UNIVERSITY OF SAO PAULO
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Study on factors affecting the mechanical behavior of soil-aggregate-cement mixtures

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UNIVERSIDADE DE SÃO PAULO
ESCOLA DE ENGENHARIA DE SÃO CARLOS

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Estudo sobre fatores que afetam o comportamento mecânico de misturas solo-agregado-cimento

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Study on factors affecting the mechanical behavior of soil-aggregate-cement mixtures

Dissertation submitted to the Department of Transportation Engineering of the Sao Carlos School of Engineering of the University of Sao Paulo (STT/EESC-USP), as fulfillment of the requirements for the Master's Degree in Sciences.

Advisor: Ana Paula Furlan

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1. Estabilização de solos. 2. Base cimentada. 3. Cimento Portland. 4. Solo-agregado-cimento. I. Título.

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"A simplicidade é o último degrau da sabedoria".

(Khalil Gibran)

ABSTRACT

VALOURA, L. R. **Study on factors affecting the mechanical behavior of soil-aggregate-cement mixtures**. 2021. 118 f. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2021.

Stabilization is a practice that improves the properties of geotechnical materials for application in pavement layers. Moreover, this technique presents a practical and economical solution for soils considered problematic in pavement constructions. The soil-aggregate-cement (SAC) mixture results from the chemical and physical stabilization and has been used in pavements for high and very high-traffic volume roads, mainly due to its mechanical behavior. However, there are few studies in the technical literature addressing the mechanical behavior of SAC mixtures, in addition to the absence of a specific standard for the dosage of this mixture. The objective of this research was to contribute to the study of the mix design of soil-aggregate-cement mixtures (SAC) and to understand the effect of factors, such as materials proportion, cement type, and composition of the aggregate, on their mechanical behavior. As a complement to the study, in order to improve the production efficiency and ensure traffic operational safety in situations of pavement construction and rehabilitation, the possibility of reducing traffic opening time was also analyzed. The experimental program aimed to compare SAC mixtures using two soil:aggregate ratios 20:80 and 30:70) with three cement contents (3, 5 and 7%) and at three curing times (0, 7 and 28 days). In order to analyze the optimum cement content, the compressive and tensile strengths obtained in the laboratory tests were compared with stresses obtained by the mechanistic analyses of hypothetical pavements. Finally, at the optimum cement content, SAC mixtures were studied at 3 days of curing and with two types of cement (HE and PCC-IP). Besides that, a comparative study of the use of basaltic aggregate replaced by recycled masonry aggregate (RMA) was performed. The results led to the conclusion that SAC mixtures exhibited high values of compressive and tensile strength, and stiffnesses over the curing time and with the increase of cement content. Moreover, SAC mixtures with a higher proportion of the stone skeleton (20:80) showed higher values for the properties analyzed. The study of the cement dosage leads to indicate a cement content of 5% for all SAC mixtures. At 3 days of curing all mixtures showed values of UCS and ITS higher than the stresses computed, but it should be highlighted that mixtures with HE presented the highest strength values. The mixtures with RMA showed feasibility for use on low-volume roads.

KEYWORDS: soil stabilization, cemented base course, Portland cement, soil-aggregate-cement.

RESUMO

VALOURA, L. R. **Estudo sobre fatores que afetam o comportamento mecânico de misturas solo-agregado-cimento**. 2021. 118 f. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2021.

A estabilização é uma prática que melhora as propriedades de materiais geotécnicos para aplicação em camadas do pavimento. Além disso, essa técnica apresenta-se como uma solução prática e econômica para solos considerados problemáticos em obras de pavimentação. A mistura solo-agregado-cimento (SAC) é resultante das estabilizações química e física, e vem sendo utilizada em pavimentos de tráfego pesado e muito pesado, principalmente por apresentar bom comportamento mecânico. Entretanto, poucos são os estudos na literatura técnica que abordam o comportamento mecânico de misturas SAC, além da ausência de uma norma específica para dosá-las. O objetivo desta pesquisa foi contribuir para o estudo da dosagem de misturas solo-agregado-cimento (SAC) e compreender o efeito de fatores como a proporção dos materiais, tipo de cimento e natureza do agregado, no seu comportamento mecânico. Como complemento do estudo, a fim de melhorar a eficiência de produção e garantir a segurança operacional do tráfego em situações de construção e reabilitação de pavimentos também foi analisada a possibilidade de abertura do tráfego em menor tempo de cura. O programa experimental teve como objetivo comparar misturas SAC para duas proporções solo:agregado (20:80 e 30:70) em três teores de cimento (3, 5 e 7%) e três tempos de cura (0, 7 e 28 dias). Para o estudo do teor ótimo de cimento, as resistências à compressão e à tração obtidas em laboratório foram confrontadas com tensões obtidas pela análise mecanicista de pavimentos hipotéticos. Por fim, no teor ótimo de cimento, misturas SAC foram estudadas aos 3 dias de curas e dois tipos de cimento (CP V-ARI e CP II Z-32), e foi realizado um estudo comparativo do uso do agregado basáltico substituído pelo agregado misto reciclado (ARM). Os resultados levam a concluir que as misturas SAC apresentaram altos valores de resistência à compressão e à tração, e de rigidez ao longo do tempo de cura e com o aumento do teor de cimento. Além disso, as misturas SAC 20:80 apresentaram maiores valores para as propriedades. O estudo da dosagem de cimento permitiu indicar o teor de 5 % para todas as misturas SAC. Aos 3 dias de cura, todas a misturas apresentaram valores de RCS e RTCD mais elevados que as tensões calculadas, mas as misturas com o CP V-ARI obtiveram os maiores valores de resistência. As misturas com ARM mostraram a viabilidade desse agregado para uso em rodovias de baixo volume de tráfego.

PALAVRAS-CHAVE: estabilização de solos, base cimentada, cimento Portland, solo-agregado-cimento.

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1. INTRODUCTION

1.1. Research context and problem statement

Soils are widely applied as a material in subgrade, subbase and base layer of pavement structures. Before using them in highway construction, it is necessary to evaluate their physical and mechanical characteristics, in order to meet the requirements for use in pavement layers.

However, local soils often do not have the desired properties to withstand traffic loading. Therefore, it is important to seek technical and economic alternatives, so that constructions can achieve efficient and quality materials logistics, while meeting the requirements and specifications of the design. Usually, solutions are aimed at material replacement or stabilization.

Stabilization is a technique capable of improving the properties of soils considered poor, especially in terms of strength. The properties that present the most relevant improvements after stabilization are strength, permeability, compressibility, and durability (GILLOT, 1987).

In general, stabilization may occur by mechanical or chemical procedures. Mechanical stabilization might be achieved by applying external compaction energy or by adjusting the particle size distribution, while chemical stabilization uses chemical additives. These types of stabilization are used separately or in combination. Choosing the most suitable stabilization procedure will depend on the characteristics of the local material, technical feasibility, and economic and environmental reasons. The combination of stabilization procedures can make the mixture denser and less permeable, thus improving its strength and reducing its expansion (BERNUCCI et al., 2008).

In chemical stabilization, Portland cement has been increasingly used in field applications as a binder, since it can confer high strength and stiffness, and reduce soil expansion in an efficient and effective way. However, the enhancement of these properties also depends on soil characteristics, such as plasticity, particle size distribution, and chemical and mineralogical composition, in addition to the amount of cement to be used for effective stabilization. The selection of the soil and type and content of cement is closely related to traffic, climate and strength and durability required for design purposes. Moreover, other factors such as compaction and curing conditions may influence the strength gain of cement-stabilized soils (GUTHRIE et. al, 2002).

Soil-aggregate-cement (SAC) mixtures, which stem from the combination of chemical stabilization (using Portland cement) and physical stabilization (due to the adjustment of the proportions of mineral aggregate and soil), may offer good mechanical performance with high strength, stiffness, and stability. SAC mixtures can also present economic and environmental advantages, since local soil can be used or materials from deteriorated pavement layers can be recycled (SIMONI et al., 2019).

SAC mixtures have been used as base and sub-base of high and very high traffic volume roads. However, few studies in the technical literature address issues regarding the dosage of SAC mixtures, as well as the factors that might influence their mechanical behavior, fatigue, and permanent deformation.

In Brazil, standardized methods are commonly used for the dosage of materials such as soil-cement and cement treated crushed rock. Regarding SAC mixtures, the technical specification ET-DE-P00/007 (DER-SP, 2006a) provides guidance on the production, execution, acceptance, and measurement of the services in subbases and/or bases in road construction. In this specification, it is mentioned that the cement content to be adopted must meet the compressive strength and the indirect tensile strength specified in the design, for 28 days of curing.

Another point of interest about SAC mixtures concerns the production efficiency in the field. The aim is to understand the evolution of the mechanical properties in shorter curing times, in order to lead to continue with the construction of other layers and reduce the traffic opening time (TOT), which can positively impact the operation of highways regarding traffic safety and comfort.

Therefore, this research aimed to understand the effects of factors in the soil-aggregate-cement mixture, such as the materials proportion, cement type and composition of the mineral aggregate, and its dosage, considering the mechanical behavior in relation to the structural responses of hypothetical pavements.

1.2. Objectives of this research

This research aims to study the feasibility of using soil-aggregate-cement (SAC) mixtures as subbase and/or base in pavements. The main objective of this investigation is to understand the mechanical behavior of soil-aggregate-cement (SAC) mixture, regarding dosage aspects for pavement layers in high and very high traffic volume roads.

To achieve this goal, specific objectives are to:

- assess the effect of curing time and cement content on mechanical properties;
- evaluate the influence of material proportion (aggregate:soil), cement type and aggregate type (basaltic aggregate or recycled masonry aggregate);
- contribute to the selection of the cement content, linking dosage aspects to mechanistic analysis of hypothetical pavements;

- understand the strength gain over time and to study the feasibility of early traffic opening time (TOT) to anticipate construction.

1.3. Dissertation structure

This text is divided into five chapters. Chapter 1 is an introduction about the subject, the research objectives and the addressed problem. Chapter 2 discusses about the soil stabilization and the addition of Portland cement, the dosage and mechanical behavior of SAC mixtures and the use of recycled aggregate in soil stabilization. Following, Chapter 3 describes the experimental program, material characterization, laboratory tests and the statistical methods used. Chapter 4 presents and discusses the results and the analyses of laboratory tests. Finally, Chapter 5 is about the conclusions and suggestions for further studies.

2. LITERATURE REVIEW

This chapter initially introduces the importance of soil stabilization and the use of Portland cement as an additive for geotechnical materials. Then, discussions are held on the dosage and mechanical properties of SAC mixtures. Lastly, the use of recycled aggregates in cemented mixtures is analyzed in order to show the advances of this material.

2.1. Soil Stabilization

Soil stabilization is a procedure applied in several engineering projects for enhancing soil original properties. In pavements, this technique is used in the construction of base and subbase layers of highways, railroads, and airports, improving properties such as strength, stiffness, permeability, compressibility and durability (GILLOT, 1987).

Usually, soil stabilization is divided into mechanical and chemical procedures. While mechanical stabilization involves physical processes, e.g. compaction and particle size distribution adjustment, chemical stabilization takes place due to the incorporation of additives to the geotechnical material. These procedures might be used individually or in combination, depending on the characteristics of the local soil and on economic and environmental reasons (GILLOT, 1987).

In mechanical stabilization, the compaction and particle size adjustment promote the material densification, thus improving its strength and decreasing its permeability and compressibility. The compaction occurs by the application of external energy, which causes reduction of voids and densification of the material, whereas the particle size adjustment involves the arrangement of particles, caused by partial filling of the voids with finer particles, forming a well-graded mixture (BERNUCCI *et al.*; 2008). The use of natural soil associated with gravel or crushed stone are traditionally used in soil-aggregate mixtures. However, alternative materials as recycled aggregates and waste or recycled materials (such as civil construction waste, industry waste, chopped tires and crushed glass) have been increasingly considered in pavement layers construction as alternative and sustainable materials (LEITE *et al.*; 2011; BESSA *et al.,* 2016; PACHECO-TORRES *et al.*, 2020).

In chemical stabilization, the use of hydraulic binders promotes cohesion between the particles of soil. The main benefits of this type of stabilization are related to the increase of material strength (compressive and tensile) and stiffness (BERNUCCI *et al.*, 2008). Materials such as hydrated lime, Portland cement, industrial by-products (e.g. fly ash, blast furnace slag), polymers, fibers, and others, can be used as stabilizers agents (RAHMAN, 1986; MILLER *et al.*, 2000; PUPPALA *et al.*, 2015; JAYANTHI *et al.*, 2016; BEHNOOD, 2018). The selection of binder most depends on the soil type, the required strength and other criteria, such as the availability of material (PUPALLA *et al.*, 2015).

2.2. Soil stabilization with Portland cement

Portland cement has been widely applied as a stabilizer agent aiming to improve the properties of soils and aggregates used as materials for base and subbase in pavement layers. Cemented materials present superior performance when compared to others (BEHNOOD, 2018). Many studies about cemented materials reported that these mixtures have high strength and durability. Additionally, since cement is a readily available product, the mixing technique is simple and may reduce material costs in some cases, which means that cement stabilization may be a good option for pavement applications (JEGANDAN *et al.*, 2010; FEDRIGO *et al.*; 2017; PUPPALA *et al.*, 2016; BEHNOOD, 2018).

The formation of cementitious compounds, produced from physicochemical reactions, is the main mechanism of chemical stabilization with Portland cement and is responsible for enhancing shear strength properties and to avoid swelling and shrinkage effects (PUPPALA, 2015).

In the typical composition of clinker, the main calcium silicates phases present in Portland cement are (i) tricalcium silicate ($3CaO.SiO_2$) or C_3S, (ii) dicalcium silicate ($2CaO.SiO_2$) or C_2S, (iii) tricalcium aluminate ($3CaO.Al_2O_3$) or C_3A, and (iv) tetracalcium aluminoferrite ($4CaO.Al_2O_3.Fe_2O_3$) or C_4AF. The C_3S and C_2S are called silicate phases, and they influence directly in the rate of strength development (hardening), while the C_3A and C_4AF are called aluminate phases, and they are related with the consistency (stiffening) and solidification (setting) (MEHTA and MONTEIRO, 2006; TAYLOR, 1997).

Each one of the cement phases has an important role during the hydration process and development of properties, producing gels in the first hours that evolve to crystals, thus increasing the material strength and durability. When the cement hydration starts, the C_3A immediately reacts with water, followed by C_4AF, C_3S, and C_2S. The characteristics of each phase are briefly explained hereafter (MEHTA and MONTEIRO, 2006; TAYLOR, 1997):

i) The C_3S, also called alite, constitutes 35 – 65 % of Portland cement and reacts relatively quick with water during hydration. The major contribution to strength occurs at early ages, up to 28 days (after this age it tends to stabilize, contributing at a lower rate). The alite reaction liberates medium heat hydration (an average of 120 cal/g) and gives rise to prismatic crystals of calcium hydroxide ($Ca(OH)_2$ and amorphous calcium silicate hydrates (C-S-H), with a fibrous aspect;

ii) The C_2S, also called belite, constitutes 15 – 30 % of Portland cement and reacts slowly during the hydration process. It contributes significantly to long-term strength (after 28 days) and low permeability. The belite liberates medium heat hydration (an average of 60 cal/g), it gives rise to crystals of calcium hydroxide (CH) and calcium silicate hydrates (C-S-H).

iii) The C_4AF, also called ferrite, constitutes 5 - 15% of Portland cement and reacts with water at a moderate speed. Similar to aluminate, ferrite also has a small influence on the strength and produces ettringite and C-A-H. The aluminate reaction liberates medium heat hydration (an average of 100 cal/g);

iv) The C_3A, also called aluminate, constitutes 0 – 15 % of Portland cement and reacts rapidly with water. It contributes significantly to early age strength, but at a lower rate compared to silicate group compounds (up to 7 days and after this time, it tends to stabilize). The aluminate liberates high heat hydration (an average of 320 cal/g) and reacts with gypsum (a source of sulfate that avoids premature stiffening), producing needle-shaped crystals called ettringite, a calcium aluminum sulfate mineral which contributes to stiffening and setting, and calcium-aluminum-hydrate (C-A-H) crystals;

According to Bugge and Bartelsmeyer (1961), cement hydration in granular soils can be considered similar to that of concrete. The soil particles are bonded by contact points of cementitious compounds. For instance, Figure 1 exemplifies the crystals of C-S-H and C-A-H forming a network among soil particles (PRUSINSKI & BATTACHARJA, 1999). These connections provide cohesion to the mixture, which contributes to strength increase and avoids negative effects from moisture absorption, i.e. underground swelling and softening (BUGGE AND BARTELSMEYER, 1961). On the other hand, if the curing does not occur in an efficient way, the cement hydration may lead to shrinkage cracking of the material.

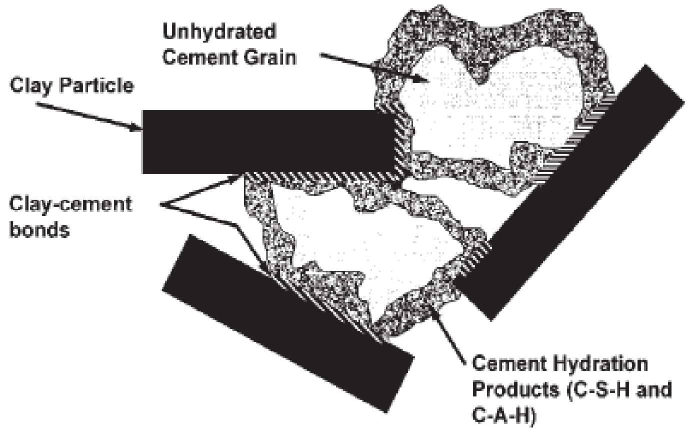

Figure 1: Cement hydration (Prusinski & Battacharja, 1999).

The main factors that may influence the hardening (strength gain over time) and heat of hydration are the temperature of the environment and the composition, fineness and content of supplementary materials of the cement. Several types of cement differ in composition and in the presence or absence of supplementary cementitious materials (e.g. blast furnace slag, pozzolana, silica fumes and fly ash). Each type of cement responds in a particular way to the hydration process, due to different reaction rates of the compounds, which can cause variations in the strength development. (MEHTA and MONTEIRO, 2006).

For instance, cements with large amounts of C_3S and C_3A lead to quick hardening at early ages, and produce more heat in the process. On the other hand, the hardening of cements with a higher amount of C_2S occurs slowly at early ages due to the low heat of hydration, and the strength continues to increase at ages above 100 days. The heat developed during the hydration process and moisture loss can lead to shrinkage, a common distress characterized by the formation of microcracks that negatively affect the strength and permeability of the material over time (BALBO, 2007). Regarding fineness, cements with finer particles have larger surface areas and thus hydration occurs faster (MEHTA and MONTEIRO, 2006).

It is also important to emphasize the role of compaction energy in the mechanical behavior of cemented materials. According to Balbo (1993), the increase of compaction energy causes better interaction among particles, and thus better results from stabilization, besides avoiding effects such as shrinkage. In Brazil, the standards for pavement base layers require intermediate (12.9 kg.cm/cm³) or modified (27.4 kg.cm/cm³) energy for high and very high traffic volume roads.

The curing process in cemented materials is of upmost importance to assure their strength gain, since the reactions are time-dependent and influenced by moisture conditions. Therefore, it is necessary to prevent water evaporation in order to promote the formation of cementitious compounds. Time and curing conditions might interfere in the mechanical properties and durability of cemented mixtures. As long as curing is performed effectively, the cemented material hardens and improves (MEHTA and MONTEIRO, 2008). Therefore, it is crucial to analyze the variation of properties over time. Proper curing time and conditions allow the cemented material to meet the strength required by the pavement design.

Table 1 summarizes the composition and main characteristics of cement types produced in Brazil that are commonly used in pavement layers. The cement types most used in pavement layers are divided into five groups, according to Brazilian Portland cement association (ABCP, 2002): Type OPC (general use or ordinary Portland cement), Type PCC (Portland composite cement, divided into slag – S, pozzolan – IP, and limestone filler - F), Type IS (Blast furnace slag Portland cement), Type IP (pozzolanic Portland cement), and Type HE (high early strength Portland cement). The cement types are classified in terms of the presence of supplementary cementitious materials and the strength property. It is noteworthy that the production of ordinary Portland cement (Type OPC) decreased in Brazil and its use has been replaced by Type PCC cement in construction industry. It should be highlighted that in the column "Brazilian nomenclature", the numbers 32 and 40 (in the cements GU to IP) refer to the minimum compressive strength (MPa) at 28 days in the mortar, guaranteed by the manufacturer.

Table 1: Types of cement produced in Brazil and used in pavement layers.

Cement type	Mineral additions	Brazilian nomenclature (ABCP, 2002)	Main characteristics
OPC	Slag, pozzolana, limestone filler (up to 5 %)	CP I-S 32 CP I-S 40	- Low proportion of mineral additions, - Clinker is the major responsible for the strength gain.
PCC – S	Slag (6% - 34%)	CP II-E 32 CP II E-40	- With slag (S): Higher final strength and durability.
PCC – IP	Pozzolana (6% - 14%)	CP II-Z 32	-With pozzolana (IP):Higher stability, impermeability and durability.
PCC - F	Limestone filler (6% - 10%)	CP II-F 32 CP II-F 40	- With filler (F): Higher workability.
IS	Slag (35% - 70%)	CP III 32 CP III 40	- Higher percentage of slag - Higher final strength and durability.
IP	Pozzolana (15% -50%)	CP IV 32	- Higher percentage of pozzolana - Higher final strength and durability.
HE	Carbonaceous materials (up to 5%)	CP V – ARI	- Higher strength in the first days of application.

According to Table 1, the most common additives are blast furnace slag, pozzolana, and limestone filler. PCC is divided into three categories, according to their composition. The additives can be filler, pozzolana, or slag (with percentages varying from 4% to 14%). In general, these additives promote the increase of final strength, the decrease of heat generation, the reduction of permeability, the enhancing of durability and, the improvement of workability. IS cement may contain from 35% to 70% of furnace slag and IP cement contains 15% to 50% of pozzolana. Thus, one may notice that increasing mineral additions improve cement characteristics and properties.

HE cement should be considered an interesting material to be used in pavement construction, considering that it achieves higher strength than other cement types at early ages (up to 7 days) and this can indirectly be advantageous regarding the production efficiency. HE cement would affect the phases of construction, maintenance and reconstruction (mainly those that involve pavement-recycling processes). HE or CP V-ARI results from the adoption of different dosages of limestone and clay in the clinker production, as well as the finer grinding during the manufacturing process, so that when reacting with water, the cement can provide high strength with greater speed. However, it is important to warn that for this type of cement there is a risk of cracking due to heat of hydration.

Cement-stabilized soils and aggregates are already widely used as material for base and subbase pavement layers. The cemented materials most commonly used in pavement layers are: cement modified soil, soil-cement, soil-aggregate-cement, cement treated crushed rock, and roller-compacted concrete.

Cement modified soil generally contains between 2 and 4% of cement. Since the cement content is low, this material does not develop high tensile or compressive strengths, but the cement addition reduces its water susceptibility and expansion. This improvement is due to the formation of soil clusters slightly bonded by cementitious compounds resulting from cement hydration (DNIT, 2010; BALBO, 2007). The cement modified soil is commonly applied as a material for subgrade reinforcement.

One can define that soil-cement differs from cement modified soil in its cement content, which is usually greater than 4% by mass. Such higher cement content is necessary so that the material can present stronger and stiffer behavior. Soil-cement becomes interesting in situations where the transport cost associated with material acquisition are high (BALBO, 2007). This mixture can also be applied as material for subgrade reinforcement. However, due to its high strength, soil-cement is commonly recommended as base and/or subbase material for high-traffic volume roads.

Soil-aggregate-cement (SAC) mixtures combine mechanical and chemical stabilization, using cement contents similar to soil-cement. The combination of stabilization techniques makes the mixture denser and less permeable, resulting in strength gain, expansion reduction and deformability control. SAC is applied in base and subbase layers of high-traffic volume roads (BERNUCCI *et al.*, 2008; SIMONI et. al., 2019).

Cement treated crushed rock is a mixture of mineral aggregate with different particle size and a low cement content, normally, from 3 to 4%. This mixture provides high stiffness and low deformation to the base and subbase pavement layers. Despite these good properties, cement treated crushed rock is a heterogeneous and porous material which has a quasi-brittle behavior and may present poor fatigue performance (BALBO, 2007; BERNUCCI *et al.*, 2008).

Finally, roller-compacted concrete can be used as base and/or subbase layers of very high-traffic volume roads. Although it consumes less binder, these mixtures resemble the Portland cement concrete in terms of particle size distribution of aggregates, production and application mode. Nevertheless, this combination results in a stiff and resistant material. (BALBO, 2007).

Figure 2 shows the unconfined compressive strength (UCS) of different types of cemented mixtures at 7 days of curing. It is observed that the cement contents varied from 0 to 10% and the UCS values ranged from 0.05 MPa to 11.32 MPa. In general, as the cement content increases, the UCS values increase as well, however the gain of UCS depends on the type of mixture. For instance, UCS values of cement-modified soil (MACEDO, 2004) varied from 0.05 to 1.06 MPa whereas UCS values of soil-cement (PARENTE, 2002) ranged from 2.67 to 7.87 MPa. Interestingly, UCS curves of cement-modified soil and soil-cement seem to overlap from 3% of cement.

The UCS values of mixtures containing mineral aggregates, such as cement treated crushed rock (NASCIMENTO *et al.*, 2018), soil-aggregate-cement (SIMONI, 2019), and roller-compacted concrete (BORRÉ, 2017) are higher than the UCS values of mixtures containing only soil. Figure 2 also shows that, for a certain cement content (3%), the UCS values of the soil-aggregate-cement mixture lie between the UCS of soil-cement and cement treated crushed rock.

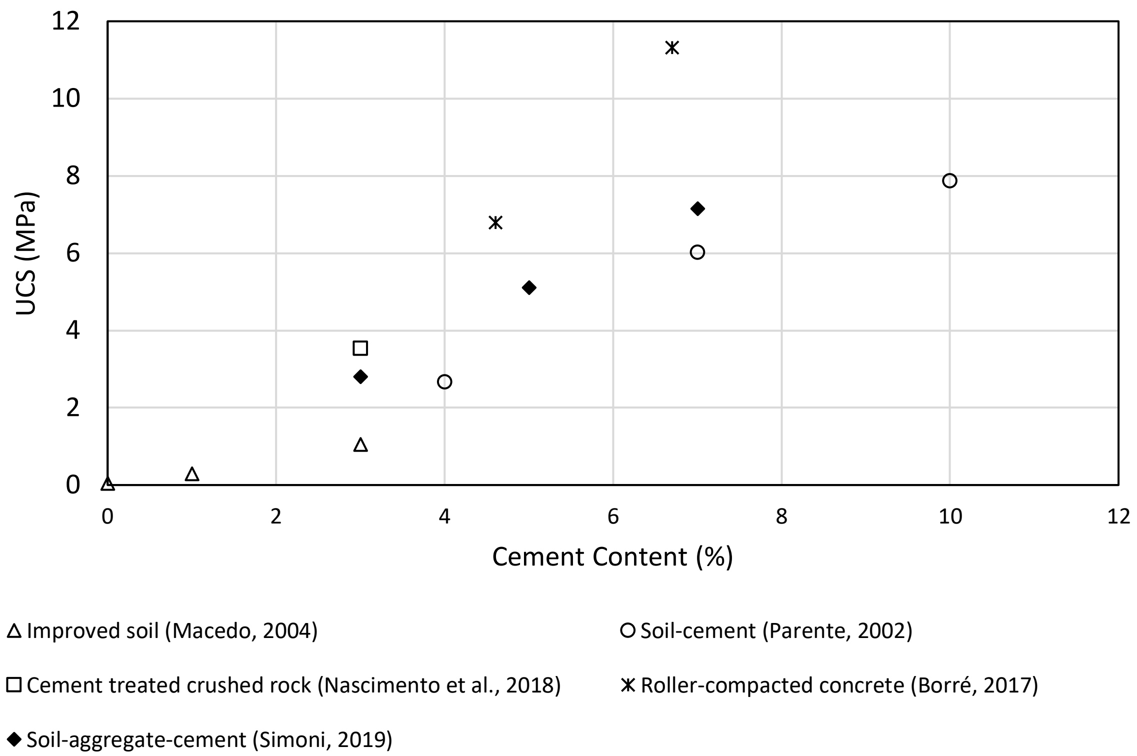

Figure 2: UCS values to cemented materials.

2.3. Soil-Aggregate-Cement Mixture

Soil-aggregate-cement (SAC) mixtures have been used to improve the performance of high-traffic volume roads in Brazil, although their mixture design protocol and cement dosage criteria have not yet been established.

The mechanical behavior of SAC mixtures is influenced by several factors, such as the type of materials, cement content, materials proportion, curing time and compaction energy. In this way, it is important to understand the effect of these factors on SAC mixture behavior.

2.3.1. Cement content and mixture design

Mixture design conventionally involves the determination of adequate materials proportion, cement content, compaction energy, optimum moisture content and material characterization to fulfill the mechanical and economic requirements.

Regarding cement content, studies have found that this factor directly influences the mixture strength gain (BASHA, *et al.*, 2005; HORPISBULSUK *et al.*, 2010; BAN & PARK, 2014). The amount of cement used must lead the mixture to meet the strength properties required to withstand traffic loading over service life. In addition, other issues may be involved in cement dosage, such as the mineral composition of geotechnical materials and type of cement. Since these factors influence on the efficiency of cement stabilization, then the availability of the material may also become a bottleneck in the dosage procedure (GUTHRIE *et al.*, 2002; SILVESTRE JR., 2002; ARANHA, 2012; SIMONI *et al.*, 2019).

In Brazil, there is not a design method for SAC mixtures; for this reason, other cemented materials, such as soil-cement and cement treated crushed rock, may guide the understanding of the structural response of pavements. The specification of Sao Paulo Department of Transportation for SAC mixture (ET-DE-P00/007, DER-SP, 2006a) recommends that the cement content to be used in the mixture is the one capable of satisfying the required strength in the pavement design.

In soil-cement applications, the PCA (Portland Cement Association) method, also known as the mechanical method, is widely used for mixture dosage. Brazilian standards such as E-35 (ABCP, 1986) and NBR 12253 (ABNT, 2012) are based on the PCA method. The dosage parameter is the UCS value at 7 days of curing, which must be at least 2.1 MPa. The two standards differ with regard to the initial cement content. The NBR 12253 (ABNT, 2012) suggests an initial cement content in function of the soil HRB classification, while E-35 (ABCP, 1986) provides abacuses for estimating the soil maximum dry density (MDD) from its amount of silt, clay, coarse sand and gravel.

Concerning the dosage of cement treated crushed rock, the design is guided by the NBR 12261 Brazilian standard, which presents a method similar to that reported by Balbo (2007). The method uses the results of UCS tests to determine the optimum cement content and the moisture content to be used. First, UCS tests are performed on samples with cement contents ranging from 3% to 5% at 7 and 28 days of curing. The content that promotes the higher strength is chosen, then UCS tests are performed again with varying optimum moisture content in order to obtain the highest strength.

According to Prusinski & Battacharja (1999), the dosage study allows to identify the cement content that modifies the soil properties towards achieving the strength and durability required, as in the case of soil-cement and cement-treated base.

Bahar *et al.* (2004) tested a clayey sandy soil using 0 to 15% of cement and they observed that contents higher than 8% provided better compressive strength at the dry state and after 48 hours of water immersion. For these authors, the improvement of strength was attributed by the partial filling of the voids with cementitious products. On the other hand, Basha *et al.* (2005) studied a cost-effective dosage for a soil-cement with rice husk addition. The research considered a cement dosage based on plasticity and strength characteristics. The authors found that 6 to 8% of cement was enough to increase the strength and reduce plasticity index.

Later, Horpibulsuk *et al.* (2010) investigated the influence of the cement content on the unconfined compressive strength (UCS) in soil-cement mixtures, as exhibited by Figure 3. The chart shows that the behavior of the mixtures is similar, despite the different compaction energy. In general, cement addition improves UCS; nevertheless, the intensity of strength gain depends on the cement content. Accordingly, the authors classified UCS development in three zones, namely:

i. the *active zone* (up to 11% cement content): UCS increases significantly due to the partial filling of pores by cementitious products;
ii. the *inert zone*, (cement content between 11% to 30%): UCS grows slightly,
iii. the *deterioration zone* (cement content above 30%), UCS decreases slightly, since the amount of water is not enough to trigger the hydration of cement particles.

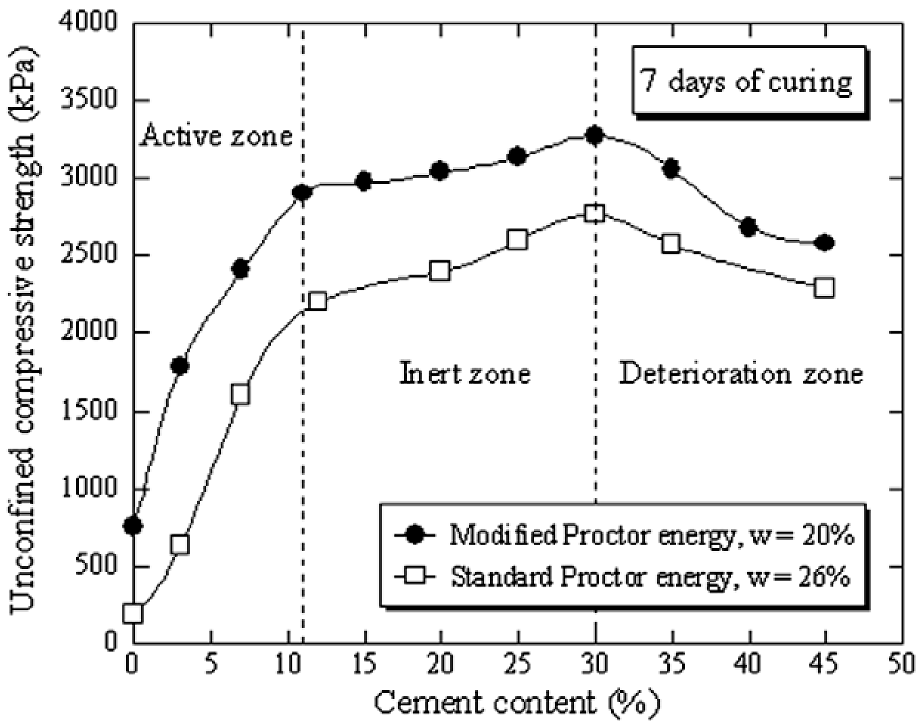

Figure 3: Development of UCS as a function of cement content in soil-cement mixture (Horpibulsuk *et al.*, 2010).

Joel *et al.* (2011) reported a behavior similar to that of Figure 3 for mixtures with lateritic soil using from 0 to 12% of cement, i.e. which the addition of cement increased significantly the UCS. Considering an economic criterion, the authors stated that 6% of cement is quite effective and sufficient for this type of mixture. Parente *et al.* (2002) also concluded that cement contents higher than 10% do not lead to significant strength increases, as they observed strength gains of 200% for cement contents ranging from 4 to 7%, and of 25%, for cement contents varying from 7% to 10%.

It is worth emphasizing that the most used cement contents lie between 3 and 8% and depend on the particle size distribution of the geotechnical material. Some studies recommend a range between 6 and 8%, based on efficiency and economic aspects, as well as improvements in plasticity, mechanical and compaction properties (BASHA *et al.*, 2005; JOEL *et al.*, 2011; ASGARI *et al.*, 2013).

Another key factor of the dosage of cemented mixtures is the cement type used. Silvestre Júnior (2002) analyzed soil-cement mixtures using different types of cement (CP III-40, CP II-E 32 and CPV-ARI), and showed that each cement led to particular mechanical behaviors. The author found that, at 28 days of curing, the strength gain of mixtures with CP III-40 (IS) was 11% and 23% higher than that of mixtures with CP II-E 32 (PCC - IS) and CP V-ARI (HE), respectively. Despite this, mixtures with CP V-ARI showed the highest strength at 7 days of curing.

By comparing studies on cement treated crushed rock, one can notice that some researchers reported cement contents varying from 3 to 5% (HOU *et al.*, 2015; MANDAL *et al.*, 2017; JI *et al.*,2018, NASCIMENTO *et al.*, 2018). Ji *et al.* (2018) analyzed the strength and the resilient modulus of cement treated crushed rock using five different cement contents (from 3 to 5%, with intervals of 0.5%). The authors observed that the 5% content provided better results at 7 days of curing.

Mixture design is also an issue to be carefully addressed, as the adjustment of amounts of mineral aggregate and soil is essential for providing the maximum density and, consequently, the highest strength and durability. Some studies have verified that the particle size distribution may influence mechanical behavior, especially permanent deformation, stiffness, and shear strength. (CUNNINGAM *et al.*, 2012 ; QAMHIA *et al.*, 2017 ; GAJEWSKA *et al.*, 2018 ; OSOULI *et al.*, 2019).

Soil-aggregate mixtures with high percentages of fines present good workability in the field. However, in terms of compaction, they may present low stability, which is often related to the poor contact between coarse aggregates (YODER E WITCZAK, 1975).

In studies on SAC mixtures, dosage is presented in a different range of cement contents and soil proportions (KAWAHASHI *et al.* 2010; BESSA *et al.*; 2016; BAGHINI *et al.*, 2017; SINGH *et al.*; 2017; SUEBSUK *et al.*; 2017, SIMONI, 2019). Kawahashi *et al.* (2010) studied SAC mixtures composed of stone aggregates and expansive clayey soil in aggregate-soil proportions of 60:40 and 40:60 and five cement contents (from 1% to 5%). Regarding materials proportion, the authors pointed out that both mixtures led to similar UCS values, then the material proportion 50:50 was investigated. Their findings indicated that 5% cement was able to control the expansiveness of the soil and the aggregate skeleton was essential to provide stability to the mixture. Singh *et al.* (2017) also studied a SAC mixture using the 50:50 material proportion. They tested mixtures containing 2%, 4%, and 6% of cement and observed that 6% of cement provided the best mechanical results.

Simoni (2019) investigated 20:80-SAC mixtures composed of lateritic sandy soil, basaltic mineral aggregates and three cement contents (3, 5 and 7%). The cement dosage was based on the laboratory test results and acting stresses computed by mechanistic analysis. The author indicated 5% of cement as an optimum content. Fedrigo *et al.* (2019) used reclaimed asphalt pavement (RAP) as aggregate in SAC. They tested mixtures with lateritic soil, RAP:soil proportions of 20:80, 50:50, and 30:70, and cement contents of 2% and 4%. Results indicated that properties such as strength, stiffness, and flexibility improved with the increase of RAP and cement.

The Sao Paulo-DOT technical specification for SAC mixtures (DER-SP, 2006) brings some important recommendations when dealing with these mixtures, namely:

1) the amount of dried soil to be incorporated into the mix should be up to 40% (by mass) and should not contain organic matter;

2) the SAC particle size distribution must lie within one of the two ranges, while complying with the tolerance specified for each sieve (in Table 2).

Table 2: Particle size range of the SAC mixture according to ET-DE-P00/007 (DER-SP, 2006).

Sieve		% in mass, passing		Tolerance
ASTM	mm	Range I	Range II	
2"	50	100	100	-
1"	25	-	75 – 95	± 7%
3/8"	9.5	30 – 65	40 – 75	± 7%
n°4	4.8	25 – 55	30 – 60	± 5%
n°10	2	15 – 40	20 – 45	± 5%
n°40	0.42	8 – 20	15 – 30	± 5%
n°200	0.075	2 – 8	5 – 15	± 2%

3) the cement content must meet the pavement design requirements, considering the unconfined compressive and indirect tensile strength at 28 days.

2.3.2. Mechanical behavior of the SAC

Cement addition influences significantly the mechanical behavior of geotechnical materials. Some factors may affect the strength gain, such as the type of material, the cement content, the mixture design, the curing time, and the compaction energy (PRUSINSKI & BATTACHARJA; 1999). Some studies investigated the influence of these factors in the strength of SAC mixtures (BESSA *et al.*, 2016; BAGHINI *et al.*, 2017; FEDRIGO *et al.*, 2019; SIMONI, 2019).

Bessa *et al.* (2016) studied the mechanical behavior of a milled material (from deteriorated soil-aggregate base layer) stabilized with cement. The authors investigated the effect of compaction energy (intermediate and modified), cement content (5 and 6%), and curing time (7 and 28 days) on UCS, ITS and resilient modulus by repeated triaxial test (Mr,t). Results showed that the compaction energy has a significant influence on strength. In addition, the modified energy showed the higher UCS results. At 28 days, the UCS values were approximately 9 and 10 MPa, and ITS values about 1 and 1.2 MPa, for 5% and 6% of cement, respectively. These cement contents led to relatively low changes of UCS and ITS values. Regarding the stiffness, the resilient modulus varied from 8000 to 9000 MPa, for 5% and 6% of cement, respectively. It is important to highlight that resilient modulus was represented by confining model and computed for a confining stress equals to 0.1 MPa. In general, the authors observed increases of 30% of UCS and ITS values from 7 to 28 days of curing.

Simoni (2019) studied the evolution of mechanical properties of a SAC 20:80 (soil:aggregate) using 3, 5, and 7 % of cement. UCS, ITS, and Mrt tests were performed at 0, 7, and 28 days of curing. The author concluded that all properties increased over curing time. However, the major gains occurred from 0 to 7 days of curing. Figure 4 shows the UCS kinetics in order to point out this behavior. Besides that, it also exemplifies that the higher the cement content, the greater the strength.

Based on test results and mechanistic analyses, Simoni (2019) indicated 5% as an optimum cement content for SAC 20:80, which means that the 5% cement content assures the high mechanical properties and the required strength in pavement design. At 7 days of curing, UCS, ITS and Mrt values were 5.11 MPa, 1.03 MPa, and ~8000 MPa, respectively. Simoni (2019) also evaluated diametric resilient modulus test (Mrd) and observed values about 17000 MPa, that is, Mrd values were 2 times higher than the Mrt ones. It is worth mentioning that results from Mr by diametric tests are commonly higher than Mr by repeated triaxial tests in cemented mixtures (SIMONI, 2019).

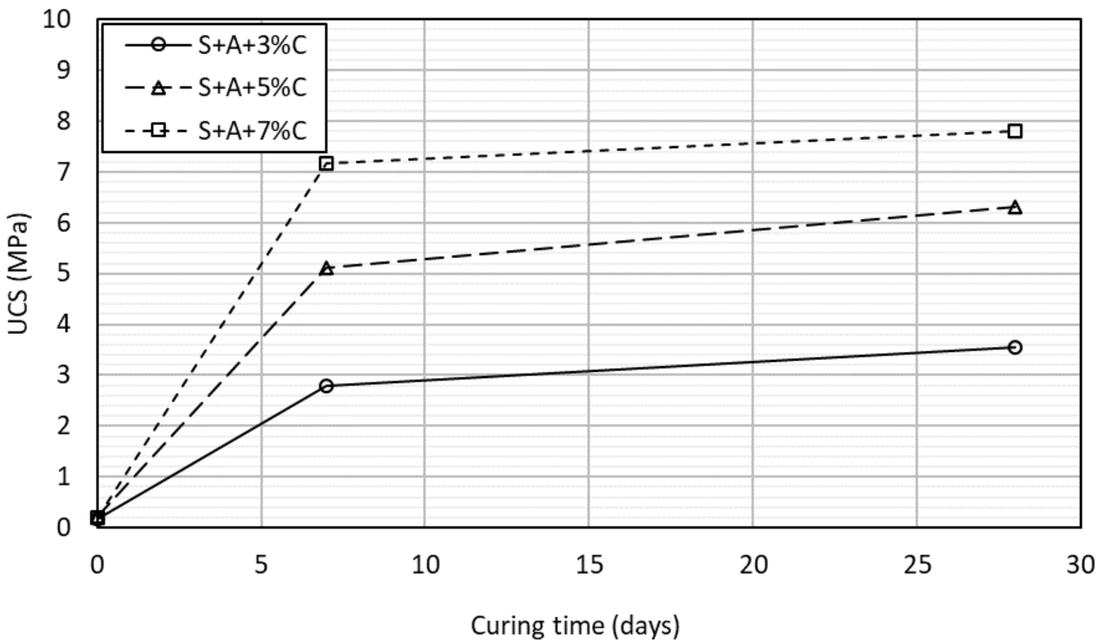

Figure 4: UCS over curing time to a SAC mixture using a cement with pozzolana (PCC-IP/CP II Z-32) (Simoni, 2019).

Singh and Patel (2017) demonstrated the effectiveness of cement stabilization in a soil-aggregate system at 3 days of curing. They evaluated UCS, CBR, and durability (by means of wetting and drying cycles). SAC mixtures contained 2, 4, and 6% of cement. Results revealed that the increase of cement content improved the UCS and CBR (in both soak and unsoaked conditions). In general, the UCS values varied from 1.007 to 1.481 MPa. Regarding durability, the mixtures stabilized with 6% cement had a minor weight loss (~5.7%) after 12 cycles of wetting and drying. Based on these results, the authors indicated 6% as the optimum cement content. It is worth noting that the aforementioned experiment focused on measuring the properties at 3 days of curing, unlike current dosage procedures, in which the measures are taken at 28 days of curing, as in Brazil.

Baghini *et al.* (2017) investigated the combined effect of cement and polymer on soil-aggregate mixtures. At 7, 28 and 60 days of curing, the mixtures reached respective UCS values of 4, 5, and 7 MPa, and ITS values of 0.5, 0.7, and 1 MPa. The UCS gain was more effective between 28 and 60 days (~40%), whereas for ITS, the gain was practically linear (~40%) in both intervals (from 7 to 28 and from 28 to 60 days). Regarding stiffness, Mr,d also showed an increase over time, reaching values of about 15000 MPa at 28 days of curing.

Kawahashi *et al.* (2010) evaluated a SAC mixture composed of an expansive soil and mineral aggregates with a material proportion of 50:50. Their results showed that 5% of cement presented a satisfactory resilient behavior to the mixture, since its Mr was ten times higher than the original soil (1500 MPa). The UCS and ITS values were compatible with soil-cement mixtures. The authors recommended physical and chemical stabilization in order to improve strength properties and to control the expansion of soils, respectively.

2.3.3. Recycled aggregates in soil stabilization

In the past few years, environmental issues have been integrating road construction practices in order to make the process more sustainable and cost-effective. The incorporation of recycled aggregates and waste (from buildings and pavement) in the base and subbase layers of pavements has been growing and may boost pavement-recycling activities.

Many researchers have studied different types of recycled materials for the use in pavement base layers, e.g. recycled masonry aggregate (RMA), recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), crushed clay brick (POON *et al.*, 2006; LEITE *et al.*; 2011; BESSA *et al.*, 2016; SUEBSUK *et al.* 2017; ORIOLI, 2018; 2019; PACHECO-TORRES e VARELA; 2020).

Since recycled aggregates are heterogeneous materials, it is mandatory to know their characteristics and properties, mainly regarding water absorption and density. Molenaar *et al.* (2002) investigated the effect of particle size distribution, degree of compaction and curing time on RCA mixtures. The authors observed that the resilient characteristics and the resistance to permanent deformation are mainly governed by the degree of compaction, while the particle size distribution has a smaller influence on them. According to Leite *et al.* (2011), ceramic-rich materials (such as bricks and roof tiles) produce porous aggregates, which may reduce the mixture density and strength.

Another problem is the physical degradation of recycled aggregates after compaction, which may occur due to their high porosity, low density and high abrasion. Some studies have shown that aggregate breakage by compaction effort changes the particle size distribution and increases the fine fraction of mixtures. Consequently, mixtures using RMA may be less resistant and more susceptible to permanent deformation (MOLENAAR *et al.*, 2002; GRUBBA, 2009; LEITE *et al.*; 2011).

Poon *et al.* (2016) conducted comparative analyses using basalt aggregates (NA), RCA, and crushed clay brick as subbase materials. Their results showed that the mixtures containing RCA and crushed clay presented an increase of optimum moisture content and a decrease of maximum dry density when compared with the mixture containing basalt aggregate. Moreover, the mixture using NA had the best results for CBR in both soaked and unsoaked conditions.

On the other hand, aggregates from concrete structures (such as RCA) may have self-cementing properties due to the presence of anhydrous cement in the mortar. Poon *et al.* (2006) studied the RCA fine fraction and demonstrated a considerable increase of UCS at 7 days, compared to uncured samples. Grubba (2009) and Orioli (2018) also observed self-cementation in soil-aggregate mixtures containing RCA and RMA. It is important to highlight that RMA also has self-cementing properties, although at a low level, since the amount of concrete in this material is smaller, as well as that of anhydrous cement.

A priori, SAC mixtures are not dependent on self-cementation, since cement at adequate curing time and conditions might assure the occurrence of improvements. This creates the possibility to test different materials, regardless of their mineralogical composition. Bessa *et al.* (2016) analyzed a "recycled" SAC, adding cement to a soil-aggregate mixture of a deteriorated pavement layer. The authors obtained satisfactory results for strength. Fedrigo *et al.* (2019) studied SAC containing RAP in different grain sizes, demonstrating the feasibility of using these recycled materials.

3. MATERIALS AND METHODS

This chapter introduces the experimental program developed in this study and presents the characterization of materials, as well as the conditions and methods of tests. In addition, the chapter also presents the statistical methods and tools applied to evaluate data representativeness, to analyze the variables and to build models.

3.1. Experimental program

This study evaluated the effect of materials proportion, cement content, curing time and aggregate type on the mechanical properties of SAC mixtures. Mixtures were divided into two different proportions of mineral aggregate and soil, namely:

(1) SAC 20:80: blend with 20% of soil and 80% of basalt aggregate;
(2) SAC 30:70: blend with 30% of soil and 70% of basalt aggregate.

Three cement contents were incorporated to the mixtures: 3%, 5%, and 7% (by mass). First, the mechanical properties were analyzed at three curing times (0, 7, and 28 days) in order to find the optimum cement content. Thereafter, the 3-days curing time was included in the investigation to observe if it would be possible to anticipate construction procedures.

Concerning the type of aggregate, the experimental program considered mixtures containing basalt aggregate (NA). Complementarily, a mixture using recycled masonry aggregates (RMA) was designed for a material proportion of 30:70 and a cement content of 5%, in an attempt to show how the use of this waste affects the properties of SAC mixtures.

This research was divided into three stages. The first stage focused on dosage issues and was based on material characterization and mixture design. The material characterization consisted of testing physical properties of soil and aggregates, while the mixture design considered the study of mixture composition, in terms of particle size distribution and the use of Proctor compaction parameters to the initial cement dosage. Proctor tests were performed using modified compaction effort (2700 kN.m/m^3), which is recommended by standard specifications for high-traffic volume roads.

The second stage consisted of evaluating mechanical properties of different SAC mixtures and their behavior over curing time. The tests performed were unconfined compressive strength (UCS), indirect tensile strength (ITS), resilient modulus by repeated triaxial test (Mr,t) and diametric resilient modulus test (Mr,d).

The third phase compared laboratory mechanical properties to computed stress of several hypothetical pavement structures, obtained by mechanistic analyses. This procedure led to suggest an optimum cement content, based on a comparison of UCS and ITS values obtained in laboratory tests and acting stress computed for different pavement structures. This analysis was replicated for all mixtures with optimum cement content at 3 days of curing in order to analyze the feasibility of the construction of upper layers earlier. Figure 5 presents the layout of the experimental program of this research.

It is worth mentioning that this investigation is part of a research group about stabilization of geotechnical materials for pavement applications. The research group works on different topics: mixture design focused on cement dosage and the effect of the cement addition on soil-aggregate mixtures; the effect of material proportion, cement type and aggregate type on mechanical properties; fatigue of cemented materials and permanent deformation of soil-aggregate mixtures. Figure 6 shows a scheme of the investigations of the research group and points out this study that was focused on "*influence of factors on SAC mixtures*".

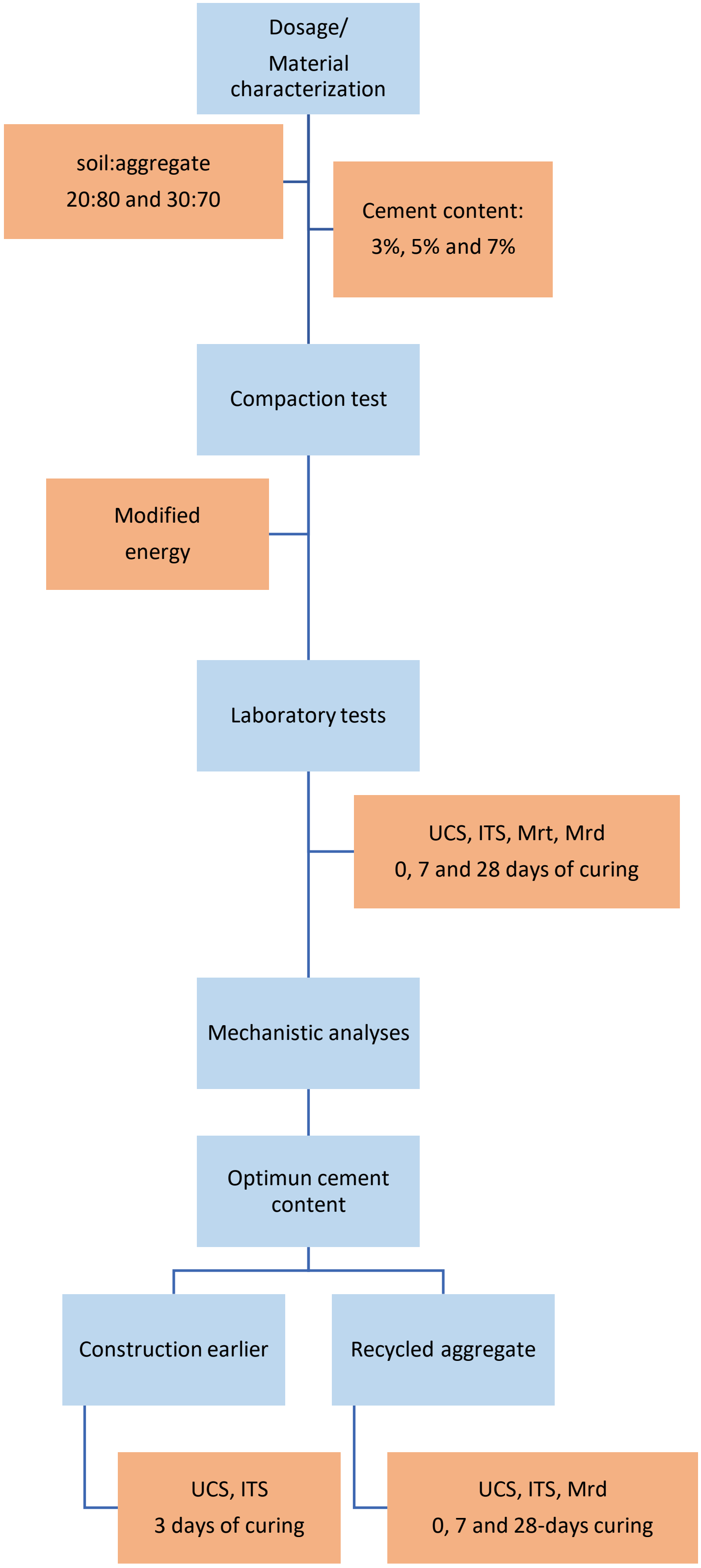

Figure 5: Layout of the experimental program.

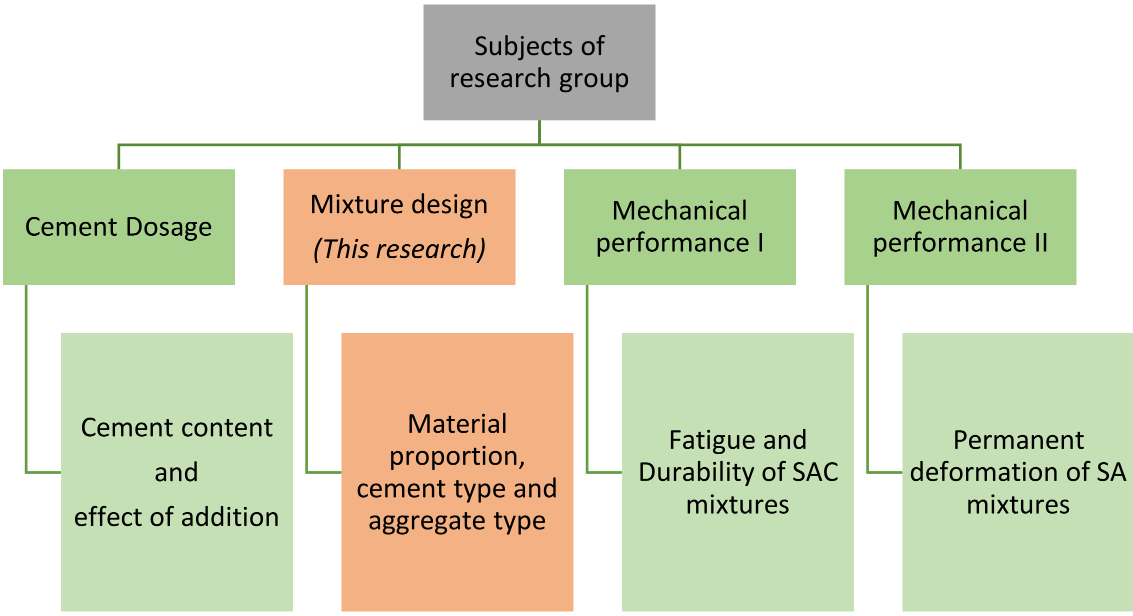

Figure 6: Layout of research group.

3.2. Characterization of materials and mixtures

3.2.1. Soil

The soil used in this study was a sandy lateritic soil (LA'), according to the MCT (Miniature, Compacted, Tropical) classification system proposed by Nogami & Villibor (1981). The material was collected from a cut slope at Professor Luis Augusto Oliveira Highway (SP-215 - km 152+500) located in Sao Carlos-SP. Table 3 presents the soil characterization obtained from previous studies (KAKUDA, 2010; SIMONI, 2019) that used the same material. Figure 7 shows the cut slope where the soil was collected and a sample of the air-dried soil.

Table 3: Characterization of the lateritic soil (LA').

Characteristic	Values
Liquid Limit (LL)	34
Plastic Limit (LP)	21
Plasticity Index	13
% Passing by #200	34
Sand (%)	66
Silt (%)	13
Clay (%)	22
HRB classification	A-2-6
USCS classification	SC
MCT classification	LA'
ρs (g/cm³)	2.663
ρd (g/cm³)	2.068 – Modified energy
OMC (%)	10.4 - Modified energy

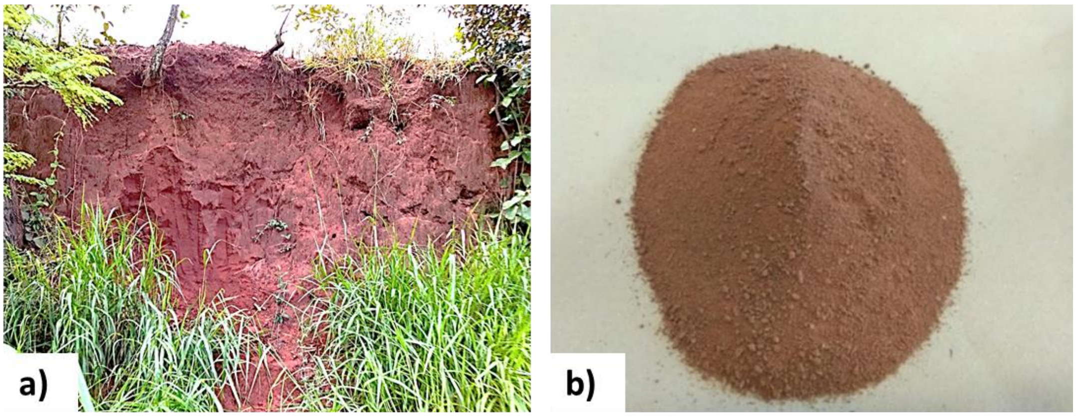

Figure 7: Lateritic soil - a) view of the collect place and b) sample of the air-dried soil.

Simoni (2019) performed CBR test for this soil at OMC and MDD, obtaining a result of 115% and zero swell, for a degree of compaction of 99.3%, and moisture deviation of 0.6%.

The steps of soil preparation consisted of air-drying, pulverization, quartering, passing through sieve 2.00 mm and storing in plastic bags. In addition, the soil hygroscopic moisture content was determined before molding each specimen. Regarding the soil grain size, Figure 8 illustrates the particle size distribution of soil.

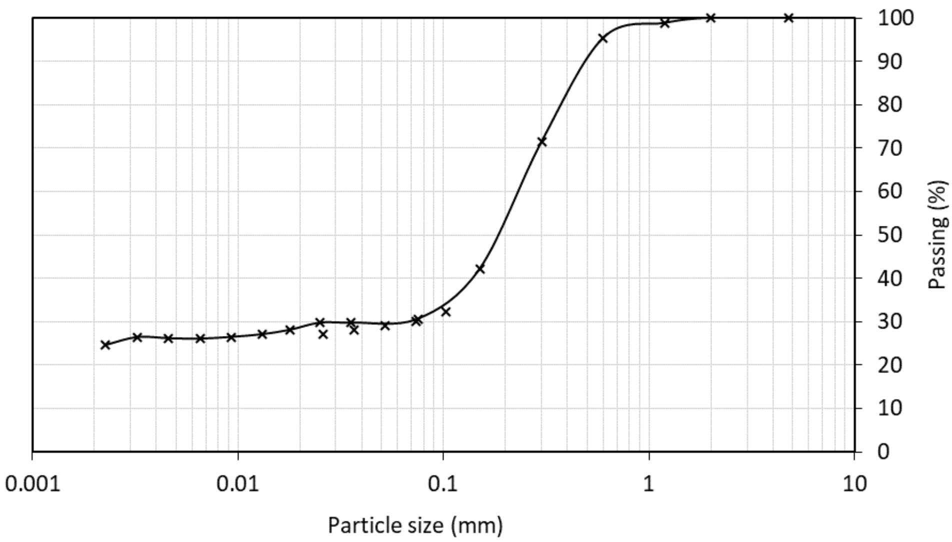

Figure 8: Particle size distribution of the lateritic soil (LA').

3.2.2. Aggregates

Two types of aggregates were used in this study: basaltic mineral aggregate (basalt aggregate - BA) and recycled masonry aggregates (RMA). The BA is from Bandeirantes Group basalt quarry and the RMA was obtained from AMX Ambiental Company, both located at Sao Carlos-SP.

The BA was divided into two fractions: coarse aggregate and fine aggregate with stone dust. The coarse aggregate has particles retained on sieve nº. 4 (4.8 mm) and fine aggregate with stone dust has particles passing through sieve nº.4 (4.8 mm). Table 3 shows the results of BA characterization. The values of apparent specific gravity and water absorption were obtained by previous investigations conducted by Orioli (2018), whereas the Los Angeles abrasion and shape index were characterized in this study. It should be noticed that Los Angeles abrasion test and shape index are in agreement with the reference values of SAC specification (ET-DE-P00/007, DER-SP, 2006a).

Table 3 – Characterization of the basalt aggregate.

Basalt Aggregate physical properties	Value	Standard	Reference Value (ET-DE-P00/007)
Apparent Specific Gravity (g/cm^3)	2.783	DNER-ME 081/98	-
Water Absorption (%)	2.2	DNER-ME 081/98	-
Los Angeles Abrasion Test (%)	17	DNER-ME 035/98	< 50%
Shape index - Flaky (%)	8	NBR 5564/2011	< 10%

Figure 9 exhibits the particle size distribution of basalt aggregate, while Figure 10 shows the quarry where it was collected and details of its fractions (coarse aggregate and fine aggregate with stone dust).

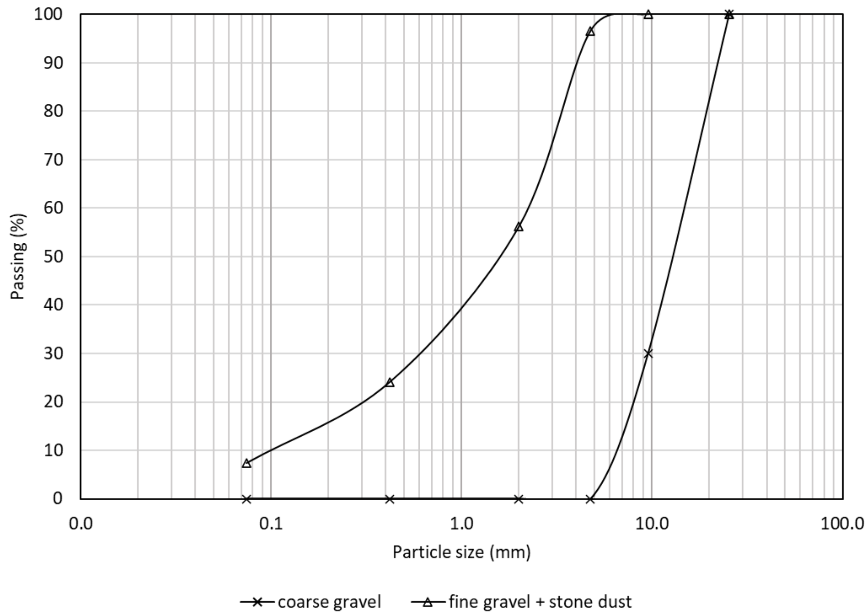

Figure 9: Particle size distribution of basalt aggregate.

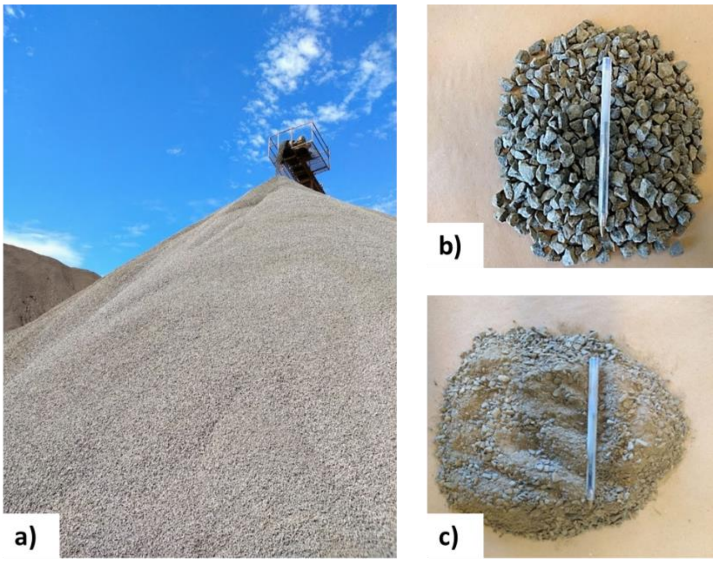

Figure 10: a) view of the basalt aggregate in the quarry, b) coarse aggregate, c) fine aggregate + stone dust.

The RMA was characterized according to NBR 15115/2004 specification, which establishes the requirements for applying recycled materials in subgrade reinforcement, base and subbase layers. Table 4 presents the composition of the RMA. It can be noticed that the RMA is composed by 20% of ceramic materials, 28% of crushed aggregates and 49% of concrete and mortar.

It is important to emphasize that the RMA is composed of 20% of low density of porous materials (bricks/roof tiles and ceramics/tiles), which means that the presence of RMA might result in low strength mixtures. Regarding the undesirable materials, the value of 3% is in accordance with NBR 15115/2004, that recommends from 2% to 3% as an acceptable range.

Table 4: Composition of recycled masonry aggregates.

Composition	ARM
Concrete/mortar (%)	49
Crushed rocks (%)	28
Bricks/roof tiles (%)	18
Ceramics/tiles (%)	2
Undesirable materials (%)	3

Figure 11 shows the materials that compose the RMA, separated according to the groups presented in Table 4.

Figure 11: Composition of recycled masonry aggregates.

Table 5 shows the results of RMA physical characterization. The table also presents the reference values of NBR 15115/04. All physical properties of RMA satisfactorily met the reference values.

Table 5: Characterization of the recycled masonry aggregates.

RMA physical properties	Value	Standard	Reference Value (NBR 15115/2004)
Maximum size (mm)	25.4	-	63.5
Uniformity coefficient	74	-	≥ 10
% Passing in sieve #40 (0.42 mm)	35	NBR 7181/2016	10 a 40
Undesirable materials (%)	3	-	2 a 3 %
Shape index - Flaky (%) - 4.8 mm	20	NBR 7809/2019	≤ 30 %
Los Angeles Abrasion Test (%)	50	DNER-ME 035/98	≤ 55 %
Water Absorption (%)	7.7	DNER-ME 081/98	-
Apparent Specific Gravity (g/cm³)	2.075	DNER-ME 081/98	-

Comparing the results of RMA and NA physical characterization, it is observed that the Los Angeles abrasion test of RMA is 3 times higher than that of NA, indicating that RMA is a soft material and may be prone to breakage by compaction. The water absorption of RMA is also higher than NA (~ 3,5 times higher), probably due to the presence of bricks, tiles and ceramic materials. According to the technical literature, the high abrasion and high water absorption of RMA may reduce strength properties of the mixture containing this material (ORIOLI, 2018). Moreover, NA presented an apparent specific gravity higher than the one of RMA (1.34 times).

The RMA was divided in three fractions. The coarse aggregate has particles retained on sieve nº. 4 (4.8 mm), the fine aggregate has particles passing through sieve nº. 4 (4.8 mm) and powder or sand.

Figure 12 presents the particle size of RMA fractions. It is noteworthy that the curves of coarse and fine aggregates are close, which may hinder the composition of SAC mixture.

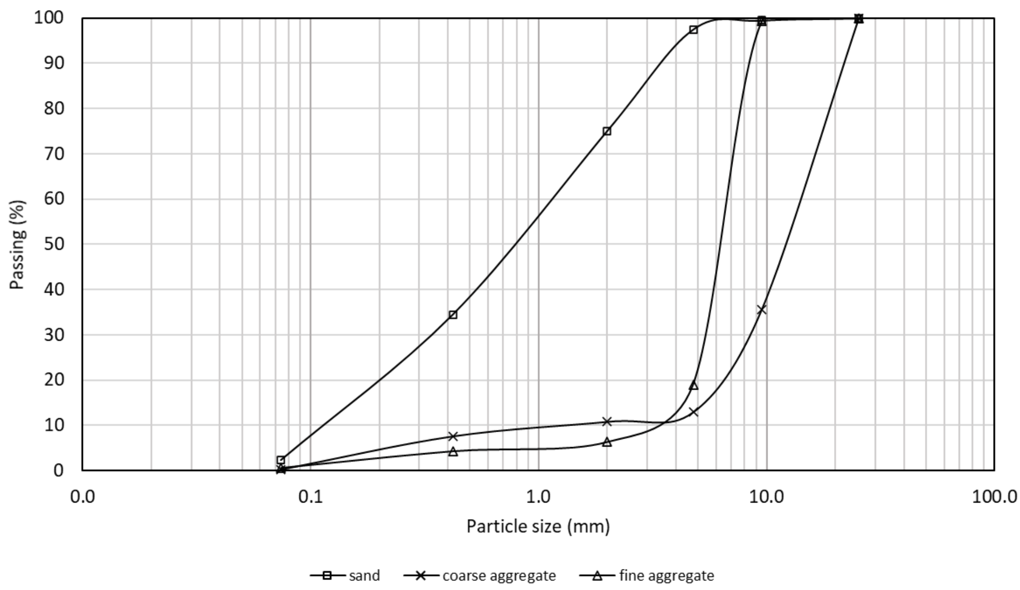

Figure 12: Particle size distribution of recycled masonry aggregate fractions.

3.2.3. Cement

The cement used in this study is classified as high early strength Portland cement - HE (or CP V-ARI, according Brazilian standard NBR 16697:2018). The HE is composed from 90 to 100% clinker and up to 10% of carbonaceous material. The Brazilian standard that recommends the minimum requirements for this type of cement is NBR 16697 (ABNT, 2018). It is worth mentioning that Holcim Company provided the CPV-ARI and, according to the manufacturer, this cement has a unit weight of 30.2 kN/m^3.

HE was select in order to evaluate if its high early strength would lead to anticipate construction phases. The high strengths at the first days of application are a result of the combination of different contents of limestone and clay in the clinker production, in addition to the finer grinding during the manufacturing process. Then, when the cement particles react with water, it acquires high strength quickly.

3.2.4. Mixture design: SAC composition

The particle size distribution of SAC containing NA was fitted to the Range II from the specification of Sao Paulo-DOT (ET-DE-P00/007 - DER-SP, 2006a). This composition was also fitted to the Range II for soil-aggregate specification (ET-DE-P00/006 - DER-SP, 2006b). This was done in an attempt to simultaneously comply with both specification criteria. On the other hand, the composition of SAC 30:70 containing RMA lied within the limits of Range III of the soil-aggregate specification (ET-DE-P00/006 - DER-SP, 2006b). Although Range III represents finer grain size distributions, it may still used for high-traffic volume roads.

Table 6 exhibits the proportion of each material in the mixtures, in terms of aggregate, soil and cement percentages. The cement contents were incorporated in the percentages of 3%, 5% and 7% by mass. The particle size distributions of SAC with basalt aggregates and SAC with recycled masonry aggregates are presented in Figure 13 and Figure 14, respectively.

Table 6: Characterization of the material proportion in each SAC mixture.

SAC mixture	% coarse aggregate	% fine aggregate + powder	% soil	% of cement
20:80 – NA	47	33	20	3, 5 e 7
30:70 – NA	47	23	30	3, 5 e 7
30:70 – RMA	30	40*	30	5

* fine aggregate and sand.

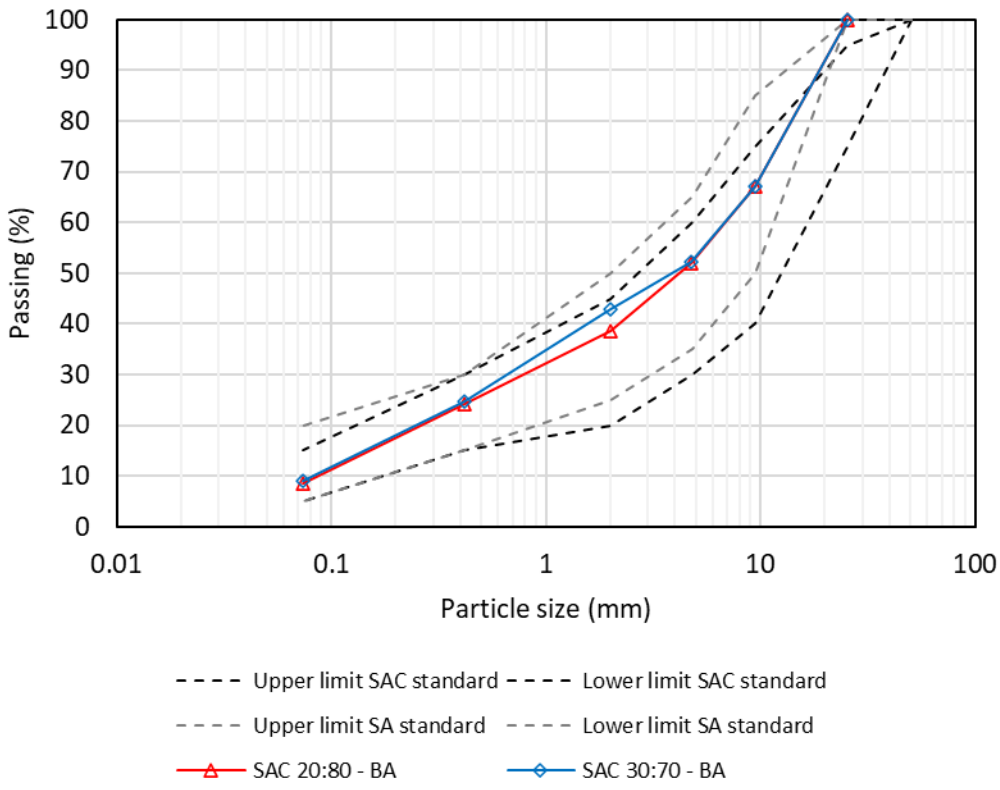

Figure 13: Particle size distribution of the SAC mixtures 20:80 and 30:70 using basalt aggregate.

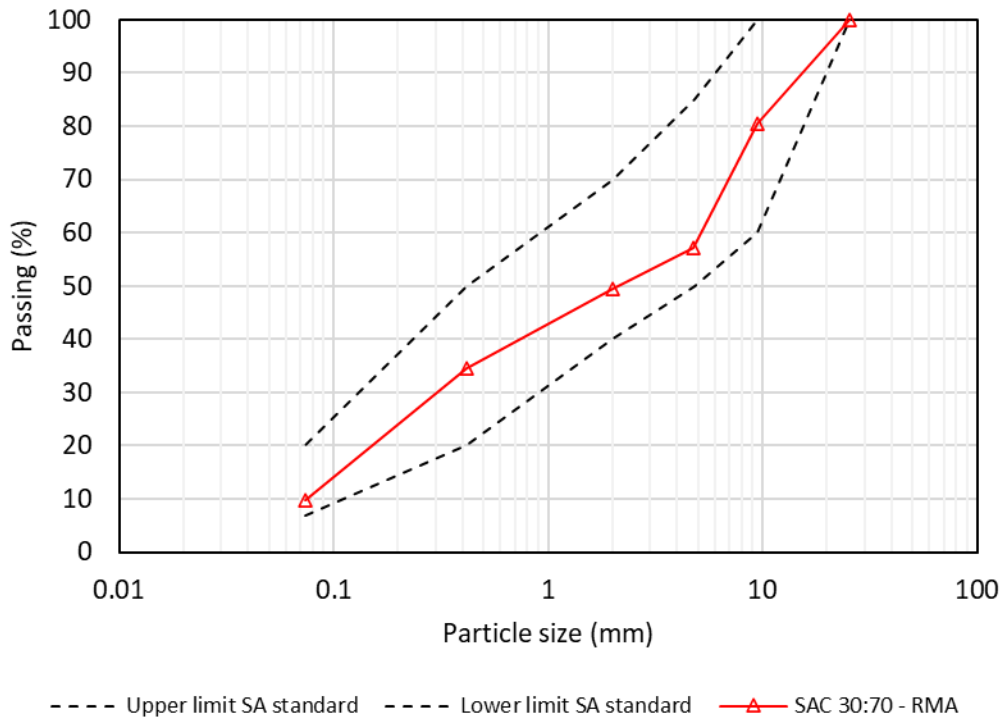

Figure 14: Particle size distribution of the SAC mixtures 30:70 using recycled masonry aggregates.

3.3. Testing methods

3.3.1. Compaction test

The compaction test was carried out according to NBR 7182/2016 standard in order to determine the optimum moisture content (OMC) and maximum dry density (MDD) of SAC mixtures. The modified compaction effort (2700 kN.m/m³) was adopted and the specimens were compacted in 5 layers (55 blows per layer).

3.3.2. Specimen molding

The molding of the specimens for UCS and Mr,t tests was performed by static compression in a hydraulic equipment, using a cylindrical mold with 10 cm in diameter and 20 cm in height. For ITS and Mr,d tests, the specimen compaction was performed in Marshall compactor, using cylindrical mold with 10.7 cm in diameter and 8.7 cm in height. Table 7 shows a summary of the characteristics of the specimen molding for each test, including the compaction type, specimen size and number of specimens.

All specimens were molded at optimum Proctor parameters. In order to ensure a homogeneous set of specimens, the following quality control was adopted: degree of compaction of 100 ±1% and moisture deviation of ±0.5%.

Table 7: Characteristics of molding specimens for each test performed.

Test	Compaction type	Specimen size (diameter x height)	Number of specimens
Unconfined compressive strength (UCS)	Static	10 x 20 cm (2:1)	3
Indirect Tensile Strength (ITS)	Impact	10.2 x 8.7 cm	3
Repeated load triaxial (Mr,t)	Static	10 x 20 cm (2:1)	1
Dynamic indirect tensile (Mr,d)	Impact	10.2 x 6.7 cm	2

3.3.3. Unconfined compressive strength (UCS) test

For UCS tests, three specimens were molded for each experimental condition. The test was performed in accordance with the Brazilian standard NBR 12023/2012 at four curing times (0, 3, 7, and 28 days). The curing occurred in a climate chamber and the specimens were wrapped with plastic sheet to avoid moisture variation.

After curing, the specimens were tested in two equipment, with capacity of 5,000 kgf or 10,000 kgf, depending on the expected material strength. The tests were performed under strain control at load application speed of 1.27 mm/min. The UCS values were calculated using Equation 1.

$$UCS = \frac{4.F}{\pi.D^2} \tag{1}$$

In which:

UCS = unconfined compressive strength (kgf/cm²);

F = maximum load (kgf);

D = specimen diameter (cm).

3.3.4. Indirect Tensile Strength (ITS) test

For the ITS test, three specimens were molded for each experimental condition. The compaction test was performed according to Brazilian standard DNER-ME 138-94 (Marshall compactor). The curing times considered were 0, 3, 7 and 28 days. The curing occurred in a climate chamber and the specimens were wrapped with plastic sheet in order to avoid moisture variation.

After curing, the specimens were tested in two equipment, with capacity of 5,000 kgf or 10,000 kgf, and at a load application speed of 1.27 mm/min. ITS values were calculated using Equation 2.

$$ITS = \frac{2.F}{\pi.\mathrm{D}.H} \tag{2}$$

In which:

ITS = indirect tensile strength (kgf/cm²);

F = maximum load (kgf);

D = specimen diameter (cm);

H = specimen height (cm).

3.3.5. Resilient Modulus (Mr,t) - Repeated load triaxial test (RLT)

The determination of the resilient modulus by the repeated load triaxial test followed the AASHTO T 307-99 standard ("Determining the resilient modulus of soils and aggregate materials"). In the test, 15 pairs of stresses were considered. Initially, 500 to 1000 loading cycles were applied for conditioning the specimen. After this stage, the test was performed with the application of 100 loading cycles for each stress pair. Table 8 shows the stress pairs and number of load applications for each phase of the Mr,t test.

Table 8: Stress pairs applied in the repeated load triaxial test (Mr,t).

Sequence	σ3 (kPa)	σd (kPa)	Nº of applications	Sequence	σ3 (kPa)	σd (kPa)	Nº of applications
0	103.4	93.1	1000	8	68.9	124.1	100
1	20.7	37.3	100	9	68.9	186.1	100
2	20.7	55.9	100	10	103.44	62	100
3	20.7	78.6	100	11	103.44	93.1	100
4	34.5	31	100	12	103.44	196.1	100
5	34.5	62	100	13	137.9	93.1	100
6	34.5	93.1	100	14	137.9	124.1	100
7	68.9	62	100	15	137.9	248.2	100

The repeated load triaxial test was performed at 7 and 28 days of curing, using a single specimen for each condition.

The displacement and loading data were fitted into four models of resilient modulus. Both data acquisition and model fitting were performed using a software, developed on LabView platform by Prof. Dr. Glauco Tulio Pessa Fabbri. The models considered are presented in Table 9.

Table 9: Models used to calculate the Mr,t.

Model	Equation	
Deviator stress model (σd)	$Mr = k_1.\sigma_d^{k3}$	(3)
Confining stress model (σ3)	$Mr = k_1.\sigma_3^{k2}$	(4)
Pezo et al. (1992) model	$Mr = k_1.\sigma_3^{k2}.\sigma_d^{k3}$	(5)
Universal model - AASHTO	$Mr = k_1.p_a\left(\frac{\theta}{p_a}\right)^{k_2}.\left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3}$	(6)

In which:

k_i = multiple regression constants;

σ_d = deviator stress;

σ_3 = confining stress;

p_a = atmospheric pressure;

θ = sum of the three principal stresses;

τ_{oct} = octahedral shear stress.

3.3.6. Resilient Modulus (Mr,d) - Dynamic indirect tensile test (DIT)

The dynamic indirect tensile test (Mr,d) was performed based on DNIT-ME 135/2017 standard for asphalt mixtures. The specimen used for this test has the same dimensions as those used in the ITS test. The Poisson's ratio adopted to calculate the resilient modulus was 0.20, as suggested by the pavement design standard (IP-DE-P00/001 - DER-SP, 2006) for cemented materials.

The resilient moduli were calculated using Equation 7.

$$Mr,d = \frac{F}{\Delta h}(0{,}9976\mu + 0{,}2692) \qquad (7)$$

In which:

Mr,d = resilient modulus (MPa);

F = vertical cyclic load applied diametrically to the specimen (N);

Δ = horizontal displacement (elastic or resilient), in the direction perpendicular to the load application (mm);

H = specimen heigh (cm);

μ = Poisson´s coefficient (0,20).

Initially, a specimen conditioning phase was performed with the application of 100 loading cycles. This procedure leads to specimen accommodate before starting the test. Data acquisition and analysis were performed using a software, developed on the LabView platform by Prof. Dr. Glauco Tulio Pessa Fabbri.

3.4. Statistical analyses of the results

This section presents the statistical methods used to analyze data from the laboratory tests, to fit models of behavior and to predict properties.

3.4.1. Grubbs's test

The Grubb's test (1969) was applied to the results of laboratory tests in order to identify and eliminate outliers. In Grubb's test, a statistical parameter (G) is calculated for each sample. If the sample presents the G value higher than the critical value Gc adopted (G>Gc), it is considered an outlier and thus discarded. Then, the average is recalculated.

For this study, Gc=1,15 was chosen, which is related to the 95% of confidence level. In this way, the G parameter can be calculated using Equation 8.

$$G = \frac{(Y_i - \bar{y})}{s} \qquad (8)$$

In which:

Y_i = an observation of the sample;

$\bar{y}$ = sample average;

s = standard deviation.

The Grubb's test was used for results of UCS and ITS tests for all experimental conditions. Results of Grubb's test are presented in Appendices A, B, and E.

3.4.2. Decision tree

The decision tree is a statistical analysis method used to represent the relationship between data in a simple way. The main mechanism of the decision tree is the use of hierarchy rules and division of groups to organize data (QUINLAN, 1983). Figure 15 exhibits a scheme of a decision tree and Table 10 shows the name of each node.

In the decision tree, the hierarchy and group split rules occur as follows: the tree starts in the root node (node 0 in Figure 9), which represents the set with all data. This node is subdivided into segments (branches) to child nodes (1 and 2), representing homogenous data that might still be divided into more homogeneous groups (e.g. child nodes 5, 6 and 7), until reaching the point of the end node.

The end node is called terminal node (3, 4, 8, 9, 10 and 11). This means that the data set can no longer be subdivided, representing the stopping criterion of the algorithm (Quinlan, 1983). The division of data occurs by means of algorithm that use models to divide data into homogeneous groups of independent variables. The later can be used in a classification or regression scenario, according to the dependent variable.

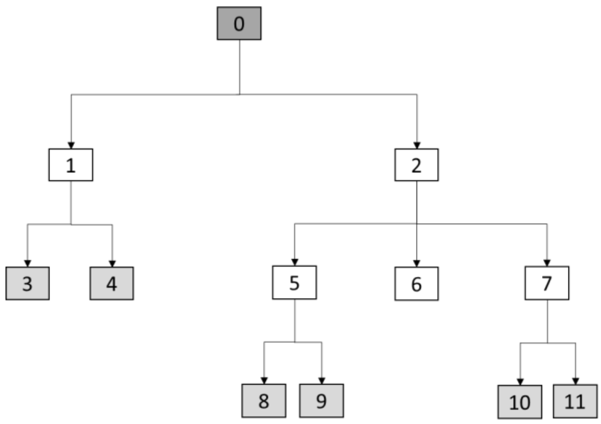

Figure 15: Decision tree scheme exemplification.

Table 10: Decision tree nodes.

Node	Meaning
0	Root node
1, 2, 5, 6 and 7	Child node
3, 4, 8, 9, 10, 11	Terminal node

The CHAID algorithm was proposed by Kass (1980), and its mechanism for forming the decision tree allows a single node to be divided into two or more child nodes. This algorithm mainly uses the Chi-Square test to perform the nodes division, following three steps: (1) merging; (2) splitting; and (3) stopping. This algorithm is present in the SPSS 21 software package, which was used to produce the decision trees presented in this study. The decision trees were made for UCS, ITS and Mrt properties.

3.4.3. Multiple linear regression model

The multiple linear regression is a statistical method to build models to describe the relation between a dependent variable and independent variables and to predict values. In this study, the

SPSS 21 software was used to build the multiple linear regression models for UCS, ITS and Mrt properties, as functions of the variables soil proportion (% soil) and cement content (%cement), in order to predict these properties at 7 days of curing. For the analyses, the adjusted R-squared (R^2) and the *p-value*, for a significance level of 95%, were considered.

3.5. Study of optimum cement content

The technical specification for SAC mixtures (ET-DE-P00/007 - DER- SP, 2006a) does not provide instructions for cement dosage, but recommends that UCS and ITS at 28 days of curing should meet the requirements of pavement design. In this way, an optimum cement content was selected by means of pavement mechanistic analysis.

This study compared the results of mechanistic analysis, applying multilayer elasticity theory, of hypothetical pavements carried out by Simoni (2019) with laboratory test results. For the mechanistic analysis, Simoni (2019) considered the input data specified in IP-DE-P00/001 (DER-SP, 2006) and the DNIT pavement design method (SOUZA, 1981), where the layer thickness was determined by DNIT pavement design method using the California Bearing Ratio (CBR) and structural coefficient (k) of the materials.

The number of equivalent single axle load (ESAL) adopted by Simoni (2019) refers to high-traffic ($N = 5x10^7$) and very high-traffic ($N = 3x10^8$) volume roads. Eight pavements were designed. The structures were composed of hot mix asphalt (HMA), cemented base layer (SAC mixture), subbase layer (present or not), and two types of subgrade (sandy or clayey soils).

The software MePads (Mechanistic-Empirical Pavement Analysis, and Design Software) was used to calculate the acting stresses and strains in each pavement layer. The input data used are Poisson's coefficient (μ), Resilient Modulus (Mr), and the thickness of each layer of the pavement structure. The values used in software MePads as input data for each property are summarized in Table 11.

Table 11: Input data for the design of hypothetical pavements from Simoni (2019).

Layer	μ	CBR (%)	Mr (MPa)	k	Layer thickness (cm)
Surface course 1	0.35	-	4000	2	12.5 (heavy)
Surface course 2	0.35	-	4000	2	15 (very heavy)
Base course 1	0.20	-	7000	1.7	17
Base course 2	0.20	-	10000	1.7	17
Subbase course	0.35	18	220	1	-
Subgrade 1 (sandy)	0.40	16	200	-	-
Subgrade 2 (clayey)	0.45	4	67	-	-

In order to compute the stresses and strains acting on pavement layers, the following points of analysis were adopted: at the top and at the bottom of asphalt layer, at the bottom of the cemented base layer and at the top of the subgrade. The loading used in the simulations was a semi-axle with dual wheels, spaced 300 mm apart from each other, with load of 20,000 N each and tire inflation pressure of 0.56 MPa.

The material data used correspond to intermediate values of a range of soil-cement and cement treated crushed rock properties. Simoni *et al.* (2019) presented the mechanistic analysis results, in terms of tensile and compressive stresses, for all pavement structures considered (Figure 16).

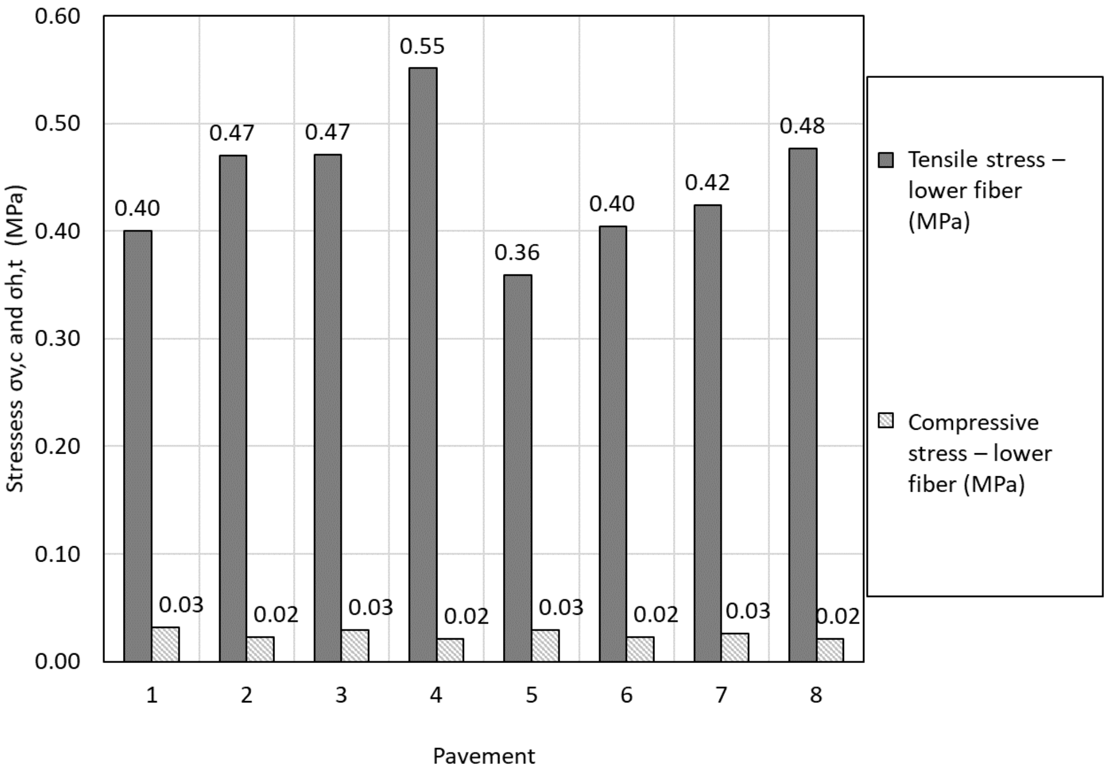

Figure 16: Stresses levels simulated acting on the cemented base from Simoni et al. (2019).

The compressive stress (σ_{vc}) values of the cemented base varied between 0.021 and 0.032 MPa. For tensile stress (σ_{ht}), the values ranged from 0.359 to 0.551 MPa. These values were compared to the UCS and ITS tests results.

4. RESULTS

This chapter presents the laboratory test results and the analyses of SAC mixture mechanical behavior. Tests were carried out with the purpose of determining compaction parameters, unconfined compressive strength (UCS), indirect tensile strength (ITS), and resilient modulus (Mr). Statistical analyses of the data and models were performed in order to ascertain their quality and to predict properties. Additionally, two investigations focused on (i) selecting the optimum cement content based on mechanical properties and (ii) understanding the effect of the aggregate type on SAC mixture performance, replacing basalt aggregates (NA) with recycled masonry aggregates (RMA).

4.1. Compaction test

The compaction test provides the optimum moisture content and maximum dry density, which are the primary parameters used in the dosage of cemented materials. In this study, this test was performed in SAC mixtures containing 3%, 5% and 7% of cement, using modified compaction effort in accordance with the Brazilian standard NBR 7182/2016. Table 12 presents a summary of the optimum moisture content (OMC) and the maximum dry density (MDD). The water/cement ratio (W/C) is also shown in this table.

Analyzing Table 12, it can be noticed that OMC values varied from 5.6% to 6.3%, while MDD ranged from 23.40 kN/m³ to 23.95 kN/m³. The OMC does not present a clear tendency and the coefficient of variation is considered low (5%). On the other hand, MDD seems to indicate 5% of cement as the optimum content for both material proportions, since they presented higher MDD values for this particular cement content, which is an indication of denser and stronger mixtures. The coefficient of variation for MDD values is 8%.

In general, the concurrent decrease of the percentage of soil and cement addition led to an increase of OMC and MDD. Regarding material proportions, the OMC and MDD for SAC 20:80 were higher than that of the SAC 30:70. In terms of cement content, the values of SAC 20:80 were also higher than SAC 30:70 at a certain content, however, this difference was not significant.

Table 12: Compaction test results and W/C ratio of SAC mixtures.

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

The water/cement ratio is a dosage indicator of cement concrete and mortars. This parameter indicates the ability of cement to hydrate and, consequently, to improve internal structure and mechanical properties of concrete. In concrete, low W/C ratios are related to the increase of strength and the reduction of workability, porosity and permeability. This study focuses on peculiar cemented mixtures, it is important to understand the response of this parameter in SAC mixtures. In Table 12, W/C values of SAC 20:80 mixtures were usually higher than the SAC 30:70 ones. This particularity may be attributed to the increase of the cement content and the slightly higher OMC of the SAC 20:80 mixtures, resulting in the reduction of the ratio.

Other authors also studied the changes of these parameters in different types of SAC mixtures and they are consistent with the results of this research. For instance, Simoni (2019) studied SAC 20:80 mixtures using a PCC-IP cement and reported OMC values of about 6.2% and MDD ranging from 23.64 kN/m³ to 23.76 kN/m³. Kawahashi *et al.* (2010) tested SAC mixtures (50:50) with IS cement and found OMC values of about 6.5% and MDD values from 20.8 kN/m³ to 21.5 kN/m³.

Concerning W/C ratios, Bessa *et al.* (2016) studied SAC mixtures (60:40) stabilized with 5% and 6% cement and found W/C ratios of 1.30 and 1.08, respectively. Analyzing SAC mixtures with 3%, 5% and 7%, Simoni (2019) found W/C ratios equal to 2.07, 1.24 and 0.89, respectively. In the present research, W/C ratios were similar to those obtained by Simoni (2019). Both studies concluded that the increase in the strength of SAC mixtures might be related to lower W/C ratios.

Figure 17 shows all compaction curves of the tested SAC mixtures. As observed, the typical behavior of the compaction curve was formed. It can be pointed out that 5% of cement led to the higher MDD and the lower OMC. It is worth noting that the compaction curves of the mixtures with 30:70-material proportion are shifted down and towards the left-side in relation to the curves of 20:80 mixtures. This suggests that 20:80-material proportion might promote better arrangement of particles and greater densification, indirectly resulting in higher strength.

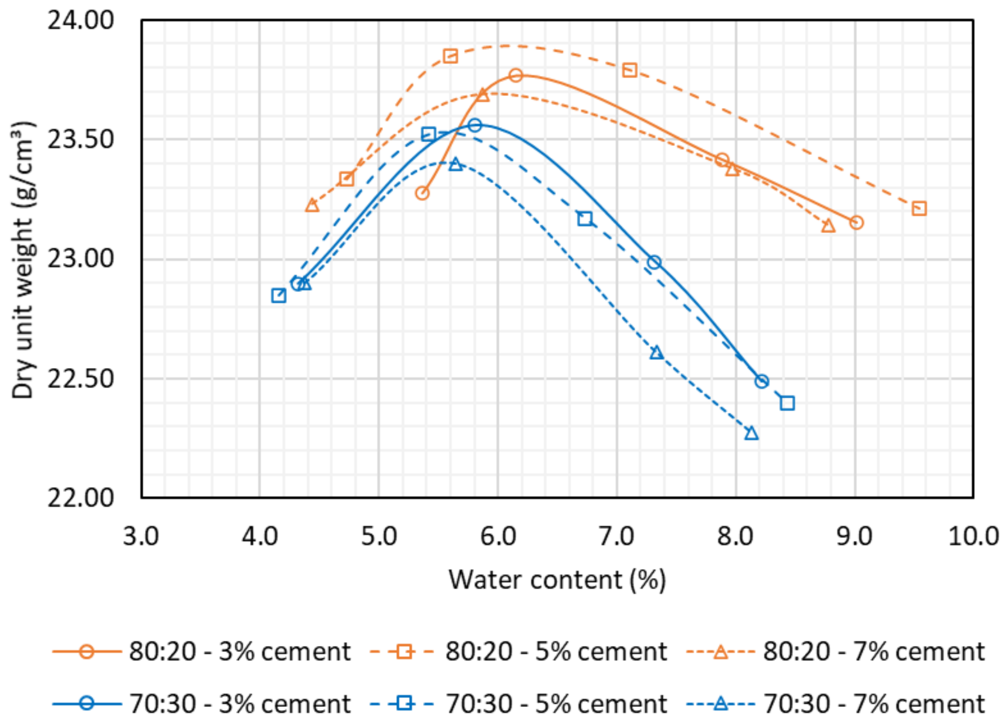

Figure 17: Compaction curves of SAC mixtures.

4.2. Unconfined Compressive Strength Test

The strength gain of cemented materials depends on the cement hydration and formation of cementitious compounds. These reactions occur over time and under adequate curing conditions. Thus, in order to understand how strength evolves, Table 13 exhibits the UCS results of all tested SAC mixtures at different curing times. In this table, each UCS value represents the average of three specimens. Grubbs' test was applied to the data, coefficient of variation (CV), and the results are presented in Appendix A.

Analyzing Table 13, one can noticed that the UCS values varied from 0.18 MPa to 8.86 MPa, also SAC 20:80 mixtures exhibited the highest UCS values. The best behavior of SAC 20:80 mixtures might be related to their superior particle arrangement, resulting from the combination of grain-to-grain contact among aggregate particles and the partial filling of voids by the soil (YODER and WITCZAK, 1975).

The concurrent increase of soil percentage in 10% and the decrease of aggregate percentage reduced the UCS values of SAC 30:70 mixtures (~19%). The same behavior was also reported in other studies that compared SAC with varying material proportions (ARANHA, 2013; FEDRIGO *et al.*, 2017; GHANIZADEH *et al.*, 2017).

Table 13: UCS (MPa) of SAC mixtures.

SAC Mixture	UCS (MPa) 0 days	7 days	28 days
20:80 – 3% cement	0.28	3.54	3.91
20:80 – 5% cement	0.32	6.35	6.72
20:80 – 7% cement	0.31	8.33	8.86
30:70 – 3% cement	0.18	2.97	3.18
30:70 – 5% cement	0.22	5.17	5.86
30:70 – 7% cement	0.25	6.71	7.34

Overall, the increase of cement content improves UCS values and this is remarkable at 7 and 28 days of curing. UCS values at 7 days are considerably higher than the 0-days ones (from 12 to 27 times) for both mixtures. Otherwise, the increase of cement content does not change significantly the immediate strength (UCS_{0days}, which represents molded and broken specimens then), probably because at this age, cement would act as a filler in the mixtures. These findings are consistent with those reported by other researchers (HORPIBULSUK *et al.*, 2010; FEDRIGO *et al.*, 2017; SIMONI, 2019, FURLAN *et al.*, 2021).

Regarding the effect of specific curing times, similar trends for 7 and 28 days were observed, as shown below:

- *at 7 days of curing*, changing cement content from 3% to 5% increased the UCS values about 76% for both mixtures (20:80 and 30:70). In addition, modifying the cement content from 5% to 7% led to an average UCS increase of 31%.

- *at 28 days of curing*, modifying cement content from 3% to 5% increased the UCS values about 78% for both mixtures (20:80 and 30:70). Moreover, changing the cement content from 5% to 7% caused an average UCS increase of 29%.

Average gain of UCS indicate that there would have an optimum cement content between 3 and 5%. Figure 18 and Figure 19 show UCS in function of cement content and over curing time, respectively. These charts help to understand the effect of these variables on the strength gain of SAC mixtures.

Figure 18 shows that, despite the different material proportions of mixtures, the trends of UCS gain are quite similar and dependent on the increase of cement content. It is worth emphasizing that the UCS gain of SAC mixtures 30:70 stabilized with 5% cement slightly decelerated from 5 to 7 %.

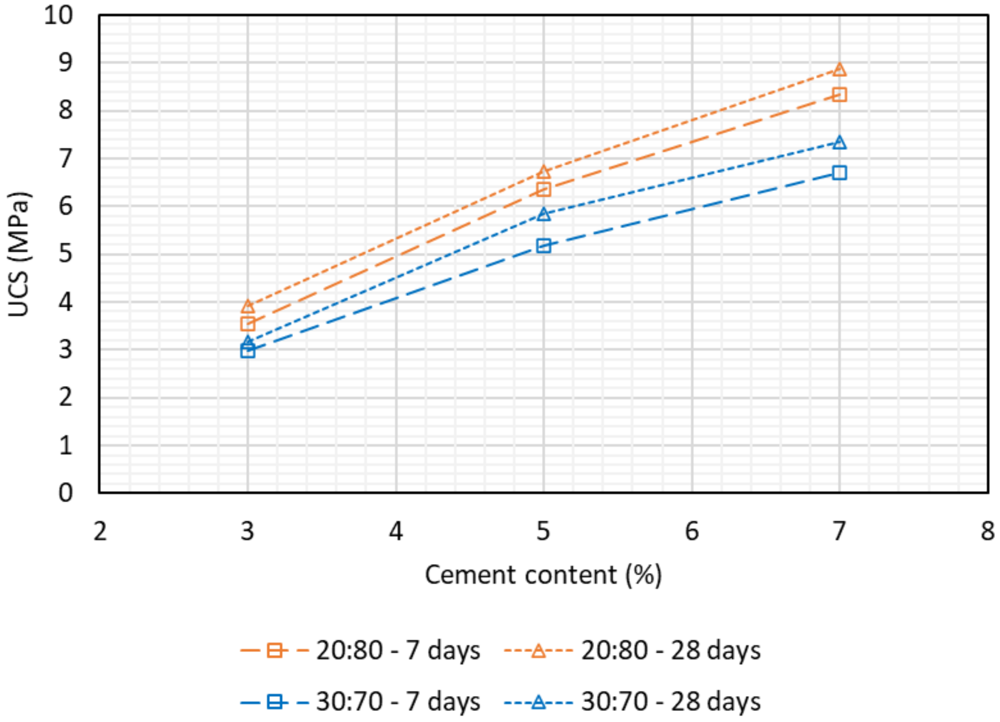

Figure 18: UCS as a function of Portland cement content for 7 and 28 days of curing.

Figure 19 shows the UCS behavior over curing time. As a whole, the UCS values increased over time. The UCS gains from 0 to 7 days of curing were significantly higher than those from 7 to 28 days. Besides that, UCS_{7days} reached 92% of $UCS_{28\ days}$. Furthermore, a stabilization trend of UCS gains was observed after 7 days of curing. This behavior is consistent with the cement type (CPV-ARI) that commonly exhibits high strength gain at early ages. This result shows an advantage at 7 days over the pavement design requirements of the Sao Paulo - DOT (DER-SP, 2006), which recommends UCS and ITS at 28 days.

Assuming a linear behavior for mixtures stabilized with 5% cement, one can define the UCS gain rate from 0 to 7 days as 0.86 MPa/day and 0.71 MPa/day for SAC 20:80 and SAC 30:70, respectively. At curing times from 7 to 28 days, the UCS gain rate was 0.02 MPa/day and 0.03 MPa/days, for SAC 20:80 and SAC 30:70, respectively. These findings are in agreement with some studies on cemented materials (HORPIBULSUK *et al.*, 2010; BAN e PARK, 2014; BAGHINI *et al.*, 2017; SIMONI *et al.*, 2019).

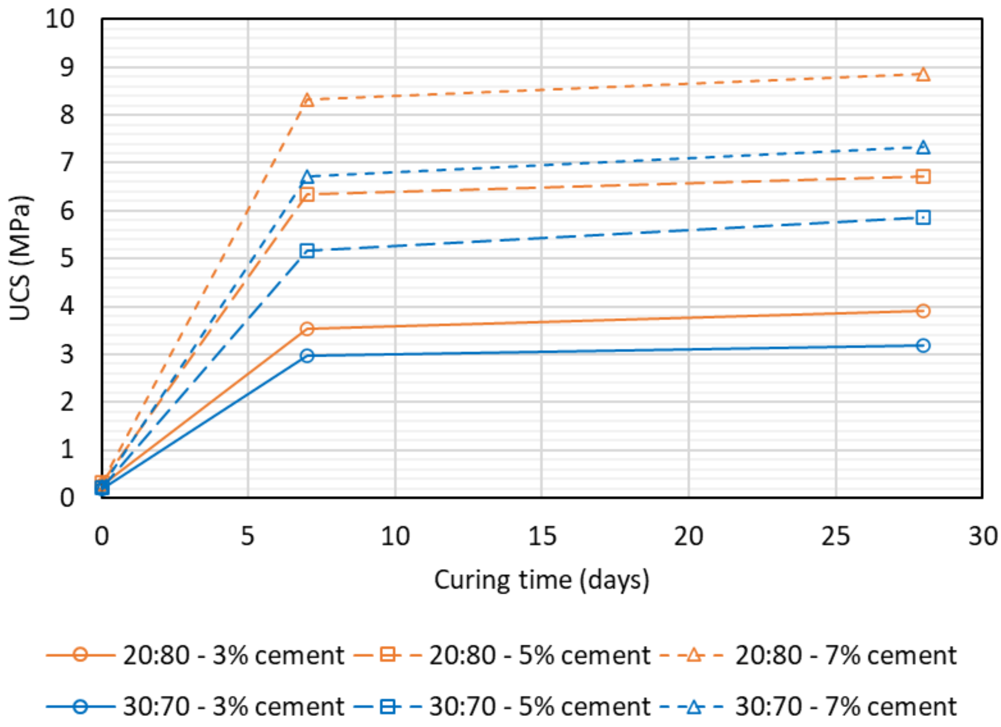

Figure 19: UCS over curing time for SAC mixtures.

If UCS values were considered as a dosage parameter, it would be reasonable to suggest a cement content between 3 and 5% for both tested mixtures (20:80 and 30:70), taking into account the favorable responses of the property in relation to cement content and curing time.

4.2.1. Statistical analyses for UCS test data

The UCS results were analyzed statistically using decision tree and multiple linear regression. Decision trees were created using CHAID algorithm and the models were fitted using SPSS 21 software.

Figure 20 schematically represents the UCS decision tree, consisting of 14 nodes distributed in three levels (1 root node, 2 child nodes, 11 terminal nodes). Table 14 describes the information of these nodes. Each node contains information about segregation criteria, the predicted UCS values for each group, the number of observations at each node (n), and the percentage of observations at the node concerning the initial sample (%). The UCS decision tree has a high coefficient of determination (R^2=0.98), which indicates the high accuracy of the model.

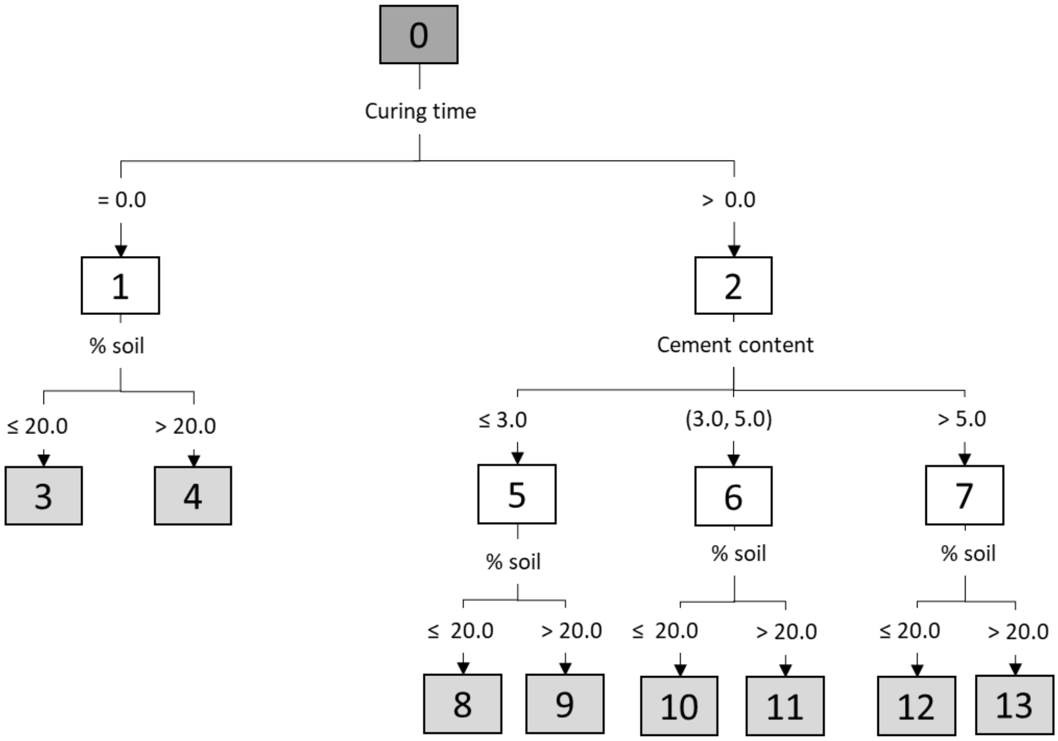

Figure 20: UCS decision tree map.

Table 14: Description of the nodes and predicted UCS.

Node	Conditions	UCS Average	Standard deviation	n	%
0	Initial node (root)	3.944	3.125	54	100
1	Curing time = 0	0.260	0.053	18	33.3
2	Curing time > 0	5.785	2.078	36	66.7
3	Curing time = 0; % Soil ≤ 20	0.304	0.019	9	16.7
4	Curing time = 0; % Soil > 20	0.216	0.036	9	16.7
5	Curing time > 0; Cement content ≤ 3	3.400	0.450	12	22.2
6	Curing time > 0; Cement content (3, 5)	6.025	0.782	12	22.2
7	Curing time > 0; Cement content > 5	7.931	1.280	12	22.2
8	Cement content ≤ 3; % soil ≤20	3.725	0.332	6	11.1
9	Cement content ≤ 3; % soil >20	3.076	0.290	6	11.1
10	Cement content (3, 5); % soil ≤20	6.533	0.584	6	11.1
11	Cement content (3, 5); % soil > 20	5.517	0.621	6	11.1
12	Cement content > 5; % soil ≤ 20	8.834	0.861	6	11.1
13	Cement content > 5; % soil > 20	7.028	0.952	6	11.1

Taking terminal Node 3 as an example: in the column "conditions", there is a description of the node, which is defined by a curing time equals to 0 days and a soil proportion less or equals to 20% ("Curing time = 0; % Soil ≤ 20"). The column "Average UCS" shows the predicted value of UCS, which was 0.304 MPa. Following, column "standard deviation" presents the values of this parameter, computed for the sample size (n). At Node 3, standard deviation was 0.019 (with n=9). Finally, the column "(%)" exhibits values that represent the correspondence between the root node and the analyzed node. This percentage was 16.7%, which means that the set of data for Node 3 corresponds to 16.7 % of the root node data (with n=54).

The hierarchy of UCS decision tree establishes that:

1) Curing time was the most important independent variable. Thus, the first division at root node resulted into 2 child nodes related to curing time, e.g. a curing time is equal to 0 days and another one above 0 days;

2) At the *0 days-curing time node*, the algorithm of the decision tree classified soil percentage as a significant variable. In this way, the data was divided into 2 terminal nodes related to material proportion, e.g. a soil proportions are equal to 20% and another one greater than 20%. It is important to highlight that cement content was discarded, since the UCS values at 0-day were considered similar for all mixtures. This means that the cement content variable was not significant for the model, probably because cement acts as a filler at this age;

3) At the *above 0 days-curing time node,* two variables were considered significant: cement content and soil percentage, resulting in the division of data into 9 terminal nodes. Firstly, the cement content was considered as the most significant variable and it was divided into three nodes: equals to 3%, from 3% to 5% and above 5%. Subsequently, each cement content node was divided into two nodes, which were then classified in terms of soil percentage (equals to 20% and above 20%).

The hierarchy of this decision tree also allowed to predict UCS values, as observed in the terminal nodes. Analyses of the decision tree ratified the aforementioned observations, namely:

a) Cement addition does not significantly alter the immediate strength of SAC mixtures, because cement acts as a filer at early ages.

b) Cement content becomes an important variable in the strength gain when analyzed in relation to the curing time, which was the most important variable for branching the child nodes. The adequate cement content seems to lie between 3 and 5% cement.

c) The predicted UCS values elucidated the effect of modifying the amount of soil in the composition of SAC mixtures, that is, the increase of soil proportion from 20 to 30% decreased the strength.

Another statistical technique used was the multiple linear regression. Equation 9 predicts the UCS values at 7 days of curing as a function of cement content and soil percentage. The significance level of this model was 95%. The F-value of the model is equal to 92.346, p-value < 0.05 for all independent variables and high accuracy (R^2=0.925).

$$UCS\ (MPa) = 2.974 + 1.066 * (\%\ cement) - 0.112 * (\%\ soil) \quad (9)$$

Since curing time is not considered in this model, Equation 9 demonstrated that the cement content is the most significant independent variable. Figure 21 shows a comparison between measured and predicted UCS values at 7 days of curing. It is worth noting that the points are very close to the identity line, which indicates a satisfactory data correlation.

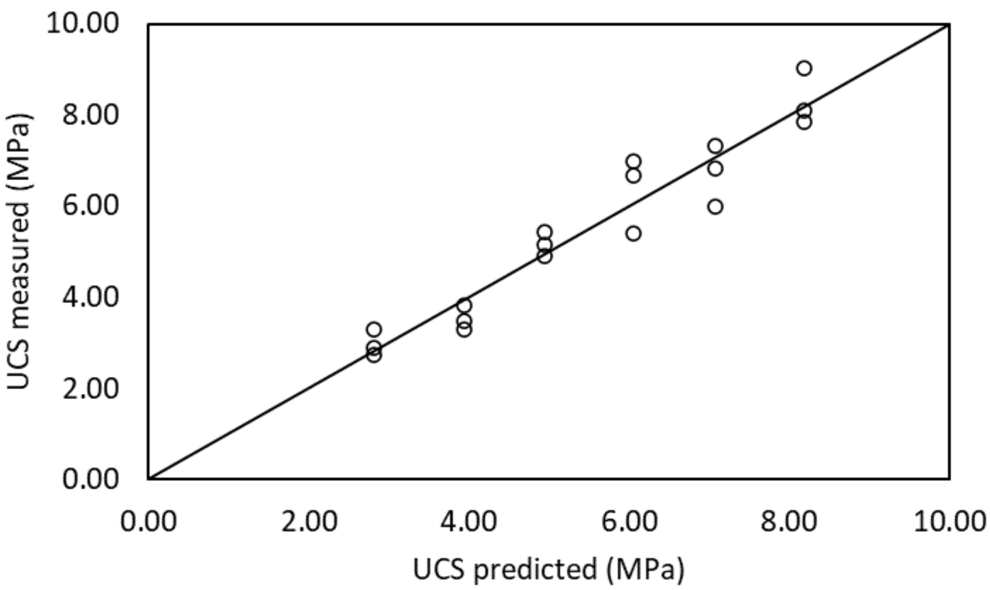

Figure 21: UCS values obtained by tests and predicted by the model.

4.3. Indirect Tensile Strength (ITS)

Cement hydration and adequate curing cause cementation of soil/aggregate clusters, increasing the tensile strength of SAC mixtures. ITS is an important property that must be analyzed in cement-treated bases, since this type of layer is prone to the onset of tensile stresses that can lead to fatigue failure. The ITS results for all SAC mixtures tested at different curing times are presented in Table 15. Each ITS value refers to the average of three specimens. Subsequently, Grubbs' test was applied in order to identify outliers. The results of all tested specimens and the coefficient of variation (CV) are presented in Appendix B.

In Table 15, it is possible to notice that ITS values varied from 0.03 MPa to 2.22 MPa. Furthermore, the results indicate that the reduction of ITS (~ 25%) is related to the increase of soil percentage (from 20% to 30%). In addition, mixtures 20:80 exhibited the highest ITS values.

Table 15: ITS (MPa) of SAC mixtures.

SAC Mixture	ITS (MPa)		
	0 days	7 days	28 days
20:80 – 3% cement	0.04	0.62	0.92
20:80 – 5% cement	0.04	1.36	1.50
20:80 – 7% cement	0.05	1.62	2.22
30:70 – 3% cement	0.03	0.51	0.72
30:70 – 5% cement	0.04	0.85	1.05
30:70 – 7% cement	0.04	1.10	1.70

In terms of cement content, it is possible to observe that larger amounts of cement resulted in higher ITS values, as also showed by the aforementioned UCS results and by other authors (BESSA *et al.*, 2016; FEDRIGO *et al.*, 2018; SIMONI, 2019). As with the UCS results, the influence of cement content was not detected in ITS values at 0 days of curing, probably because cement needs time for hydration progress and corresponding strength increase. In this way, the filler effect is null on ITS gain.

In relation to specific curing times, one can notice that ITS values change depending on cement content and material proportion. Overall, it is observed that:

- *at 7 days of curing*, changing cement content from 3% to 5% caused an increase of ITS values of about 119% and 67% for mixtures 20:80 and 30:70, respectively. On the other hand, the modification of cement content from 5% to 7% increased ITS in 19% and 29% for mixtures 20:80 and 30:70, respectively.

- *at 28 days of curing*, modifying cement content from 3% to 5% increased ITS values by about 63% and 46% for 20:80 and 30:70 mixtures, respectively. When cement content changed from 5% to 7%, the ITS increased by about 48% to 62% for 20:80 and 30:70 mixtures, respectively.

ITS values indicated that the highest strength gain occurred between 3 and 5% of cement content, except for SAC 30:70 with 5% to 7% of cement, at 28 days of curing. Accordingly, ITS values also increased over curing time (similar to UCS behavior). These findings are consistent with the results of other researchers (BESSA *et al.*, 2016; FEDRIGO *et al.*, 2018; SIMONI *et al.*, 2019).

Since variations of ITS values are different in terms of intensity, Figure 22 and Figure 23 show the curves of ITS as a function of cement content and curing time, respectively. By analyzing Figure 22, it is possible to understand the effect of cement content on ITS values. For instance, the change in slope of SAC mixtures curves with different cement contents indicates an additional increase of ITS at 28 days, when 7% of cement was added. This means that the addition of more cement contributed to enhance ITS, as if the cementation reactions continued to occur due to the available amount of cement.

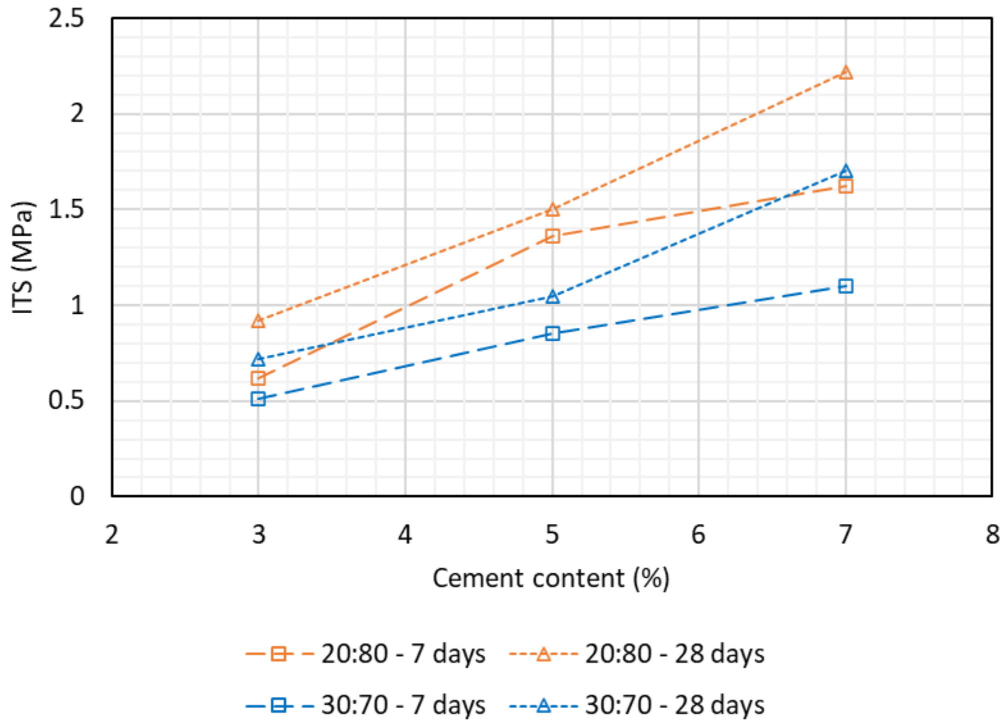

Figure 22: ITS as a function of Portland cement content for 7 and 28 days of curing.

In Figure 23, it can be noticed the increase of ITS over time, with emphasis on SAC mixtures 20:80 that exhibited the higher ITS values compared to those of SAC mixtures 30:70, regardless of the cement content. Additionally, it should be emphasized that ITS values increased because of increasing cement contents. Another important observation is that the gain of ITS of SAC mixtures with 7% cement did not reach stabilization level.

The ITS gain was higher between 0 and 7 days for all mixtures. However, ITS values continued to increase from 7 to 28 days of curing. The major gain was about 35%, for mixture 30:70 with 7% cement and the minor gain was about 10%, for mixture 20:80 with 5% cement.

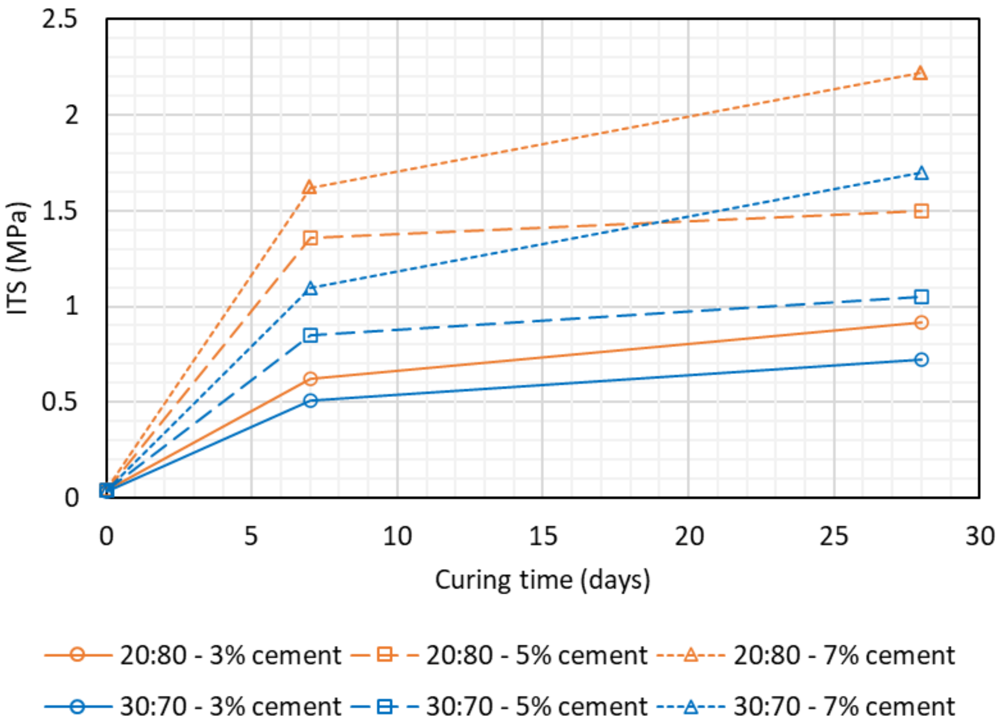

Figure 23: UCS over curing time for SAC mixtures.

As seen for UCS results, ITS can be interpreted in terms of gain rate, by assuming a linear behavior. For instance, in SAC mixtures using 5% of cement, the ITS gain rate from 0 to 7 days of curing was 0.19 MPa/day and 0.12 MPa/day for SAC 20:80 and SAC 30:70, respectively. On the other hand, for SAC mixtures cured from 7 to 28 days, the ITS gain rate was 0.01 MPa/day for both SAC compositions. By observing the results at 0 days of curing, one can notice that ITS presented a quite slight variation of values.

The ITS values found in the present research are compatible with the values from technical literature. For example, Kawahashi *et al.* (2010) reported ITS values ranging from 0.42 to 0.6 MPa for SAC mixtures with 5% of cement. Moreover, Bessa *et al.* (2016) presented ITS values from 0.7 to 1.0 MPa for a SAC mixture with 5% of cement. respectively, and Simoni (2019), from 0.03 to 1.72 MPa, for a SAC using 5% of CP II Z-32 cement.

Lastly, if ITS was considered as a dosage parameter, it would be reasonable suggesting a cement content between 3 and 5%, taking into account the favorable ITS results in relation to cement content and curing time.

4.3.1. Statistical analyses for ITS values

Figure 24 shows the ITS decision tree in three levels, with 13 nodes: 1 root node, 3 child nodes, and 9 terminal nodes. Table 16 presents the nodes identification, their corresponding information about segregation criteria, the predicted ITS values for each group, the number of observations at each node (N) and the percentage of observations at the node in relation to the initial sample (%). The ITS decision tree presented a high coefficient of determination (R^2=0.93), which is an indication of its high accuracy.

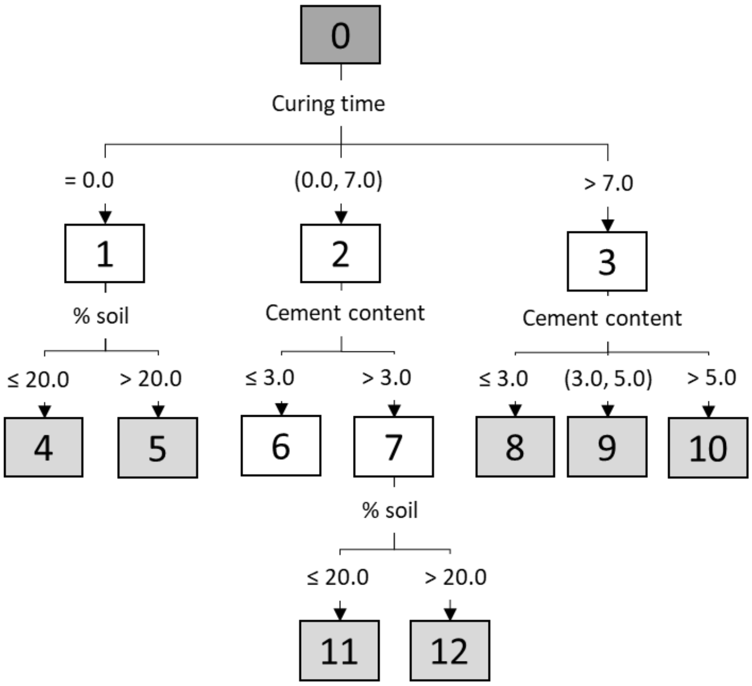

Figure 24: ITS decision tree map.

Table 16: Description of the nodes and predicted ITS values.

Node	Conditions	ITS Average	Standard deviation	n	%
0	Initial node (root)	0.802	0.686	54	100
1	Curing time = 0	0.042	0.007	18	33.3
2	Curing time (0, 7)	1.011	0.434	18	33.3
3	Curing time > 7.0	1.353	0.548	18	33.3
4	Curing time = 0; % Soil ≤ 20	0.045	0.007	9	16.7
5	Curing time = 0; % Soil > 20	0.039	0.005	9	16.7
6	Curing time (0,7); Cement content ≤ 3	0.569	0.079	6	11.1
7	Curing time (0,7); Cement content >3	1.231	0.358	12	22.2
8	Curing time >7; Cement content ≤ 3	0.818	0.115	6	11.1
9	Curing time >7; Cement content (3, 5)	1.283	0.344	6	11.1
10	Curing time >7; Cement content > 5	1.959	0.314	6	11.1
11	Cement content >3; % soil ≤ 20	1.489	0.203	6	11.1
12	Cement content >3; % soil > 20	0.974	0.286	6	11.1

In this decision tree, CHAID algorithm also classified curing time as the most significant variable, however, some particularities are observed in terms of number of nodes and branches, namely:

1) The most important independent variable was curing time, as it was for UCS. The first root node division was made in three child nodes related with curing time, e.g. curing time is equal to 0 days, from 0 to 7 days and above 7 days;

2) At the *0 days-curing time node*, only the soil percentage was classified as a significant variable by the algorithm of the decision tree, thus resulting in a division of data into two terminal nodes related to material proportion, e.g. material proportions are equal to 20% and greater than 20%, respectively. Analogously to UCS decision tree, cement content was discarded, since the ITS values at 0 days of curing were similar for all mixtures. This means that the cement content was not significant to the model at 0 days curing, probably because cement acts as a filler in this age;

3) At the *0 to 7-days-curing time node,* cement content was considered the most significant variable, resulting in the division of data into two nodes: one equals to 3% and another above 3%. Meanwhile, soil percentage was considered a significant variable only for the node of cement content above 3%. Therefore, in this case, the node was divided into two more conditions, in terms of soil percentage (equals to 20% and above 20%);

4) At the *above 7 days of curing node*, only the cement content variable was considered as significant, resulting in two more terminal nodes.

The hierarchy of this decision tree also allowed to predict ITS values, as observed in the terminal nodes. Observations from the decision tree ratified the aforementioned findings, namely:

a) Cement addition does not significantly modify the immediate strength of SAC mixtures, once cement acts as a filer at early ages.

b) Cement content also becomes a relevant variable in the strength gain when analyzed in relation to curing time, thus turning into the most important variable for branching the child nodes. The adequate cement content seems to lie within 3 and 5% cement.

c) The predicted ITS values highlighted the effect of increasing the amount of soil in the composition of SAC mixtures, which means that a decreasing strength is likely to occur when the soil percentage changes from 20 to 30%.

Regarding the multiple linear regression model, Equation 10 can be used for predicting the ITS values at 7 days of curing, as a function of the cement content and soil percentage. The independent variables showed p-value < 0.05. The model had F-value = 28.451 and good accuracy (R^2=0.791).

$$ITS\ (MPa) = 0.971 + 0.198 * (\%\ cement) - 0.038 * (\%\ soil) \qquad (10)$$

Since curing time is not considered in this model, Equation 10 shows that the most significant variable is cement content. Figure 25 shows the relation between measured and predicted values at 7 days of curing, as well as the data arrangement. One can notice that ITS values are more dispersed in relation to the identity line, which is mostly due to the model accuracy.

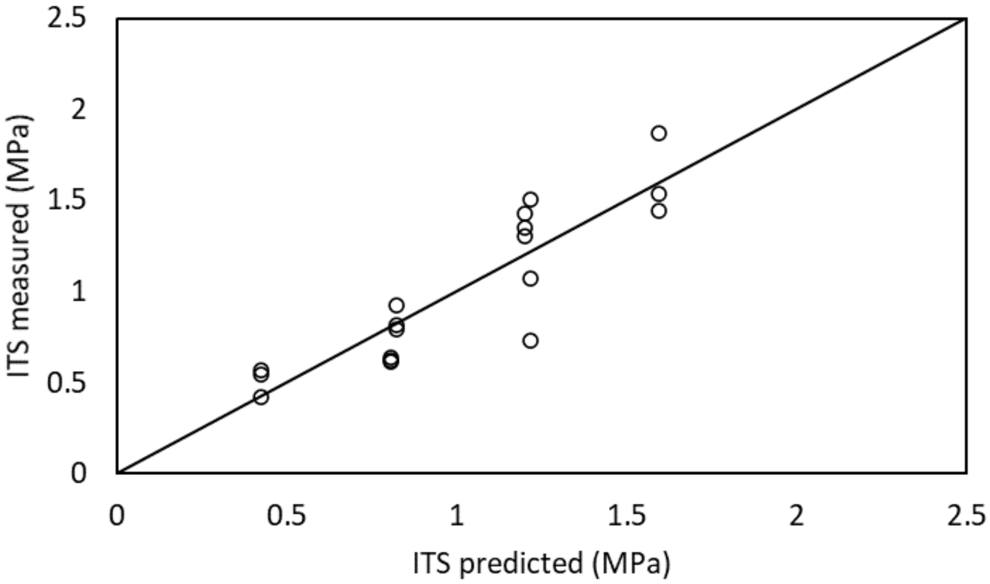

Figure 25: ITS values obtained by tests and predicted by the model.

4.4. ITS/UCS ratio

The ITS/UCS ratio is a relation between these strength properties calculated to better understand the mechanical behavior of SAC mixtures. Furthermore, the ITS may be inferred using this ratio, and vice versa. Table 17 presents the ITS/UCS ratio of tested mixtures using the average values of UCS and ITS (previously exhibited in Table 13 and Table 15).

Table 17 shows that ITS/UCS ratios ranged from 0.14 to 0.24. For SAC 20:80, the average ratio was 0.20 and for SAC 30:70, 0.18. In general, it is observed that the increase of ITS/UCS ratio depends on the increase of cement content and curing time.

Table 17: ITS/UCS ratios of the tested mixtures.

SAC mixture	ITS / UCS ratio		
	0 days	7 days	28 days
20:80 – 3% cement	0.14	0.18	0.24
20:80 – 5% cement	0.13	0.21	0.22
20:80 – 7% cement	0.16	0.19	0.25
30:70 – 3% cement	0.17	0.17	0.23
30:70 – 5% cement	0.18	0.16	0.18
30:70 – 7% cement	0.16	0.16	0.23

The results of this study are higher than the other cemented mixtures reported in the technical literature. For instance, the ITS/UCS ratio of 0.10 was found for some soil-cement mixtures (PARENTE *et al.*, 2002; SANBONSUGE *et al.*; 2017). However, it should be highlighted that ITS/UCS ratios found in studies on SAC mixtures are compatible with the values of this research (KAWAHASHI *et al.*, 2010; SIMONI, 2019).

4.5. Resilient Modulus

4.5.1. Repeated load triaxial test

Resilient modulus is an important parameter of pavement design that represents the material stiffness. The repeated load triaxial (RLT) test was performed in order to determine the resilient modulus (Mr,t) of SAC mixtures at 7 and 28 days of curing. Test data were fitted to four models, namely: deviator stress model - f(σd); confining pressure model – f(σ3); Pezo et al. (1992) model – f(σd;σ3); and AASHTO model – f(Pa; θ; τoct). Appendix C presents the constitutive parameters and coefficients of determination (R^2) of all specimens.

The deviator stress model was selected to represent SAC mixtures, based on its coefficients of determination ($0.89 < R^2 < 0.99$). The high values of R^2 demonstrated that deviator stress influences the resilient modulus of SAC mixtures and this relationship is represented by a two-dimensional graph. Other studies on cemented mixtures demonstrated a similar behavior (PARENTE et al., 2002; KAWAHASHI et al., 2010; ROUT et al., 2012).

Table 18 and Table 19 show the values of Mr,t calculated using deviator stress model for SAC 20:80 and SAC 30:70, respectively.

Table 18: Mr,t of the SAC 20:80 mixture as a function of stresses.

σ3 (kPa)	σd (kPa)	7 days			28 days		
		Cement content (%)					
		3	5	7	3	5	7
		Mr,t (MPa)					
20.7	37.3	2815	3195	3210	3153	2774	3654
20.7	55.9	4097	4870	4735	4030	4067	4898
20.7	78.6	5622	6944	6568	4954	5613	6270
34.5	31	2371	2636	2688	2819	2329	3196
34.5	62	4511	5424	5230	4291	4485	5280
34.5	93.1	6578	8283	7728	5490	6587	7088
68.9	62	4511	5424	5230	4291	4485	5280
68.9	124.1	8589	11173	10185	6535	8643	8728
68.9	186.1	12509	17037	15031	8354	12677	11706
103.4	62	4511	5424	5230	4291	4485	5280
103.4	93.1	6578	8283	7728	5490	6587	7088
103.4	196.1	13132	17992	15806	8623	13320	12158
137.9	93.1	6578	8283	7728	5490	6587	7088
137.9	124.1	8589	11173	10185	6535	8643	8728
137.9	248.2	16341	22994	19821	9947	16643	14421
Mean Mr,t		7155	9276	8474	5619	7195	7391

Table 19: Mr,t of the SAC 30:70 mixture as a function of stresses.

σ3 (kPa)	σd (kPa)	7 days			28 days		
		Cement content (%)					
		3	5	7	3	5	7
		Mr,t (MPa)					
20.7	37.3	4708	3261	4275	3485	4018	3831
20.7	55.9	6195	4882	5667	4654	5682	5549
20.7	78.6	7806	6858	7186	5940	7609	7580
34.5	31	4152	2711	3758	3052	3429	3234
34.5	62	6645	5413	6091	5012	6210	6100
34.5	93.1	8756	8120	8086	6705	8798	8851
68.9	62	6645	5413	6091	5012	6210	6100
68.9	124.1	10642	10816	9878	8235	11254	11515
68.9	186.1	14009	16204	13100	11005	15926	16687
103.4	62	6645	5413	6091	5012	6210	6100
103.4	93.1	8756	8120	8086	6705	8798	8851
103.4	196.1	14516	17072	13587	11425	16657	17506
137.9	93.1	8756	8120	8086	6705	8798	8851
137.9	124.1	10642	10816	9878	8235	11254	11515
137.9	248.2	17032	21595	16011	13523	20383	21721
Mean Mr,t		9060	8988	8391	6980	9416	9600

Table 18 and Table 19 indicate that increases of deviator stress led to higher Mr,t values for all conditions (cement content and curing time). With regard to material proportions, in general, the average Mr,t values of SAC 30:70 were approximately 16 % higher than those of SAC 20:80. Figure 26 exhibits the relationship between resilient modulus and deviator stress at 7 and 28 days of curing.

The curves show a clear upward trend of Mr,t values as the deviator stress increases. A similar behavior was reported by Rout *et al.* (2012) and Simoni (2019. According to Puppala *et al.* (2011), this upward trend can be defined as stress hardening.

Overall, the mean values of all tested Mr,t varied from 5619 MPa to 9600 MPa. These values are consistent with the Mr,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).

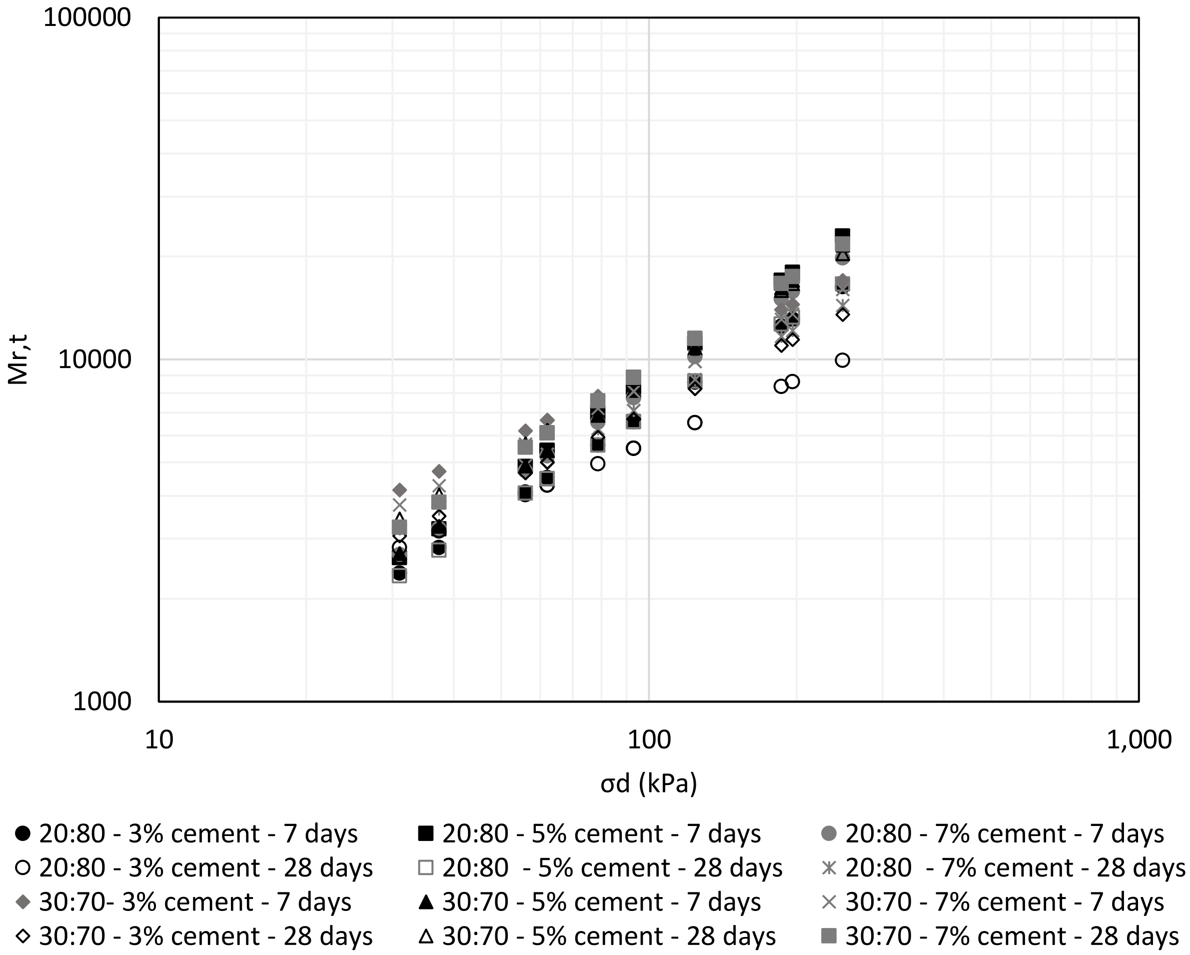

Figure 26: Mr,t of the SAC mixtures at 7 and 28 days of curing.

Regarding curing time, it is observed that:

- *at 7 days of curing*, modifying cement content from 3% to 5% increased the Mr,t values around 30% for mixtures 20:80 and decreased by 1.2% for mixtures 30:70. Moreover, when cement content changed from 5% to 7%, Mr,t decreased by 8.5% and 6.3% for mixtures 20:80 and 30:70, respectively.

- *at 28 days of curing*, when cement content was modified from 3% to 5%, the Mr,t values increased about 28% and 35% for mixtures 20:80 and 30:70, respectively. On the other hand, when cement changed from 5% to 7%, the average increase of Mr,t for mixtures 20:80 and 30:70 was only 3.0% and 2.0%, respectively. These findings are in accordance with the recommendation to use a cement content between 3 and 5%.

In Figure 26, it is possible to notice that SAC 20:80 tends to present higher Mr,t values than SAC 30:70, for deviator stresses lower than 93.1 kPa at 7 days of curing. However, this trend is not very discernible at 28 days of curing. Furthermore, the effect of increasing cement content is evidenced at 28 days of curing, thus indicating that mixtures with less cement content have lower Mr,t than those with higher amounts of cement.

In relation to the curing interval (7 to 28 days), the Mr,t values increased around 20%, except for SAC mixtures 30:70 stabilized with 5% and 7% of cement, in which the increase of Mr,t was 5% and 14%, respectively. The type of test and the load applied may have caused the variation of results.

By comparison, Simoni (2019) found Mr,t values above 5000 MPa for SAC mixture with 5% of CP II Z-32. Likewise, Bessa *et al.* (2016) obtained Mr,t values that lied within 8000 and 9000 MPa for cement contents of 5% and 6 % at 28 days of curing. Therefore, it can be stated that the Mr,t values presented herein are compatible with those found in other studies on SAC mixtures.

4.5.1.1. Statistical analyses for Mr,t values

Figure 27 shows the Mr,t decision tree in three levels, with eigth nodes: one root node, five child nodes and two terminal nodes. Table 20 gathers information such as node identification, segregation criteria, predicted Mr,t values for each group, number of observations at each node (N) and the percentage of observations at the node in relation to the initial sample (%). The Mr,t decision tree presented a coefficient of determination equals to 0.84, indicating a high accuracy of the model.

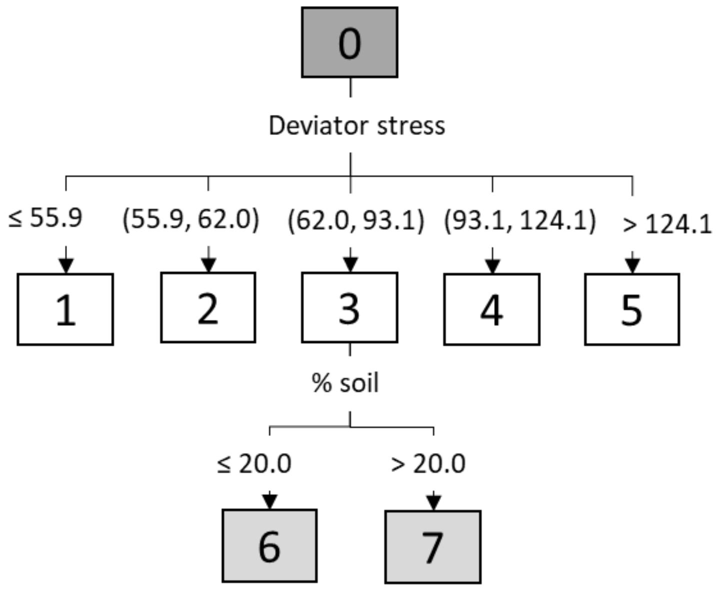

Figure 27: Mr,t decision tree map.

Table 20: Description of the nodes and predicted Mr,t.

Node	Conditions	Mean	Standard deviation	N	%
0	Initial node (root)	7952	4187	180	100
1	Deviator stress ≤ 55.9	3796	1021	36	20
2	Deviator stress (55.9, 62.0)	5315	770	36	20
3	Deviator stress (62.0, 93.1)	7202	1111	48	26.7
4	Deviator stress (93.0, 124.1)	9468	1449	24	13.3
5	Deviator stress (93.0, 124.1)	14734	3224	36	20
6	Deviator stress (62.0, 93.1); % soil ≤ 20	6449	763	24	13.3
7	Deviator stress (62.0, 93.1); % soil > 20;	7955	870	24	13.3

For this decision tree, the CHAID algorithm classified the deviator stress as the most significant variable followed by percentage of soil. The others variables, such as curing time and cement content were not considered as significant in this model (since these factors presented similar values). Regarding branches and nodes, one can point out that:

1) Deviator stress was considered the most important independent variable, dividing the root node into five child nodes;

2) Only the node 3, which corresponds to the interval of deviator stress (62.0 to 93.1 kPa), was considered a significant variable. Therefore, node 3 was divided in two terminal nodes related to material proportion, one equals to 20% and another greater than 20%.

The hierarchy of this decision tree also enabled the prediction of Mr,t values, as observed in the terminal nodes. Additionally, the decision tree led to the following observations:

a) The resilient modulus of SAC mixtures is governed by deviator stress, which was the most significant variable of the model.

b) The predicted Mr,t values lead to evaluate the effect of increasing amounts of soil in the composition of SAC mixtures, for a specified range of deviator stress ($62 < \sigma d < 93.1$ kPa). This means that changing soil proportion from 20 to 30% caused an increase of resilient modulus.

Since cement content and curing time were not considered important variables for branching the nodes, no further observations were made about these variables. Lastly, it is important to emphasize that the effect of deviator stress is more relevant than the effect of the others factors.

Subsequently, multiple linear regression model (Equation 11) was developed in order to predict Mr,t values at 7 days of curing, as a function of deviator stress (kPa), cement content (%) and soil percentage (%). The model presented an F-value of 542.57 and a high coefficient of determination (R^2=0.962), in addition, the independent variables showed p-value < 0.05.

$$Mr,t\ (MPa) = -2285.15 + 68.25 * (deviator\ stress) + 81.17 * (\%\ cement) + 121.84 * (\%\ soil) \quad (11)$$

By analyzing Equation 11, it is noticeable that soil percentage is the most significant independent variable of this model, unlike what was observed for UCS and ITS models. Figure 28 shows a comparison between measured and predicted values, in MPa.

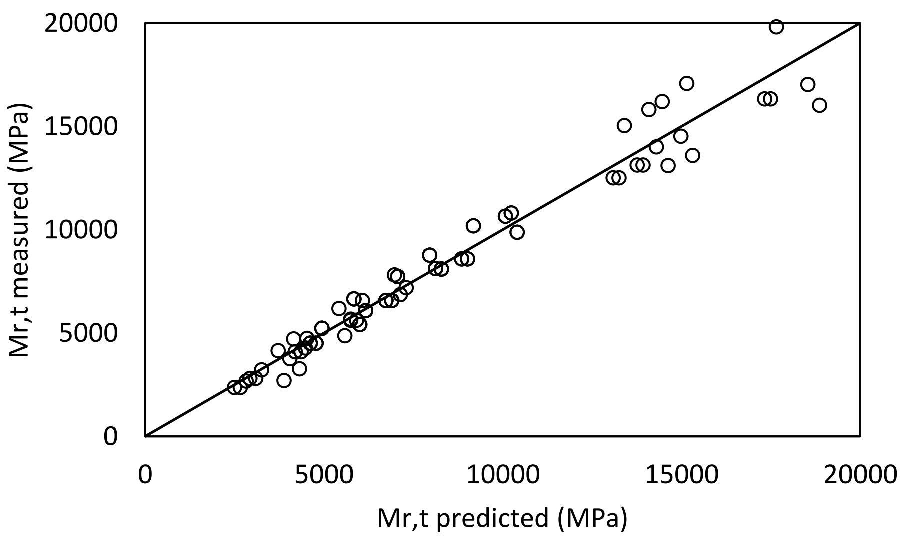

Figure 28: Mr,t values obtained by tests and predicted by the model.

Finally, it must be pointed out that none of the statistical methods were capable of describing the resilient behavior of SAC mixtures as a function of the independent variables (cement content, curing time and proportion of materials). These findings reveals that the RLT test (proposed for soils, aggregates and soil-aggregate mixtures) may not be suitable for determining the resilient modulus of cemented mixtures.

4.5.2. Dynamic indirect tensile test

Dynamic indirect tensile tests were carried out to determine the resilient modulus of SAC mixtures. Table 21 shows the resilient modulus (Mr,d) for SAC mixtures at 7 and 28 days of curing. Tests were performed on two specimens, and the results were statistically controlled by means of standard deviation and coefficient of variation analyses, as presented in appendix D. It is noteworthy that the coefficient of variation showed that Mr,d values ranged from 1% to 11% around the average.

Overall, Mr,d values varied from 15000 MPa to 25000 MPa. Concerning material proportion, the values of SAC 20:80 were, on average, 8.2% higher than those of SAC 30:70, as well as occurred to UCS and ITS properties.

Table 21: MR,d values for SAC mixtures at 7 days of curing.

SAC mixture	Mr,d (MPa)	CV(%)
20:80 – 3% cement	19145	6.45
20:80 – 5% cement	21810	10.88
20:80 – 7% cement	18775	11.26
30:70 – 3% cement	15457	3.50
30:70 – 5% cement	24857	0.97
30:70 – 7% cement	14902	6.87

Figure 29 exhibits the behavior of Mr,d in function of cement content variation. One may observe that SAC mixtures with 5% cement presented the highest values of Mr,d (up to 20000 MPa). Once again, this suggest that there may be an optimum cement content capable of outcome a higher stiffness in this type of stabilization. Another point to highlight is the slightly superior performance of SAC 20:80 mixtures, which may be inferred by a better development of cementitious compounds in the matrix.

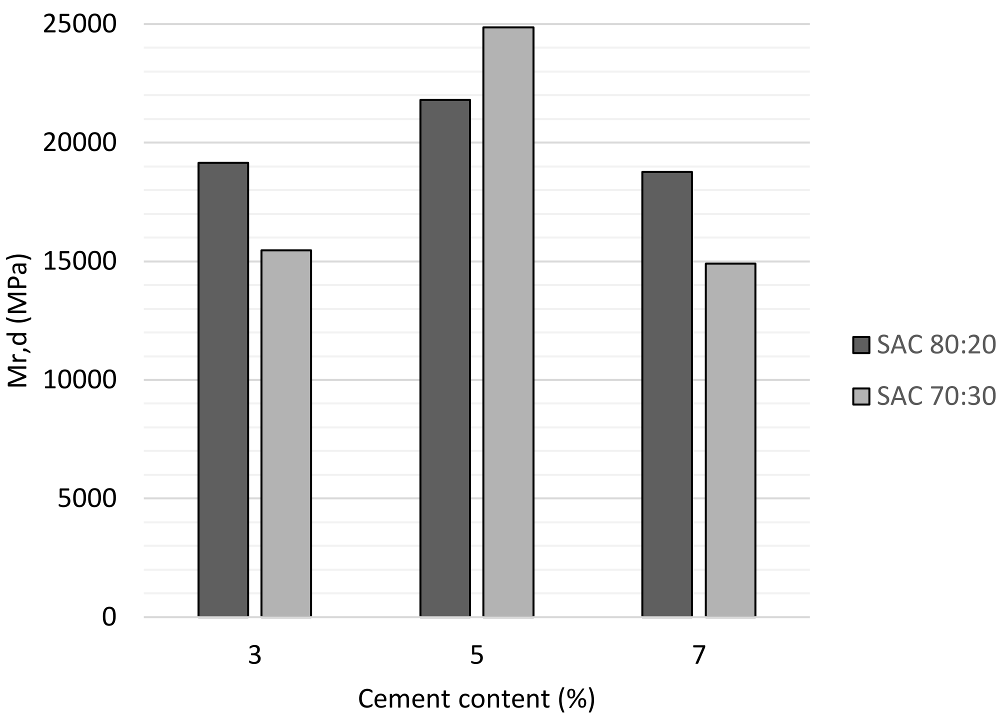

Figure 29: Mr,d for SAC mixtures at 7 days of curing.

Other studies on cemented mixtures have demonstrated that the highest MR,d values are met at 28 days (FEDRIGO, 2015; BAGHINI *et al.*, 2017). According to this observation, the resilient modulus of SAC mixtures of the present research would be even higher at 28 days of curing. Overall, the Mr,d values were quite high, which may be a problem since very stiff materials are prone to have a brittle behavior, leading to failure at low strain levels (FEDRIGO, 2015).

In addition, MR,d values of previous studies can be used for comparison purposes. A research report from New Zealand Transport Agency – NZTA (2011) showed that the Mr,d of soil-cement mixtures at 28 days of curing ranged from 14000 and 24000 MPa. Simoni (2019) reported Mr,d values between 15000 and 17000 MPa for SAC (20:80) mixtures stabilized with 5% of CP II Z-32. On the other hand, Baghini *et al.* (2017) presented Mr,d values of 8000 MPa (at 7 days of curing) and 15000 MPa (at 28 days of curing). In short, one may conclude that Mr,d values of this study are consistent with those found by NZTA (2011) and Simoni (2019).

4.6. Complementary study

4.6.1. Optimum cement content

The study of the dosage of cemented materials considered a comparison between the stresses obtained by mechanistic analyses of hypothetical pavements and the strength parameters derived from laboratory tests. Simoni (2019) determined the stresses by means of mechanistic analysis of hypothetical pavement structures and numbers of ESAL. The author computed the compressive and tensile stresses arising on cemented base layers (composed by SAC mixtures). In this way, Mr values typical of cement-stabilized bases were used as inputs. Results demonstrated that, on the adopted cemented base layers, the compressive stress (σc) ranged from 0.021 to 0.03 MPa, while the tensile stress (σv) varied from 0.359 to 0.551 MPa.

The comparison between the test results of cured mixtures and the computed stresses from mechanistic analysis indicates that:

1) The UCS values varied from 3.54 to 8.86 MPa, for SAC 20:80, and from 2.97 to 7.34 MPa, for SAC 30:70. These values are much higher than the computed compressive stresses (σc) resulting of pavement mechanistic analysis (0.021 to 0.032 MPa). Therefore, one can conclude that for all pavement structures adopted, the acting compressive stresses met the strength requirement;
2) The ITS values ranged from 0.62 to 2.22 MPa, for SAC 20:80, and from 0.51 to 1.70 MPa, for SAC 30:70. These values were higher than the calculated tensile stresses (0.359 to 0.551 MPa), thus meeting the strength requirement. Conservatively, SAC 30:70 with 3% cement would not be a suitable alternative, since its average ITS value is close to the maximum calculated tensile stress.

The technical specification of São Paulo DOT for SAC mixtures (ET-DE-P00/007 - DER-SP, 2006) does not specify a dosage method for these materials. On the other hand, it recommends that cement content of SAC mixtures must comply with the UCS and ITS at 28 days of curing, specified in the pavement design.

UCS and ITS values of SAC mixtures using 5% of cement at 7 days of curing met the requirements of pavement design. In addition, Mr,t values were compatible or even superior to the range recommended by instruction ET-DE-P00/007 for mechanistic analyses. Observations of the mechanical behavior of SAC mixtures also contributed for choosing 5% as the optimum cement content. For instance, UCS and ITS values significantly increased with 3% and 5% cement, whereas the strength increment rate reduced with cement contents above 5%. Results of Mr,t and Mr,d tests also indicated the cement content of 5% as the optimum one, since at this content, the mixtures reached higher stiffness values.

Therefore, based on the aforementioned test results, pavement design requirements and technical specification (São Paulo-DOT), it is concluded that the optimum cement content is 5%. This value indirectly influences the economic aspects of SAC mixtures, as it is the lowest cement content that met the required strengths. Furthermore, this cement content is analogous to that indicated by Simoni (2019) for SAC 20:80 mixtures using PCC-IP cement.

Another point to discuss refers to time or efficiency of cement stabilization, because during pavement construction or maintenance/rehabilitation, it is common to occur operational restrictions in order to organize the traffic. For example, the “stop-and-go” system slows down and/or blocks (temporarily) the traffic flow and may contribute to the occurrence of accidents, mainly in two-lane roads with high-traffic volume.

In this way, as a complementary analysis, UCS and ITS values were evaluated at 3 days of curing in order to determine the time in which the material would be able to meet the strength required by pavement design. This would speed up the construction process and reduce the traffic opening time, allowing the construction of upper layers to start earlier.

Table 22 shows the results of UCS and ITS of the SAC 20:80 and SAC 30:70 with 5% of HE, at 3 days of curing. It also presents the results of Simoni (2019) for SAC 20:80 using 5% of PCC-IP. This type of cement has pozzolana as its supplementary cementitious material.

UCS values varied from 3.09 to 4.12 MPa, and ITS values ranged from 0.69 to 1.26 MPa. Based on hypothetical pavement analyses, the maximum compressive stress of cemented base layers was 0.032 MPa and the maximum tensile stress was 0.551 MPa. Since all strength values were higher than the onset stresses, it could be recommended to complete the construction of upper layers or the pavement maintenance activities at 3 days of curing.

Table 22: UCS and ITS values for SAC mixtures at 3 days of curing.

SAC Mixture	UCS (MPa)	ITS (MPa)
	3 days	3 days
20:80 – HE – 5%	4.12	1.26
30:70 – HE – 5%	3.91	0.70
20:80 – PCC-IP – 5%	3.09	0.69

Figure 30 and Figure 31 show the kinetics of UCS and ITS, respectively. Figure 30 evidences that the UCS_{3days} of SAC mixtures using HE are higher than the one with PCC-IP (~25%). At 7 days, UCS values of mixtures 30:70 – HE and 20:80 – PCC-IP are quite similar. At 28 days, UCS values of SAC 20:80 – PCC-IP are close to the SAC 20:80 – HE.

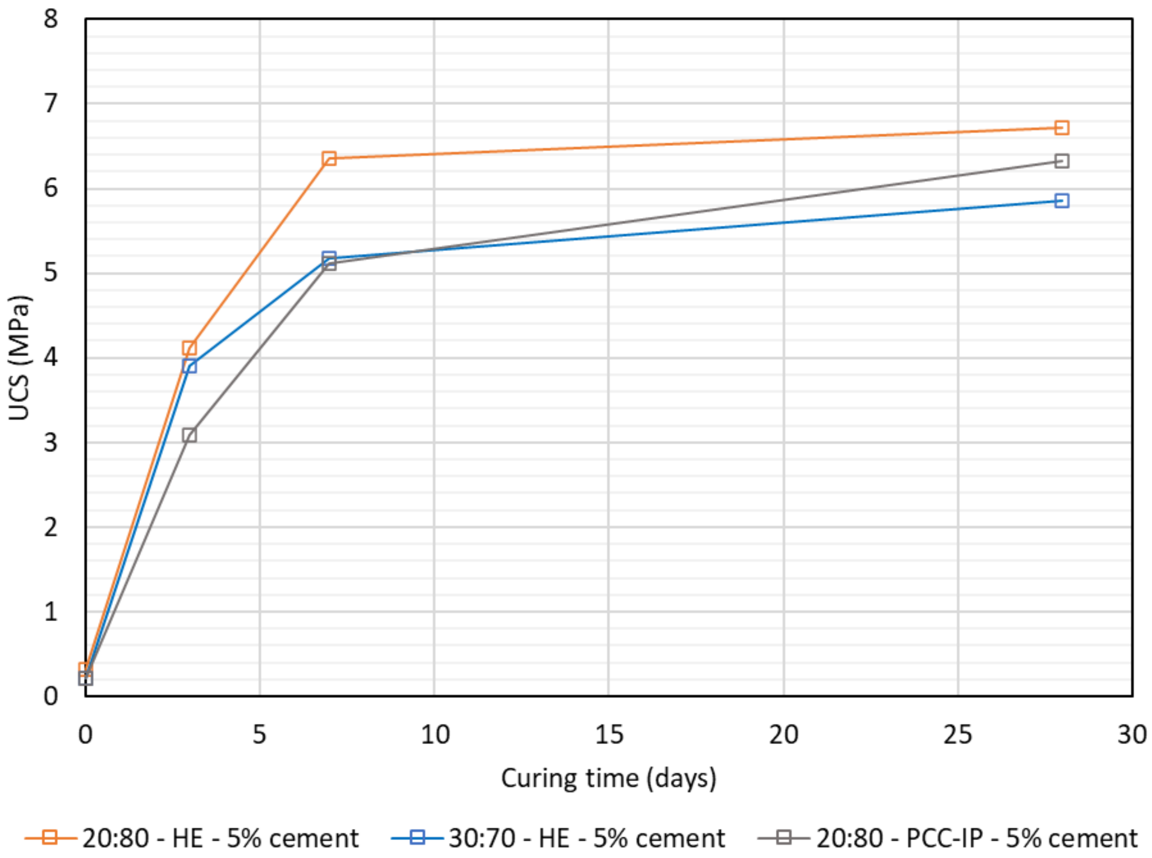

Figure 30: UCS of SAC mixtures with 5 % of cement over curing time including 3 days.

For all tested mixtures, UCS values evolved asymptotically and SAC 20:80 – HE had the best behavior, exhibiting superior strengths (regardless of curing time) and advantages (especially about production efficiency). On the other hand, SAC 30:70 with HE had the lower UCS values, comparatively. The strength gain of mixtures using HE at early ages is attributed to the fast cementation reactions of this type of cement.

With regard to the SAC mixture using PCC-IP, the strength gain is slower, but it continues to occur until 28 days, surpassing the strength values of the mixture 30:70 with HE. This is a typical contribution of the pozzolana present in this cement, once it promotes gradual strength gains. Nevertheless, it is worth keeping in mind that any change of material proportion must also imply different strength, regardless of the type of cement (as seen in previous discussions).

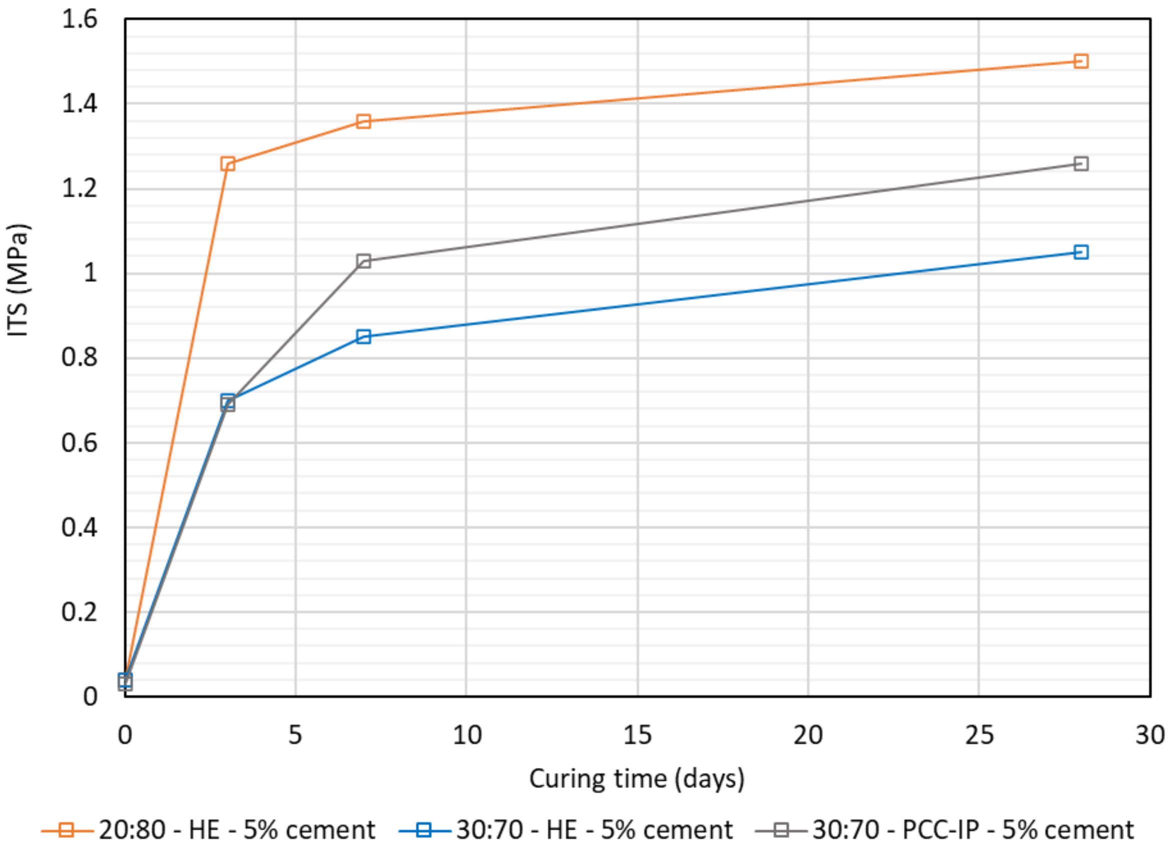

Figure 31: ITS of SAC mixtures with 5 % of cement over curing time including 3 days.

Figure 31 shows ITS kinetics. It is worth mentioning that the ITS3days values of mixture SAC 20:80 using HE are higher than those of SAC mixtures using PCC-IP (~55%). Moreover, ITS3days values of SAC 30:70 using HE and SAC 20:80 with PCC-IP is practically the same. At 7 days of curing, ITS curves shift up in the same behavior trend observed for UCS (Figure 14), without stabilizing at 28 days, though. By comparing the values obtained at 3 days to those at 7 days of curing, it is noticed that the UCS_{3days} represents around 70% of the UCS_{7days}., whereas the ITS_{3days} reached a representation around 80% of the ITS_{7days}.

4.6.2. RMA in SAC mixtures

Another investigation of the complementary study consisted of replacing the basaltic mineral aggregate by recycled masonry aggregate (RMA) in SAC mixtures. Additionally, Proctor tests were carried out in order to characterize the compaction parameters of the new SAC mixtures.

To compare the effect of the type of aggregate, results are presented comparatively, considering two SAC mixtures 30:70 stabilized with 5% of CP V ARI: one was composed of basaltic mineral aggregates (BA) and the other one was composed of recycled masonry aggregates (RMA). A summary containing the optimum moisture content (OMC), the maximum dry density (MDD) and the water/cement ratio (W/C) of both mixtures is presented in Table 23.

Replacing BA by RMA increased OMC (~75%) and reduced MDD (~15%). These results can be explained by the low density and high porosity of RMA, mainly due to the presence of ceramics from bricks and roof tile in the RMA composition. They also contribute to the high-water absorption, low abrasion resistance, flat shape of crushed particles and high breakage by compaction (LEITE *et al.*, 2011).

Table 23: Compaction test results and W/C ratio for SAC mixtures with basalt aggregate and recycled masonry aggregates.

SAC Mixture	OMC (%)	MDD (kN/m³)	W/C ratio
30:70- 5% cement - BA	5.6	23.40	1.12
30:70- 5% cement - RMA	9.8	19.91	1.97

From Table 23, it is possible to verify that the increase of OMC led to a higher W/C ratio. It is important to emphasize that the W/C ratio is slightly higher than those reported by other researchers. For instance, W/C ratio ranged from 1.30 to 1.70 for cement-stabilized mixtures containing RAP, RCA, and recycled glass (FEDRIGO *et al.* 2017, BESSA et al.; 2016).

Figure 32 shows the compaction curves of SAC mixtures at the modified compaction effort. The SAC mixture with RMA exhibited a flatten-shaped compaction curve, probably due to the high-water absorption of RMA. On the other hand, SAC mixture with BA outlined a bell-shaped curve, as expected when basalt materials are used.

Table 24 shows UCS values over time. It is worth mentioning that each UCS value represents the average of three specimens. Moreover, Grubbs' test was applied to the UCS data, the coefficient of variation (CV) and the results are presented in Appendix E. UCS_{0days} values revealed that initial strength of the mixture with RMA is three times greater than that of the mixture with BA. It is noteworthy that the low abrasion resistance, flat shape, breakage by compaction and high amount of fines of RMA particles contribute to the densification and some increase of the UCS. Over time, both mixtures presented increase of UCS, although the mixture with BA had the greatest strength gain.

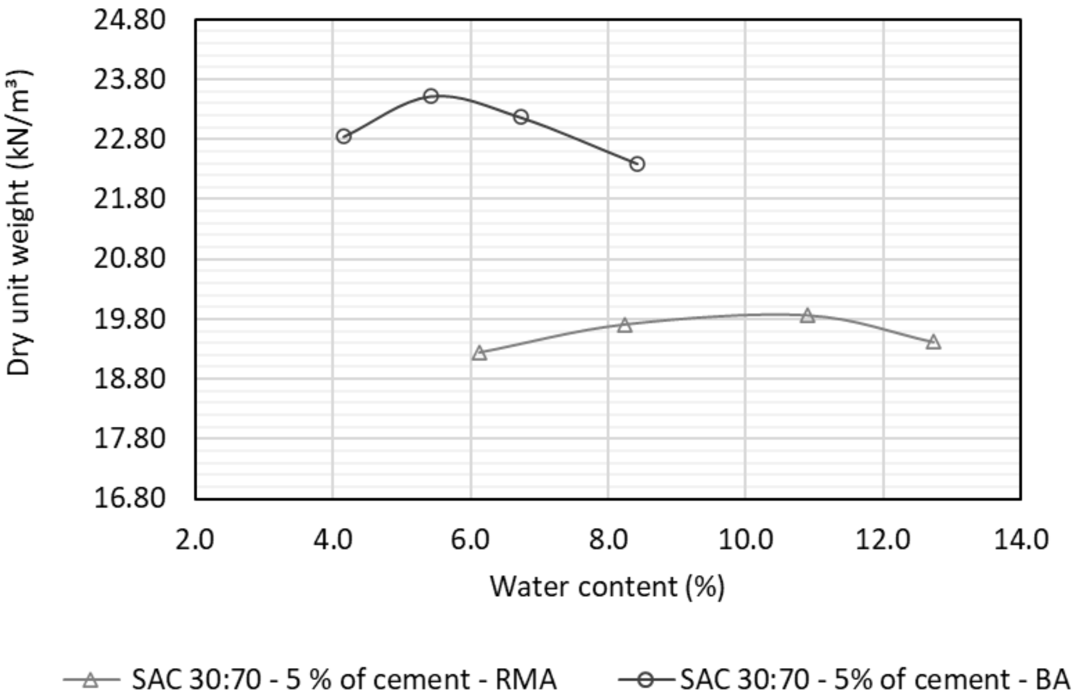

Figure 32: Compaction curves of SAC mixtures with RMA and BA.

Table 24: UCS values of SAC mixtures with NA and RMA with 5% of cement over curing time.

SAC Mixture	UCS (MPa)		
	0 days	7 days	28 days
30:70- 5% cement - BA	0.22	5.17	5.86
30:70- 5% cement - RMA	0.66	3.25	3.80

Figure 33 presents UCS evolution over time. In this figure, one can identify that the greatest strength gain ratio was achieved at the curing interval from 0 to 7 days. Additionally, by analyzing the strength development of each SAC mixture, it is possible to verify that UCS_{7days} values of mixture containing BA were about 24 times greater than its UCS_{0days}. On the other hand, the difference between UCS_{7days} and UCS_{0days} of mixtures with RMA was about 5 times. From 7 to 28 days, the strength gain was quite similar for both mixtures, about 15%. However, at 28 days, UCS values were significantly different, with the mixture containing BA exhibiting a UCS about 1.5 times greater than that presented by the mixture containing RMA.

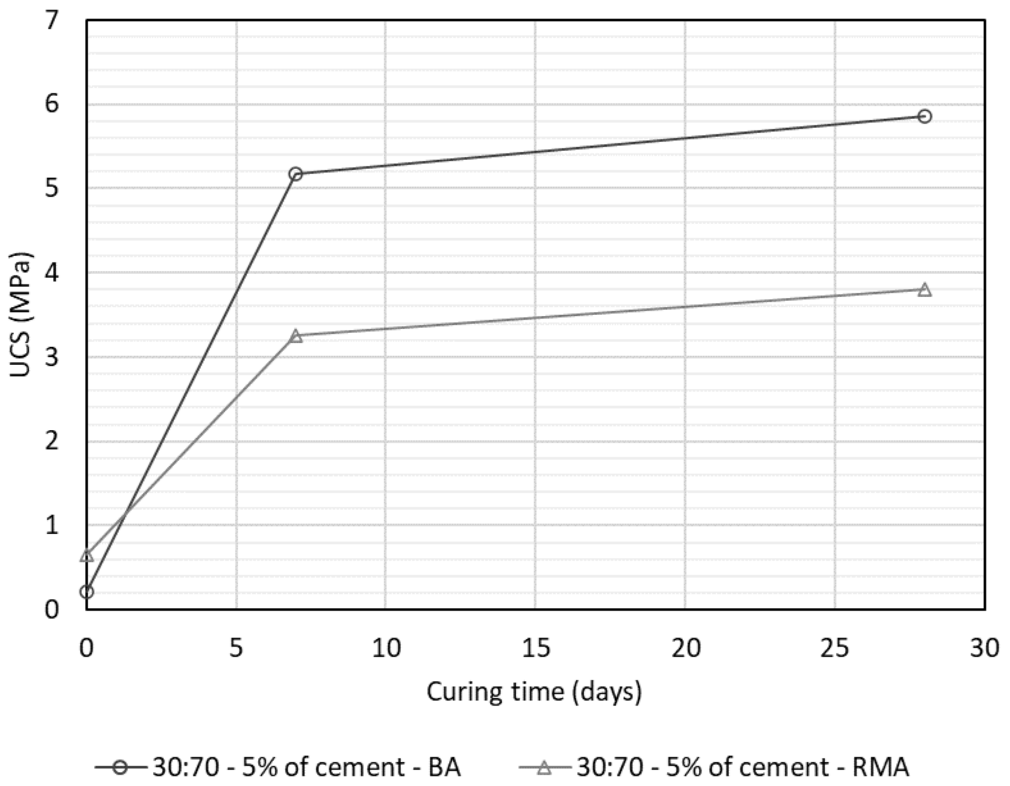

Figure 33: UCS of SAC mixtures with BA and RMA with 5% of cement over curing time.

Based on linear behavior, the strength gain rates of UCS from 0 to 7 days were 0.70 MPa/day and 0,37 MPa/day for mixtures containing BA and RMA, respectively. In addition, the UCS values of both mixtures are higher than the computed compressive stresses of the hypothetical pavement (0.021 to 0.032 MPa), thus meeting the strength requirement.

Table 25 summarizes the ITS values of SAC mixtures at different curing times. Once again, each ITS value represents the average of three specimens. Grubbs' test was applied to the ITS data and the results and the coefficient of variation (CV) are presented in Appendix E. At 0 days of curing, ITS values revealed that the immediate strength is very low. Over time, ITS increased and the mixture containing BA presented the greatest strength gain.

Table 25: ITS values of SAC mixtures with BA and RMA with 5% of cement over curing time.

SAC Mixture	ITS (MPa)		
	0 days	7 days	28 days
30:70- 5% cement - BA	0.04	0.85	1.05
30:70- 5% cement - RMA	0.01	0.42	0.61

Figure 34 exhibits the relationship between ITS and curing time. Analogously to UCS, the greatest ITS gain was observed at 7 days of curing. Moreover, from 0 to 7 days of curing, ITS increased about 20 and 40 times for mixtures containing BA and RMA, respectively. From 7 to 28 days, the strength gain was also different for both SAC mixtures: 24% for mixtures containing BA and 45% for mixtures containing RMA. Additionally, at 28 days of curing, the ITS value of the mixture containing BA was almost 2 times higher than that presented by the mixture containing RMA.

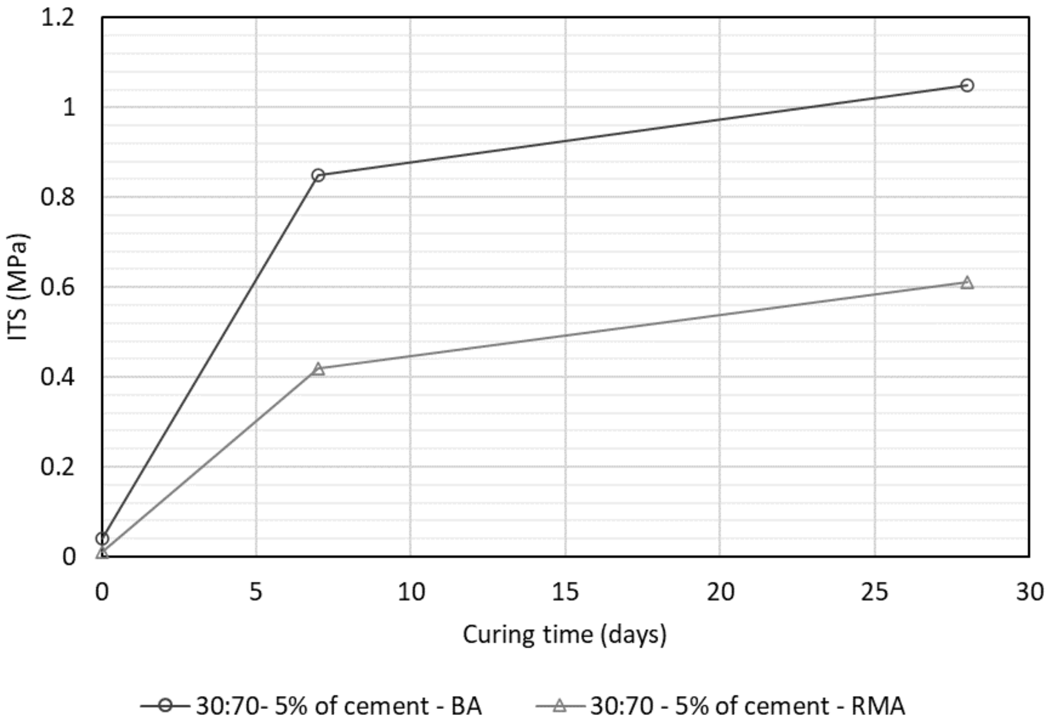

Figure 34: ITS of SAC mixtures with BA and RMA with 5% of cement over curing time.

If a linear behavior is assumed, it is possible to notice that the strength gain rates are 0.12 MPa/day and 0.06 MPa/day for mixtures containing BA and RMA, respectively. From 0 to 28 days, the ITS values of mixtures with BA varied from 0.04 to 0.85 MPa, while mixtures with RMA ranged from 0.01 to 0.61 MPa. Furthermore, the computed tensile stresses varied from 0.359 to 0.551 MPa.

By comparing ITS values with tensile stresses calculated by means of mechanistic analysis, one can conclude that the mixture containing RMA may be a suitable alternative as construction material of pavement base layers, as long as it has been cured for 28 days. This requirement is due to the proximity of strength values and maximum acting stresses.

Although cement addition has increased the strength of SAC mixtures over time, typical characteristics of RMA (i.e. heterogeneity, high porosity, low abrasion resistance and potential of particle breakage by compaction) hinder the improvement of these mixtures. In this case, due to the necessary caution when applying RMA, it is suggested to use this type of SAC mixture exclusively for low-volume roads.

Based on mechanical tests results, Table 26 exhibits the ITS/UCS ratio for both SAC mixtures. Concerning SAC mixtures using RMA, the ITS/UCS ratio varied from 0.02 to 0.16. At 7 and 28 days of curing, it was noticed that the ITS/UCS ratio of both SAC mixtures increased over time. Besides that, the ITS/UCS ratio of SAC mixtures containing BA were higher than those of mixtures using RMA. The mean values of ITS/UCS ratios were 0.17 and 0.14 for mixtures using BA and RMA, respectively.

Table 26: ITS/UCS ratio for SAC mixtures with BA and RMA.

SAC Mixture	ITS / UCS ratio		
	0 days	7 days	28 days
30:70- 5% cement - BA	0.18	0.16	0.18
30:70- 5% cement - RMA	0.02	0.13	0.16

Table 27 shows the results of resilient modulus (Mr,d) for SAC mixtures at 7 days of curing. The coefficient of variation for these results ranged from 1% and 15%. It is noteworthy that replacing BA by RMA caused a reduction of almost 3 times in Mr,d. This reduction can be explained by the low stiffness of RMA aggregates. Figure 35 presents the rupture surface of SAC specimens containing BA and RMA. It is observed that SAC mixtures containing BA presented a mixed rupture pattern, in which a portion of basalt aggregates detached from soil-cement matrix, while the other portion experience aggregate breakage. For SAC mixtures containing RMA, only aggregate breakage occurs, which can be attributed to soft materials such as ceramics and gypsum.

Table 27: MR,d values for SAC mixtures with BA and RMA at 7 days of curing.

SAC mixture	Mr,d (MPa)
30:70- 5% cement - BA	24857
30:70- 5% cement - RMA	9255

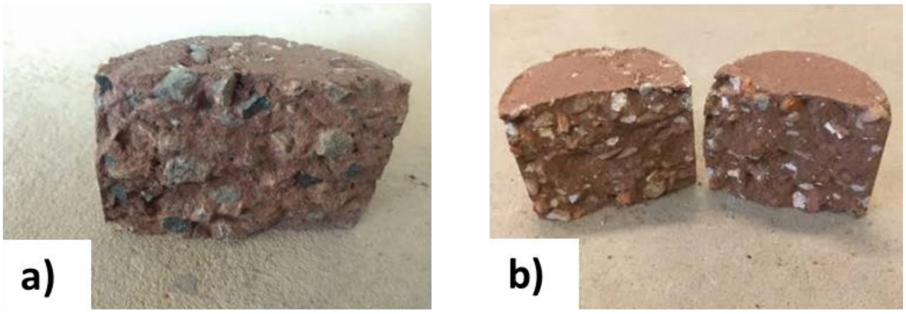

Figure 35: Rupture surface of ITS specimen for a) SAC with BA and b) SAC with RMA.

4.7. Final considerations

SAC mixtures result from the combination of physical and chemical stabilization of geotechnical materials. Both stabilization techniques are based on well-known and standardized methods and procedures. However, despite the use of SAC mixtures in base and subbase layers, there is still no directions for design and dosage of these mixtures. Therefore, this investigation focused on understanding the mechanical behavior of SAC mixtures in an attempt to recommend parameters and protocols to support best practices of design and dosage.

Proctor compaction tests provide the first design parameters of pavement materials. OMC and MDD are indirectly related to strength. Therefore, when a new material is tested, it is mandatory to know how it behaves, in terms of not only densification but also compaction control purposes. In this sense, Proctor tests showed that, overall, SAC mixtures presented OMC values ranging from 5.6% to 6.3%, while MDD values varied from 23.40 kN/m^3 to 23.95 kN/m^3. The different material proportions adopted revealed that SAC 20:80 might promote better arrangement and densification due to its higher MDD, when compared to SAC 30:70. In addition, the higher values of MDD for SAC mixtures stabilized with 5% cement may be an indication that this content is the optimum one for both material proportions.

W/C ratio is a design parameter for concrete and mortar that indicates cement hydration capacity and, consequently, the strength gain. It is a well-known fact that the lower the W/C, the higher the strength. In this research, W/C ratios varied from 0.80 to 2.07. Although this range covers the W/C of concretes, it must emphasize that there is no equivalent behavior of SAC mixtures and concrete. This is attributed to the amounts of cement and water used in SAC mixtures, which are not enough for bonding all soil particles and aggregates, thus decreasing the hardening potential of the cemented system. Therefore, one may not expect very high strength of SAC mixtures based on their W/C ratio. In short, by preserving the right proportions, one can conclude that the low W/C of SAC mixtures stabilized with 7% cement would result in better strength.

Design and dosage of cemented materials (e.g. soil-cement and cement treated crushed rock) commonly use a mechanical parameter to select the most suitable mixture. UCS has been often used for this purpose, as a heritage from Concrete Technology. However, for pavement applications, ITS has also been considered in the design methods, since tensile stresses may act in cemented base layers. In this study, the evaluation of UCS and ITS of SAC mixtures showed that the increase of compressive or tensile strength depends on curing time, cement content and material proportion.

The kinetics of strength is evident, UCS ranged from 0.18 MPa to 8.86 MPa, from 0 to 28 days of curing. Regarding ITS, the property varied from 0.03 MPa to 2.22 MPa. It is noteworthy that the ranges of UCS and ITS contain very low strength values. This happens because cement addition does not significantly change the immediate strength (at 0 days of curing), as cement presents a filler-like behavior in mixtures at this age. Therefore, it is mandatory to study cemented materials in light of curing time. Furthermore, it is important to point out that, at 7 days of curing, SAC mixtures reached (on average) 90% of their UCS_{28days} and 75% of their ITS_{28days}, which can be considered as an advantage regarding the criterion of the pavement design requirements of the Sao Paulo - DOT (DER-SP, 2006), of the strengths at 28 days. It should be emphasized that the SAC mixtures stabilized with high early strength Portland cement (CP V-ARI) exhibited the greatest strength gains.

UCS and ITS also increased due to modifications of cement content. However, the strength gain was more pronounced at cement contents ranging from 3% to 5%, indicating the likely existence of an optimum cement content in this range. Moreover, an adequate material proportion might enhance strength. For instance, in this study, UCS and ITS of SAC 20:80 mixtures higher than SAC 30:70 mixtures. Considering dosage purposes, it is advisable selecting the minimum cement content capable of leading the mixture to the required strength, thus fulfilling economic and environmental demands. Furthermore, if possible, the material proportion that imparts a higher strength to the mixture should be considered.

Resilient modulus is also a fundamental parameter used in pavement design; thus, its determination is essential at the material selection phase. Repeated load triaxial (RLT) tests are usually performed for geotechnical materials and diametric resilient modulus (DRM) tests are recommended for asphalt mixtures. These tests, that measure the material stiffness, were performed for the SAC mixtures of this research. Results indicated that the resilient modulus from RLT tests was more influenced by deviator stress, i.e. Mr,t increases with increasing deviator stresses. The significant influence of deviator stress hindered the understanding of the effect of cement content and curing time in mixture stiffness. Overall, Mr,t ranged from 5600 to 9600 MPa, suggesting that the stiffness of SAC mixture is consistent with soil-cement and cement treated crushed rock. Interestingly, RLT was the only test in which SAC 30:70 had better performance than SAC 20:80.

DIT test results indicated that SAC 20:80 is stiffer than SAC 30:70, as seen in UCS and ITS analyses. In general, Mr,d ranged from 15000 MPa to 25000 MPa at 7 days of curing. Additionally, the highest Mr,d values were observed in mixtures stabilized with 5% cement. It is important to point out that very stiff materials may exhibit brittle behavior and failure at low strain.

Regarding cement dosage, it was observed that all mixtures presented high values of UCS and ITS in laboratory tests. Actually, the strength values were much higher than the computed stresses for hypothetical pavement structures under high- and very high-traffic volumes. However, conservatively, SAC 30:70 using 3% cement would not be a suitable alternative, since its ITS was close to the calculated tensile stress. Thus, in order to meet economic and environmental demands, the minimum recommended cement content is 5%.

The analysis of UCS and ITS at 3 days of curing aimed to determine if the material would meet the strength required by pavement design. This comparison was carried out in order to streamline the construction of the upper layers and reduce the traffic opening time. The present research showed that all SAC exhibited strength values that were superior to those required by the hypothetical pavement design. In this sense, the SAC mixtures using CP V ARI deserve to be highlighted, since they always presented the highest UCS and ITS (regardless of curing time) and advantages (especially concerning production efficiency and early traffic opening).

Finally, yet importantly, this research evaluated the feasibility of using recycled masonry aggregate (RMA) in SAC mixtures. Proctor tests showed that replacing the basaltic mineral aggregate by RMA increased the OMC by 75% and reduced MDD by 15%. Modifications in compaction parameters are due to RMA characteristics, such as low density and high porosity. The poor characteristics of RMA led SAC mixtures to present lower strengths. The highest UCS and ITS were reached only at 28 days of curing, with respective values of 3.8 and 0.6 MPa. In addition, Mr,d was also low (around 9000 MPa), when compared with SAC with BA.

Images of the rupture surface of specimens confirmed RMA breakage and the presence of undesirable materials. Therefore, since UCS and ITS were quite low, SAC mixtures containing RMA should not be recommended as base and/or subbase material of high- and very high-traffic volume roads. However, such mixtures may be a viable alternative for low-volume roads, as long as they are cured for 28 days, in order to assure high strength levels.

5. CONCLUSIONS

The main purpose of this research was to contribute to the study of dosage and to understand the effects of factors on soil-aggregate-cement mixtures (SAC). The factors considered in analyses were cement content, material proportion and type of aggregate. Based on the results of SAC mixtures containing basaltic mineral aggregates, it was possible to conclude that:

- SAC 20:80 always presented higher mechanical properties values when compared with SAC 30:70. The better performance of SAC 20:80 was attributed to its satisfactory arrangement of particles and high proportion of aggregates in the mixture skeleton;

- all SAC mixtures studied showed satisfactory mechanical performance capable of allowing their use as base and subbase pavement layers, since all mixtures met the requirements of Sao Paulo-DOT technical specification for SAC (ET-DE-P00/007 - DER SP, 2006a);

- the UCS, ITS and Mr were in agreement with other cemented mixtures commonly used 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;

- all SAC mixtures presented superior values of UCS and ITS than the stresses computed by means of mechanistic analysis, reaching the strength requirements at 7 days of curing. The cement content is equal to 5% was recommended in order to fulfill economic and environmental demands.

SAC mixtures containing basaltic mineral aggregate and stabilized with HE or PCC-IP were tested at 3 days of curing and using the optimum cement content, in order to study the possibility reducing traffic opening time. Findings indicated that:

- all mixtures presented values of UCS and ITS higher than the stresses calculated for hypothetical pavement structures. Mixtures using HE had the best mechanical behavior, presenting advantages regarding the production efficiency, enabling the continuity of construction and/or rehabilitation of pavement and early traffic opening.

The feasibility of using recycled masonry aggregate (RMA) in SAC mixtures was also studied. A comparison of properties of SAC mixtures using RMA and basalt aggregates (BA) led to conclude that:

- the low density and high porosity of RMA resulted in less resistant SAC mixtures. The highest UCS and ITS were reached only at 28 days of curing;

- the rupture surface of ITS specimens confirmed the breakage of RMA and the presence of undesirable materials. This may be the reason why SAC mixtures using RMA had a weak performance, despite cement addition;

- SAC using RMA might be recommended for low-volume roads, as long as it has been cured for 28 days, in order to assure higher strength levels.

It is important highlight 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.

5.1. Suggestions for future studies

To complement the study on SAC mixtures, it could be interesting:

- To propose fatigue models for soil-aggregate-cement mixtures;
- To carry out durability tests on SAC mixtures;
- To examine volumetric properties, such as absorption, capillarity, swelling and shrinkage;
- To perform a field evaluation on trial sections of pavements containing SAC mixtures.

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APPENDIX A

UNCONFINED COMPRESSIVE STRENGTH (UCS)

Table A.1 – Grubbs Test for UCS values of SAC mixtures at 0 days of curing.

SAC 20:80 – Basalt Aggregate						
Cement content (%)	UCS (MPa)	Average UCS (MPa)	Standard Deviation	G	Final UCS (MPa)	CV (%)
	0.28			0.193		
3	0.27	0.28	0.011	1.083	0.28	4
	0.29			0.889		
	0.32			0.873		
5	0.31	0.32	0.006	1.091	0.32	2
	0.32			0.218		
	0.31			0.002		
7	0.32	0.31	0.004	0.017	0.31	1
	0.31			0.015		
SAC 30:70 – Basalt Aggregate						
Cement content (%)	UCS (MPa)	Average UCS (MPa)	Standard Deviation	G	Final UCS (MPa)	CV (%)
	0.18			0.105		
3	0.16	0.18	0.012	1.048	0.18	7
	0.19			0.943		
	0.21			0.965		
5	0.22	0.22	0.012	0.067	0.22	6
	0.23			1.032		
	0.25			0.139		
7	0.23	0.25	0.023	0.923	0.25	9
	0.28			1.062		

Table A.2 - Grubbs Test for UCS values of SAC mixtures at 3 days of curing.

SAC 20:80 – Basalt Aggregate							
SAC Mixture	Cement content (%)	UCS (MPa)	Average UCS (MPa)	Standard Deviation	G	Final UCS (MPa)	CV (%)
		4.08			0.813		
20:80 – HE		4.10	4.12	0.046	0.304	4.12	1
		4.17			1.117		
		4.15			0.963		
30:70 – HE	5	3.93	3.91	0.244	0.070	3.91	6
		3.66			1.033		
		3.06			1.149		
20:80 – PCC -IP		3.10	3.09	0.024	0.473	3.09	1
		3.10			0.676		

Table A.3 - Grubbs Test for UCS values of SAC mixtures at 7 days of curing.

Cement content (%)	UCS (MPa)	Average UCS (MPa)	Standard Deviation	G	Final UCS (MPa)	CV (%)
SAC 20:80 – Basalt Aggregate						
	3.30			0.884		
3	3.48	3.54	0.267	0.202	3.54	8
	3.83			1.085		
	6.66			0.382		
5	5.40	6.35	0.834	1.135	6.35	13
	6.97			0.752		
	9.03			1.135		
7	7.86	8.33	0.620	0.751	8.33	7
	8.09			0.384		

Cement content (%)	UCS (MPa)	Average UCS (MPa)	Standard Deviation	G	Final UCS (MPa)	CV (%)
SAC 30:70 – Basalt Aggregate						
	3.29			1.122		
3	2.88	2.97	0.280	0.324	2.97	9
	2.75			0.798		
	5.44			1.005		
5	4.90	5.17	0.273	0.995	5.17	5
	5.17			0.010		
	7.31			0.889		
7	5.99	6.71	0.668	1.082	6.71	10
	6.84			0.193		

Table A.4 - Grubbs Test for UCS values of SAC mixtures at 28 days of curing.

Cement content (%)	UCS (MPa)	Average UCS (MPa)	Standard Deviation	G	Final UCS (MPa)	CV (%)
SAC 20:80 – Basalt Aggregate						
	4.25			1.082		
3	3.85	3.91	0.313	0.190	3.91	8
	3.63			0.891		
	6.77			0.229		
5	6.91	6.72	0.223	0.866	6.72	3
	6.48			1.095		
	8.79			0.652		
7	10.30	9.34	0.836	1.151	8.86	9
	8.92			0.500		
SAC 30:70 – Basalt Aggregate						
	3.53			1.096		
3	3.10	3.18	0.317	0.233	3.18	10
	2.90			0.863		
	5.95			0.124		
5	6.54	5.86	0.727	0.932	5.86	12
	5.10			1.056		
	8.72			1.119		
7	6.35	7.34	1.234	0.807	7.34	17
	6.96			0.311		

*Note: In red, specimens discarded (outliers).

APPENDIX B

INDIRECT TENSILE STRENGHT (ITS)

Tabela B.1 - Grubbs Test for ITS values of SAC mixtures at 0 days of curing.

SAC 20:80 – Basalt Aggregate						
Cement content (%)	ITS (MPa)	Average ITS (MPa)	Standard Deviation	G	Final ITS (MPa)	CV (%)
	0.045			0.549		
3	0.045	0.04	0.002	0.605	0.04	5
	0.041			1.154		
	0.053			0.897		
5	0.045	0.04	0.011	0.181	0.04	27
	0.030			1.078		
	0.054			1.095		
7	0.045	0.05	0.005	0.866	0.05	9
	0.048			0.229		
SAC 30:70 – Basalt Aggregate						
Cement content (%)	ITS (MPa)	Average ITS (MPa)	Standard Deviation	G	Final ITS (MPa)	CV (%)
	0.035			0.232		
3	0.031	0.03	0.003	1.096	0.03	10
	0.037			0.863		
	0.044			1.083		
5	0.035	0.04	0.004	0.888	0.04	11
	0.038			0.195		
	0.043			0.079		
7	0.040	0.04	0.002	1.037	0.04	5
	0.045			0.958		

*Note: In red, specimens discarded (outliers).

Table B.2 - Grubbs Test for ITS values of SAC mixtures at 3 days of curing.

SAC 20:80 – Basalt Aggregate							
SAC Mixture	Cement content (%)	ITS (MPa)	Average ITS (MPa)	Standard Deviation	G	Final ITS (MPa)	CV (%)
		1.190			0.740		
20:80 – HE		1.371	1.26	0.096	1.138	1.26	8
		1.222			0.398		
		0.689			0.224		
30:70 – HE	5	0.667	0.70	0.035	0.869	0.70	5
		0.736			1.093		
		0.631			0.927		
20:80 – PCC -IP		0.594	0.61	0.018	1.060	0.61	3
		0.616			0.132		

Table B.3 - Grubbs Test for ITS values of SAC mixtures at 7 days of curing.

SAC 20:80 – Basalt Aggregate						
Cement content (%)	ITS (MPa)	Average ITS (MPa)	Standard Deviation	G	Final ITS (MPa)	CV (%)
	0.635			0.958		
3	0.613	0.62	0.002	1.038	0.62	2
	0.625			0.080		
	1.350			0.150		
5	1.304	1.36	0.011	0.916	1.36	4
	1.424			1.067		
	1.446			0.768		
7	1.537	1.62	0.005	0.362	1.62	14
	1.870			1.131		

SAC 30:70 – Basalt Aggregate						
Cement content (%)	ITS (MPa)	Average ITS (MPa)	Standard Deviation	G	Final ITS (MPa)	CV (%)
	0.424			1.139		
3	0.571	0.51	0.003	0.733	0.51	15
	0.545			0.406		
	0.925			1.131		
5	0.791	0.85	0.004	0.766	0.85	8
	0.819			0.366		
	0.733			0.957		
7	1.505	1.10	0.002	1.038	1.10	35
	1.072			0.082		

Table B.4 - Grubbs Test for ITS values of SAC mixtures at 28 days of curing.

SAC 20:80 – Basalt Aggregate						
Cement content (%)	ITS (MPa)	Average ITS (MPa)	Standard Deviation	G	Final ITS (MPa)	CV (%)
	0.913			0.718		
3	0.916	0.92	0.009	0.424	0.92	1
	0.931			1.142		
	1.828			1.025		
5	1.497	1.51	0.308	0.052	1.51	20
	1.213			0.973		
	2.145			1.147		
7	2.248	2.22	0.064	0.460	2.22	3
	2.263			0.687		
SAC 30:70 – Basalt Aggregate						
Cement content (%)	ITS (MPa)	Average ITS (MPa)	Standard Deviation	G	Final ITS (MPa)	CV (%)
	0.671			1.137		
3	0.731	0.72	0.039	0.392	0.72	5
	0.744			0.745		
	1.293			1.145		
5	0.961	1.05	0.209	0.443	1.05	20
	0.907			0.702		
	1.916			1.087		
7	1.522	1.70	0.200	0.881	1.70	12
	1.658			0.205		

APPENDIX C

RESILIENT MODULUS – REPEATED LOAD TEST

Table C.1 - Models for resilient modulus by repeated load test for SAC mixtures at 7 days of curing.

Cement content (%)	Model	SAC 20:80 – Basalt Aggregate			
		k1	k2	k3	R^2
3	$f(\sigma_3)$	143.56	-	0.90	**0.66**
	$f(\sigma_d)$	97.93	0.93	-	**0.95**
	Pezo et al. (1992)	74.67	0.21	0.79	**0.96**
	Universal	16987.20	0.55	1.77	**0.93**
5	$f(\sigma_3)$	232.49	-	0.81	**0.52**
	$f(\sigma_d)$	73.78	1.04	-	**0.94**
	Pezo et al. (1992)	64.88	0.10	0.97	**0.94**
	Universal	17462.29	0.51	2.40	**0.86**
7	$f(\sigma_3)$	1298.37	-	0.41	**0.27**
	$f(\sigma_d)$	99.29	0.96	-	**0.98**
	Pezo et al. (1992)	106.24	-0.08	1.02	**0.99**
	Universal	21451.58	-0.01	3.31	**0.96**
Cement content (%)	Model	SAC 30:70 – Basalt Aggregate			
		k1	k2	k3	R^2
3	$f(\sigma_3)$	794.88	-	0.56	**0.53**
	$f(\sigma_d)$	404.01	0.68	-	**0.98**
	Pezo et al. (1992)	398.77	0.01	0.67	**0.98**
	Universal	32979.90	0.22	1.73	**0.94**
5	$f(\sigma_3)$	315.33	-	0.74	**0.51**
	$f(\sigma_d)$	88.21	1.00	-	**0.97**
	Pezo et al. (1992)	82.27	0.06	0.96	**0.97**
	Universal	18204.04	0.47	2.40	**0.86**
7	$f(\sigma_3)$	1318.23	-	0.44	**0.38**
	$f(\sigma_d)$	343.52	0.70	-	**0.98**
	Pezo et al. (1992)	349.94	-0.01	0.71	**0.98**
	Universal	33186.87	0.04	2.10	**0.96**

Table C.2 - Models for resilient modulus by repeated load test for SAC mixtures at 28 days of curing.

Cement content (%)	Model	SAC 20:80 – Basalt Aggregate			
		k1	k2	k3	R^2
3	$f(\sigma_3)$	374.73	-	0.61	**0.75**
	$f(\sigma_d)$	351.54	0.61	-	**0.91**
	Pezo et al. (1992)	301.37	0.16	0.48	**0.93**
	Universal	22579.83	0.47	0.75	**0.90**
5	$f(\sigma_3)$	365.18	-	0.65	**0.49**
	$f(\sigma_d)$	90.66	0.95	-	**0.96**
	Pezo et al. (1992)	88.89	0.02	0.93	**0.96**
	Universal	16153.72	0.31	2.65	**0.87**
7	$f(\sigma_3)$	903.56	-	0.46	**0.32**
	$f(\sigma_d)$	265.58	0.72	-	**0.89**
	Pezo et al. (1992)	352.38	-0.28	0.93	**0.94**
	Universal	23820.74	-0.04	2.67	**0.82**
Cement content (%)	Model	SAC 30:70 – Basalt Aggregate			
		k1	k2	k3	R^2
3	$f(\sigma_3)$	859.71	-	0.47	**0.49**
	$f(\sigma_d)$	261.57	0.72	-	**0.99**
	Pezo et al. (1992)	264.05	-0.01	0.72	**0.99**
	Universal	24936.63	0.16	2.00	**0.93**
5	$f(\sigma_3)$	636.99	-	0.61	**0.53**
	$f(\sigma_d)$	180.79	0.86	-	**0.97**
	Pezo et al. (1992)	182.18	-0.01	0.87	**0.97**
	Universal	27372.38	0.28	2.11	**0.88**
7	$f(\sigma_3)$	573.46	-	0.62	**0.45**
	$f(\sigma_d)$	139.45	0.92	-	**0.98**
	Pezo et al. (1992)	146.18	-0.04	0.95	**0.98**
	Universal	21947.92	0.26	2.73	**0.85**

APPENDIX D

RESILIENT MODULUS – DINAMIC INDIRECT TENSILE TEST

TableD.1 - Results of the resilient modulus by dynamic tensile teste for SAC mixtures at 7 days of curing.

SAC 20:80 – Basalt Aggregate				
Cement content (%)	Mr,d (MPa)	Average	Standard Deviation (MPa)	CV (%)
3	18272.00 20017.80	19145	1234.47	6.45%
5	23487.60 20133.10	21810	2371.99	10.88%
7	17281 20269.7	18775	2113.33	11.26%
SAC 30:70 – Basalt Aggregate				
Cement content (%)	Mr,d (MPa)	Average	Standard Deviation (MPa)	CV (%)
3	15074.70 15839.50	15457	540.80	3.50%
5	24687.50 25027.20	24857	240.20	0.97%
7	15626.2 14178.00	14902	1024.03	6.87%

APPENDIX E

RESULTS FOR RECYCLED MASONRY AGGREGATES

Table E.1 - Grubbs Test for UCS and ITS values of SAC mixtures using RMA with 5% of cement.

UCS for SAC 30:70 – 5% cement - Recycled Masonry Aggregates						
Curing time (days)	UCS (MPa)	Average UCS (MPa)	Standard Deviation	G	Final UCS (MPa)	CV (%)
	0.70			1.02		
0	0.62	0.66	0.037	0.97	0.66	6
	0.66			0.05		
	3.23			0.03		
7	2.55	3.25	0.704	0.99	3.25	22
	3.96			1.01		
	3.87			0.23		
28	4.06	3.80	0.290	0.86	3.80	8
	3.49			1.10		
ITS for SAC 30:70 – 5% cement – Recycled Masonry Aggregates						
Curing time (days)	ITS (MPa)	Average ITS (MPa)	Standard Deviation	G	Final ITS (MPa)	CV (%)
	0.01			0.22		
0	0.01	0.01	0.004	0.87	0.01	1
	0.00			1.09		
	0.50			0.98		
7	0.33	0.42	0.081	1.02	0.42	20
	0.42			0.04		
	0.58			0.44		
28	0.68	0.61	0.065	1.14	0.61	11
	0.56			0.71		

Table E.2 - Results of the resilient modulus by dynamic tensile test using RMA for SAC mixtures at 7 days of curing.

MR,d for SAC 30:70 – 5% cement – Recycled Masonry Aggregates				
Cement content (%)	Mr,d (MPa)	Average	Standard Deviation (MPa)	CV (%)
5	10263.30 8247.10	9255	1425.67	15.40%