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Laboratory investigation of soil-aggregate-cement mixture

Investigação laboratorial de mistura solo-agregado-cimento

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ABSTRACT
Cement stabilization improves physical and mechanical properties of geotechnical materials. However, numerous combinations of geotechnical materials and cement hinder to establish a pattern of mechanical behavior of cement-stabilized materials. Thus, this study aims to evaluate the mechanical behavior of soil-aggregate-cement mixtures (SAC) using high early-strength cement (HE), to contribute to dosage aspects and to ascertain their recommendation as base and/or subbase layers in heavy and very heavy volume roads. For this, SAC mixtures composed of different proportions of soil and aggregate (20:80 and 30:70) with 3, 5 and 7% of cement were produced and cured at different times (0, 7 and 28 days). Mechanical properties were assessed in terms of unconfined compressive strength (UCS), indirect tensile strength (ITS) and resilient modulus by repeated load triaxial test ($M_{r,t}$) and by dynamic indirect tensile test ($M_{r,d}$). A cement dosage study compared compressive and tensile strengths with acting stresses computed by mechanistic analysis of hypothetical pavements. This same procedure was also used for verifying the possibility of anticipating construction phases and reducing the traffic opening time, in this case a SAC mixture using Portland composite cement (PCC) was also evaluated. Results indicated that SAC-20:80 presented better mechanical behavior than SAC-30:70. Also, the cement content that led to the best mechanical behavior was 5%. All SAC mixtures with 5% HE had higher strength than the acting stresses interval computed for hypothetical pavements. SAC mixtures reached, at 7 and 3 days of curing, respectively, 80% and 60% of 28-days strength, which is the control parameter of Sao Paulo-DOT instructions for SAC. Findings indicated that, due to their good mechanical behavior, SAC mixtures are viable alternatives as layers in heavy and very heavy traffic pavements. Additionally, SAC's high strengths at earlier curing times have shown their potential to reduce construction time.

RESUMO
O objetivo deste estudo foi avaliar os resultados de ensaios de laboratório de uma mistura solo-agregado estabilizada com cimento (SAC), a fim de recomendar seu uso como camadas de base e/ou sub-base de pavimentos. Foram avaliadas propriedades de resistência à compressão simples (RCS), resistência à tração por compressão diametral (RTCD), módulo de resiliência pelo ensaio triaxial e o módulo de resiliência diametral, sob a influência de fatores como tempo de cura (0, 7 e 28 dias), proporção de agregado:solo (80:20 e 70:30) e conteúdo de cimento (3, 5 e 7%). Além disso, foi realizado um estudo de dosagem de cimento, comparando os resultados de RCS e RTCD obtidos em laboratório com as tensões de análises mecanicistas de pavimentos hipotéticos, e testes no teor ótimo de cimento aos 3 dias de cura a fim de analisar a possibilidade de reduzir o tempo de abertura do tráfego. Os resultados mostraram que as misturas SAC apresentam comportamento mecânico satisfatório que podem reduzir o tempo de construção. Finalmente, a dosagem de cimento recomendou 5% como teor ótimo de cimento para todas as misturas testadas.

1. INTRODUCTION

Portland cement has been used as a stabilizer in base and subbase layers of high and very high traffic roads. The main objective of cement stabilization is to improve properties of geotechnical materials, e.g., soils and mineral aggregates. Generally, cement-stabilized materials have superior performance when compared to mixtures using lime, fly ash or other types of binders (Prusinski and Bhattacharja, 1999; Asgari et al.; 2015; Ban and Park, 2014, Furlan et al. 2021). Also, the technical literature have shown that cement-stabilized materials tend to present high strength and durability (Bahar et. al., 2004; Horpibulsuk et al.; 2010; Fedrigo, 2015). These improvements occur due to the formation of cementitious compounds in cement hydration phase, enhancing shear strength properties and preventing swelling and shrinkage effects (Puppala et al., 2015, Furlan et al. 2018). Besides, as a technique with features such as simple mixing procedures, wide market availability of cement and reduced material and transportation costs, cement stabilization is a viable option for pavement applications (Puppala et al, 2015; Behnood, 2018).

Among the combinations of geotechnical materials and cement are soil-aggregate-cement (SAC) mixtures, consisting of predesigned amounts of soil, mineral aggregate and Portland cement. They have been used as base and/or subbase of pavements under heavy and very heavy traffic. SAC might present economic and environmental advantages, since local soil can be used and materials from deteriorated pavement layers can be recycled (Kawahashi et al., 2010; Baghini et al., 2017). Some studies showed that the combination of physical stabilization and cement addition provide an excellent performance in terms of strength, durability and stiffness of SAC. However, these mixtures exhibit a typical brittle behavior of cemented materials, which is characterized by high stiffness and very low strains at failure (Jitsangiam et al., 2016; Singh and Patel, 2017; Simoni et al., 2019, Salehi et al.; 2021).

Despite the aforementioned advantages, SAC mixtures still lack standardized protocols for the dosage of their components. Therefore, it is understandable that, in practice, the design of SAC is predominantly empirical and dependent on laboratory tests. This is due to the need of first determining the best proportion of mineral aggregate and soil, then selecting the cement content that is capable of meeting the requirements of pavement design.

The importance of determining the proper cement content to be added to the mixture is supported by previous studies, which demonstrated that it directly influences the strength gain (Basha, et al., 2005; Horpibulsuk et al., 2010; Ban and Park, 2014). Moreover, the resulting cement content must lead the mixture to meet pavement strength criteria, which vary according to traffic loading and environmental conditions. On the other hand, it should be considered that the strength of cement-stabilized mixtures depends on the binder interaction with available water and geotechnical material. These interactions change due to different properties that soils and mineral aggregates may present. That is, the cement content that a geotechnical material needs to achieve a given strength may not be enough for another geotechnical material. Horpibulsuk et al. (2010), Nascimento and Albuquerque (2018) and Suebsuk et al. (2019) evaluated the unconfined compressive strength (UCS) at 7 days of curing of geotechnical materials stabilized with 3% of cement and compacted under modified effort (2700 $kN.m/m^3$). The results showed that the soil studied by Horpibulsuk et al. (2010), the crushed rock from Nascimento and Albuquerque (2018) and the SAC from Suebsuk et al. (2019) presented UCS equal to 1.8, 3.5 and 2.9 MPa, respectively.

Curing time also significantly influences the strength gain of cemented mixtures, since cement needs time to hydrate and form cementitious compounds. Due to differences in cementitious compounds formation rates, cement-stabilized mixtures show increasing strength values over curing time. Baghini et al (2017) verified this upward trend for a SAC mixture with 4% cement, resulting in UCS values of 4.0, 5.3 and 7.2 MPa at 7, 28 and 60 days, respectively.

The evaluation of UCS is addressed in studies on SAC mixtures, once several manuals and protocols consider UCS as the main parameter for design and construction control of cemented layers, as can be seen in ACI (1990); PCA (1992); LCPC (2000) and DNIT (2010). However, to satisfactorily understand the mechanical behavior of cemented mixtures, it is necessary to evaluate properties such as tensile strength and resilient modulus, in order to represent the loading conditions that these layers experience in service life (George, 1990; Parente, 2002; Sant'Anna et al., 2003, Consoli et al., 2011).

It is worth highlighting that few studies (Bessa et al., 2016; Baghini et al., 2017; Simoni, 2019) have thoroughly characterized the behavior of SAC by performing complementary tests such as indirect tensile strength (ITS) and/or resilient modulus (M_r). Furthermore, to the extent of our knowledge, there is a lack of technical literature focused on understanding the evolution of mechanical properties of SAC at early curing times. The analysis of this curing stage may be advantageous with regard to the production efficiency of SAC mixtures in the field, since the 28-days strength is the control parameter to allow the construction of the upper layers to begin. Thus, the possibility of reducing the time needed for SAC to meet the technical requirements for releasing the subsequent construction steps may positively affect the work schedule, consequently reducing traffic opening time.

In view of this, this paper aims to contribute to the understanding of the mechanical behavior of SAC mixtures, considering the influence of curing time, material proportion and cement content. It also promotes comparisons between laboratory results and the stresses acting on cemented layers of different pavement structures in order to determine the optimum cement content (OCC). Furthermore, with the intention of reducing the time required for SAC mixtures to present satisfactory strength, this paper evaluates the mechanical response of specimens stabilized with two types of cement: a Portland composite cement and a high early-strength cement.

2. EXPERIMENTAL PROGRAM

The study was conducted in three stages (Figure 1). The first stage focused on material characterization, preliminary mixture design and cement dosage. The second stage consisted of mechanical characterization of different SAC mixtures, to define the cement content that would promote the best mechanical performance. The third stage compared the results of mechanical strength tests of SAC with the stresses computed by mechanistic analyses of hypothetical pavements with SAC base layers, leading to the suggestion of an optimum cement content (OCC). This procedure was replicated for mixtures with OCC at 3-days curing, aiming to speed up the beginning of the construction steps of upper layers. In this case, it was also evaluated a SAC with a different type of cement.

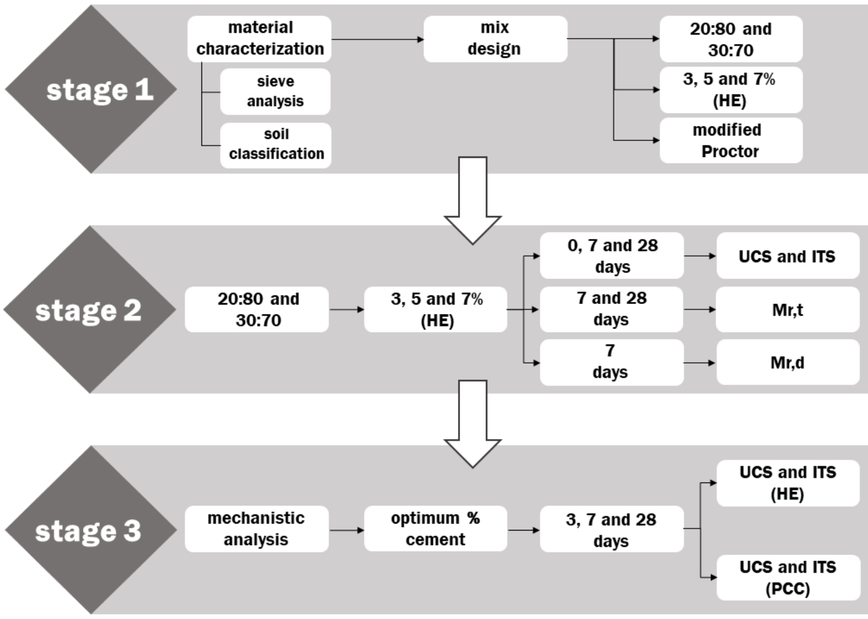


Figure 1. Experimental program

2.1. Materials

The soil used in this study was classified as a lateritic sandy soil (LA'), according to the MCT-Miniature, Compacted, Tropical classification system (Nogami and Villibor, 1981), or A-2-6 by TRB (Transportation Research Board), with liquid limit LL=34% and plastic index PI=13%. To compose the soil-aggregate matrix, two fractions of a basaltic mineral aggregate were used: coarse aggregate (particles retained on sieve nº4) and fine aggregate with stone dust (particles passing through sieve nº4).

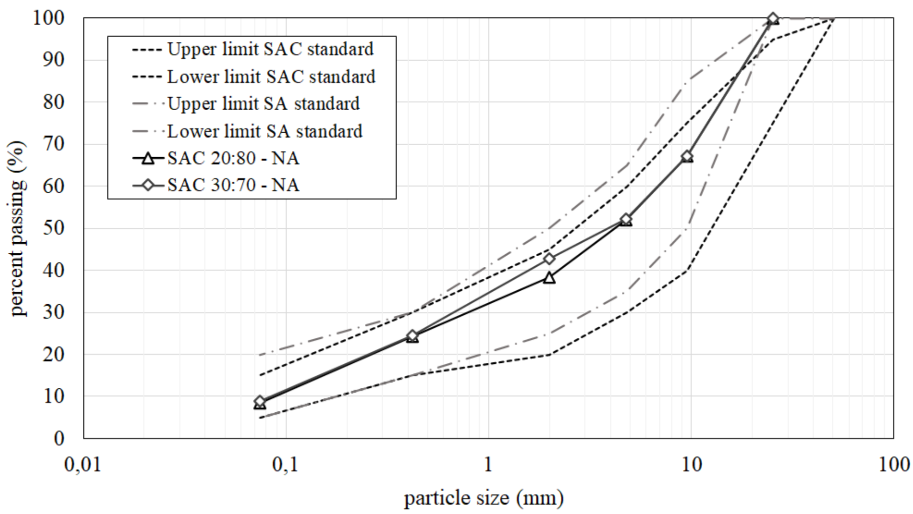


Figure 2. Particle size distributions of SAC 20:80 and SAC 30:70.

Three cement contents (3, 5 and 7%) were used to stabilize the soil-aggregate mixtures. Two cements were adopted: a high early-strength cement (CP-V-ARI) and a Portland composite cement with pozzolana (CP-II-Z-32), both classified according to Brazilian specification NBR 16697 (ABNT, 2018). The mixture with CP-II-Z-32 was tested to evaluate the possibility of anticipating construction phases. It should be emphasized that, while CP-V-ARI has as its main characteristic the ability to achieve higher strength in a shorter curing time, CP-II-Z-32 presents higher stability, impermeability and durability. Hereafter, HE will refer to CP-V-ARI and PCC will refer to CP-II-Z-32.

To verify the influence of material proportion on the mechanical behavior of SAC, two soil: aggregate ratios were adopted: 20:80 and 30:70. When the aggregate is detailed according to the fractions limited by sieve nº4, one might obtain the following compositions: SAC-20:80 (composed of 20% soil, 47% coarse aggregate and 33% fine aggregate with stone dust) and SAC-30:70 (composed of 30% soil, 47% coarse aggregate and 23% fine aggregate with stone dust). The particle size distribution of SAC-20:80 and SAC-30:70 fitted to the Range-II for soil-aggregate-cement and to the Range-III for soil-aggregate specifications from the Sao Paulo-DOT (DER-SP, 2006a; 2006b). Figure 2 illustrates the particle size distribution of SAC mixtures.

2.2. Specimen molding

To define the optimum moisture content (OMC) and maximum dry density (MDD) of each SAC mixture, Proctor compaction tests, using the modified effort, were carried out in accordance with NBR 7182 (ABNT, 2016). OMC and MDD were used as target parameters in the compaction procedure of the specimens for mechanical tests.

Specimen molding for UCS and $M_{r,t}$ tests was performed by static compression, in a cylindrical mold with 10 cm x 20 cm (diameter x height). For ITS and $M_{r,d}$ tests, the specimen compaction was performed in Marshall compactor, in a cylindrical mold with 10.7 cm x 8.7 cm.

Subsequently, the specimens were subjected to curing periods of 3 days (only for SAC stabilized with OCC), 7 and 28 days. Curing procedure took place in a climatic chamber and the specimens were wrapped with plastic to prevent moisture changes. Mechanical tests were also performed on specimens at 0-days of curing, aiming to represent the immediate properties of SAC.

In order to ensure a homogeneous set of specimens, a quality control criterion was adopted, namely: degree of compaction of 100 ± 1% and moisture deviation of ±0.5% around OMC. This narrow range adopted shall produce results more repeatable and reproducible.

2.3. Testing procedures

First, UCS and ITS tests were performed according to NBR 12023 (ABNT, 2012) and DNER ME 138-94 (DNER, 1994). Three specimens were prepared for each experimental condition.

Stiffness of SAC mixtures was evaluated using two types of M_r tests: a repeated load triaxial (RLT) test and a dynamic indirect tensile test (ITT). The resilient modulus ($M_{r,t}$) by RLT tests followed the AASHTO T 307-99 (AASHTO, 1999) and a single specimen was used for each experimental condition. The number of specimens used in the $M_{r,t}$ tests was determined based on the findings of Parreira et al. (1998), which demonstrated a satisfactory repeatability of $M_{r,t}$ test for different specimens of the same experimental condition.

Subsequently, $M_{r,t}$ data were fitted to three resilient modulus models: Deviator stress model (Svenson, 1980), Confining stress model (Hicks and Monismith, 1971) and Pezo et al. (1992) model, represented in Equations 1, 2 and 3, respectively. The model that best represented the resilient behavior of SAC was chosen based on the evaluation of the coefficient of determination (R^2).

$$M_{r,t} = k_1 \times \sigma_d^{k_2} \quad (1)$$
$$M_{r,t} = k_1 \times \sigma_3^{k_2} \quad (2)$$
$$M_{r,t} = k_1 \times \sigma_3^{k_2} \times \sigma_d^{k_3} \quad (3)$$

where $M_{r,t}$ = resilient modulus, σ_d= deviator stress, σ_3= confining stress, k_1, k_2 and k_3: regression coefficients.

Resilient modulus ($M_{r,d}$) by ITT tests were performed according to DNIT ME 135-17 (DNIT, 2017). The Poisson's ratio adopted to calculate the resilient modulus ($M_{r,d}$) was 0.20, as suggested by the pavement design standard for cemented materials (DER-SP, 2006). In this case, two specimens were tested for each experimental condition at 7 days of curing.

Note that the idea of measuring M_r by performing these two tests is an attempt to observe numerical interrelations between them. It is useful for practitioners to know the material property under different imposed loads. This type of interrelation is well known, for instance, for cemented crushed rock and concrete or for converting CBR to M_r values (Balbo, 2013; 2007).

2.4. Cement content study

To select the OCC, compressive and tensile strengths were compared with acting stresses on hypothetical pavements. Simoni et al. (2019) performed mechanistic analyses of a set of hypothetical pavements with SAC bases. Eight pavements simulated by the authors were composed of hot mix asphalt (HMA) surface course, SAC base course, soil subbase course (that could be absent or present). Moreover, two types of subgrade composed of either sandy or clayey soils were considered. All input data (Poisson's ratio, resilient modulus, structural coefficient and minimum layer thickness) were adopted in accordance with Sao Paulo-DOT (DER-SP, 2006) and the National-DOT (SOUZA, 1981). The traffic levels selected were heavy (N = $5x10^7$ ESAL) and very heavy (N = $3x10^8$ ESAL). Figure 3 exhibits the typical sections of the hypothetical pavements, as well as their materials properties and loading conditions.

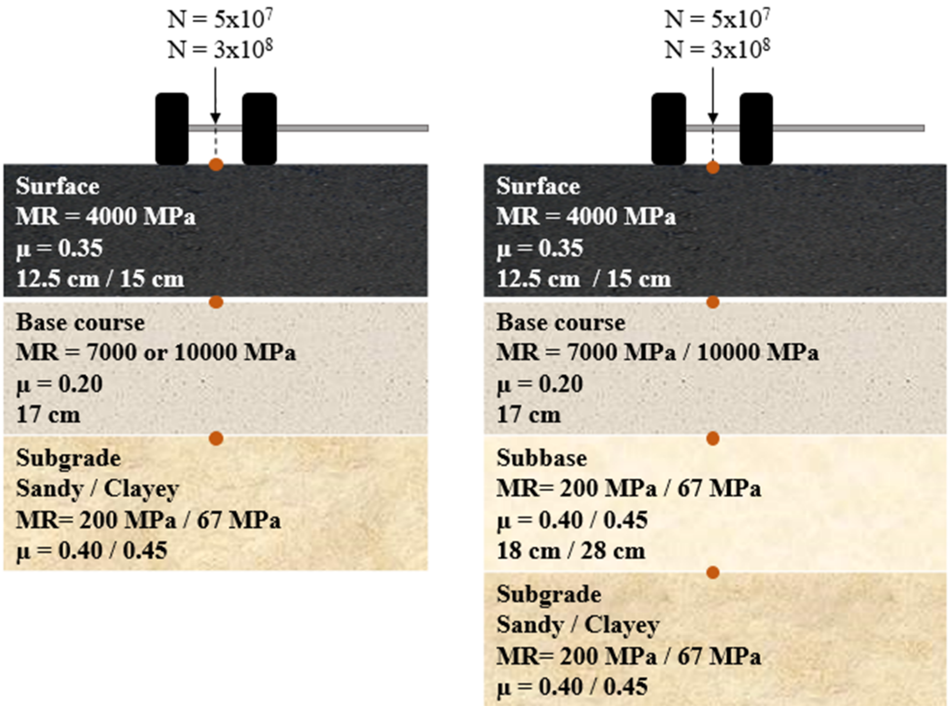


Figure 3. Hypothetical pavements

The Mechanistic-Empirical Pavement Analysis, and Design Software (MePads®) calculated the stresses acting on pavement layers. For comparison purposes, the stresses were taken at the bottom of the cemented base course. The loading used in the simulations was a semi-axle with dual wheels (spaced 300 mm between them), with 20,000 N each, and tire inflation pressure of 0.56 MPa.

The simulations resulted in a range of compression stresses (σ_c) from 0.021 to 0.032 MPa at the bottom of the cemented base course. The tensile stresses (σ_t) resulted in a range from 0.359 to 0.551 MPa.

3. RESULTS

3.1. SAC with high early-strength cement (HE)

Compaction, UCS, ITS and M_r tests were performed on SAC mixtures with different contents of HE. Results are presented and discussed in the following sections.

3.1.1. Compaction test

Table 1 presents a summary of the optimum moisture content (OMC), maximum dry density (MDD) and water/cement ratio (w/c) for the tested SAC mixtures. For the purpose of simplifying mixture nomenclature, the soil:aggregate:cement format was adopted.

Table 1 - Compaction test results of OMC, MDD and w/c ratio for each SAC mixture

SAC mixture	OMC (%)	MDD (kN/m³)	w/c ratio
20:80:3	6.2	23.77	2.07
20:80:5	6.1	23.95	1.22
20:80:7	6.3	23.75	0.90
30:70:3	6.0	23.60	2.00
30:70:5	5.6	23.60	1.12
30:70:7	5.6	23.40	0.80

Regarding material proportions, the OMC and MDD for SAC 20:80 were slightly higher than those of SAC 30:70. This suggests that 20:80-material proportion promoted better particle arrangement and greater material densification, indirectly resulting in higher strength.

Although SAC mixtures did not show a clear trend in the variation of compaction parameters as a function of cement content, it was verified that both SAC mixtures (20:80 and 30:70) reached the lowest OMC and the highest MDD at 5% of cement. If the cement dosage were based only on compaction parameters, the cement content of 5% would be recommendable for both mixtures.

The water/cement (w/c) ratio is the main dosage parameter of cement concrete and is responsible for significantly influencing all types of cement-based mixtures (Scrivener, 2003). In concrete, lower w/c ratios usually lead to a strength increase and reduction of workability, porosity and permeability (Mehta and Monteiro, 2006). By analyzing Table 1, it is noticed that the w/c ratios of SAC 20:80 are higher than those of SAC 30:70. This particularity may be attributed to the slightly higher OMC of the SAC 20:80.

3.1.2. Unconfined compressive strength (UCS) and indirect tensile strength (ITS)

Figure 4(a) and (b) shows the UCS and ITS behavior of SAC mixtures with HE over different curing times. Regarding material proportions, one might notice that the concurrent decrease of soil percentage and the increase of mineral aggregate percentage (both in 10%) increased the

UCS of SAC 20:80 in 20%, as shown in Figure 4(a). This probably occurred due to the better particle arrangement in the SAC 20:80, resulting from the grain-to-grain contact (among mineral aggregates) and the partial filling of voids by soil and cement, which may provide greater stability to the mixtures (Yoder and Witczak, 1975).

UCS gains from 0 to 7 days of curing were remarkably higher than from 7 to 28 days, once UCS_{7days} represents 92% of $UCS_{28\ days}$. Then, after 7 days, the UCS tends to stabilize. This behavior is attributed to HE, which is responsible for the considerable strength gain at early stages of curing.

In general, the increase of cement content improves UCS. For instance, changing cement content from 3% to 5% increased the UCS_{28days} about 78% for both mixtures (20:80 and 30:70). On the other hand, the increase of UCS is less pronounced (~29%) when cement content changes from 5% to 7%. It is worth mentioning that the increase in cement content does not significantly change the immediate strength (UCS_{0days}) of mixtures. This is probably because the products of cement hydration have not yet been formed, which means that the cement acts as a filler at this stage. These findings are consistent with those reported by other researchers using cement (Horpibulsuk et al., 2010; Simoni et al., 2019, Furlan et al., 2021).

Based on the results, if UCS were considered as a dosage parameter, it would be reasonable to suggest a cement content between 3 and 5% for both tested mixtures, considering the favorable strength responses in relation to cement content and curing time.

A prediction model of $UCS_{7\ days}$ of SAC mixtures (Equation 4) was developed. This curing time is especially important because these mixtures had the greatest strength gains at 7 days. The prediction model is useful to compensate for field deviations in cement content and/or material proportions that may occur in the construction stages. Additionally, since the model is a function of cement content and soil percentage, it is possible to evaluate different configurations of SAC during pavement design. The prediction model resulted from a multiple linear regression analysis and presented a significance level of 95%, a F-value of 92.346, high accuracy (R^2=0.925) and a p-value < 0.05 for all independent variables. Finally, once curing time was not considered in this model, the cement content was the most significant variable.

$$UCS_{7days}\ (MPa) = 2.974 + 1.066 \times (\%\ cement) - 0.112 \times (\%\ soil) \tag{4}$$

In Figure 4(b), ITS showed a behavior quite similar to that of the UCS. Again, SAC-20:80 exhibited the highest ITS and strength gain. For all mixtures, the ITS gains were greater between 0 and 7 days. Notwithstanding, ITS continued to increase from 7 to 28 days of curing. At 28 days, the major gain was about 35% for SAC-30:70 with 7% of cement, whereas the minor gain was about 10% for SAC-20:80 with 5% of cement.

Figure 4(b) also shows that ITS changes as a function of the material proportion and the cement content of SAC mixtures. When cement content changes from 3% to 5%, the ITS_{7days} increased about 119% for SAC-20:80, and 67% for SAC-30:70. For cement content from 5% to 7%, the effect is less intense, resulting in an ITS_{7days} increase of 19% for SAC-20:80, and 29% for SAC-30:70. At 28 days of curing, changing cement content from 3% to 5% increased the ITS about 63% for SAC-20:80, and 46% for SAC-30:70. Regarding the cement content from 5% to 7%, the average ITS increase was of 48% for SAC-20:80, and 62% for SAC-30:70.

Thus, it is possible to state that larger amounts of cement resulted in greater ITS. Furthermore, as observed for UCS, cement content does not influence ITS_{0day}, since cement needs time to hydrate and to increase the strength. The largest ITS gain occurred between 3 and 5% of cement. Accordingly, ITS also increased over curing time and these findings are consistent with other researchers' results (Bessa et al., 2016; Fedrigo et al., 2018; Simoni et al., 2019).

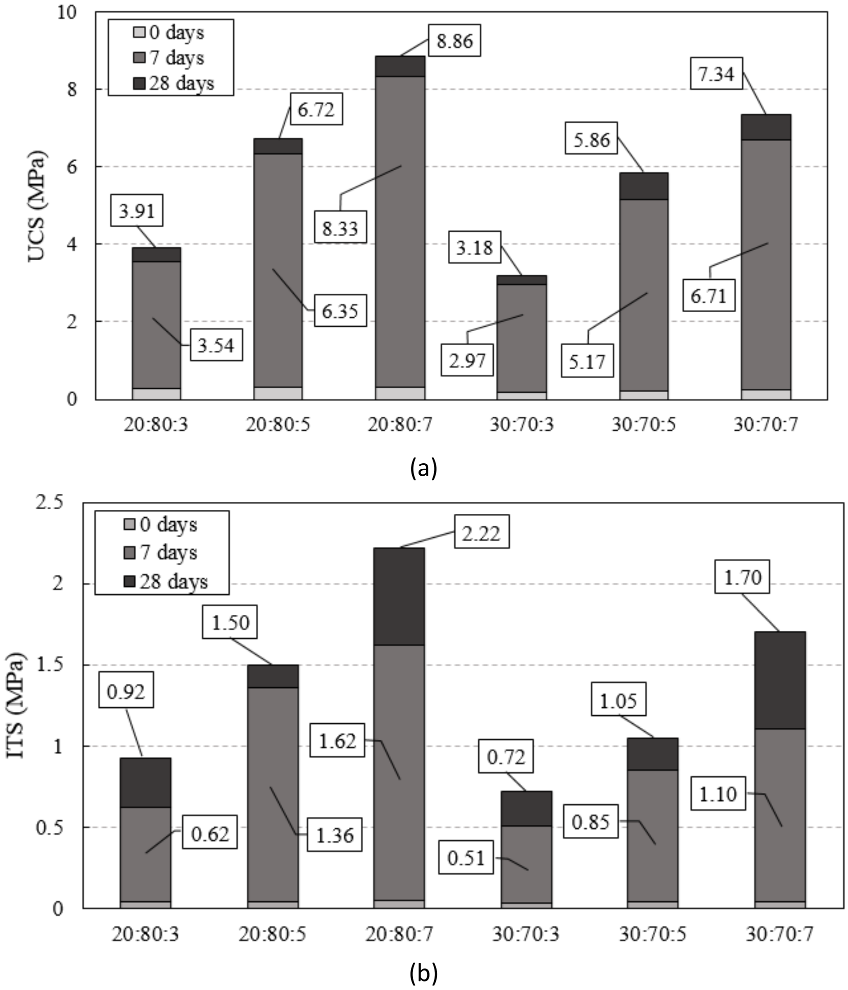


Figure 4. (a) UCS and (b) ITS over curing time for SAC stabilized with HE

In order to assist in construction and design phases, a ITS_{7days} prediction model (Equation 5) was fitted. The model presented F-value=28.451 and good accuracy (R^2=0.791). Furthermore, the independent variables showed p-value < 0.05. Again, since curing time was not considered in this model, the most significant variable is cement content.

$$ITS_{7days}\,(MPa) = 0.971 + 0.198 \times (\%\,cement) - 0.038 \times (\%\,soil) \tag{5}$$

3.1.3. Resilient Modulus ($M_{r,t}$) by Repeated load triaxial (RLT) test

RLT test was performed to determine the $M_{r,t}$ of SAC mixtures with HE. Table 2 presents the regression parameters of $M_{r,t}$ models and corresponding R-squared for SAC at 7 and 28 days of curing. The model selected to represent the SAC mixtures was the deviator stress model, which presented the highest coefficients of determination (0.89< R^2<0.98), indicating that the resilient behavior of SAC is more influenced by deviator stress.

Figure 5 exhibits the relationship between the average $M_{r,t}$ (calculated by means of the deviator model) and cement content. Generally, $M_{r,t}$ varied from 5619 to 9600-MPa. These values are consistent with the $M_{r,t}$ ranges for soil-cement (5000 – 10000-MPa) and cement treated crushed rock (7000 – 18000-MPa), recommended by Sao Paulo-DOT (IP-DE-P00/001, DER-SP, 2006a).

Table 2 - Regression parameters of $M_{r,t}$ models for SAC at 7 and 28 days

Cement content – cc (%)	Model	20:80:cc at 7 days				20:80:cc at 28 days			
		k_1	k_2	k_3	R²	k_1	k_2	k_3	R²
3	Confining stress	143.56	-	0.90	**0.66**	374.73	-	0.61	**0.75**
	Deviator stress	97.93	0.93	-	**0.95**	351.54	0.61	-	**0.91**
	Pezo et al. (1992)	74.67	0.21	0.79	**0.96**	301.37	0.16	0.48	**0.93**
5	Confining stress	232.49	-	0.81	**0.52**	365.18	-	0.65	**0.49**
	Deviator stress	73.78	1.04	-	**0.94**	90.66	0.95	-	**0.96**
	Pezo et al. (1992)	64.88	0.10	0.97	**0.94**	88.89	0.02	0.93	**0.96**
7	Confining stress	1298.37	-	0.41	**0.27**	903.56	-	0.46	**0.32**
	Deviator stress	99.29	0.96	-	**0.98**	265.58	0.72	-	**0.89**
	Pezo et al. (1992)	106.24	-0.08	1.02	**0.99**	352.38	-0.28	0.93	**0.94**
Cement contente (%)	Model	30:70:cc at 7 days				30:70:cc at 28 days			
		k_1	k_2	k_3	R²	k_1	k_2	k_3	R²
3	Confining stress	794.88	-	0.56	**0.53**	859.71	-	0.47	**0.49**
	Deviator stress	404.01	0.68	-	**0.98**	261.57	0.72	-	**0.99**
	Pezo et al. (1992)	398.77	0.01	0.67	**0.98**	264.05	-0.01	0.72	**0.99**
5	Confining stress	315.33	-	0.74	**0.51**	636.99	-	0.61	**0.53**
	Deviator stress	88.21	1.00	-	**0.97**	180.79	0.86	-	**0.97**
	Pezo et al. (1992)	82.27	0.06	0.96	**0.97**	182.18	-0.01	0.87	**0.97**
7	Confining stress	1318.23	-	0.44	**0.38**	573.46	-	0.62	**0.45**
	Deviator stress	343.52	0.70	-	**0.98**	139.45	0.92	-	**0.98**
	Pezo et al. (1992)	349.94	-0.01	0.71	**0.98**	146.18	-0.04	0.95	**0.98**

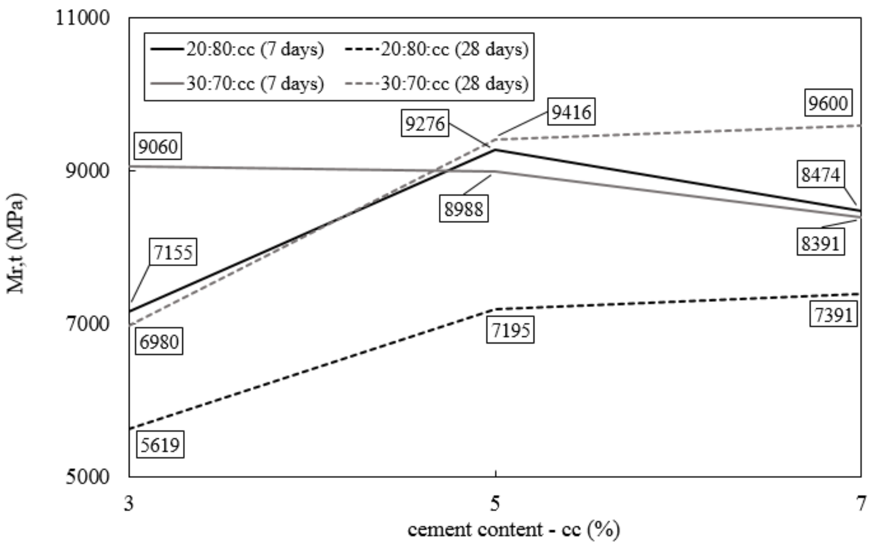
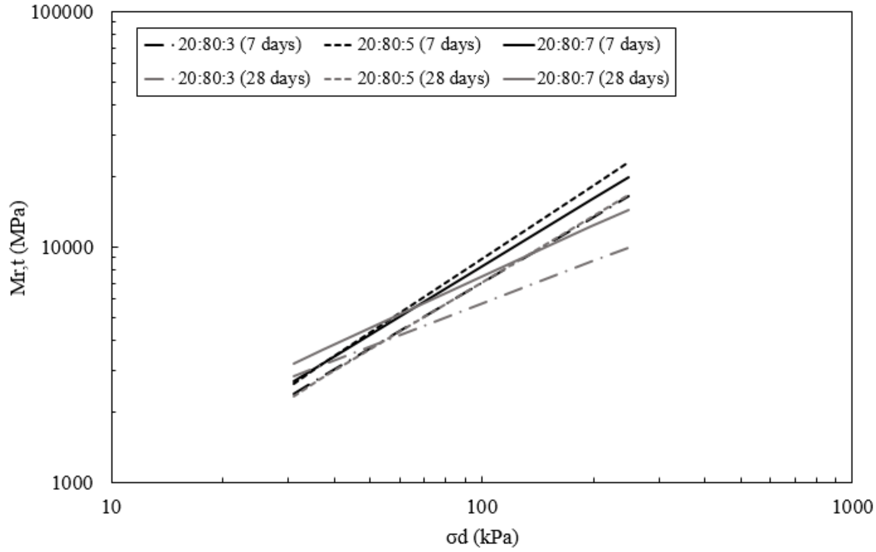


Figure 5. $M_{r,t}$ versus cement content

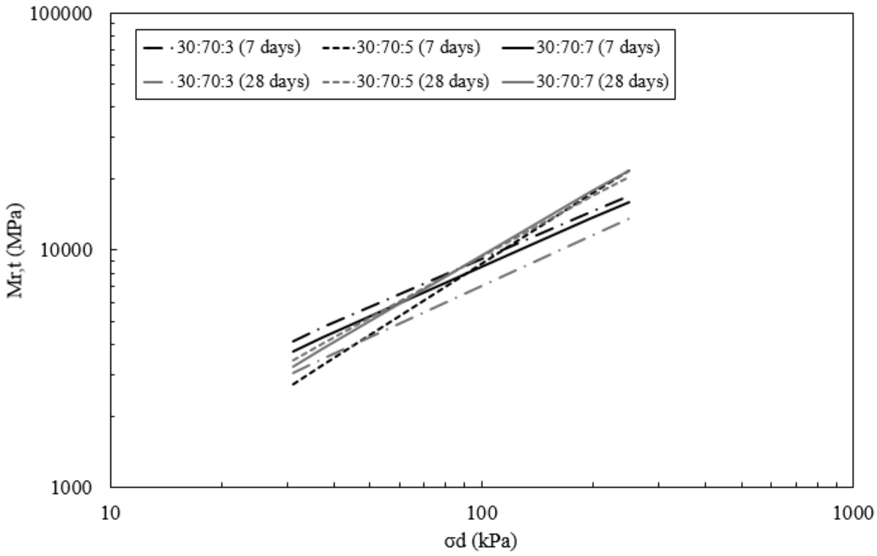
With regard to material proportions, in general, the average $M_{r,t}$ values of SAC 30:70 were approximately 16% higher than the SAC 20:80 ones. This test was the only one in which SAC 30:70 presented higher property than the SAC 80:20. It probably might be explained based on the combined effect of SAC 30:70 material proportion and repeated load.

Actually, it is reasonable to assume that the higher amount of soil and the lower amount of aggregates have produced a denser structure where clusters of soils and aggregates particles would be bonded by cementitious compounds in sparse points. Then, this type of mixture would experience smaller displacements in response to repeated load. In some cases, it is likely that the imposed confining stresses might further reduce the displacements, since despite being cemented, the SAC mixtures are not equivalent to Portland cement concrete.

Regarding curing time, it is observed that changing cement content from 3% to 5% increased the $M_{r,t}$7days of SAC-20:80 about 28%, whereas for SAC-30:70 $M_{r,t}$7days is practically the same (~1%). The increase of cement content from 5% to 7% slightly decreased $M_{r,t}$7days in 8 % and 6% for SAC-20:80 and SAC-30:70, respectively. Increasing cement content from 3% to 5%, the $M_{r,t}$28days increased, about 28% and 35% for SAC-20:80 and SAC-30:70, respectively. For the increase of cement content from 5% to 7%, the average increase in $M_{r,t}$28days was quite small, around 3% for both mixtures. In Figure 6, it is possible to indicate 5% of cement as the optimum one.



(a)



(b)

Figure 6. $M_{r,t}$ of the (a) SAC 20:80 and (b) SAC 30:70

$$Mrt_{\ 7days}(MPa) = -2285.2 + 68.2 \times (\sigma d) + 81.2 \times (\%\ cement) + 121.8 \times (\%\ soil) \quad (6)$$

Figure 6(a) and (b) exhibits the relationship between resilient modulus and deviator stress of all SAC mixtures. Generally, it is evident the upward trend of $M_{r,t}$ as deviator stress increases. $M_{r,t}$ curves revealed a slight effect of amounts of soil in the stiffness of mixtures, for a specified region close to a deviator stress about 100-kPa. In this region, changing soil proportion from 20 to 30% caused an increase of $M_{r,t}$. Nevertheless, it is worth emphasizing that the dominant influence of deviator stress on $M_{r,t}$ hindered the understanding of the effect of cement content and curing time in mixture stiffness.

Equation 6 presents the prediction model for $M_{r,t\,7\text{days}}$ as a function of the deviator stress (kPa), cement content (%) and soil percentage (%). The independent variables showed p-value < 0.05, and the model F-value=542.57 and high accuracy (R^2=0.962). Moreover, soil percentage is the most significant variable of this model, unlike what was observed in UCS and ITS models.

3.1.4. Resilient Modulus ($M_{r,d}$) by dynamic indirect tensile test (ITT)

Figure 7 shows $M_{r,d}$ in function of cement content. In general, $M_{r,d}$ varied from 14000 MPa to 25000 MPa. Regarding the material proportion, the values for SAC 20:80 are, on average, 8.2% higher than the SAC 30:70 ones, as observed in UCS and ITS results. For mixtures with 5% of cement, $M_{r,d}$ were 21810 and 24857 MPa for SAC 30:70 and SAC 20:80, respectively. The highest $M_{r,d}$ were reached in the cement content of 5%. Again, one may infer that there would be an OCC close to 5% that was able to provide a higher stiffness for both SAC mixtures.

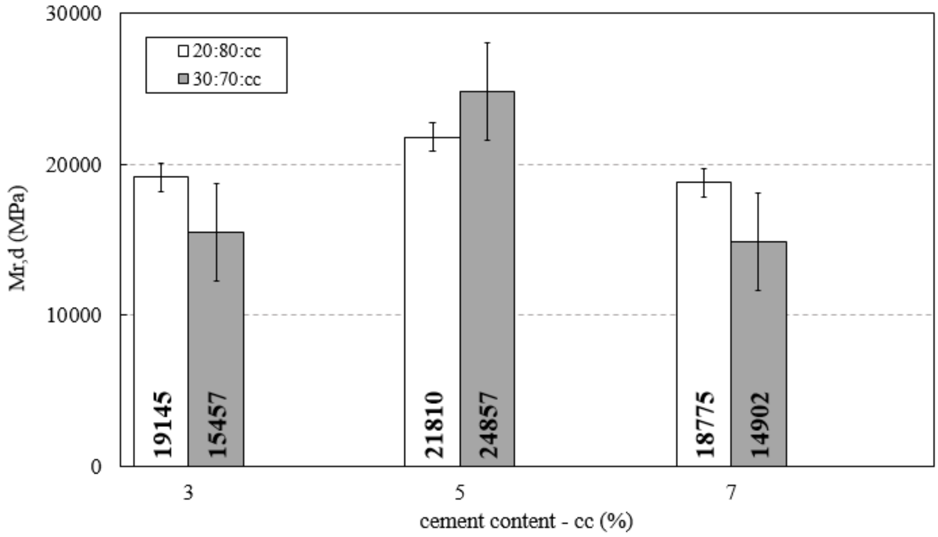


Figure 7. $M_{r,d\,7\text{days}}$ for SAC using HE.

The variation of test results lead to consider all $M_{r,d}$ values similar for both SAC mixtures, including those with 5% of cement. In this case, it is important to highlight that dynamic tensile efforts seem to be more indicated to measure the stiffness of cemented material. This load configuration shall mobilize particularly the cementing bonds that would experience smaller displacements under the test stress level (up to 30% of ITS). Again, these mixtures are cemented but they are not equivalent to Portland cement concrete.

Studies on cemented mixtures have demonstrated that the highest $M_{r,d}$ are met at 28 days (Fedrigo et al., 2018; Baghini et al., 2017). Accordingly, the $M_{r,d}$ of SAC mixtures of the present research would be even higher at 28 days of curing. These high $M_{r,d\,7\text{days}}$ is due to the use of HE;

as mentioned, this type of cement produces high properties at early stages. Overall, the $M_{r,d}$ were quite high, which may be a problem since stiffer materials are prone to present brittle behavior, leading to failure at low strain levels (Fedrigo, 2015).

Another point to discuss refers to the differences between the M_r results from RLT and ITT. $M_{r,t}{}_{7\text{days}}$ for SAC 20:80 was on average 9276 MPa, and for SAC 30:70 was 8988 MPa (Table 2). The $M_{r,d}$ values for SAC 80:20 was on average 21810 MPa, and for SAC 30:70 was 24857 MPa (Figure 8). Therefore, it is possible to state that $M_{r,d}$ is double the $M_{r,t}$.

3.2. Dosage study

The stage for selecting the cement content considered a comparison between the laboratory strengths and acting stresses on hypothetical pavements computed by mechanistic analyses. The range of compression stresses (σ_c) obtained in the simulation for the cemented base course was from 0.021 to 0.032 MPa. UCS for SAC 20:80 varied from 3.54 to 8.86 MPa, and for SAC 30:70 varied from 2.97 to 7.34 MPa. These values are much higher than the resulting compression stresses (σ_c) of the pavement design, easily meeting the requirement.

On the other hand, the range of tensile stresses (σ_t) obtained in the simulation for the cemented base course was from 0.36 to 0.55 MPa. ITS for SAC 20:80 varied from 0.62 to 2.22 MPa, and for SAC 30:70 varied from 0.51 to 1.70 MPa. These values were higher than the computed tensile stress ones, meeting the requirement. However, SAC 30:70 with 3% of cement would not be recommended because its ITS are close to the interval of computed tensile stress.

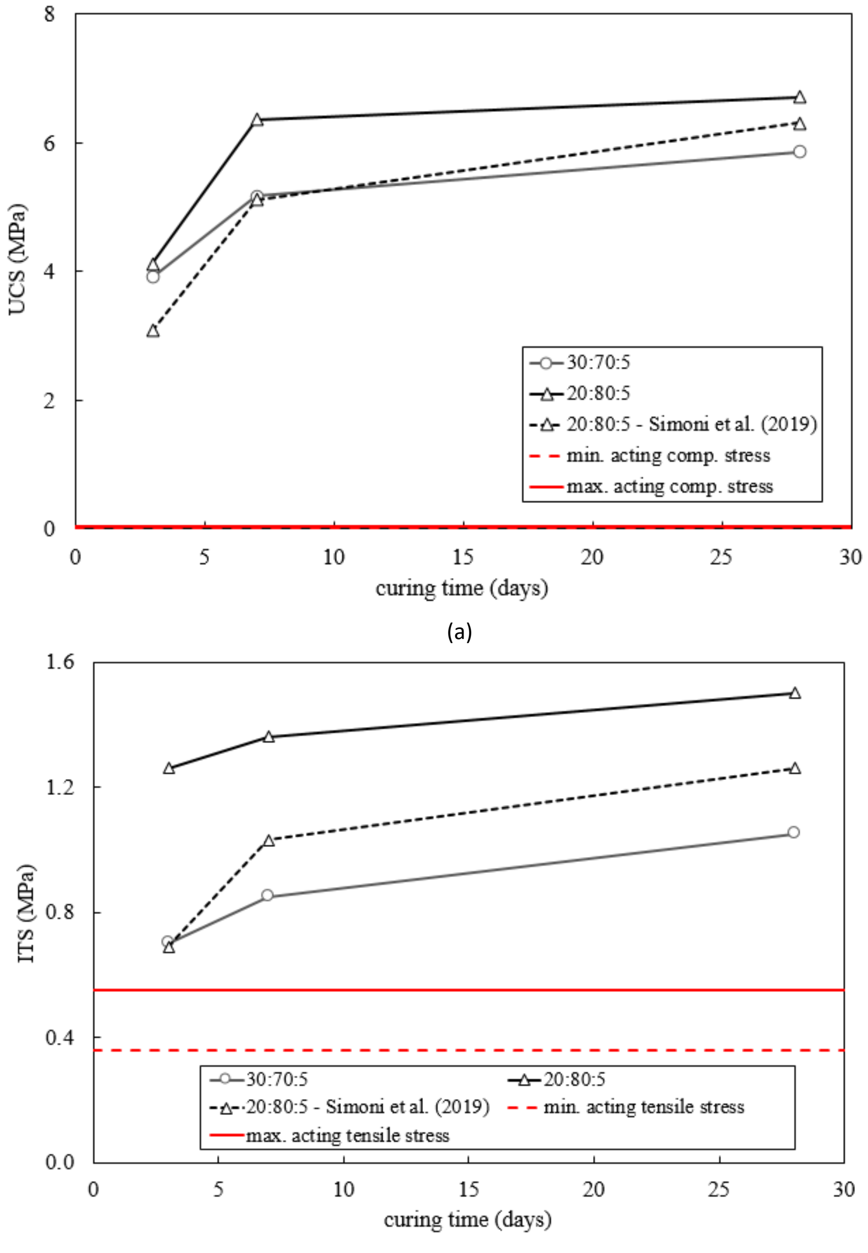
UCS and ITS of SAC mixtures using 5% of cement already met the requirements of pavement design at 7 days of curing. Therefore, based on the aforementioned test results, pavement design requirements and technical specification (São Paulo-DOT), it is concluded that, for all tested SAC mixtures, the OCC is 5%. This content indirectly influences the economic aspects of SAC mixtures dosage, since 5% was the lowest cement content that met all requirements.

These findings are promising because they indicate that SAC mixtures tested exhibited satisfactory control properties before 28 days, which is the curing time recommended for SAC design and construction purposes of Sao Paulo-DOT (DER-SP, 2006a). This leads to discuss about the time or the efficiency of cement stabilization, because during the construction or maintenance/rehabilitation of the pavement, it is common to occur operational restrictions to organize traffic, such as the “stop-and-go” system. This system slows down and/or blocks (temporarily) traffic and may contribute to accidents, mainly in two-lane roads with high traffic volume.

In this way, as a complementary analysis, UCS and ITS were evaluated at 3 days of curing, in order to determine the curing time in which the material meets the resistance according to pavement design. This would speed up the construction process and the traffic opening because it would allow the construction of the upper layers to start earlier. In this study, it was included a new SAC mixture stabilized with a Portland composite cement (PCC) to ascertain if an ordinary cement would also present satisfactory strength earlier. It is worth mentioning that the main characteristics of PCC are to present higher stability, impermeability and durability.

Figure 8(a) and (b) show UCS and ITS over curing time of SAC mixtures with 5% of cement, respectively. Figure 8a evidences that, $UCS_{3\text{days}}$ of SAC mixtures using HE is about 25% higher than the one using the PCC. $UCS_{7\text{days}}$ of SAC 30:70 with HE and SAC 20:80 with PCC are quite similar. At 28 days, UCS of SAC 20:80 with PCC is close to the SAC 20:80 with HE.

Figure 8(b) shows ITS kinetics. ITS_{3days} of SAC 20:80 with HE is 55% higher than the SAC with PCC, and practically the same for SAC 30:70 with HE and SAC 20:80 with PCC. At 7 days, ITS curves shift up in the same behavior trend observed for UCS (Figure 9), without stabilizing at 28 days, though.



(b)

Figure 8. (a) UCS and (b) ITS of SAC with 5% of cement over curing time, including 3 days of curing.

UCS varied from 3.09 to 4.12 MPa, while ITS from 0.69 to 1.26 MPa. By comparing the values obtained at 3 days with the 7 days of curing, it is noticed that the UCS_{3days} represents around 70% of the UCS_{7days}, whereas the ITS_{3days} represents around 80% of the ITS_{7days}. Hypothetical pavement analyses showed that the maximum compression stress of cemented base course was 0.032 MPa and the maximum tensile stress was 0.551 MPa. Since all strengths were greater than stresses, leading to recommended to complete the construction of upper layers or the maintenance activities of the pavement at 3 days of curing.

For all tested mixtures, UCS values evolved asymptotically and SAC 20:80 with HE had the best behavior, exhibiting superior resistances (regardless curing time) and advantages (especially about production efficiency). Concerning the mixture using PCC, the gain of resistance is slower, but it continues to occur until 28 days, surpassing the strength of SAC 30:70 with HE. This is expected when pozzolana is used as an additive in cement. Nevertheless, it is worth emphasizing that any change in material proportion must also imply different strengths, regardless of the type of cement.

4. CONCLUSIONS

A laboratory investigation was conducted to contribute to the study of dosage and to understand the effects of factors on mechanical behavior of soil-aggregate mixtures with cement addition (SAC). The factors considered in analyses were cement content, material proportion and curing time. According to this research, the following conclusions can be drawn:

- All SAC mixtures studied showed a good mechanical performance to be used as base and subbase material for pavement, meeting the requirements of the technical specification for SAC (ET-DE-P00/007, DER-SP, 2006a);
- UCS, ITS and M_r were in agreement with other cemented mixtures in pavement construction, such as soil-cement and cement treated crushed rock. Overall, increases in curing time and cement content resulted in higher mechanical properties;
- SAC 20:80 presented higher mechanical properties (UCS, ITS, $M_{r,t}$ and $M_{r,d}$) when compared with SAC 30:70. This may be attributed to a satisfactory arrangement of particles and high proportion of aggregates in the mixture;
- The cement dosage based on the comparison between mechanical properties and stress acting on hypothetical pavement indicated the same cement content that the analysis based only on the compaction parameters and mechanical properties. For all tested mixtures, the cement content recommended is 5%. At this content, mixtures presented strengths higher than the computed stresses, reaching the strength requirement at 7 days of curing.
- It would be possible to speed up the construction process by reducing traffic opening time, once SAC using 5% of cement also presented strengths above the computed stresses for hypothetical pavement. Despite the mixtures with HE have the best behavior, it could be recommended to complete the construction of upper layers or the maintenance activities of the pavement at 3 days of curing for all tested mixtures.
- Linear regressions for UCS, ITS and $M_{r,t}$ allowed to estimate these properties at 7 days of curing, however, it is more indicated to use in similar mixtures.

It is important to keep in mind that design and dosage of cemented mixtures depends on the intrinsic characteristics of the materials and test protocols carried out. Therefore, it is crucial to indicate that further studies on the behavior of SAC mixtures continue so that builders may have access to more reliable data. Finally, it is recommended caution when using relationships and models proposed herein, because they were built based on specific experimental conditions.

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REFERENCES

AASHTO (1999) AASHTO T 307-99: Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, US: American Association of State Highway and Transportation Officials.

ACI (1990) *State-of-the-art report on soil cement. ACI Materials Journal*, v. 87, n. 4, pp. 395-417, 1990.

Asgari, M. R.; A. B. Dezfuli and M. Bayat. (2015) Experimental study on stabilization of a low plasticity clayey soil with cement/lime. *Arabian Journal of Geosciences*, vol. 8, p. 1439 – 1452. DOI: 10.1007/s12517-013-1173-1.

ABNT-(2012) Norma NBR-1202: Solo-cimento – ensaio de compactação. Rio de Janeiro: Associação Brasileira de Normas Técnicas.

ABNT-(2016) Norma NBR-7182: Solo – ensaio de compactação. Rio de Janeiro: Associação Brasileira de Normas Técnicas.

ABNT-(2018) NBR-16697: Cimento Portland – requisitos. Rio de Janeiro: Associação Brasileira de Normas Técnicas.

Baghini, M. S.; A. Ismail; M. P. Asghar; G. Fendereski and M. Sadeghi. (2017) Measuring the effects of styrene butadiene copolymer latex-Portland cement additives on properties of stabilized soil-aggregate base. *International Journal of Pavement Research and Technology*, v. 11, n. 5, p. 458-469. DOI: 10.1016/j.ijprt.2017.12.001.

Bahar, R.; M. Benazzoug and S. Kenai. (2004) Performance of compacted cement-stabilised soil. *Cement and Concrete Composites*, v. 26, n. 7, p. 811–820. DOI: 0.1016/j.cemconcomp.2004.01.003.

Balbo, J. T. (2007) *Pavimentação asfáltica: materiais, projeto e restauração* (1ª ed.). São Paulo: Oficina de Textos.

Balbo, J. T. (2013) Relations between indirect tensile and flexural strengths for dry and plastic concretes. *Rev. IBRACON Estrut Mater*, 6 (6). DOI: 10.1590/S1983-41952013000600003.

Ban, H. and S. Park. (2014) Characteristics of modified soil-aggregate system and their application in pavements. *ASCE Journal of Materials in Civil Engineering*, v. 18, n. 6, p. 1672–1678. DOI: 10.1007/s12205-014-0639-3.

Basha, E. A.; R. Hashim; H. B. Mahmud and A. S. Muntohar. (2005) Stabilization of residual soil with rice husk ash and cement. *Construction and Building Materials*, v.19, p. 448-453. DOI: 10.1016/j.conbuildmat.2004.08.001.

Behnood, A. (2018) Soil and clay stabilization with calcium- and non-calcium-based additives: A state-of-the-art review of challenges, approaches and techniques. *Transportation Geotechnics*, v. 17, part A, p. 14-32. DOI:10.1016/j.trgeo.2018.08.002.

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

Consoli, N. C.; A. V. da Fonseca; R. C. Cruz and S. R. Silva (2011) Voids/cement ratio controlling tensile strength of cement-treated soils. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 137, n. 11, pp. 1126-1131. DOI: 10.1061/(ASCE)GT.1943-5606.0000524.

DER-SP-(2006a) Norma ET-DE-P00/007ª: Sub-base ou base de solo-brita-cimento. São Paulo: Departamento de Estradas de Rodagem de São Paulo.

DER-SP (2006b) Norma ET-DE-P00/006B: Sub-base ou base de solo-brita. São Paulo: Departamento de Estradas de Rodagem de São Paulo.

DER-SP-(2006c) Norma IP-DE-P00/001: Instrução de projeto de pavimentação. São Paulo: Departamento de Estradas de Rodagem de São Paulo.

DNER-(1994) Norma ME-138/94: Pavimentos flexíveis - misturas betuminosas – determinação da resistência à tração por compressão diametral. Rio de Janeiro: Departamento Nacional de Estradas de Rodagem.

DNIT-(2010) Norma 143/2010-ES: Pavimentação – base de solo-cimento – especificação de serviço. Rio de Janeiro: Departamento Nacional de Infraestrutura de Transportes.

DNIT (2018) Norma 135/2018-ME: Pavimentação asfáltica - misturas asfálticas - determinação do módulo de resiliência - método de ensaio. Rio de Janeiro: Departamento Nacional de Infraestrutura de Transportes.

George, K. P. (1990) Characterization and structural design of cement-treated base. *Transportation Research Record*, n. 1288, pp. 78-87.

Horpibulsuk, S.; R. Rachan; A. Chinkulkijniwat; Y. Raksachon and A. Suddeepong. (2010) Analysis of strength development in cement-stabilized silty clay from microstructural considerations. *Construction and Building Materials*, v. 24, n. 10, p. 2011–2021. DOI:10.1016/j.conbuildmat.2010.03.011.

Fedrigo, W. (2015) *Reciclagem de pavimentos com adição de cimento Portland: definição das bases para um método de dosagem*. Dissertação (Mestrado). Universidade Federal do Rio Grande do Sul, Porto Alegre.

Fedrigo, W.; W. P. Nuñez; M. A. C. López; T. R. Kleinert and J. A. P. Ceratti. (2018) A study on the resilient modulus of cement-treated mixtures of RAP and aggregates using indirect tensile, triaxial and flexural tests. *Construction and Building Materials*, 171, p. 161 – 169. DOI: 10.1016/j.conbuildmat.2018.03.119.

Furlan, A. P.; A. Razakamanantsoa; H. Ranaivomanana; D. Levacher and T. Katsumi. (2018) Shear strength performance of marine sediments stabilized using cement, lime and fly ash. *Construction and Building Materials*, v. 184, pp. 454-463. DOI: 10.1016/j.conbuildmat.2018.06.231.

Furlan, A. P.; A. Razakamanantsoa; H. Ranaivomanana; O. Amiri; D. Levacher and D. Deneele. (2021) Effect of fly ash on microstructural and resistance characteristics of dredged sediment stabilized with lime and cement. *Construction and Building Materials*, v. 272. DOI: 10.1016/j.conbuildmat.2020.121637.

Hicks, R. J. and C. L. Monismith (1971) Factors influencing the resilient response of granular materials. *Transportation Research Record*, n. 435, pp. 15-31.

Jitsangiam, P.; K. Nusit; S. Chummuneerat; P. Chindaprasirt and P. Pichayapan. (2016) Fatigue assessment of cement-treated base for roads: an examination of beam-fatigue tests. Journal of Materials in Civil Engineering, v. 28, n. 10. DOI: 10.1061/(ASCE)MT.1943-5533.0001601.

Kawahashi, J.; R. B. Tomei Junior; E. K. Tatsuta; J. T. Balbo and D. C. Balzan. (2010) Estabilização de solos siltosos expansivos de São Paulo com ligantes com elevado teor de escória para pavimentação. *Transportes*, v. 18, n. 2, p. 5-16. DOI: 10.14295/transportes.v18i2.418.

LCPC (2000) Traitement des sols à la chaux et/ou aux liants hydrauliques: application à la realization des remblais et des couches de forme. Paris, FR: Laboratoire Central des Ponts et Chaussées.

Mehta, P. K. and P. J. M. Monteiro. (2006) Concrete: microstructure, properties and materials (3ª ed.). New York, U: McGraw-Hill.

Nascimento, R. S. and F. S. Albuquerque. (2018) Estudo de desempenho à fadiga de base cimentada tipo BGTC na BR-101/SE. *Transportes*, v. 26, n. 1, p. 21-36. DOI: 10.14295/transportes.v26i1.1358.

Nogami, J. S. and D. F. Villibor. (1981) A new soil classification system for pavement applications. *Proceedings of the Brazilian Symposium of Tropical Soils in Engineering*. Rio de Janeiro: COPPE/CNPq/ABMS.

Parente, E. B. (2002) *Avaliação do comportamento mecânico das misturas de solo-cimento e fosfogesso e cimento para uso na construção rodoviária*. Dissertação (Mestrado). Universidade de São Paulo, São Carlos.

Parreira, A. B.; C. A. T. Carmo and F. J. C. Cunto. (1998) Estudo do módulo de resiliência de materiais usados em pavimentação. In *Anais da XXXI Reunião Anual de Pavimentação*, v. 1, p. 233-247.

Pezo, R. F.; G. Claros; W. R. Hudson and K. H. Stokoe. (1992) Development of a reliable resilient modulus test for subgrade and non-granular subbase materials for use in routine pavement design. Austin, US: TxDOT (Research Report 1177-4F).

PCA (1992) Soil-cement laboratory handbook. Skokie, US: Portland Cement Association.

Prusinski, J. and R. S. Bhattacharja. (1999) Effectiveness of Portland cement and lime stabilizing clay soils. *Transportation Research Record*, vol.1, p. 215-227. DOI: 10.3141/1652-28.

Puppala, A. J.; A. Pedarla and T. Bheemasetti. (2015) *Chapter 10 - Soil modification by admixtures: concepts and field applications. Ground Improvement Case Histories Chemical, Electrokinetic, Thermal and Bioengineering*. Texas: Department of Civil Engineering, The University of Texas at Arlington, p. 291-309.

Salehi, M.; M. Bayat; M. Saadat and M. Nasri. (2021) Experimental study on mechanical properties of cement-stabilized soil blended with crushed stone waste. *Geotech Engineering and Testing*, v.25, n.6, p. 1974 – 1984. DOI: 10.1007/s12205-021-0953-5.

Sant'Anna, G. L.; C. C. Machado; C. A. B. de Carvalho; D. C. Lima and D. C. M. Fernandes (2003) Comportamento resiliente de um solo argiloso da região de Viçosa-MG no estado natural e estabilizado com cimento e alcatrão fracionado. *Revista Árvore*, v.27, n.3, p. 269-278. DOI: 10.1590/S0100-67622003000300001.

Scrivener, K. (2003) Calcium aluminate cements. In: Newman, J. and B. S. Choo (Editors) *Advanced concrete technology*. v. 3, pp. 1-31. Butterworth-Heinemmann, Oxford, UK, 2003. DOI: 10.1016/B978-075065686-3/50278-0.

Singh, R. and D. Patel. (2017) Modification of strength properties of soil-aggregate system on cement addition. *Engineering Science and Technology*, v.9, n.3, pp 1-10, 2017. DOI: 10.4314/ijest.v9i3.1.

Simoni, J. P. S. C. (2019) *Contribuição acerca da dosagem e do comportamento de misturas solo-agregado-cimento para uso em camadas de pavimentos*. Dissertação (Mestrado). Universidade de São Paulo, São Carlos.

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 XXXIII ANPET-Associação Nacional de Pesquisa e Ensino em Transportes (Balneário Camboriú, SC)*, Rio de Janeiro: ANPET, p. 2028 - 2039.

Souza, M. L. (1981) *Método de projeto de pavimentos flexíveis*. Rio de Janeiro: DNER - IPR.

Suebsuk, J.; S. Horpibulsuk; A. Suksan; C. Suksiripattanapong; T. Phoongernkham and A. Arulrajah. (2019) Strength prediction of cement-stabilised reclaimed asphalt pavement and lateritic soil blends. *International Journal of Pavement Engineering***,** v. 20, n. 3, pp. 332-338. DOI: 10.1080/10298436.2017.1293265.

Svenson, M. (1980) *Ensaios triaxiais dinâmicos de solos argilosos*. Dissertação (Mestrado). Universidade Federal do Rio de Janeiro, Rio de Janeiro.

Yoder, E. J. and M. W. Witczak. (1975) *Principles of pavement design*, 2nd ed. New York: Wiley.