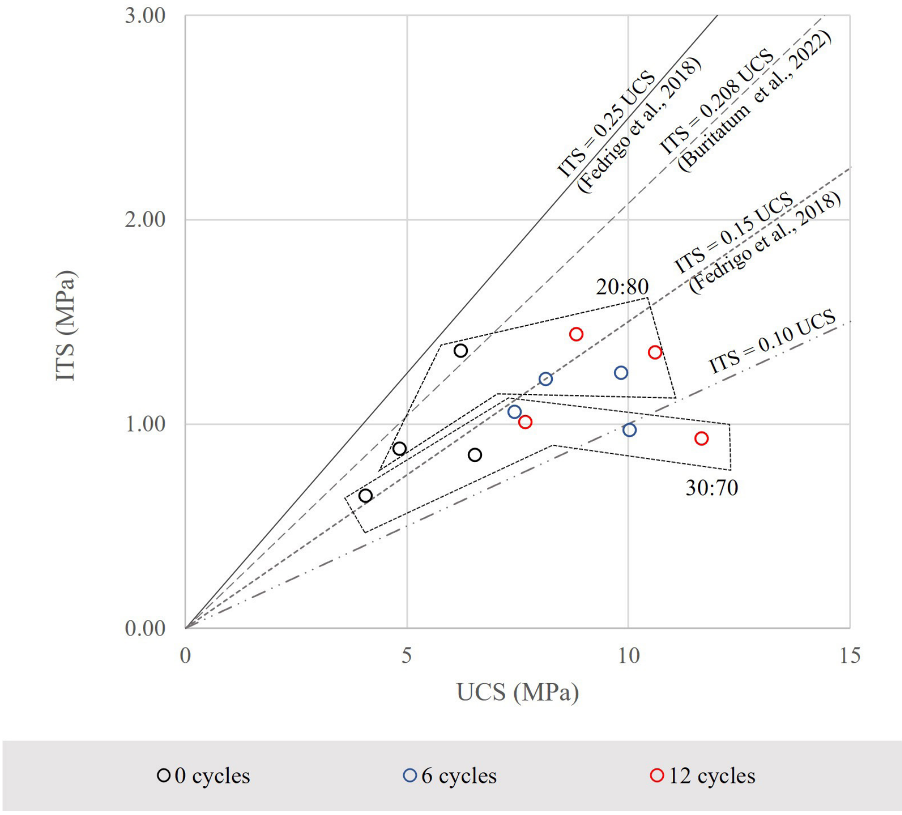
Figure 7a shows that mixtures that have not been subjected to W-D cycling are distributed in the range where the ITS values vary between 10 and 25% of the UCS. After cycling, most of the mixtures are concentrated in a smaller range, between 10 and 15% of the UCS, demonstrating that the cycles altered the mixture behavior. The 20:80 mixtures are concentrated in the higher ITS interval. This characteristic may be considered positive since these mixtures would support higher levels of tensile stress in pavements. Conservatively, it is reasonable to propose specific relationships for SAC mixtures to get a better understanding of the effect of W-D cycles and to obtain more reliable results.

Findings on ITS and Mr after cycling raised questions about the need to accurately represent design properties throughout the service life of the pavement. The ITS and Mr results led to a similar ranking of the mixtures and these properties were affected by the same factors. Due to the consistency between the tendencies of these results, the relationship between the ITS and Mr was tested, as shown in Figure 7b.

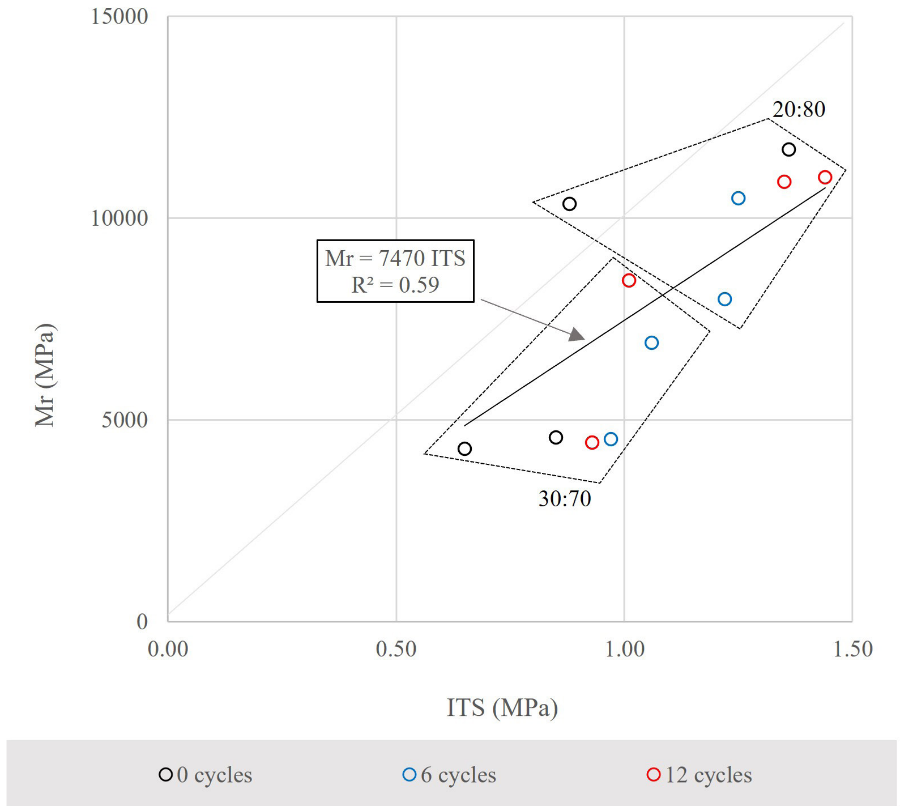
The linear regression of Mr in function of ITS considered all test results and the R^2 was equal to 0.59. Although the R^2 is not a high value, the relationship can be considered satisfactory, since these properties were obtained from mixtures composed of different materials proportions, different types of cement and subjected to different numbers of W-D cycles, increasing the dispersion of results.

Figure 7b shows that the cycling condition (0, 6 and 12 W-D cycles) produces results over a wide range of Mr. The sets of specimens were then grouped according to soil-aggregate proportion. Thus, one may identify that the tendency of this interrelationship is ruled by the prevalent variable in the gain of each property. The 20:80 mixtures are concentrated in an interval of higher MR. This characteristic may lead these mixtures to absorb higher levels of tensile stress in pavements.

The relationships presented here are intended to deepen the knowledge of SAC mixtures. Therefore, its application is not recommended as a predictive model.



a)



b)

Figure 7. Relationship (a) UCS versus ITS and (b) ITS versus Mr.

5. CONCLUSIONS

This paper described a laboratorial study of SAC mixtures durability. Experimental program was conducted to comprehend the effect of W-D cycles on physical and mechanical properties. Based on the experimental results, the following conclusions were drawn:

- *The durability of SAC mixtures against W-D cycles was good*: Volume changes and weight loss of SAC mixtures were quite small. Specimen volume changes varied in the range of ±1.3% and the maximum weight loss after W-C cycles and brushing was equal to 5.5%. All tested mixtures comply with the permissible values found in literature;
- *W-D cycles did not damage the SAC mechanical properties:* All specimens survived the 12 W-D cycles, and the strength and stiffness of tested mixtures were preserved or increased at the end of the cycles. As specimens were tested after the last drying cycle, the strength gain can be related to the low residual moisture content;
- *Soil-aggregate proportion ruled the tensile and resilient behavior of SAC mixtures:* the gain of these properties in 20:80 mixtures is probably due to a better cementation reaction caused by the lower amount of soil in these mixtures. The stiffness of 20:80 mixtures was compatible with CTCR, and 30:70 mixtures were compatible with soil-cement;
- *Strength and stiffness properties of SAC mixtures increased or did not change after W-D cycles*: this increase of mechanical properties matters since very high strengthen and stiff materials might reduce fatigue lifespan.

Finally, further studies on SAC mixtures are recommended to create a reliable database and to propose models for pavement design applications.

AUTHORS' CONTRIBUTIONS

André Lapa de Moraes Tavares: Formal analysis, Funding acquisition, Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Investigation, Methodology, Software, Supervision, Visualization; Ana Paula Furlan: Project administration, Formal analysis, Conceptualization, Data curation Writing – review & editing, Methodology, Validation, Visualization; Glauco Tulio Pessa Fabbri: Data curation, Writing – review & editing, Software, Validation.

CONFLICTS OF INTEREST STATEMENT

Nothing to declare.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence tools were used in the research reported here or in the preparation of this article.

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REFERENCES

AASHTO (2014) *AASHTO T 22-03: Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens*. Washington, D.C.: American Association of State Highway and Transportation Officials.

ABNT (2016) *NBR 7182: Solo-Ensaio de Compactação*. Rio de Janeiro: Associação Brasileira de Normas Técnicas.

ACI (2009) *ACI 230.1R-09: Report on Soil Cement.* Farmington Hills, MI: American Concrete Institute.

Aldaood, A.; M. Bouasker and M. Al-Mukhtar (2014) Impact of wetting-drying cycles on the microstructure and mechanical properties of lime-stabilized gypseous soils. *Engineering Geology*, v. 174, p. 11-21. DOI: 10.1016/j.enggeo.2014.03.002.

ASTM (2004) *D559: Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures.* West Conshohocken: American Society for Testing Materials.

Balbo, J.T. (2006) Britas graduadas tratadas com cimento: uma avaliação de sua durabilidade sob o enfoque de porosidade, tenacidade e fratura, *Transportes*, v. 14, n. 1, p. 45-53. DOI: 10.14295/transportes.v14i1.59.

Bessa, I.S.; A.L. Aranha, K.L. et al. (2016) Laboratory and field evaluation of recycled unbound layers with cement for use in asphalt pavement rehabilitation. *Materials and Structures*, v. 49, n. 7, p. 2669-2680. DOI: 10.1617/s11527-015-0675-6.

Biswal, D.R.; U.C. Sahoo and S.R. Dash (2019) Durability and shrinkage studies of cement stabilized granular lateritic soils. *The International Journal of Pavement Engineering*, v. 20, n. 12, p. 1451-1462. DOI: 10.1080/10298436.2018.1433830.

Buritatum, A.; S. Horpibulsuk; A. Udomchai et al. (2021) Durability improvement of cement stabilized pavement base using natural rubber latex. *Transportation Geotechnics*, v. 28, p. 100518. DOI: 10.1016/j.trgeo.2021.100518.

Chen, D.-H.; F. Hong and F. Zhou (2011) Premature cracking from cement-treated base and treatment to mitigate its effect. *Journal of Performance of Constructed Facilities*, v. 25, n. 2, p. 113-120. DOI: 10.1061/(ASCE)CF.1943-5509.0000140.

Chindaprasirt, P.; A. Kampala; P. Jitsangiam et al. (2023) Effects of sulfate attack under wet and dry cycles on strength and durability of Cement-Stablized laterite. *Construction & Building Materials*, v. 365, p. 129968. DOI: 10.1016/j.conbuildmat.2022.129968.

Chittoori, B.C.S.; A.J. Puppala and A. Pedarla (2018) Addressing clay mineralogy effects on performance of chemically stabilized expansive soils subjected to seasonal wetting and drying. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 144, n. 1, p. 04017097. DOI: 10.1061/(ASCE)GT.1943-5606.0001796.

Corps of Engineer (1994) *Soil Stabilization for Pavement*. Washington, D.C.: Department of the Army, the Navy, and the Air Force.

Dempsey, B.J. and M.R. Thompson (1968) 'Durability properties of lime-soil mixtures. *Highway Research Record*, v. 235, p. 61-75.

DER (2006a) *IP-DE-P00/001: Projeto de Pavimentação*. São Paulo: Departamento de Estradas de Rodagem.

DER (2006b) *ET-DE-P00/006: Sub-base ou Base de Solo-brita*. São Paulo: Departamento de Estradas de Rodagem.

DER (2006c) *ET-DE-P00/007: Sub-base ou Base de Solo-brita-cimento*. São Paulo: Departamento de Estradas de Rodagem.

DNIT (2018a) *DNIT 136/2018: Pavimentação Asfáltica: Misturas Asfálticas: Determinação da Resistência à Tração por Compressão Diametral: Método de Ensaio*. Rio de Janeiro: Departamento Nacional de Infraestrutura de Transportes.

DNIT (2018b) *DNIT 181/2018: Pavimentação: Material Estabilizado Quimicamente: Determinação do Módulo de Resiliência: Método de Ensaio*. Rio de Janeiro: Departamento Nacional de Infraestrutura de Transportes.

Donrak, J.; S. Horpibulsuk; A. Arulrajah et al. (2020) Wetting-drying cycles durability of cement stabilised marginal lateritic soil/melamine debris blends for pavement applications. *Road Materials and Pavement Design*, v. 21, n. 2, p. 500-518. DOI: 10.1080/14680629.2018.1506816.

Fedrigo, W.; W.P. Núñez; M.A. Castañeda López et al. (2018) A study on the resilient modulus of cement-treated mixtures of RAP and aggregates using indirect tensile, triaxial and flexural tests. *Construction & Building Materials*, v. 171, p. 161-169. DOI: 10.1016/j.conbuildmat.2018.03.119.

Hoy, M.; D.V. Nhieu; S. Horpibulsuk et al. (2023) Effect of wetting and drying cycles on mechanical strength of cement-natural rubber latex stabilized recycled concrete aggregate, *Construction & Building Materials*, v. 394, p. 132301. DOI: 10.1016/j.conbuildmat.2023.132301.

Hoy, M.; R. Rachan; S. Horpibulsuk et al. (2017) Effect of wetting–drying cycles on compressive strength and microstructure of recycled asphalt pavement: fly ash geopolymer. *Construction & Building Materials*, v. 144, p. 624-634. DOI: 10.1016/j.conbuildmat.2017.03.243.

Kasu, S.R.; K. Manupati and A.R. Muppireddy (2020) Investigations on design and durability characteristics of cement treated reclaimed asphalt for base and subbase layers. *Construction & Building Materials*, v. 252, p. 119102. DOI: 10.1016/j.conbuildmat.2020.119102.

Khoury, N. and M.M. Zaman (2007) Durability of stabilized base courses subjected to wet-dry cycles. *The International Journal of Pavement Engineering*, v. 8, n. 4, p. 265-276. DOI: 10.1080/10298430701342874.

Khoury, N.N. and M.M. Zaman (2002) Effect of wet-dry cycles on resilient modulus of class c coal fly ash-stabilized aggregate base. *Transportation Research Record: Journal of the Transportation Research Board*, v. 1787, n. 1, p. 13-21. DOI: 10.3141/1787-02.

PCA (1992) *Soil-cement Laboratory Handbook.* Skokie, IL: Portland Cement Association.

Porras, Y.; C. Jones and N. Schmiedeke (2020) Freezing and thawing durability of high early strength portland cement concrete. *Journal of Materials in Civil Engineering*, v. 32, n. 5, p. 04020077. DOI: 10.1061/(ASCE)MT.1943-5533.0003168.

Puppala, A.J.; L.R. Hoyos and A.K. Potturi (2011) Resilient moduli response of moderately cement-treated reclaimed asphalt pavement aggregates. *Journal of Materials in Civil Engineering*, v. 23, n. 7, p. 990-998. DOI: 10.1061/(ASCE)MT.1943-5533.0000268.

Rasul, J.M.; G.S. Ghataora and M.P.N. Burrow (2018) The effect of wetting and drying on the performance of stabilized subgrade soils. *Transportation Geotechnics*, v. 14, p. 1-7. DOI: 10.1016/j.trgeo.2017.09.002.

Simoni, J.P.S.C. (2019) *Contribution Regarding the Design and the Mechanical Behaviour of Soil-Aggregate-Cement Mixture for Pavement Course.* Dissertation (Master degree). Sao Carlos School of Engineering, University of Sao Paulo. Sao Carlos. Available at: <https://www.teses.usp.br/teses/disponiveis/18/18143/tde-23012020-131342/pt-br.php> (accessed 08/05/2024).

Simoni, J.P.S.C.; L.R. Valoura and A.P. Furlan (2019) Contribuição ao estudo da dosagem e do comportamento mecânico de misturas solo-agregado-cimento. In *Anais do 33o Congresso de Pesquisa e Ensino em Transporte da ANPET*. Rio de Janeiro: ANPET.

Sobhan, K. and B.M. Das (2007) Durability of soil-cements against fatigue fracture. *Journal of Materials in Civil Engineering*, v. 19, n. 1, p. 26-32. DOI: 10.1061/(ASCE)0899-1561(2007)19:1(26).

Souza, M. L. (1981) *Método de Projeto de Pavimentos Flexíveis* (3a ed., IPR. Publ. 667). Rio de Janeiro, IPR.

Valoura, L.R. (2021) *Study on Factors Affecting the Mechanical Behavior of Soil-Aggregate-Cement Mixtures.* Dissertation (Master degree). Sao Carlos School of Engineering, University of Sao Paulo. São Carlos. Available at: <https://www.teses.usp.br/teses/disponiveis/18/18143/tde-12112021-095527/fr.php> (accessed 08/05/2024).

Valoura, L.R.; M.F. Silva and A.P. Furlan (2022) Laboratory investigation of soil-aggregate-cement mixture. *Transportes*, v. 30, n. 3, p. 2646. DOI: 10.14295/transportes.v30i3.2646.

Yoder, E.J. and M.W. Witczak (1991) *Principles of Pavement Design* (2nd ed.). New York: Wiley.