SÃO PAULO STATE UNIVERSITY
“JÚLIO DE MESQUITA FILHO”
School of engineering of Ilha Solteira
Post-graduate program in Civil Engineering

KARINA HWANG ARCOLEZI

INFLUENCE OF AGGREGATE SIZES AND PACKING COMBINATION ON THE PROPERTIES OF PERVIOUS CONCRETE

Ilha Solteira
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Dissertation presented to the São Paulo State University (UNESP) - School of Engineering - Campus of Ilha Solteira, in fulfillment of one of the requirements for obtaining the Master's degree in Civil Engineering.
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Jorge Luís Akasaki

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TÍTULO DA DISSERTAÇÃO: INFLUENCE OF AGGREGATE SIZES AND PACKING COMBINATION ON THE PROPERTIES OF PERVIOUS CONCRETE

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RESUMO

O concreto permeável é um material de construção que pode ser utilizado como pavimento permeável e aparece como um potencial mitigador de enchentes e outros problemas relacionados à impermeabilização do solo. O desenvolvimento de concreto permeável eficiente é uma questão crucial para promover seu uso em larga escala. Este estudo tem como objetivo avaliar o efeito do empacotamento de agregados basálticos através da metodologia de densidade máxima nas propriedades do concreto permeável. Para tal, é apresentado um programa experimental relacionado ao uso da metodologia de densidade máxima para o empacotamento dos agregados com o intuito de melhorar as propriedades mecânicas do concreto permeável. Os concretos permeáveis foram produzidos usando três diferentes granulometrias de agregados e suas combinações usando o empacotamento com a metodologia de densidade máxima. As propriedades físicas, mecânicas e hidráulicas do concreto permeável foram determinadas para concretos após 28 dias de cura, rendendo até 18 MPa na resistência à compressão com porosidades variando entre 25 e 35% e sem prejudicar significativamente a permeabilidade do concreto permeável. Para análise estatística dos resultados, foi realizado, um modelo de regressão múltipla, os resultados indicam que a resistência à compressão é significativamente mais influenciada pela densidade e tamanho do agregado. Enquanto que a resistência ao impacto foi influenciada por todos os parâmetros (densidade, porosidade e tamanho do agregado). Assim, além das propriedades aprimoradas demonstradas, o uso de concreto permeável também pode reduzir os problemas ambientais associados ao alagamento provenientes de águas pluviais em pavimentos contribuindo para o desenvolvimento sustentável.

Palavras-chave: concreto permeável, empacotamento de agregados, densidade máxima, estrutura de poros, propriedades mecânicas.

ABSTRACT

Pervious concrete is a construction material that can be used as a pervious pavement and appears as a potential mitigator of floods and other problems related to soil waterproofing. Developing an efficient pervious concrete is crucial to promote its use on a large scale. This study aims to evaluate the effect of basaltic aggregates packing throughout maximum density methodology on the properties of pervious concrete. To this end, an experimental program related to using maximum density methodology for packing aggregates is presented to improve the mechanical properties of pervious concrete. The pervious concrete was produced using three different aggregates granulometry and their combinations using the packing with the maximum density methodology. The pervious concrete's physical, mechanical and hydraulic properties were determined for concretes after 28 days of curing, yielding up to 18 MPa in compressive strength with porosities varying between 25 and 35% and without significantly impairing the permeability of the pervious concrete. A multiple regression model was carried out for statistical analysis of the results. The results indicate that the compressive strength is significantly more influenced by the density and size of the aggregate. In contrast, the impact resistance was influenced by all parameters (density, porosity, and aggregate size). Thus, in addition to the improved properties demonstrated, the use of pervious concrete can also reduce the environmental problems associated with flooding from rainwater on pavements, contributing to sustainable development.

Keywords: pervious concrete, aggregate packing, maximum density, pore structure, mechanical properties.

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1 INTRODUCTION

This chapter aims to present the scope and structure of the dissertation. The context in which the research is inserted is discussed, presenting the research problem and the proposed objectives. Thus, the section is divided into subsections, at first, the contextualization and justification of the theme raising the issue of urban drainage and stormwater. Next, the objectives, the research strategy, and the dissertation structure are presented.

1.1 CONTEXTUALIZATION AND JUSTIFICATION

The accelerated process of urbanization in cities with human intervention developing their cities added to the formation of constructions with constructive techniques in which most of the materials used are waterproof and watertight, it is evident that soil waterproofing takes place. As a result, the occurrence of environmental problems (GARTLAND, 2010).

One of the environmental problems arising from the urbanization process is the so-called heat island effect. It is related to the thermal heat capacity and conductivity of urban surfaces that absorb radiation during the day and release it into the atmosphere at night, causing local climate change. This is because the sun's rays directly hit urban centers, and heat accumulates due to the difficulty of dissipating, increasing the local average temperature (AYOADE, 2004; GARTLAND, 2010).

Other problems arising from soil sealing are mainly those related to rainfall, which cannot infiltrate the soil, causing flooding, and carrying pollutants from the pavement's surface to streams, lakes, and rivers (NRMCA, 2004; FERGUSON, 2005; GARTLAND, 2010; SANDOVAL et al., 2020a). Urban drainage systems (gutters, ditches, drainage galleries, trenches, etc.), even on a large scale and with large storage capacity, often do not contribute to effective flood control, which may also be related to the lack of maintenance thereof.

Therefore, it is necessary to look for construction techniques and materials that reduce impervious areas. Construction techniques that control rainwater flow, preventing it from accelerating. Hydrological control practices have been notably discussed in recent years, not only as alternatives to mitigate flooding in cities but as drainage infrastructure proposals that are more sustainable and functional (DONG et al., 2017; BRAGA, 2019; BIGOTTO, 2021).

One of the proposals and studies in sustainable urban drainage is mainly focused on using Low Impact Development (LID), which seeks to minimize the adverse effects on water quality through green infrastructure practices and sustainability. LID practices are considered more sustainable as they primarily consist of rainwater management in a decentralized manner and managed to reduce the impact of impervious areas and promote the natural movement of water within an ecosystem or watershed. Therefore, less aggressive to the environment (US EPA, 2012; BRAGA, 2019).

A technique that can be used and considered as LID, with the primary objective of reducing the runoff of rainwater before further progress in the urbanization process and soil waterproofing, is the use of pervious pavements made, for example, with pervious concrete. This can play an essential role in this issue, becoming potential mitigation of the adverse effects of surface runoff of rainwater related to the waterproofing of surfaces, since it has water percolation capacity (US EPA, 1999; TENNIS; LEMING; AKERS, 2004; ACIOLI, 2005; BRAGA, 2019; SANDOVAL et al., 2020a).

In Brazil, pervious concrete is considered an increasingly developing system and has been propagated through scientific research on this technology. These researches can improve and contribute to urban drainage studies through new techniques and construction materials (BRAGA, 2019).

In this context, this dissertation is intended to contribute to the understanding of the properties of pervious concrete by investigating its mechanical and hydraulic characteristics and addressing the following question: "How is it possible to enhance pervious concrete's physical and mechanical properties without affecting its permeability substantially?"

1.2 OBJECTIVES

1.2.1 General objective

To evaluate the effect of packing aggregates of different granulometry from the maximum density methodology on the properties of pervious concrete.

1.2.2 Specific objectives

a) Propose a pervious concrete with higher density from the study of packaging of aggregates;

b) Analyze the physical, mechanical, and hydraulic properties (density, porosity, permeability, compressive strength, and impact energy);

c) Carry out a study of pore characteristics using digital image analysis software;

d) Develop a correlation between physical and mechanical properties through a multiple regression statistical model.

1.3 RESEARCH STRATEGY

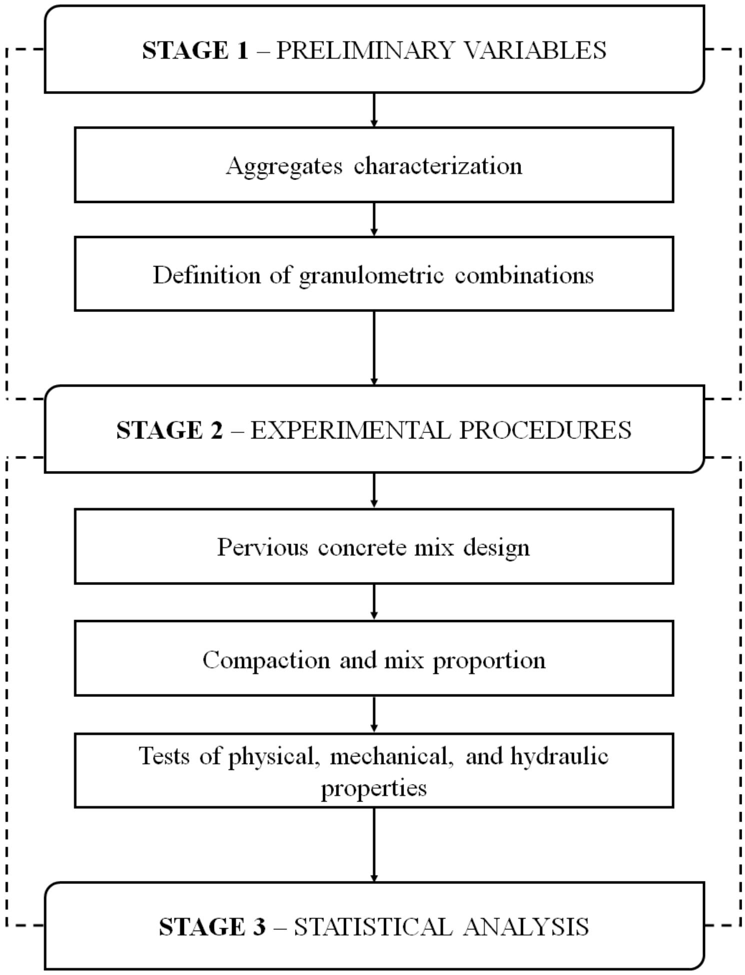
This work aims to evaluate the effect of aggregate packing of different granulometry on pervious concrete properties and develop a higher density pervious concrete with adequate performance both in strength and permeability according to parameters already established by standards. For this, the research strategy evaluated the influences of using different dimensions and granulometric combinations of coarse aggregate in pervious concrete. To this end, other control variables, such as the water/cement ratio (w/c) and the cement/aggregate ratio, were kept fixed for all samples.

The granulometric compositions and combinations were defined from three granulometric ranges. Combinations were made based on the degree of compactness of the mixtures, which was determined by the packing test. In this test, three specimens of each aggregate size were molded following the same molding method used to mold pervious concrete. The combination chosen is the one with the highest density.

The study was divided into three stages. Firstly, the preliminary analyses were carried out on the dimensions and physical properties of the coarse aggregates used to define the granulometric combinations. Then, tests of physical, mechanical, and hydraulic properties of pervious concrete. Finally, the multiple regression method obtained statistical analysis of the results. The flowchart of the experimental program can be analyzed in Figure 1.1.

The presentation of the results took place in the structure of a scientific article for publication in a scientific journal. This type of research provides more practical and quick dissemination of the results obtained, bringing greater visibility.

Figure 1.1 - Flowchart of the proposed research methodology



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1.4 MASTER THESIS OUTLINE

The dissertation is divided into five chapters, including the Introduction. The following chapters are structured as follows:

- Chapter 2 refers to the literature review that addresses the fundamental concepts of the study material, highlighting the main characteristics of pervious concrete. And finally, it presents a brief review of the literature on research developed and results achieved in several works carried out;
- Chapter 3 includes the laboratory work that deals with the methodology proposed through the experimental program: the choice of granulometry that allows combinations with the best packaging of the aggregates and the tests that allow analyzing the main properties of the object of study.

- Chapter 4 is about the results obtained. The presentation of this chapter is based on the structure of a scientific paper;
- Finally, Chapter 5 presents the main conclusions and relevant points of this research.

2 LITERATURE REVIEW

In this chapter, the theoretical basis that supports the present work will be presented from the problem in urban drainage, approaching pervious concrete as a possible alternative to avoid or minimize these problems based on an overview and previous research in the literature. Such discussions are mainly related to the physical, mechanical, and hydraulic properties of the object of study, with the primary objective of contributing to the conceptual understanding of this material.

2.1 GENERAL CONSIDERATIONS ABOUT PERVIOUS PAVEMENTS

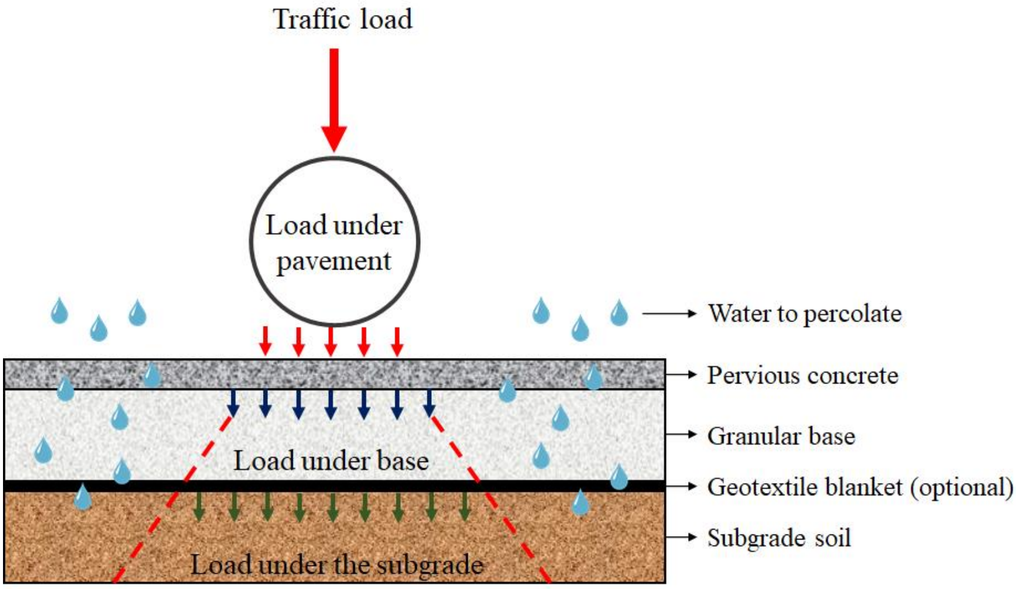
Pervious pavement is an urban infiltration element capable of partially or totally absorbing rainwater runoff (BATEZINI, 2013). Pervious pavements can be classified into three basic types according to their infiltration capacity. They are: the total infiltration system, where rainwater is completely infiltrated into the soil; the partial infiltration system, which is when the soil cannot contain all the water; finally, the water quality control system, which collects the initial flow of rainwater and the rest is directed through drains to rainwater collectors (SUZUKI; AZEVEDO; KABBACH JÚNIOR, 2013).

The choice for each of these classifications depends on the amount of water that the soil can infiltrate. It is also worth mentioning that these pavements are used in specific locations that depend on several factors, such as soil type, rainfall intensities, relief, and the feasibility of the application.

While there are many ways to make paving permeable, the three primary technologies on the market are porous asphalt, pervious interlocking concrete pavement, and pervious concrete. In the case of porous asphalts, unlike conventional asphalt, fine aggregates are removed to increase the volume of voids in the system. On the other hand, pervious interlocking concrete floors, the concrete blocks are in the form of interlocking pavers, and the drainage is done through the interconnected pores and the drainage between the pavers (ASCE, 2013; DA COSTA, 2019).

The pervious pavements made of pervious concrete, the focus of this work, comprises a layer of coarse aggregates, called a base, located above the subgrade or soil, which serves as a temporary water reservoir. In addition, it is responsible for supporting the loads exerted by traffic on the pavement and the pervious coating layer, distributing traffic loads, and ensuring the percolation of rainwater in its internal structure, as shown in Figure 2.1 (TENNIS; LEMING; AKERS, 2004).

Figure 2.1 - Example of pervious pavement made with pervious concrete



Source: Developed by the author.

The thickness of the layers that make up pervious pavements depends on the design specifications. It may still contain, in some cases, a layer of geotextile membranes as an alternative to collecting possible solid waste from traffic on these pavements (ARAÚJO; TUCCI; GOLDENFUM, 2000; SILVA, 2019; BIGOTTO, 2021).

2.2 PERVIOUS CONCRETE

According to its definition, pervious concrete is mainly composed of cement, coarse aggregate, little or no fine aggregate, and water. Combining these materials results in a hardened material with interconnected pores in its matrix that allows the passage of water (TENNIS; LEMING; AKERS, 2004; ACI 2010; NEITHALATH; SUMANASOORIYA; DEO, 2010; YAHIA; KABAGIRE, 2014).

Pervious concrete is a type of concrete with a high level of pores (typically ranging from 15% to 35%), making it porous enough to infiltrate rainwater. Furthermore, pores can store water as a detention valley, reducing the effects of rapid storm runoff (NRMCA, 2004; FERGUSON, 2005; ACI, 2010; CHANDRAPPA; BILIGIRI, 2018).

Different from conventional concrete, pervious concrete is developed in a way that allows the percolation of water through its porous internal structure to be routed to the subgrade or directed to a specific location through drainage devices, serving as a complement to urban drainage devices already existing (FERGUSON, 2005; ZHONG et al., 2018). Figure 2.2 shows a sample of pervious concrete.

Figure 2.2 - Pervious concrete percolating water

Source: Developed by the author.

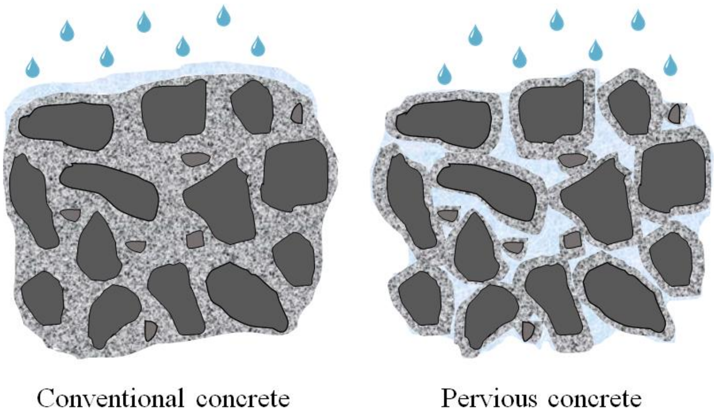
Figure 2.3 presents a schematic of conventional concrete and pervious concrete. In the case of conventional concrete, water cannot infiltrate inside the concrete. As it cannot infiltrate rainwater, it can lead to the transport of pollutants from the surface to downstream, increase the phenomenon of flooding, increase the effect of heat islands, and other problems (ZHONG et al., 2018). Pervious concrete can percolate water through its interconnected internal pores with the main advantages of:

- Reduce the volume and pollution caused by surface water runoff;
- Reduce the effects of heat islands;
- Reduce the number of elements in urban drainage systems;
- Contribute to the replenishment of groundwater, among others.

As for disadvantages, pervious concrete with its high volume of voids and permeability, there may be a risk of clogging if proper maintenance care is not carried out. In addition, the high porosity can significantly reduce its mechanical properties. For this reason, it is recommended to be used in situations that do not require high resistance, such as in the case of light traffic or pedestrian pavements, bicycle paths, parking lots, among others

(NEITHALATH; WEISS; OLEK, 2004; TENNIS; LEMING; AKERS, 2004; FERGUSON, 2005; ACI, 2010).

Figure 2.3 - Representation of water in contact with conventional concrete and pervious concrete



Source: Developed by the author.

2.3 COMPOSITION AND CHARACTERISTICS OF MATERIALS

Pervious concrete is generally composed of water, binder, commonly Portland cement (choice depends mainly on design request and availability), coarse and fine aggregate. Among these materials, aggregates are the most common materials in pavement construction and, therefore, greatly influence both the porous system and the mechanical properties (TENNIS; LEMING; AKERS, 2004; ACI, 2010; ĆOSIĆ et al., 2015).

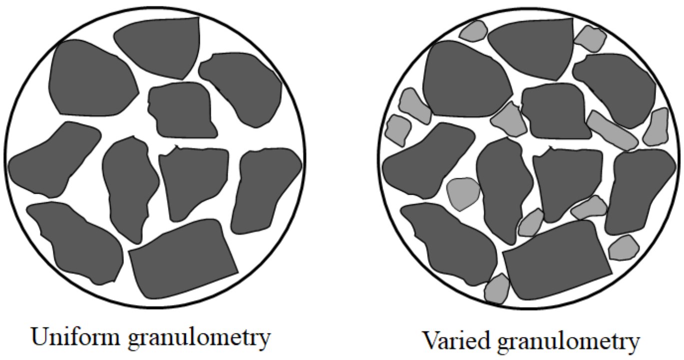
In a limited way, fine aggregates can be used in pervious concrete. However, this tends to compromise the interconnectivity of the pores, leading to an increase in mechanical strength and density. On the other hand, it can reduce the permeability of pervious concrete (ACI, 2010). The rate proportion of the addition of fine aggregates is usually around 10% of the cement mass, and it is the most recommended rate, characterized by improving mechanical properties without significantly affecting permeability (SAHDEO et al., 2020; SILVA, et al., 2021). Silva et al. (2021) presented that fines aggregates were added to the composition of pervious concrete ash from sugarcane straw and bagasse. The addition of these fines increased the density of the samples and consequently decreased their porosity. Thus, increasing compressive strength and decreasing infiltration rate. Despite a slight reduction, the results obtained with up to 10% of ash addition were satisfactory, both in compressive strength and hydraulic conductivity.

Hung et al. (2021) performed pervious concretes with sand and observed that as the proportion of sand addition increased (more than 5%), the density and compressive strength increased while the porosity and drainage capacity decreased. Thus, the authors found that adding up to 5% sand was considered adequate for the infiltration rate.

In short, the addition of fine aggregates in small proportions (usually 10%) can improve the mechanical properties of pervious concrete, although the hydraulic conductivity properties (porosity, permeability) can decrease considerably (ĆOSIĆ et al., 2015; LIU et al., 2018; SAHDEO et al., 2020).

ACI (2010) states that coarse aggregates frequently used in pervious concrete have a rounded or lamellar shape. Additionally, it can also be uniform or well-graded (varying granulometry, as shown in Figure 2.4. Several studies have used coarse aggregate with size variations so that the particles fit better together to improve the mechanical properties without necessarily adding fines to its composition (DEO; NEITHALATH, 2011; HUNG et al., 2021).

Figure 2.4 - Types of granulometry for pervious concrete



Source: Developed by the author.

The combination and packaging of aggregates with varied granulometry without the addition of fine aggregates can result in better mechanical strength without significantly impairing the drainage properties of the pervious concrete. Compaction of samples, mixing ratios, and dosing method are the challenges.

2.4 COMPACTION AND MIX PROPORTION METHODS

The compaction energy and the procedure adopted in the molding of pervious concrete can positively or negatively influence the properties of pervious concrete (XIE et al., 2020). The absence of norms and technical procedures that standardize the methods of mix proportion and compaction of pervious concrete causes these parameters to be quite varied in the literature.

A method that has been used for the compaction and molding of fresh pervious concrete and which has shown satisfactory results is to proceed with molding on a vibrating table. According to Batezini (2013), excessive vibration can cause segregation of the paste and the aggregate in the pervious concrete, and the vibration should not last more than a few seconds.

Liu et al. (2018) divided the fresh concrete into two layers in the mold, and each layer was vibrated for 20 seconds on the vibrating table, then the concrete was compacted with a compression pressure of 0.08 MPa. Zheng et al. (2012) molded specimens in a single layer by the vibration method, with approximately 20 seconds. Silva (2019) proceeded to mold the specimens with 45 manual strokes with a steel rod divided into three layers, and each layer was vibrated for 10 seconds on a vibrating table.

Yap et al. (2018) the vibration time for the compaction of fresh samples was significantly reduced. The concrete was poured into the mold in two layers. First, it was placed, filling half the height of the mold followed by a slight vibration (about 1 second). The same procedure was repeated for the second layer.

Vieira et al. (2020) compacted fresh concrete on a vibrating table for approximately 10 seconds, avoiding manual densification due to possible fragmentation of the recycled aggregate used. Bigotto (2021), the first two layers were compacted with fifteen manual blows with a steel rod and vibrated on a vibrating table for 10 seconds each.

Regarding the dosage of the traces, pervious concrete is not widespread precisely because of the lack of regulation regarding the proportions of the constituent materials. For this reason, the methods vary a lot, and studies are usually focused on evaluating the different properties for the dosages used (SANDOVAL, 2020b). One of the methods used is empirically based, with trial and error, and based on the existing literature (SILVA, 2019).

Pervious concrete requires excellent care with the w/c ratio in its dosage, which influences the workability of the concrete and has a significant influence on the final strength of the sample. The amount of water must be sufficient to hydrate the cement to mold it easily. On the other hand, it cannot exceed the amount to impair its mechanical strength. Kia et al. (2017) state that the w/c ratio generally ranges from 0.26 to 0.45.

Using tactile-visual analysis to determine the ideal water proportion, Tennis et al. (2004) recommend that a portion of the concrete must be taken in the hands and, with a light squeeze, the behavior of the mixture must be observed. The ideal consistency will be the one that acquires an agglomerated shape without appearing dry (lack of water) and without running paste (excess water). In short, the paste must cover the aggregates and have a shiny appearance, not showing a dry appearance, indicating that the hydration process of Portland cement was impaired and not clogging the pores in a very fluid way.

Figure 2.5 shows fresh pervious concrete mixtures. As can be seen, the six samples, even with aggregates of different granulometry and combinations, have a shiny appearance and molds quickly with light tightening, indicating an adequate w/c ratio.

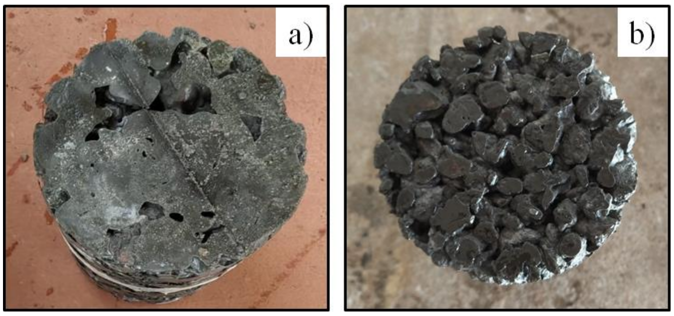
Figure 2.5 - Fresh concrete cohesion test

Source: Developed by the author.

Clogging is another challenge in the dosage and compaction of pervious concrete, which is the clogging inside the concrete, more precisely in its porous matrix. This phenomenon can occur for several reasons: when the paste ran to the bottom, by sediments deposited with the use of this concrete, or even by excessive compaction of pervious concrete (SILVA, 2019; BIGOTTO, 2021).

In the case of paste flow, this can be related to three reasons: 1) excess water in the mixture; 2) over-compaction of the sample. Putman; Neptune (2011) state that even mixes with low amounts of water can clog if improperly densified and 3) due to excess paste/mortar in the mix composition. As shown in Figure 2.6a, the sample suffered from the paste flow while the sample b) presented correct dosage and compaction, and there was no paste flow.

Figure 2.6 - Representation of the background of samples: a) clogging occurred due to excess paste in the mixture; b) there was no clogging



Source: Developed by the author.

2.5 INFLUENCE OF AGGREGATES SIZES AND PACKAGING IN PERVIOUS CONCRETE

The size of the aggregates directly influences their packaging, controlling the porosity and homogeneity of the pervious concrete (SHEN et al., 2020). Figure 2.7 shows samples of pervious concrete molded with traces of the same composition, with different dimensions and granulometric combinations. It is possible to observe the different homogeneities of the mixtures. The samples with the aggregate of larger sizes present a greater roughness in their surface, different from the samples made with the aggregate of smaller dimensions.

Figure 2.7 - Visual comparison of pervious concrete samples with aggregates of different dimensions and combinations

Source: Developed by the author.

The methodology for aggregate packing is a proposal to provide optimal grain packing and improve pervious concrete properties. The implementation of the particle packing test aims to increase the compaction of the mixtures, improving the mechanical strength of pervious concrete (XU et al., 2020). Several studies of the influence of different sizes and granulometric combinations on pervious concrete were observed in the literature.

Neithalath, Sumanasooriya, and Deo (2010) performed six mixing ratios with three different sizes of aggregates. Three of them had one-dimensional aggregates, and the other three mixtures composed 50% of each one-dimensional. Pore size was increased in mixtures with larger aggregates, making it viable to increase permeability. Therefore, the authors found that when the porosity is increased (25% to 35%), there is a significant loss of mechanical strength, which is not desirable.

Ibrahim et al. (2014) observed that improving the grading of aggregates, with a better distribution of their dimensions, makes it possible to give better uniformity to the trace without filling the voids, preventing water percolation.

Ćosić et al. (2015) investigated the influence of the type and size of the aggregate on the properties of pervious concrete. Five different concrete mixtures were prepared with different sizes and types of aggregates. Higher proportions of larger aggregates resulted in higher effective porosity. The greater the porosity, the greater the volume of the voids and the lower the compressive strength. Shen et al. (2021) observed the same pattern, that when the largest aggregate in the mixture exceeded 50% of the composition, the mechanical strength decreased.

Debnath and Sarkar (2019) investigated the influence of the combination of different dimensions of coarse aggregate and fine aggregate on the permeability and porosity of the mixture. Thus, they observed an increase in aggregate size in the aggregate combinations results in the highest permeability due to greater porosity.

Sahdeo et al. (2020) observed that a binary mixture of aggregates 30/70 (%) of 10 mm and 4.75 mm, presented the best result, maintaining a balanced relationship between mechanical strength and permeability coefficient when compared with uniformly sized aggregates.

Shen et al. (2020) used three granulometric ranges. Two 50/50 (%) combinations were performed to improve packing between the aggregates and the mortar. The results showed that pervious concrete prepared with two-grade aggregate could improve compressive strength. For example, the compressive strength of samples containing more than one aggregate grade reached a strength value of 49.8 MPa, which was higher than that of the concrete sample containing aggregate with a single grade. The 50/50 combinations (%) obtained the highest densities, compressive strengths, and homogeneity. On the other hand, porosity was reduced.

Xu et al. (2021) obtained superior results of fracture resistance with the use of larger dimensions of aggregate in the proportion of mixture of the aggregates, also taking into account the care to maintain the porosity of the pervious concrete in constant bands.

Huang et al. (2021) performed binary and ternary combinations of aggregates. They observed that in combinations in which the highest proportion of aggregates is of large dimension, the samples were less dense, and the permeability of pervious concrete was significantly higher due to the increase of porosity. On the other hand, in the proportions of mixtures in which the smaller aggregates are more significant, the mixtures were denser and with lower permeability.

The methodology used to measure pervious concrete using different granulometric combinations has not been extensively discussed in the literature. The mixing proportions vary according to the objective to be achieved. Two methods found were: performing the combination based on the packing density of the particles, and another, dosing the combinations by the desired porosity method.

Yahia and Kabagire (2014) propose the method for dosing pervious concrete based on the packing density of the coarse aggregate. Two methods are used, the ASTM C29 test and a modified gyratory compactor procedure. This method involves placing the aggregate in a cylinder and subjecting it to compaction by a continuous kneading action of 0.02 MPa axial pressure and shearing action. This compaction is given by combining two steps, pressure and shear movement. This constant pressure induces the particles to move and compact more to obtain a higher packing density.

The authors compared binary mixtures and one-size-fits-all mixtures and observed that the compressive strength values were relatively similar. However, in the 50/50 (%) combinations of aggregates (sizes 2.5-10 mm and 5-14 mm), the mechanical properties were superior to those obtained with the single size due to the higher packing density.

Meddah et al. (2017) produced the mixtures by combining two aggregates of uniform size (maximum size 10 mm and 20 mm) consisting of proportions of 50/50 (%), 25/75 (%), 75/25 (%), and 60/40 (%) for the desired porosity. The densest mixture was also the lowest porosity (27%). The mixture that presented the best mechanical performance was obtained by mixing 75% (20 mm) and 25% (10 mm). At the same time, the lowest mechanical strengths were obtained with the mixture 75% (10 mm) and 25% (20 mm). The authors conclude that combinations of aggregates can strongly affect the strengths and resulting porosities.

In summary, the various studies in the literature claim that a pervious concrete of higher strength with sufficient permeability can be prepared using aggregates with two or more size ranges. However, as can be seen, most studies perform combination proportions empirically to produce more compact concrete. That way, showing the importance of carrying out a previous study of the aggregates for better ratios of combinations, either by achieving the desired porosity or by the higher density.

2.6 CHARACTERISTICS IN HARDENED STATE

According to the literature, for concrete to be considered permeable, some characteristics must be considered, such as the infiltration rate to measure permeability, porosity, and mechanical strength determined by normative. These properties and characteristics will be presented in the following subchapters.

2.6.1 Porosity

According to Zhong et al. (2018), porosity is one of the most important factors for pervious concrete and can influence the hydraulic and mechanical properties of pervious concrete. Not all pores present in pervious concrete percolate through the water, and they are called isolated or unconnected pores. The connectivity of the pores is essential for the functioning of pervious concrete. Therefore, compaction is very restrictive, resulting in greater bonding between the cement paste and the aggregate, closing the pores and affecting their permeability (ĆOSIĆ et al., 2015).

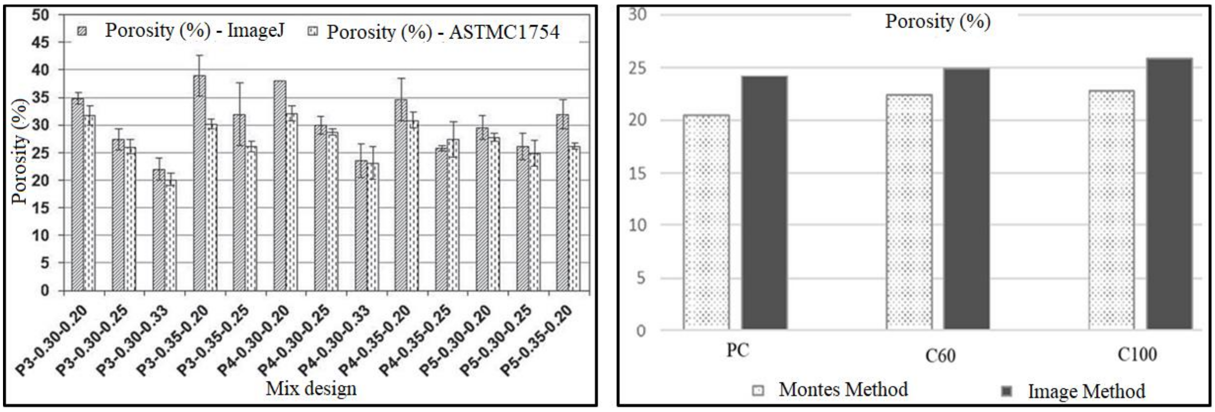
Porosity depends on several factors: the paste content, the w/c ratio, cement/aggregate ratio, compaction level, and the physical and granulometric properties of the aggregates used (ACI, 2010). Studies in the literature and technical standards recommend that porosity in pervious concretes be between 15 to 35% (ACI, 2010; ĆOSIC et al., 2015).

The standard methodology for performing the porosity test on pervious concrete is the procedures presented or the American standard ASTM C1754 (ASTM, 2012) to determine this property, which consists of drying the specimen in an oven for 24 hours. Then, the dry mass is measured, and the sample is immersed in water for saturation and submerged weighing.

One way to compare the results obtained by the American standard ASTM C1754 is from image analysis methodologies through computer programs and specific procedures for characterizing the main properties identified in the internal pores of the concrete matrix (BRAGA, 2019).

Chandrappa and Biligiri, 2018 compared two methods for the porosity of pervious concrete by ASTM C1754 and ImageJ software. In most cases, the porosity by the image method was slightly higher than the total porosity determined from the ASTM procedure C1754. In the same way, Lori; Hassani. Sedghi (2019) compared the porosity performed by the Montes method and with image analysis and obtained similar results, higher porosity with the ImageJ method (Figure 2.8).

Figure 2.8 - Comparison of porosities by image analysis method and others



Source: adapted respectively from (Chandrappa, Biligiri, 2018; Lori, Hassani, Sedghi 2019).

2.6.2 Permeability

The main function of pervious concrete is to allow the percolation of water through interconnected pores in its porous structure. This is directly linked to porosity and the interconnectivity of pores. Sandoval (2020b) found that the void ratio and permeability have an exponential correlation. Similarly, Kia et al. (2018) conclude that permeability increases exponentially as the porosity of pervious concretes increases.

According to NBR 16416 (ABNT, 2015), the infiltration rate in pervious concrete for paving must be at least 0.1 cm/s. Tennis et al. (2004) state that the infiltration rate range varies from 0.2 cm/s to 1.2 cm/s, although values still outside this range in the literature are expected.

Silva et al. (2021) studied the effects of adding residues from the sugarcane industry on pervious concrete's mechanical and hydraulic properties. The control samples reached 0.81-1.49 cm/s for the infiltration rate. Kia et al. (2018) for the mixtures studied, with porosity ranging from 8% to 32%, infiltration rates ranged from 0.1 to 1.7 cm/s.

Xie et al. (2020) used six aggregate sizes to achieve the desired compressive strength and permeability. The conclusion was that the greater the aggregate, the greater the porosity, the greater the permeability.

Liu et al. (2018) determined the permeability coefficient of pervious concrete from the porosity and size of the aggregate together. It was observed that permeability increased with increasing aggregate size and design porosity.

The methodology to measure the permeability coefficient or infiltration rate in pervious concretes can be varied. On a laboratory scale, constant or variable load permeameters usually are used. One of the methods of constant load used is the one established by ISO 17785-1 (ISO, 2016).

This test is simple to perform and consists of calculating the infiltration rate from the time required for the percolation of 2,000 ml of water, poured, maintaining a water column of approximately 2 cm at the top of the specimen. Three samples of each mixture were analyzed, and the permeability calculation was determined through Equation 1. To this end, the samples must be wrapped in the heat-shrinkable plastic film along their length (three layers around the sample), leaving a 5 cm border above the top surface (Figure 2.9).

Figure 2.9 - Preparation of samples for infiltration rate testing according to ISO 17785-1

Source: Developed by the author.

$$k = \frac{V}{At} \qquad (1)$$

Where:

k: infiltration rate (cm/s);

V: volume of infiltrated water (cm^3);

A: cross-sectional area of specimen (cm^2);

t: time required for measured volume of water to infiltrate the concrete (s).

2.6.3 Mechanical properties

The mechanical properties of pervious concrete depend on several factors: dosage, w/c ratio, compaction process, type, and granulometry of the aggregates (FERGUSON, 2005; ACI, 2010; LORI; HASSANI; SEDGHI, 2019). Aggregates are essential to balance the porosity and solid phase of pervious concrete and greatly influence pervious concrete's physical, mechanical and hydraulic properties (TENNIS; LEMING; AKERS, 2004, ĆOSIĆ et al., 2015).

2.6.3.1 Compressive strength

The minimum strength for foot traffic and light traffic should be 35 MPa in compression or 2 MPa in traction in flexing (ABNT, 2015). Due to the high volume of pores present in pervious concrete, the compressive strengths are lower when compared to conventional concrete, reaching 2 to 28 MPa (TENNIS; LEMING; AKERS, 2004; FERGUSON, 2005; ĆOSIĆ et al., 2015; DEBNATH; SARKAR, 2019).

References in the literature show that the compressive strength can vary from 2 to 49 MPa (SHEN et al., 2020). However, in research in which pervious concrete reaches higher strengths, the material tested has other additions in its composition, such as supplementary cementitious materials (e.g., pozzolans). On average, the compressive strengths are approximately 15 MPa (SANDOVAL, 2020b)

In short, the mechanical strength is directly linked to the porosity of the concrete, as less porous concretes have higher strengths, and there must be a balance between these two properties. Porosity must also be maintained to allow water percolation through its internal structure (TENNIS; LEMING; AKERS, 2004; FERGUSON, 2005; BATEZINI, 2013).

In short, the mechanical strength is directly linked to the porosity of the concrete, as less porous concretes have higher strengths, and there must be a balance between these two properties. The contact points between the particles (points of connection between the paste and the aggregate) can increase or decrease the mechanical strength (SANDOVAL, 2020a; SHEN, 2021). Porosity must also be maintained to allow water percolation through its internal structure (TENNIS; LEMING; AKERS, 2004; FERGUSON, 2005; BATEZINI, 2013).

2.6.3.2 Drop-weight impact resistance

Impact strength can be measured by some test methods to measure dynamic energy absorption, classified according to the impact mechanism and parameters monitored during impact. Conventionally, the impact resistance by the free-fall weight method is characterized by a measure of the number of blows in the impact test to reach a prescribed level of wear (rupture). This number serves as a qualitative estimate of the energy absorbed by the sample at stress levels (ROSSIGNOLO, 2003; AGAR et al., 2013).

One of the methodologies for this test, also used by Martins (2005), consists of placing a box with sand to support the sample, a guide tube, and a steel ball. First, the sample must be leveled and fixed in the sandbox placed below the guide tube. The steel ball is positioned inside the tube at a predetermined height and then launched by the action of gravity on the sample.

The test consists of first leveling and maintaining the specimen fixed in the sandbox below the guide tube. The steel ball is positioned inside the tube and then dropped onto the sample by gravity. Several repetitions were performed up to the fracture of the sample. According to Rossignolo (2003), the energy of each impact applied until the rupture of the specimens can be calculated using Equation 2. Where "IE" is the impact energy (J), "h" is the drop height (m), "m" is the mass of the steel ball (kg), and "g" is the gravity constant (9.81 m/s^2).

$$IE = h \cdot m \cdot g \tag{2}$$

Karanth et al. (2019) conducted a study to improve the strength of pervious concrete. One of the tests to analyze the improvement of pervious concrete was the impact resistance test with a methodology similar to this used in this work. Fine aggregates and fibers were added to the pervious concrete composition. Results showed that an increase in impact resistance could be observed by adding up to 20% of fine aggregate and up to 2.85 times with 1.5% of fibers.

Singh and Murugan (2021) adopted the impact test to estimate the impact strength of pervious concrete slabs. The test was carried out by dropping a 6.5 kg steel ball from a drop height of 1.5 m. The number of blows necessary for the formation of cracks and rupture indicated the performance of the slabs in the impact resistance test. With the results, they concluded that the size of the aggregates played an essential role in the length and width of cracks under impact load. The presence of pores increases the stress since impact energy is not transferred through the voids, resulting in less absorption of impact energy for both the first crack and the last crack.

2.7 CHAPTER SUMMARY AND OUTLOOK

This dissertation chapter discussed several pervious concrete properties, physical, mechanical, and hydraulic. As evidenced in the literature, there are several research gaps related to this area. The studies mentioned above indicate that pervious concrete is a promising material to be used as a pavement construction material.

Pervious concrete has spread worldwide as a stormwater management LID tool, and it is one of the advantages of its diffusion. In addition, it can reduce the effects of urban heat islands, replenish groundwater, increase water quality, among others.

In the presented topics, pervious concrete, compared to conventional concrete, can be considered a new material in pavement applications. There are still several challenges that approach its applicability that need to be solved. As mentioned above, the lack of standardization in both dosage and sample compaction causes the results in the literature to be quite varied.

3 MATERIALS AND METHODS

In item 3.1 and subsequent, the materials commonly used in the manufacture of pervious concrete, the characteristics of the cement used, the characterization of the aggregates and water are presented. From item 3.2 onwards, the methods used are presented, from the characterization and combination of aggregates, development of the mix design, dosage, and compaction, to the tests performed to assess pervious concrete's physical, mechanical and hydraulic properties.

3.1 MATERIALS

For the production of pervious concrete, materials commonly sold in the research region, or made available by the university, were used, in short, consisting of the binder, Portland cement, described in section 3.1.1, coarse aggregate of natural origin (basalt) presented in section 3.1.2, and water in section 3.1.3.

3.1.1 Binder

The binder used was Portland Cement of High Initial Strength (CP V - ARI), according to the Brazilian standard NBR 16697 (ABNT, 2018a). This type of cement was selected because it contains more than 90% clinker and has no pozzolanic addition in its composition. It is also a purer cement that does not contain too many additions. The chemical composition was determined by X-ray fluorescence by Silva et al. (2021) and is presented in Table 3.1.

Table 3.1 - Chemical composition of Portland cement CP V – ARI.

SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SO_3	MgO	P_2O_5	Cl	Outros	LOl
20.8	4.6	4.8	65.6	0.1	1.0	1.7	1.2	-	-	0.2	-

Source: (SILVA *et al*., 2021).

The binder used in the research comes from the company “Brennard Cimentos, Cimento Nacional.” Table 3.2 presents the physicochemical properties according to the results obtained by the manufacturer.

Table 3.2 - Physico-chemical properties of CP V - ARI cement

Physico-chemical properties	
Ph	13
Specific gravity	1,2 g/cm³
Density	2,99 g/cm³

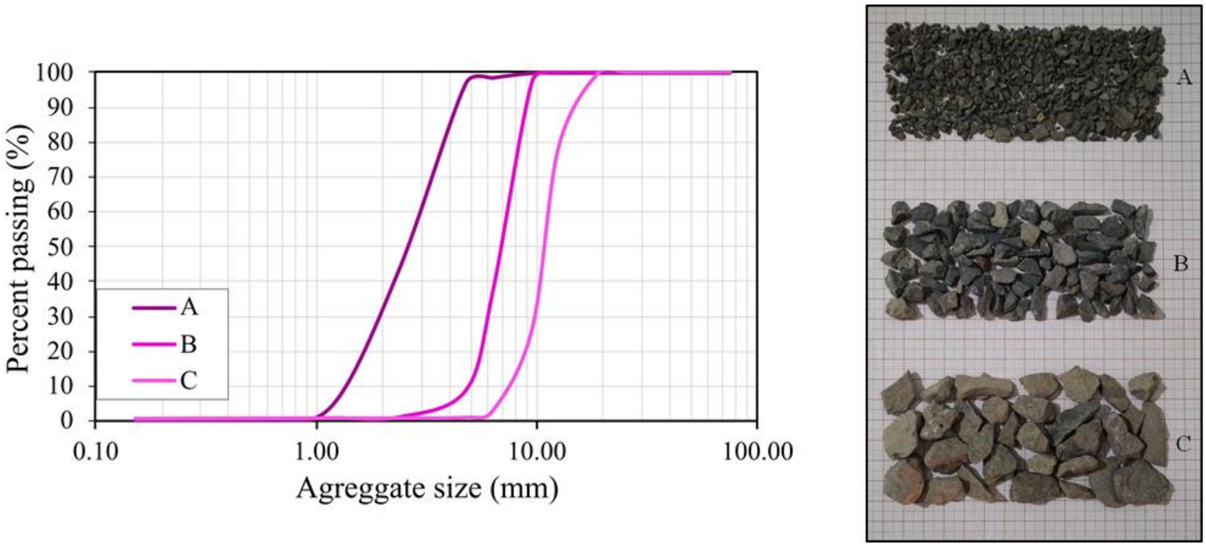
Source: Adapted from (Cimento Nacional, 2018).

3.1.2 Aggregates

The addition of fine aggregates in small proportions can improve some properties of pervious concrete. Although in this work, it was decided not to use them so that it is possible to analyze only the influence of aggregates with different granulometry as aggregate in pervious concrete. The coarse aggregates used in this study to make pervious concrete are of basaltic origin, extracted from the quarry in Itapura, São Paulo.

Three aggregates of different granulometry were used for the present work, called A, B, and C, respectively, as shown in Figure 3.1.

Figure 3.1 - Aggregates used with different granulometry



Source: Developed by the author.

To characterize the aggregates, some tests were carried out to choose the granulometric combinations. They are the test to determine the specification and granulometric composition, performed following the procedures presented by NBR NM 248 (ABNT, 2003); test of Specific gravity, and water absorption of coarse aggregates according to NBR NM 53 (ABNT, 2009). The properties of the aggregates are listed in Table 3.3.

Table 3.3 - Physical properties of aggregates

Properties	A	B	C
Unit weight (g/cm³)	1,75	1,68	1,69
Fineness module	4,53	5,89	6,69
Max dimension. characteristic (mm)	4,75	9,5	19
Water absorption (%)	4,45	2,31	1,97
Specific gravity (g/cm³)	2,97	3,04	3,03
Specific gravity OD (g/cm³)	2,62	2,84	2,86
Specific gravity SSD* (g/cm³)	2,74	2,91	2,92

Source: Developed by the author.

3.1.3 Water

The water used to make the pervious concrete came from the municipal distribution network of Ilha Solteira - SP. According to the city's Department of Water and Sewerage, the Ph is between 6 and 9.5.

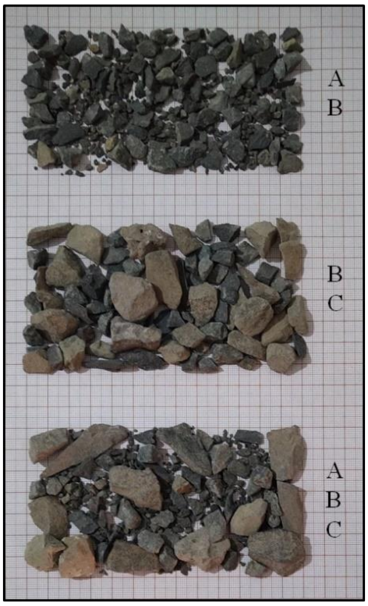
3.2 DESCRIPTION OF LABORATORY PROCEDURES

3.2.1 Aggregates characterization and packing procedure

In order to improve the mechanical properties of the pervious concrete of this study, a study of the packing of the aggregates was carried out to use granulometric combinations that presented greater density while maintaining the infiltration rate so that the draining capacity of the concrete matrices is not significantly affected. Six mixtures were produced, maintaining the same cement/aggregate ratio and w/c ratio. Three of them are mixtures of aggregates of uniform granulometry, two binary mixtures, and one ternary mixture.

For the study, the two binary granulometric combinations comprised aggregates A and B, and, second, aggregate B and C. The third and last combination is the junction of the three granulometry with proportions of higher density in the binary combinations. Unit mass tests were performed for each single-size aggregate and combined aggregate. Figure 3.2 visually presents the mixtures used.

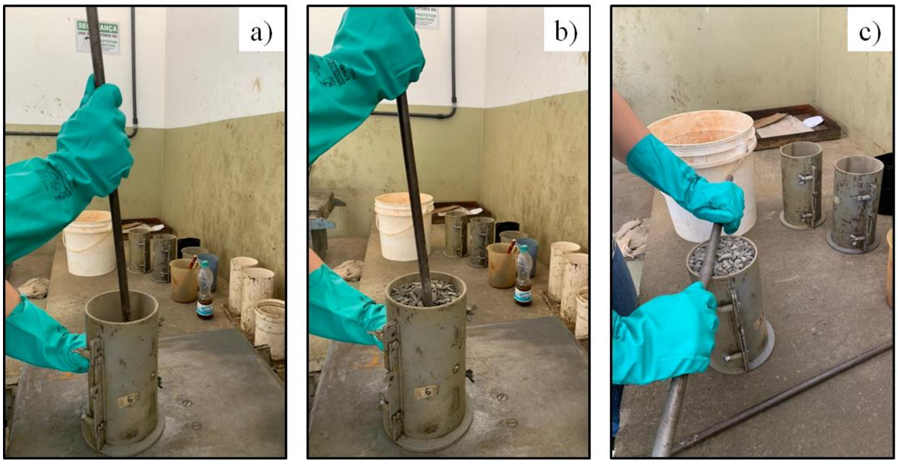
Figure 3.2 - Granulometric combinations



Source: Developed by the author.

For the compaction test, molds and procedures similar to those for pervious concrete molding were used (see section 3.2.4). The sample was divided into two layers and compacted on a vibrating table and light strokes with a steel rod as follows: 15 seconds on a vibrating table, the first 10 seconds with ten light strokes with the rod simultaneously (approximately one light stroke per second), the remaining 5 seconds, vibrating on a table without applying any stroke (Figure 3.3).

Figure 3.3 - Procedures for maximum density testing: a) compaction of the first layer; b) second layer; c) surface regularization



Source: Developed by the author.

The proportions of the combined aggregates were chosen using the maximum density methodology. The cylindrical container was filled and compacted with the aggregate of the largest granulometric size and the mass measured to obtain the maximum density. Then, the aggregate is successively replaced by small amounts (by mass) of the aggregate with the smallest particle size until the highest mass value is obtained (largest unit of mass in kg/m^3), the maximum packing of the particles.

3.2.2 Pervious concrete mix design

As there are no standardized dosing and compaction procedures for pervious concrete, it was decided to carry out the work like Silva (2019), with proportions of mixtures in which all samples had a shiny appearance and were easily molded without showing excess paste (as presented in section 2.4). For all mixes, a w/c ratio of 0.26 and a cement/aggregate ratio of 1:5 was fixed.

Six different traits were evaluated, and the difference between them is related to the aggregates. As mentioned before, three different single-sized aggregates (labeled A, B, and C) were selected, and three combinations of packaged matched aggregates (labeled AB, BC, and ABC) were designed using the maximum density methodology. The nomenclature adopted for the different pervious concretes related to the aggregate used: PC-Z, where “Z” is the type of aggregate (A, B, C, AB, BC, or ABC). For all cases, the selected aggregates were used considering the condition of the dry saturated surface (SSD).

Table 3.4 - Summary of laboratory tests

Test	Mold	Number of samples	Standard/Author
Porosity, density	Cylindrical*	3	ASTM C1754
Permeability	Cylindrical*	3	ISO 17785-1
Compressive strength	Cylindrical*	5	NBR 5739
Impact resistance	Hexagonal**	5	Martins, 2005

*10 x 20 cm (diameter x height)
**14,5 x 6,0 cm (side length x height).

Source: Developed by the author.

Table 3.4 presents the tests performed in the laboratory and the number of samples for each test. Figure 3.4 shows the molds used for the respective tests.

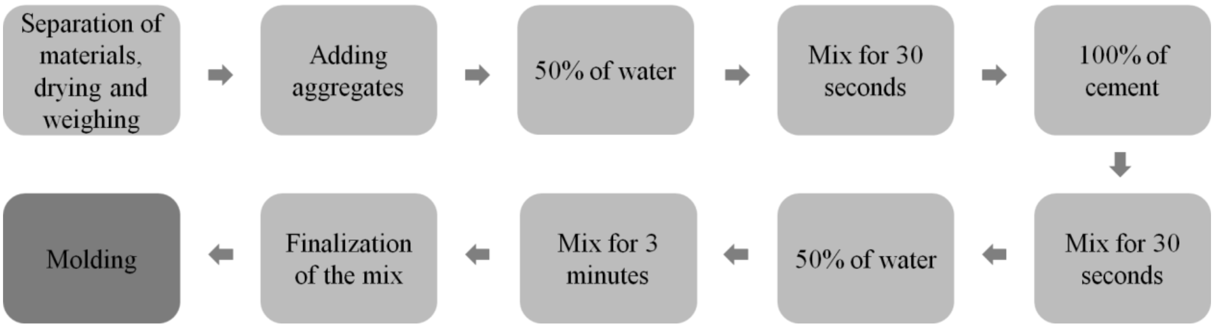
Figure 3.4 - Cylindrical and hexagonal molds for making pervious concrete mold

Source: Developed by the author.

3.2.3 Mixing pervious concrete

The materials were previously dried, weighed, and separated to start the experiments. The order of placement of the materials was carried out similarly to the study carried out by Silva (2019), as shown in Figure 3.5.

Figure 3.5 - Pervious concrete mixing steps



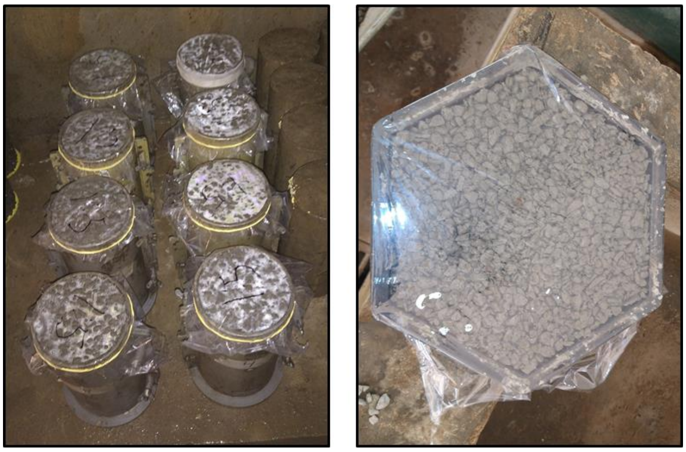
Source: Developed by the author.

3.2.4 Molding and curing of samples

As previously presented (Section 2.4), the procedures for molding specimens have different methodologies according to the literature. Considering this, the molding of all cylindrical specimens of this work will be 20 blows with a metal rod divided into two layers, with ten strokes in each layer on a vibrating table and another 5 seconds of vibration without strokes, that is, vibration for 15 seconds.

The molding procedures for the hexagonal specimens were: the mold filled to the top and placed on a vibrating table for 15 seconds applying 20 strokes with the rod simultaneously (to accommodate the concrete) and then another 5 seconds to finish the compaction, totaling 20 seconds of vibration. Figure 3.6 shows some samples after being molded.

Figure 3.6 - Newly molded and plastic-covered specimens



Source: Developed by the author.

After molding, specimens were demolded after 24 hours and subjected to curing in a humid chamber for 28 days with a relative humidity of around 95% (Figure 3.7). After this period, the tests were performed.

Figure 3.7 - Samples placed in a humid chamber for 28 days

Source: Developed by the author.

3.2.5 Porosity and density

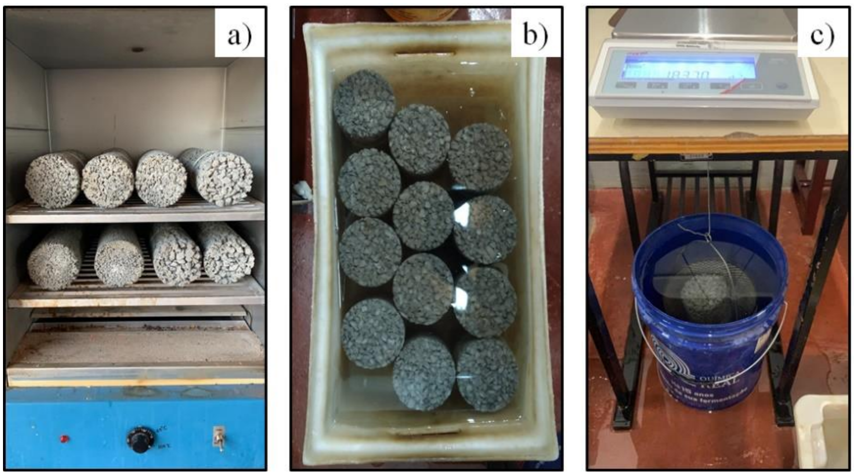
The porosity and density of the samples were tested according to ASTM C1754. The dry mass "A" was determined after drying the sample in an oven at approximately 105°C for 24 hours. Then, the submerged mass "B" in the water was recorded. Thus, the porosity can be calculated according to Equation 3. "K" is a constant equal to 1,273,240, "ρw" is the density of water (kg/m³) at the temperature of the water bath," D" is the average diameter (mm) of the sample, and "L" is the average length (mm) of the sample. The density (kg/m³) can be calculated by Equation 4.

$$Porosity = \left[1 - \left(\frac{K \cdot (A-B)}{\rho_w \cdot D^2 \cdot L}\right)\right] \times 100 \tag{3}$$

$$Density = \frac{K \cdot A}{D^2 \cdot L} \tag{4}$$

The test was carried out following ASTM C1754 procedures, in which the samples were dried in an oven. After cooling to room temperature, the dry masses were measured and submerged for 30 minutes in the water bath to saturate the sample. The submerged masses and from Equations 3 and 4, the porosity and density of the samples were calculated. Figure 3.8 shows some phases of the test.

Figure 3.8 - Representation of the test for density and porosity of pervious concrete: a) samples dried in an oven; b) submerged in water; c) submerged weighing



Source: Developed by the author.

3.2.6 Permeability

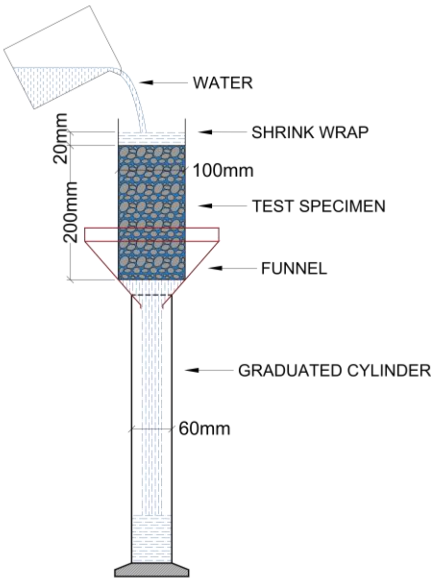
The hydraulic conductivity test was carried out in the laboratory according to the recommendations proposed by ISO 17785-1, the test apparatus indicated by the standard is represented in Figure 3.9. Three samples of each mixture were analyzed. The infiltration rate was determined through Equation 1 (section 2.6.2). The infiltration rate is calculated by the time required to percolate 2,000 ml of water, which is poured and maintains a water column of approximately 2 cm at the top of the specimen.

$$k = \frac{V}{At} \quad (1)$$

Where:

k: infiltration rate (cm/s);
t: time required for the measured volume of water to infiltrate the concrete (s);
V: volume of infiltrated water (cm^3);
A: cross-sectional area of the specimen (cm^2)

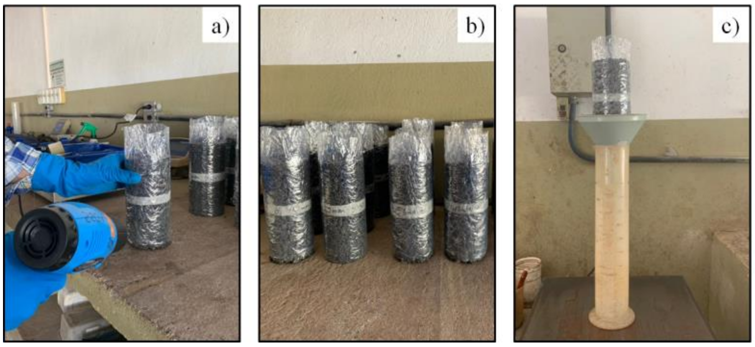
Figure 3.9 - Apparatus for infiltration rate testing



Source: Developed by the author.

The samples were wrapped in three layers by retractable plastic film along their length, leaving a 5 cm border above the upper surface. To prevent water infiltration on the sides and to adjust the wrap to the sample surfaces, the wrap was heated with a hot air gun. The samples were then placed in a funnel to free the underside (Figure 3.10).

Figure 3.10 - Representation of the permeability test: a) samples wrapped in plastic and heated with hot air; b) prepared samples; c) representation of the apparatus used for testing



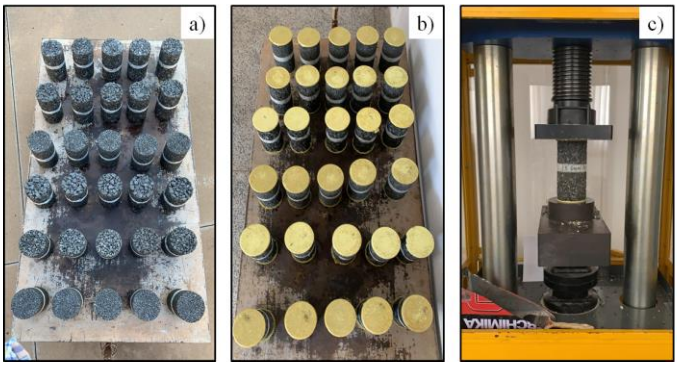
Source: Developed by the author.

3.2.7 Mechanical tests

3.2.7.1 Compressive strength

The compressive strength was evaluated through tests of five samples of each pervious concrete mix performed in a universal testing machine of the brand "EMIC" model DL 20000 capable of performing axial compression tests specified in NBR 5739 (ABNT, 2018b), with a maximum capacity of 200 tons. All samples were regularized with sulfur to ensure optimal contact between the sample and the machine (Figure 3.11).

Figure 3.11 - Compressive strength test: a) samples without preparation; b) samples capped with sulfur; c) test being performed

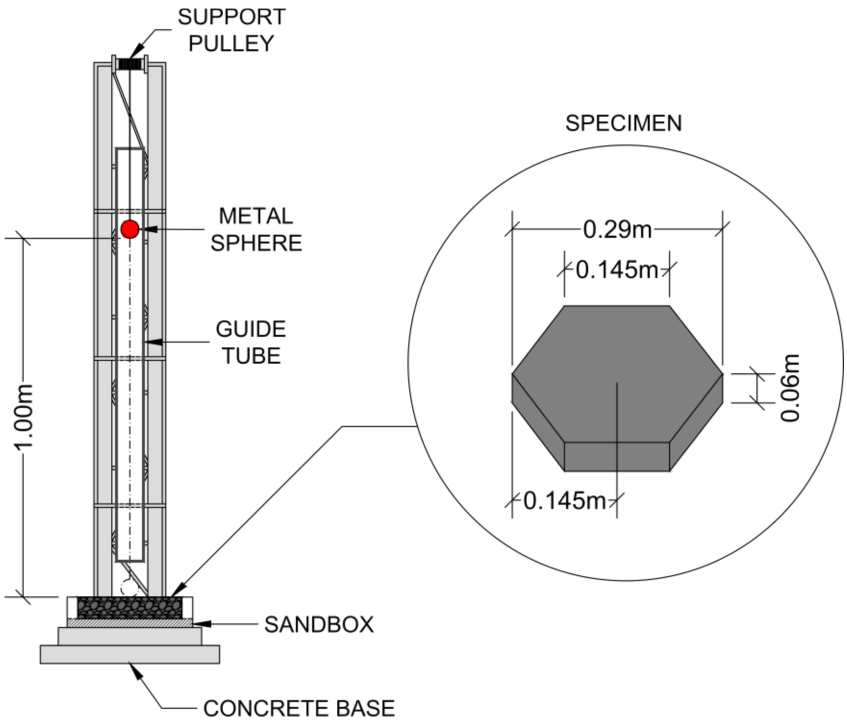


Source: Developed by the author.

3.2.7.2 Drop-weight impact resistance

The impact resistance test was performed by using a box with sand to support the sample, guide tube, and a hardened steel ball of 6.5 cm in diameter with a mass of 1.06 kg (Figure 3.12). The test consists of first leveling and keeping the sample fixed in the sandbox placed below the guide tube. The steel ball is positioned inside the tube at a certain height and then dropped by gravity onto the sample. The height of the fall was adjusted to 1 meter, and repetitions were made until the fracture of the sample.

Figure 3.12 - Representation of the apparatus used for impact resistance testing

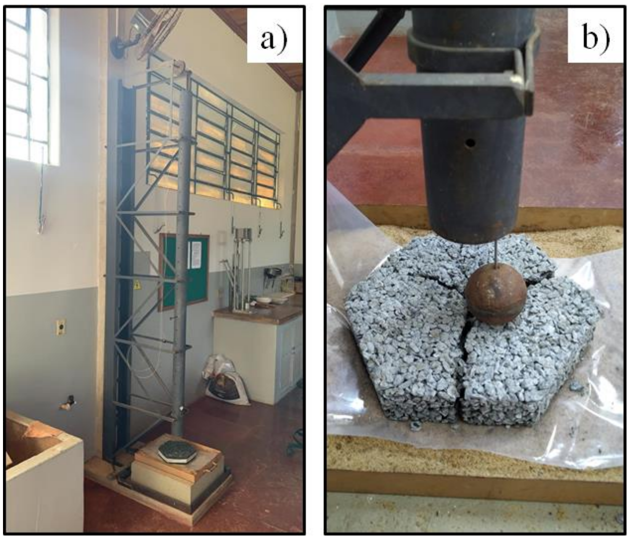


Source: Developed by the author.

Thus, this test method summarizes the impact energy absorbed by repeated falling impacts at a pre-set height. Equation 2 (ROSSIGNOLO, 2003), presented in Section 2.6.3.2, calculates the energy of each impact applied until the rupture of the specimens. Where "IE" is the impact energy (in Nm or J), "h" is the fall height (m), "m" is the mass of the steel ball (kg), and "g" is the gravity constant (considered 9.81 m/s²). Figure 3.13 shows the test being performed.

$$IE = h \cdot m \cdot g \tag{2}$$

Figure 3.13 - Impact resistance test being carried out: a) apparatus used; b) sample at the end of the test



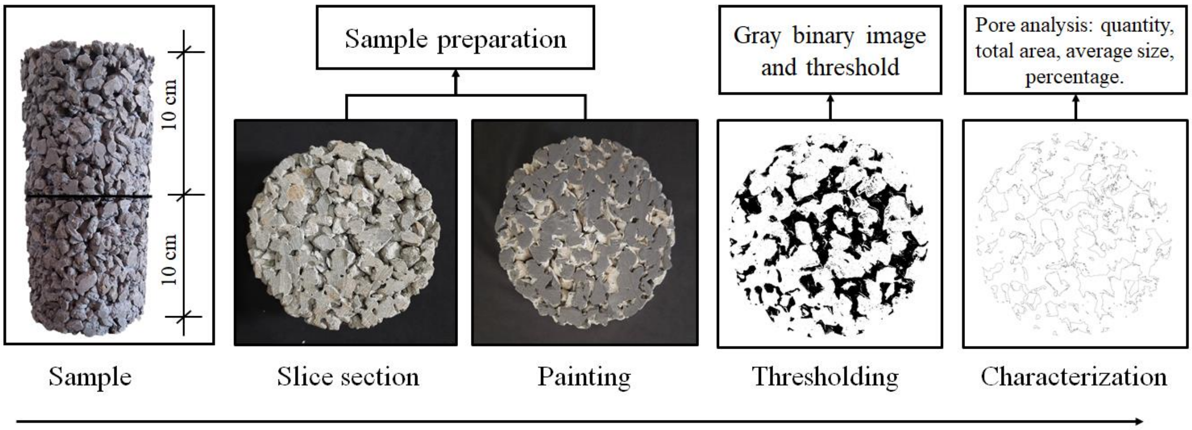
Source: Developed by the author.

3.2.8 Pore structure characterization

The image analysis method can also obtain the porosity of the pervious concrete obtained by the ASTM C1754 method. In this study, the ASTM C1754 method was used to obtain the total porosity, and a comparison was performed by the digital image analysis method. In addition to total porosity, pore image analysis can provide additional information about the internal structure, such as pore size, pore number, and pore distribution. This information can be obtained in different regions of the specimens, and it helps to understand how different aggregates can influence pore characteristics in the different areas of pervious concrete.

The pore structure of the pervious concrete was analyzed using an image analysis technique using the free software ImageJ. The procedure is represented in Figure 3.14. The samples were sectioned in half, 10 cm high, photographed, and transformed into two-dimensional images for processing and analysis of the pores in the software. Photos were taken from the upper faces of the specimen section to characterize the pore structure precisely in the middle of the sample.

Figure 3.14 - Schematic analysis of specimen pores using ImageJ software.



Source: Developed by the author.

3.2.9 Correlation among pervious concrete properties

To assess the dependence of compressive strength and impact strength on the other variables (density, porosity, and aggregate size). A multiple regression analysis with a 95% confidence level was performed. A linear least-squares regression equation was used to predict pervious concrete's compressive strength and impact strength based on the abovementioned parameters. In this case, the linear regression model is presented by Equation 5, where y (x1, x2, x3, xn) are the predicted values (compressive strength and impact strength), the independent variables (density, porosity, and aggregate size) are called x1, x2, x3, xn and a1, a2, a3, an are the regression coefficients.

$$y(x_1, x_2, x_3, x_n) = \beta_0 + a_1 \times x_1 + a_2 \times x_2 + a_3 \times x_3 + \cdots + a_n \times x_n \quad (5)$$

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4 RESULTS

4.1 ENHANCING PERVIOUS CONCRETE PROPERTIES – EFFECT OF AGGREGATES PACKING THROUGHOUT MAXIMUM DENSITY METHODOLOGY

The article entitled "Enhancing Pervious Concrete Properties – effect of aggregates packing throughout maximum density methodology," with authorship K. H. Arcolezi, R. G. da Silva, L. Soriano, J. Payá, M. M. Tashima, G. F. B. Sandoval, J. L. Akasaki, will be submitted in a scientific journal.

Abstract
The development of efficient pervious concrete is a crucial issue to promote its large-scale use. In this paper is presented an experimental study related to the use of maximum density methodology for enhancing pervious concrete properties. Pervious concretes were produced using three different narrow-size basaltic aggregates and their combination using the maximum density methodology. Physical, mechanical, and hydraulic properties of pervious concrete were determined for concretes cured at 28 days, yielding up to 18 MPa in the compressive strength and without damage to the infiltration rate of pervious concrete. A multiple regression model was established, indicating that compressive strength is most influenced by density and aggregate size. Moreover, the drop-weight impact resistance was influenced by all parameters (density, porosity, and aggregate size). Hence, besides the enhanced technical properties demonstrated, the use of packed aggregates in pervious concrete could also reduce the environmental issues associated to the flooding of stormwater in pavements contributing to the sustainable development.
Keywords: pervious concrete, packed aggregates, pore structure, mechanical properties.

4.2 INTRODUCTION

The growth of the world population associated with the urbanization process and waterproof materials in building construction have contributed to soil sealing [1,2]. Consequently, social, economic, and environmental problems have been caused by the flooding of stormwater [1, 3-5]. Environmental Protection Agencies around the world have suggested several innovative solutions to minimize this impact. Among these solutions, the use of pervious concrete in pavements is an alternative solution that can reduce heat islands and flooding in urban environments, assist in recharging the groundwater by infiltration of rainwater and minimize the pollution of water bodies [2, 4-8].

Pervious concrete (PC) is defined as a type of concrete containing cementitious materials, water, open-graded coarse aggregates, and, in some cases, small amounts of fine aggregates [9]. The high level of interconnected pores, usually ranging from 15 to 35% [3, 4, 9, 10], provides a hardened concrete with a high infiltration rate (0.2 to 2.64 cm/s) [6, 11, 12]. Otherwise, due to the high volume of interconnected pores, the compressive strength of PC is in the range 2-28 MPa [6, 8, 13, 14]. This value is reduced when compared to ordinary concrete [4, 6, 9, 15].

PC's mechanical and hydraulic properties depend on several factors: quantity of Portland cement, water/binder ratio (w/b), compaction process, type, and grading of aggregates [4, 9, 17]. Aggregates are essential in balancing the porosity and solid phase of pervious concrete and greatly influence PC's physical and hydraulic properties [6, 14]. Nevertheless, some discrepancies were found, mainly related to the influence of aggregate size on the mechanical properties [13, 18, 20].

In order to improve the mechanical properties of PC, the combination of aggregates containing different grading curves is reported in the literature. Most studies presented an empirical approach to producing more compact concrete with a packed structure [18, 21]. According to Sahdeo et al. [22], binary blended single-sized aggregates (30% of 10 mm and 70% of 4.75 mm) showed the best result maintaining a balanced relation between the strength and permeability coefficient, yielding compressive strength in the range 13.4 – 17.5 MPa. In the same way, Hung et al. [23] used different particle size ranges aggregates (2-5 mm and 5-10 mm and sand) to analyze the effects of compressive strength, porosity, and water permeability and strength from three mixtures with different aggregate proportions. It was observed that the incorporation of finer aggregates and sand combined with coarser aggregates collaborate to increase compressive strength (11.0 MPa to 18.4 MPa), reduce porosity from 22.2% to 11.6% and the permeability from 2.72 mm/s to 0.16 mm/s. An optimized study combining two narrow-size aggregates was performed by Yahia et al. [24]. Enhanced mechanical properties were achieved by combined aggregates when compared to narrow-size aggregates.

Thus, to contribute to the development of efficient pervious concrete and promote its large-scale use, this study aims to evaluate the effect of basaltic aggregates packing throughout maximum density methodology on the properties of PC. Physical, mechanical, and hydraulic properties (density, porosity, infiltration rate, compressive strength, and drop-weight impact resistance) were assessed. Moreover, the pore structure was characterized using digital image analysis. In the same way, a correlation among mechanical and physical properties was established throughout a multiple regression statistical model.

4.3 EXPERIMENTAL PROGRAM

4.3.1 Materials

Pervious concrete was prepared using a Brazilian Portland Cement type HE - High early strength (Cement Portland type V ARI - Brazilian denomination). This cement presents a density of 3 g/cm^3, and according to Brazilian standards, small amounts of calcareous filler (up to 10 wt.%) can be added into its composition [25]. Table 4.1 shows the chemical composition of Portland cement, determined by X-ray fluorescence (XRF-7000 from Shimadzu). Natural basaltic coarse aggregates supplied by Mineração Grandes Lagos, located in Itapura city/São Paulo – Brazil, were used to produce pervious concrete. Three different single-size aggregates (named A, B, and C) were selected.

Table 4.1 - Chemical composition of Portland cement (wt.%).

SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SO_3	MgO	P_2O_5	Cl	Others	LOI
20.8	4.6	4.8	65.6	0.1	1	1.7	1.2	-	-	0.2	-

4.3.2 Experimental Procedure

4.3.2.1 Aggregates characterization and packing procedure

Three basalt aggregates with different size distribution were used. The combination of these narrow-size coarse aggregates was performed to produce enhanced PC. The aggregate combination was performed using the maximum density methodology, allowing to obtain the highest unit weight (kg/m^3) for the combination of aggregates, indicating their optimum packing.

The highest density methodology is based on the refinement of pores and, consequently increase of density optimizing the particle size of the aggregates used (see Figure 4.1). In that sense, the unit weight of all single-size aggregates was determined. To combine two narrow-size aggregates and obtain the maximum density, the largest one should be progressively replaced in low percentages by mass (10% rate) of the finer one up to reach the maximum unit weight.

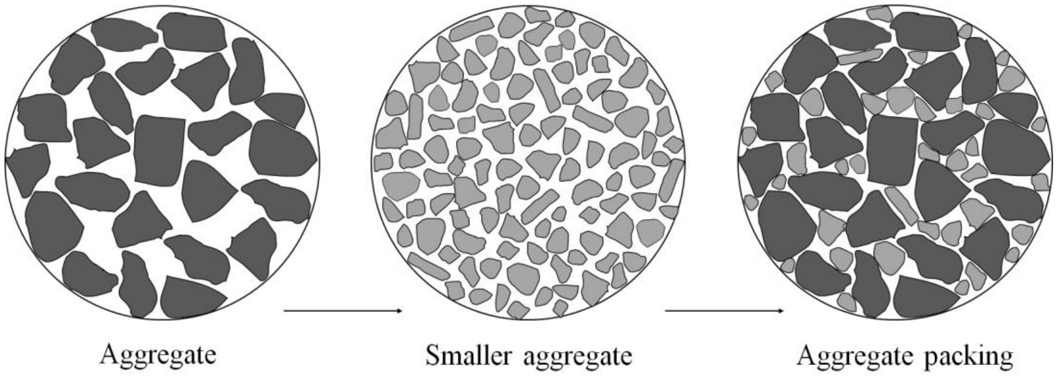


Figure 4.1 - Schematic diagram of the effect of packing aggregates in pervious concrete.

In this study was used the same cylindrical mold (10x20 cm) to mold the samples for the compressive strength test to evaluate the unit weight of the coarse aggregates. The compaction was carried out in a vibration table in two layers (10 seconds per layer) Simultaneously, ten blows (approx. 1 per second) were performed using a steel rod to accommodate the aggregates in the cylindrical mold. Finally, five additional seconds on the vibrating table were performed, and the unit weight was obtained for each measurement performed (average based on three measurements per assessed household). The relation between coarse aggregate replacement and unit weight of packed aggregates was obtained, and according to it, the maximum density can be achieved for packed aggregates. The compaction process used in the determination of maximum unit weight was the same to produce the PC, that to guarantee the efficiency of the proposed method.

For the concrete, cement paste is added that coats the aggregates, providing workability and when in the hardened state, supports loads. The more cement paste is incorporated, the more workable the mixture is. On the other hand, it reduces the porosity and permeability of the pervious concrete. The method proposed by Nguyen et al. (2014) [26] of mixing dosage to obtain the cement paste volume consists of determining the total surface area of the aggregates and the thickness of the paste layer and calculating the CPV. The specific surface area of an aggregate corresponds to the total surface of the grains, which takes into account the volume of each grain, the mass of each particle, and the total surface area of the aggregates in the concrete [26, 27].

4.3.2.2 Pervious concrete production

A cement/aggregate mass ratio of 1:5 and an effective water/cement ratio of 0.26 were fixed for all mixes of PC. In total, six mixture PC were assessed (considering the mixture of the coarse aggregates). As mentioned before, three different narrow-size aggregates (named A, B, and C) were selected, and three combinations of packed aggregates (named AB, BC, and ABC) were designed using the maximum density methodology. The nomenclature adopted for the different PC is related to the aggregate used: PC-Z, where "Z" is the type of aggregate used (A, B, C, AB, BC, or ABC). For all mixes, the aggregates were used considering the saturated surface dry condition (SSD). The pervious concrete mix proportion is presented in Table 4.2.

Table 4.2 – Mix proportions of PC.

Mix design	Aggregate (kg/m³)			Cement (kg/m³)	Water (kg/m³)	Water/ Cement	Cement/ Aggregate
	A	B	C				
PC-A	1581.25	-	-	316.25	82.23	0.26	1:5
PC-B	-	1530.79	-	306.16	79.60		
PC-C	-	-	1523.96	304.79	79.25		
PC-AB	841.78	841.78	-	336.71	87.54		
PC-BC	-	633.10	949.65	316.55	82.30		
PC-ABC	333.73	333.73	1001.20	333.73	86.77		

The PC mixtures were prepared in a mechanical drum mixer considering the following steps: at first, the aggregate was added with 50% of the water and mixed for 30 s. After that, 100% of the Portland cement was added and mixed for another 30 s. Finally, the rest of the water was added and mixed for 1 min. Cylindrical specimens (10x20 cm) were molded for compressive strength tests (5 specimens) and three specimens for the density, porosity, infiltration rate, and pore characterization by image analyses. They were molded in two layers. The compaction process is the same used to measure the unit weight for aggregates.

Hexagonal samples (14.5 x 6.0 cm - side length x height) were molded for the drop-weight impact resistance test (5 each mixture). The molding procedure of the hexagonal specimens considered the following steps: the mold was filled to the top and placed on a vibrating table for 15 s, applying 20 blows with the steel rod simultaneously (to accommodate the concrete) and then another 5 s to finish the compaction. All specimens were demolded after 24 hours and taken to a cure room with RH ~95% for 28 days until the age test. After this period, the physical, hydraulic, and mechanical, tests were performed.

4.3.2.3 Porosity and density of pervious concrete

The PC porosity and unit weight were tested according to ASTM C1754 [28]. Three samples of each mixture were tested. The dry mass “X” was determined after drying the sample in an oven at ±105°C (24 hours). Then, it was recorded the submerged mass “Y” in water. Thus, the porosity can be calculated according to Equation 1, where "K" is a constant (1,273,240), "ρ_w" is the density of water (kg/m^3) at the water bath temperature, "D" is the average diameter (mm) of the sample, and "L" is the average length (mm). The density (kg/m^3) can be calculated by Equation 2.

$$porosity\ (\%) = \left[1 - \left(\frac{K \times (X - Y)}{\rho_w \times D^2 \times L}\right)\right] \times 100 \qquad (1)$$

$$density = \frac{K \times X}{D^2 \times L} \qquad (2)$$

4.3.2.4 Permeability

The infiltration rate test was performed in the laboratory according to the recommendations proposed by ISO 17785-1 [29] (Figure 4.2). Three samples of each mix proportion were analyzed, and the infiltration rate “k” was determined using Equation 3. The preparation of the specimens was wrapped with a plastic film in three layers along their length, leaving a 5 cm lip above the top surface. To prevent water percolation on the sides and to adjust the wrap to sample surfaces, the wrap was heated with a heat gun. Then the specimens were placed in a funnel so that the bottom face was free. The infiltration rate “k” was calculated by the time “t” necessary for the percolation of 2000 ml of water “V” poured by maintaining a head of wastewater head of approximately 2 cm at the top of the specimen with the known cross-sectional area “A”.

$$k = \frac{V}{At} \tag{3}$$

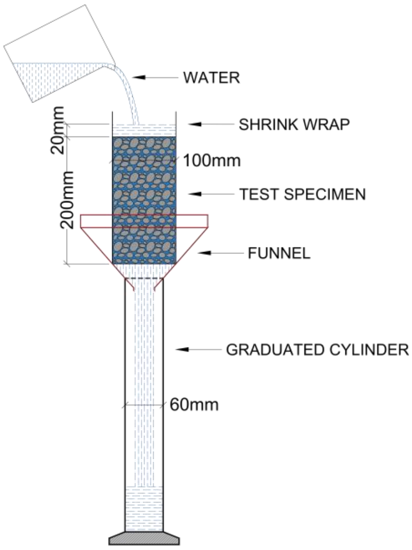


Figure 4.2 - Schematic representation of the infiltration rate test.

4.3.2.5 Cementitious paste volume (CPV)

To calculate the CPV, the first step is to calculate the specific area of the aggregates as presented by [26], which corresponds to the total surface of the grains, which takes into account the volume of each grain, the mass of each particle and the total surface area of the aggregates in the concrete. Thus, the CPV can be determined by:

$$CPV = \frac{C}{\rho_C} + \frac{W}{\rho_W} \tag{4}$$

Where C is cement, W is water, ρ_c and ρ_w are respectively the density of cement and water.

4.3.2.6 Compressive strength test

Compressive strength was evaluated by testing five samples for each mix proportion using a universal testing machine with a maximum capacity of 200 tons with a load rate of 0.45 MPa/s, as described by NBR 5739 [30].

4.3.2.7 Drop-weight impact resistance test

The drop-weight impact resistance is characterized by the number of blows in the repeated drop-weight impact test to achieve a prescribed level of distress. This number serves as an estimate of the energy absorbed by the sample at the levels of distress [31, 32].

A box with sand to support the sample (hexagonal sample), a guide tube, and a 6.3 cm diameter steel ball with a mass of 1.06 kg were used to drop-weight impact resistance test (Figure 4.3). The test consists of first leveling and maintaining the specimen fixed in the sandbox below the guide tube. The steel ball is positioned inside the tube at 1 m and then dropped onto the sample by gravity. Several repetitions were performed up to the fracture of the sample. According to Rossignolo [31], the energy of each impact applied until the rupture of the specimens can be calculated using Equation 5. Where "IE" is the impact energy (J), "h" is the drop height (m), "m" is the mass of the steel ball (kg), and "g" is the gravity constant (9.81 m/s^2).

$$IE = h \cdot m \cdot g \quad (5)$$

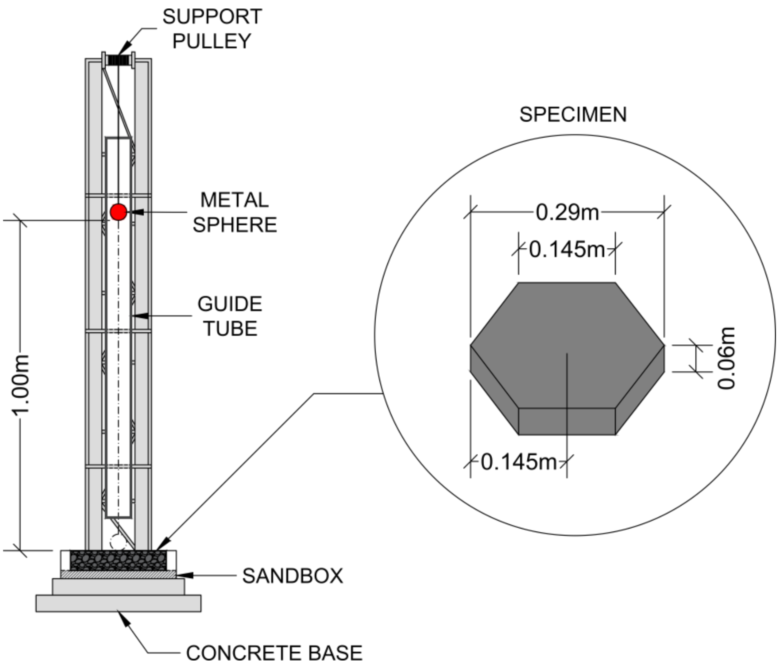


Figure 4.3 - Schematic apparatus for drop-weight impact resistance test.

4.3.2.8 Pore structure characterization

The ASTM C1754 [28] method was used to obtain the porosity, and a comparison was performed using the digital image analysis method throughout ImageJ software. Besides the total porosity, digital image analysis of pores can provide additional information about the internal pore structure in the analyzed area, such as the total number of pores, average pores diameter, and average pore area.

Figure 4.4 shows the schematic procedure for pore analysis using digital image analysis. For these analyses, specimens were half-sectioned, yielding two slices of 10 cm height. To improve the contrast of samples, each face of the PC was painted. High-quality 2-dimensional optical images were taken to process and analyze the pore structure in the ImageJ software.

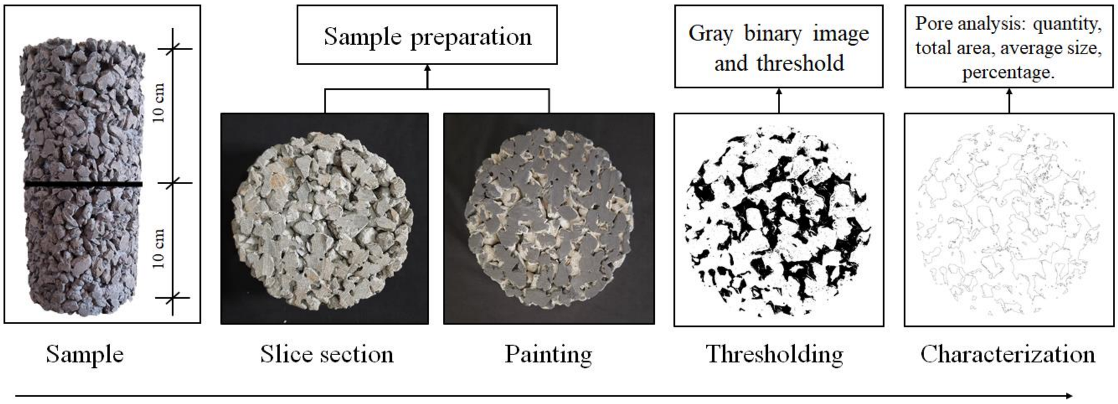


Figure 4.4 - Schematic pore analysis of specimens using software ImageJ.

4.3.2.9 Correlations among pervious concrete properties

A multiple regression analysis with a confidence level of 95% was performed to assess the dependence of compressive strength and impact resistance by the other properties (density, porosity, and aggregate size). A linear least-squares regression equation to predict the compressive strength and impact resistance of pervious concrete based on the parameters mentioned above were performed. In this case, the linear regression model is presented by Equation 6 where y (x_1, x_2, x_3, x_n) are the predicted values (compressive strength or impact resistance), the independent variables (density, porosity, and aggregate size) are named x_1, x_2, x_3, x_n and a_1, a_2, a_3, a_n are the regression coefficients.

$$y(x_1, x_2, x_3, x_n) = \beta_0 + a_1 \times x_1 + a_2 \times x_2 + a_3 \times x_3 + \cdots + a_n \times x_n \quad (6)$$

4.4 RESULTS AND DISCUSSION

4.4.1 Aggregates characterization and packing results

Three different narrow-size aggregates were used. The grain sizes distribution are shown in Figure 4.5, and their physical properties are presented in Table 4.3. According to the literature [33, 34], coefficients of uniformity lower than 2.0 are desirable for higher porosity of pervious concrete. The aggregates “B” and “C” presented a coefficient of uniformity lower than 2.0 (1.5 and 1.4, respectively), indicating a narrow range of particles. Aggregate “A” has a coefficient equal 2.4, which indicates a slightly wide range of particles.

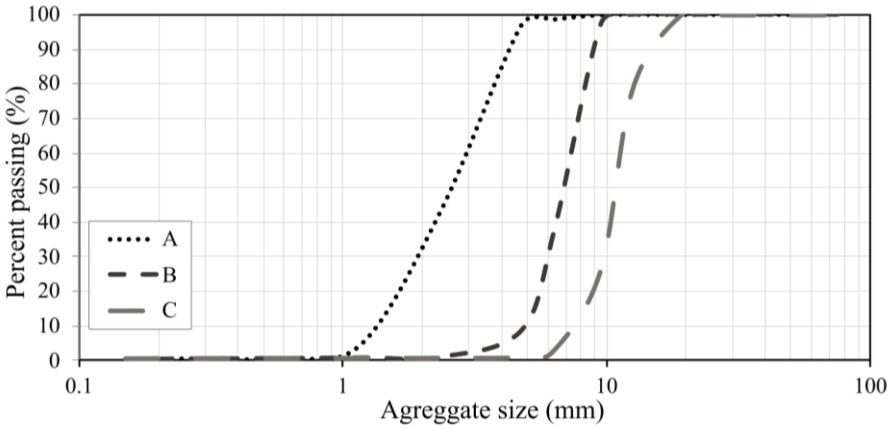


Figure 4.5 - Gradation curves of basaltic aggregates.

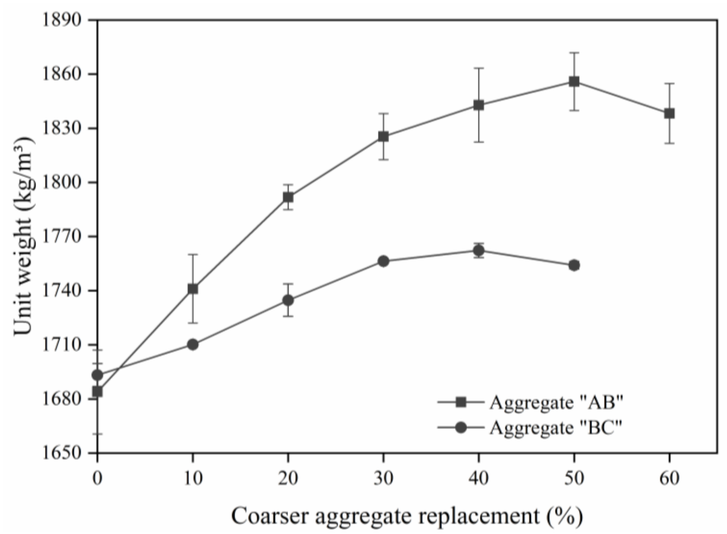


Figure 4.6 - Combination of aggregates using the maximum unit weight methodology.

Figure 4.6 showed the obtained results for the maximum density methodology for the assessed aggregates. The packed aggregate “AB” indicates the combination of aggregate “B” and “A”, where “B” is replaced in small amounts to the obtaining an improved unit weight. Similarly, the packed aggregate “BC” is also depicted.

The maximum density was obtained for 50% of aggregate "A" replacing "B", yielding an increment of 10.7% on the unit weight concerning the aggregate "B". It can be justified by the high coefficient of uniformity presented by aggregate "A" which could significantly improve the contact points between the aggregate grains in the PC. For packed aggregate "BC", the optimum replacement was achieved for 40% of aggregate "B", reaching 1762.2 kg/m³, corresponding to 4.1% of increment concerning the unit weight of aggregate "C". The combination "ABC" was based on the previously obtained results for "BC" and "AB". Hence, 60% of aggregate "C", 20% of "B", and 20% of "C" were mixed in order to produce the packed aggregate "ABC". For this case, 1835.8 kg/m³ was obtained, representing an 8.9% increment to aggregate "C". The physical parameters for packed aggregates are presented in Table 4.3.

Table 4.3 - Physical properties of basaltic aggregates.

Properties	A	B	C	AB	BC	ABC	Standard
Unit weight (g/cm³)	1.75	1.68	1.69	1.86	1.76	1.84	ASTM C29 [35]
Water absorption (%)	4.45	2.31	1.97	3.38	2.11	2.53	ASTM C127 [36]
Specific gravity	2.97	3.04	3.03	3.01	3.03	3.02	ASTM C127 [36]
Specific gravity OD	2.62	2.84	2.86	2.73	2.85	2.81	ASTM C127 [36]
Specific gravity SSD	2.74	2.91	2.92	2.83	2.92	2.88	ASTM C127 [36]
% voids	40.96	44.63	44.11	38.22	41.72	39.09	ASTM C29 [35]

4.4.2 Pervious concrete properties

4.4.2.1 Porosity and density

Figure 4.7a and 4.7b showed the porosity and density for all produced PC. For PC containing only a narrow-size aggregate (A, B, or C), increased porosity and decreased density was observed when the aggregate size was increased. PC prepared using aggregate "A" (PC-A) presented lower porosity and higher density. It can be justified by its higher unit weight and coefficient of uniformity, respectively.

PC-B and PC-C presented similar porosity and density (about 34% and 1830 kg/m^3, respectively), presenting different size range distributions. The presence of similar voids content and the similar unit weight of aggregates are a predominant factor in the porosity and density of PC [37].

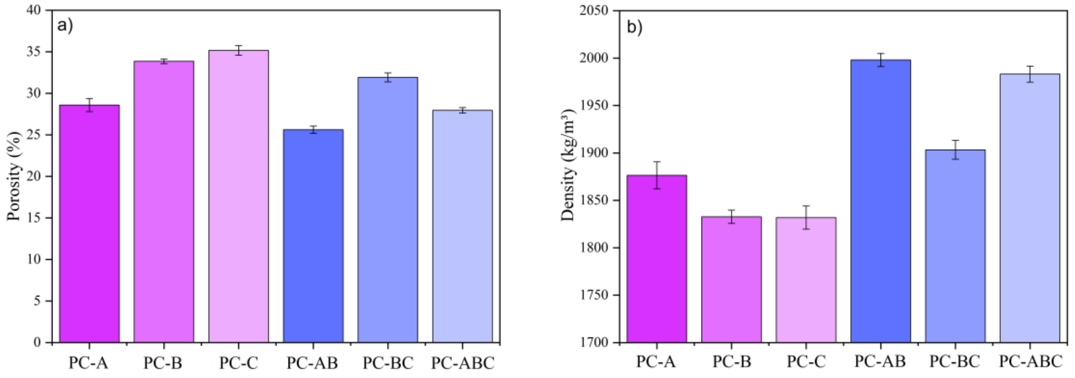


Figure 4.7 - a) Porosity of PC mixtures; b) Density of PC mixtures.

The combination of aggregates using the maximum density methodology resulted in a decrease in the total porosity and an increment in the density of the concretes. The incorporation of aggregate A combined with the aggregate B (aggregate "AB") provided a decrease of 24.3% on the total porosity and an increase of 9.0% in the density of pervious concretes concerning the mixture made only with aggregate B. Similarly, the combination of aggregate B with C (aggregate "BC") provided a decrease of 9.2% on porosity and an increase of 3.9% in density concerning concretes made only with aggregate C. The incorporation of aggregate A (PC-ABC) collaborates even more with the packing of particles of aggregate C, providing a decrease of 20.5% on porosity and an increase of 8.3% on density (compared to PC-C). The experimental data obtained agree with the literature: porosity (between 25.6% to 31.9%) and density (between 1903.2 kg/m³ to 1998.0 kg/m³) [6, 11, 38].

As shown in Figure 4.8, the relationship between porosity and density was inversely proportional with a linear regression fit (R^2=0.78). The PC-A mixture was farther from the linear fit, probably caused by the high coefficient of uniformity (2.41) compared to aggregates B and C (1.5 and 1.4, respectively).

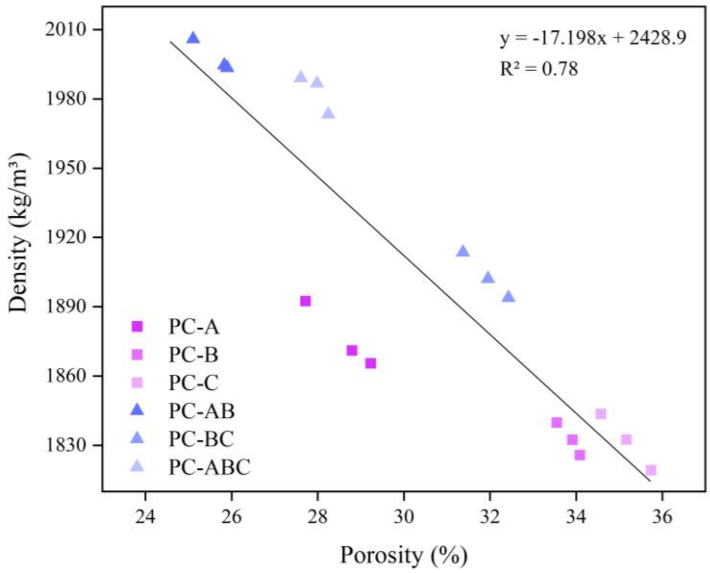


Figure 4.8 - Relationship between void content and density of PC.

4.4.2.2 Permeability

The infiltration rate results obtained by hydraulic conductivity tests are shown in Figure 4.9. According to NBR 16416 [39], the infiltration rate in pervious concrete for paving should be at least 0.1 cm/s. Pervious concrete prepared with narrow-size aggregates (PC-A, PC-B, and PC-C) presented an infiltration rate ranging 0.46 - 2.62 cm/s. Enhanced infiltration rates were observed for coarser narrow-size aggregate due to larger and connected pores when using coarser aggregates [8, 22].

The combination of narrow-size aggregates resulted in a reduction in the infiltration rate. PC-AB presented the lowest infiltration rate (0.43 cm/s) of all PC assessed. PC-BC presented a reduction of 36.3% compared to PC-C. It was interesting to note that pervious concretes made with packed aggregates had an infiltration rate similar to those prepared with smaller narrow-size aggregates. Only PC-ABC had higher infiltration rates when compared to pervious concrete made with the smallest aggregate (PC-A). Nevertheless, in all cases, the samples present the minimum requirements stipulated by the standard and the data found in the literature [13, 40].

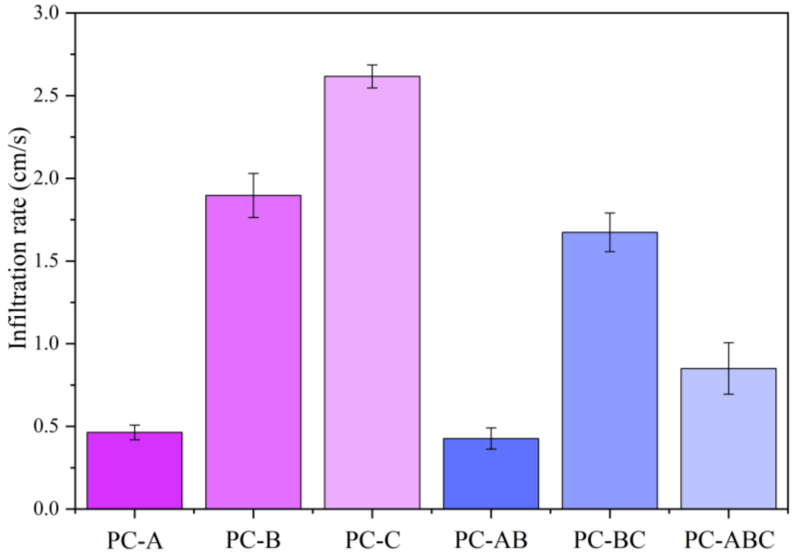


Figure 4.9 - Permeability of PC mixtures.

4.4.2.3 Cementitious paste volume (CPV)

The CPV in pervious concrete are two interesting parameters for analyzing the properties of mixtures and aggregate behavior. Table 4.4 presents the calculated CPV of the six different mixtures tested.

Table 4.4 - Calculated CPV

ID mixture	Coarse aggregate to binder	Surface area of coarse aggregates	CPV (%)
A	5	1422.21	18.80
B	5	499.02	18.20
C	5	305.72	18.12
AB	5	1031.52	20.02
BC	5	396.89	18.82
ABC	5	609.81	19.84

The CPV experienced small changes with each mix even though all mixes were prepared keeping the aggregate to binder rate fixed at 5 by mass. This happens because the coarse aggregates have different granulometries and therefore different unit weight. The increase in the unit weight of the aggregate requires a greater amount of cement paste per cubic meter to maintain the aggregate to binder ratio. Figure 4.10 presented the relationship between CPV and aggregate unit weight. Even with a relatively low variation of the CPV, the linear adjustment (R^2=0.98) proves the dependence of the

CPV in relation to the unit weight of the aggregates for mixtures with the same aggregate to binder ratio. As observed, the mixtures prepared with aggregates B and C, which have similar unit weight, also have very close CPV, as well as the mixtures with combined aggregates AB and ABC, which have higher unit weights and also a greater amount of cement paste (CPV around 20%).

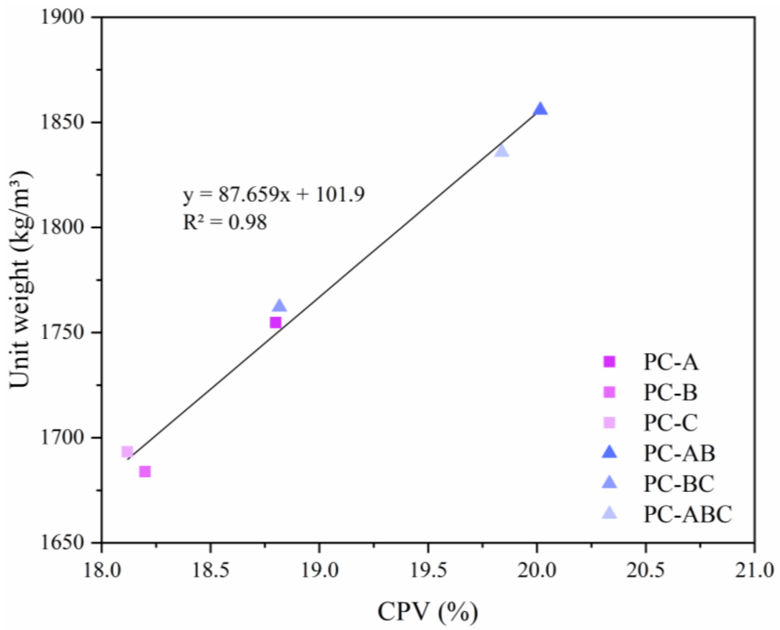


Figure 4.10 - Correlation between CPV and unit weight.

4.4.2.4 Compressive strength

The results obtained by 28-day compressive strength tests of PC made with different aggregate sizes are presented in Figure 4.11. The PC-A showed the highest compressive strength result considering the mixtures prepared with narrow-size aggregates. The mixtures PC-B and PC-C presented a reduction of 23.8% and 32.6% in compressive strength, respectively, to PC-A. The highest unit weight and the lowest porosity of aggregate A contributed to the better compressive strength. It is observed that coarser aggregate leads to a drop in compressive strength [14, 22]. This is probably due to the larger surface area of smaller aggregates, which contributes to more binder bonds in the internal structure, improving the compressive strength [41].

PC using combined aggregates showed an improvement in compressive strength compared to pervious concretes made only with its coarser narrow-size aggregate. An increase of 74.4% was observed for the PC-AB when compared to PC-B. For PC-BC, a slight increase of 16.4% was also registered to PC-C, and when the finer particle size aggregate was combined (PC-ABC), this increase was 81.2%, reaching a compressive strength of 16.76 MPa, very close to PC-AB. The combination of aggregates leads to a significant increase in compressive strength compared to coarser and finer narrow-size aggregate. This is due to the greater packing of aggregates, densifying the concrete.

When combined aggregates are compared to the finer narrow-size aggregates, increments on the compressive strength were also observed. Moreover, no significant reduction in the infiltration rate was observed. Hence, enhanced pervious concrete can be produced by combining narrow-size aggregates using the maximum density methodology.

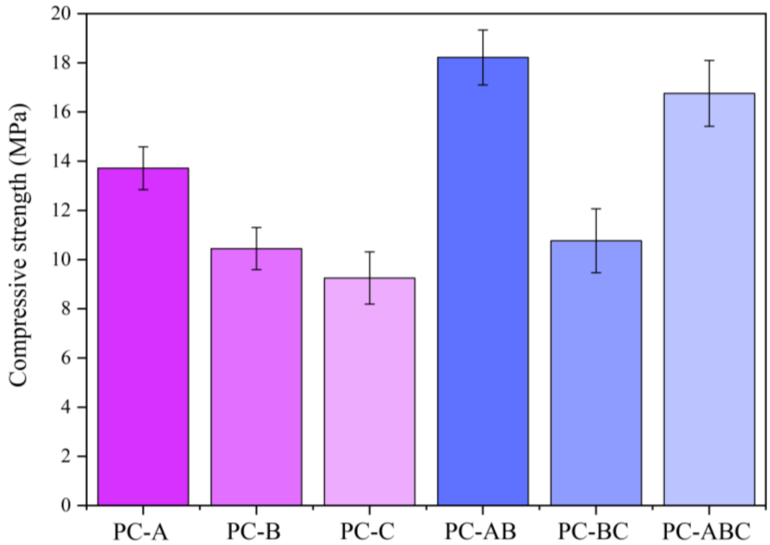


Figure 4.11 - 28-days Compressive strength for PC mixtures.

4.4.2.5 Drop-weight impact resistance

Figure 4.12 shows the influence of aggregates size on the impact energy of PC for hexagonal samples. For narrow-size aggregates, an increment in the aggregate size is associated with a slight decrease in the impact energy: 144.7 J, 141.2 J, and 117.1 J for PC-A, PC-B, and PC-C, respectively.

The combination of two narrow-size aggregates increased impact resistance. The PC-AB required 227.3 J for rupture, an increase of 61.0% to PC-B. PC-BC required 141.2 J, an increase of 20.6% compared to mixture PC-C. The incorporation of finer narrow-size aggregate "A" provided a more significant increment on the impact resistance, increasing the energy to 189.4 J in the PC-ABC mixture, equivalent to 61.8% to the PC-

C mixture. It is probably due to the presence of finer aggregates that promotes enhanced bricking connections supporting more impact energy.

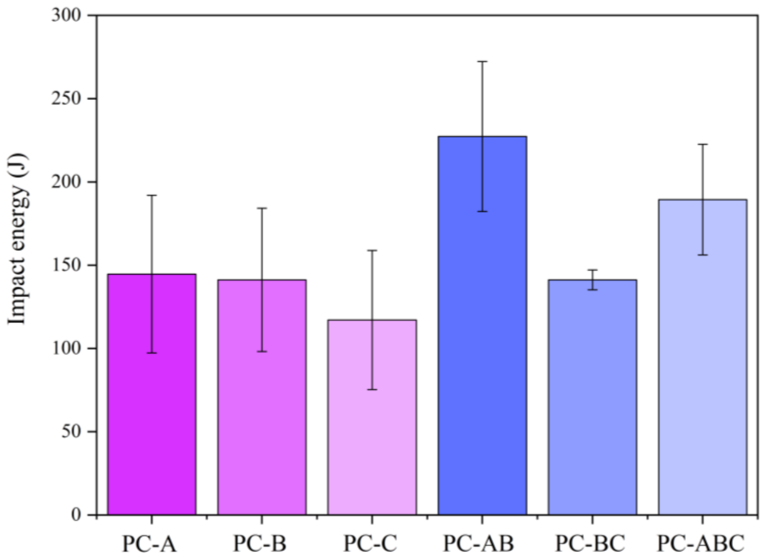
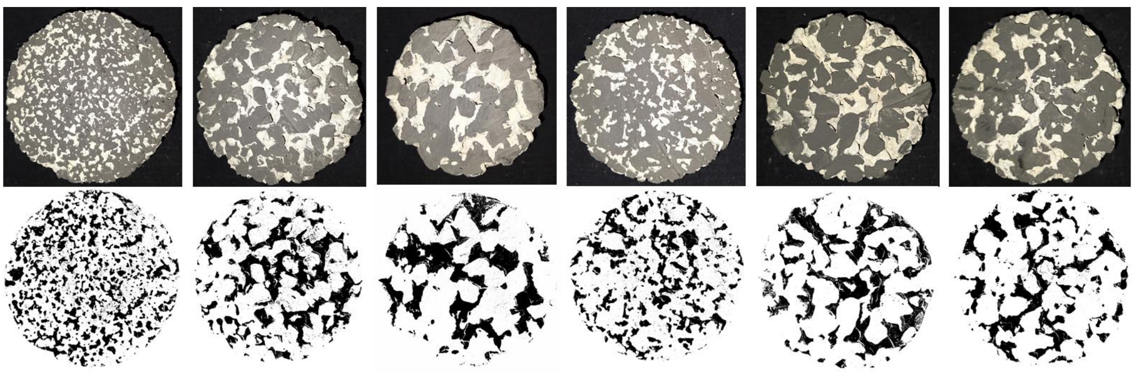


Figure 4.12 - 28-days impact energy for PC mixtures.

4.4.2.6 Pore structure characterization by digital image analyses

In addition to the total porosity, the pore structure analyzes can be helpful to understand better the behavior of the materials used in the mixtures and how they influence the properties of pervious concretes [16, 17]. The 2-dimensional optical images were used to determine the total porosity, average diameter and area pore for the different mix proportions assessed. The digitized and thresholding images of the samples are shown in Figure 4.13.



PC-A	PC-B	PC-C	PC-AB	PC-BC	PC-ABC
26.7%	30.9%	33.9%	26.6%	29.2%	27.9%

Figure 4.13 - Scanned and binary (threshold) images of surfaces of different PC samples and their respective total porosity.

The total porosity determined by digital image analysis can be compared to that calculated following ASTM C1754 [26]. Figure 4.14 shows both results, indicating a similar trend and a linear fitting with $R^2 = 0.82$. Chandrappa and Biligiri [10] also obtained similar results.

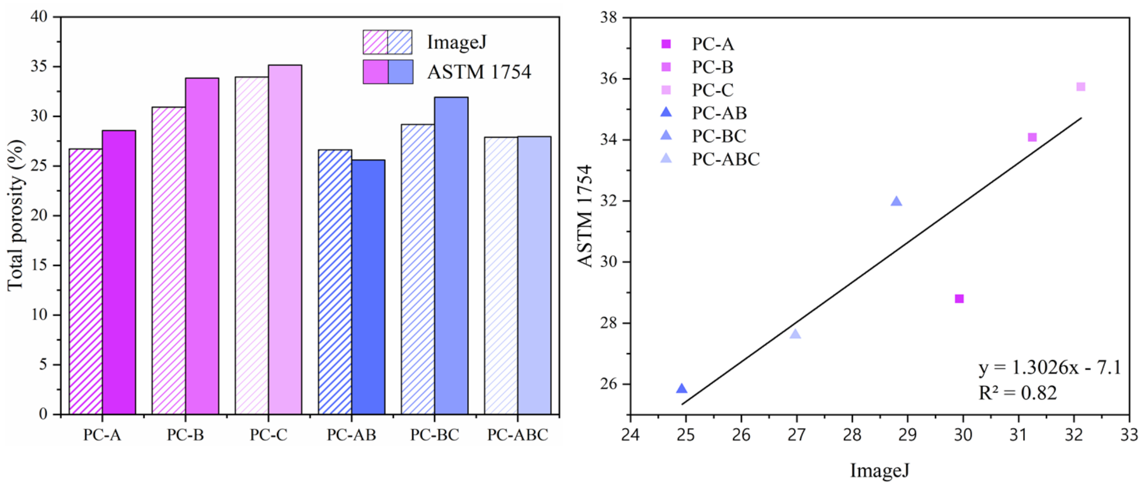


Figure 4.14 - Comparative analysis of porosity using digital image analysis (imageJ) and ASTM 1754.

Table 4.5 is presented the pore structure characterization obtained throughout the image analysis software. Coarser aggregates in PC achieved a reduced number of total pores, for a slice section, compared to the finer aggregate (from 61 to 263 pores). Similar behavior was also reported by Lu et al. [40] for recycled aggregates. Otherwise, both average pore diameter and pore area were reduced when finer aggregates were used, yielding 2.52 mm and 7.39 mm^2, respectively, for aggregate “A”, representing 61.7% and 18.4% of the values found for aggregate “C”. The reduced pore diameters for PC-A, and their lower connectivity, were responsible for the reduction in the infiltration rate compared to PC-C [41, 43].

The packing process provided some interesting changes to the pore structures of PC. PC-AB has more pores than PC-B (from 89 to 144) and an increment in the total number of pores which is associated with both a reduction in the average pore diameter (from 3.45 to 3.03 mm) and a reduction in the average pore area (from 25.79 to 13.45 mm^2). These values represent a reduction of 12.2% and 47.8% in average pore diameter and average pore area, respectively.

Table 4.5 - Number of pores, average pore area, average pore diameter and distribution of pores for all mixtures

	Number of pores	Average pore diameter (mm)	Average pore area (mm^2)
PC-A	263	2.52	7.39
PC-B	89	3.45	25.79
PC-C	61	4.08	40.22
PC-AB	144	3.03	13.45
PC-BC	61	4.09	33.56
PC-ABC	77	3.61	26.56

Comparing PC-BC to PC-C, there is no difference in the total number of pores and average pore diameter. Nevertheless, the average pore area achieved a reduction of 16.6%. The finer aggregates fill the voids of coarser aggregates (packing process) and, consequently, cause a reduction in the pore area. This result is also displayed on the total porosity of PC determined using the ASTM C1754 [28]. The PC-ABC presented a higher total number of pores when compared to PC-C (61 versus 77). It represents a reduction in the average pore diameter and average pore area (11.5% and 34.0%, respectively), indicating the refinement of the pore structure.

4.4.3 Correlations among pervious concrete properties

The relationship among density, porosity, infiltration rate, and mechanical properties are generally linear or exponential for pervious concretes [19, 24, 44]. Figure 4.15 shows the relationship among compressive strength, impact energy, density, porosity, and infiltration rate for PC mixtures using different size aggregates.

The infiltration rate increases with decreasing density and increasing porosity [8, 14, 20, 37]. On the other hand, the compressive strength presented a linear increment with increasing density and a reduction with the increase in the porosity (R^2= 0.66 and R^2= 0.93, respectively). The impact energy for rupture exhibits similar behavior to density (R^2=0.82) and porosity (R^2=0.78).

With respect to the infiltration rate, an increase in density and the reduction in the porosity lead to a diminishing in the infiltration rate (R^2=0.53 and R^2=0.89, respectively). These results suggest that there is a good relationship between infiltration rate and porosity.

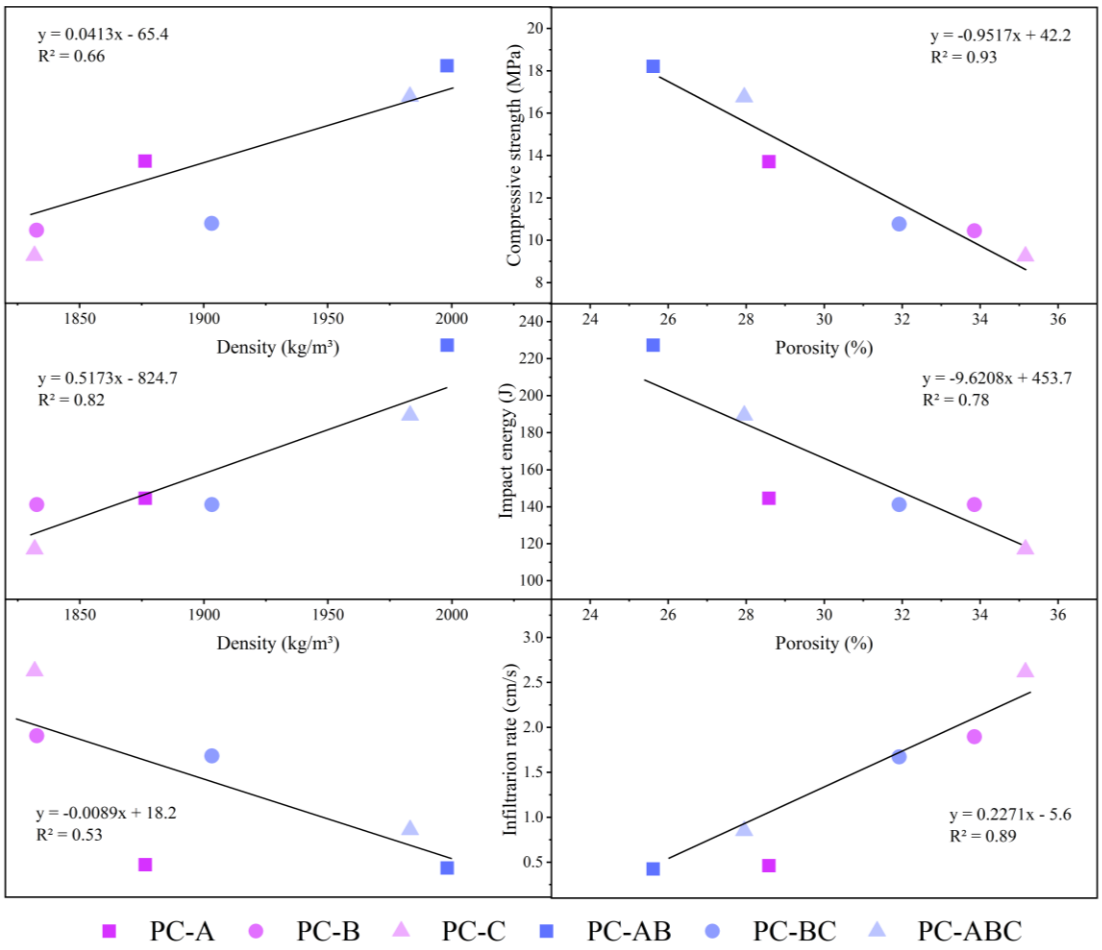


Figure 4.15 - Relationship between compressive strength, impact energy, density, void content, and infiltration rate for pervious concrete.

4.4.3.1 *Influence of Cementitious paste volume (CPV)*

The effect of CPV on pervious concrete properties is shown in Figure 4.16. Density, porosity and permeability are properties that are slightly subject to the influence of CPV. Density and porosity follow opposite trends with good linear fit of R^2=0.99 and R^2=0.85, respectively. Once the CPV increases, there is an increase in density, and a reduction in porosity because there is more cement paste in the mixture. Similarly, permeability also decreases with increasing CPV. As aforementioned for the mechanical properties, the contribution of the amount of paste is lower than the characteristics of the aggregate used. Mainly, the permeability that presented the smallest linear fit (R^2=0.62), is quite dependent on other variables of the coarse aggregate, which can influence, among other characteristics, the pore size, tortuosity, etc.

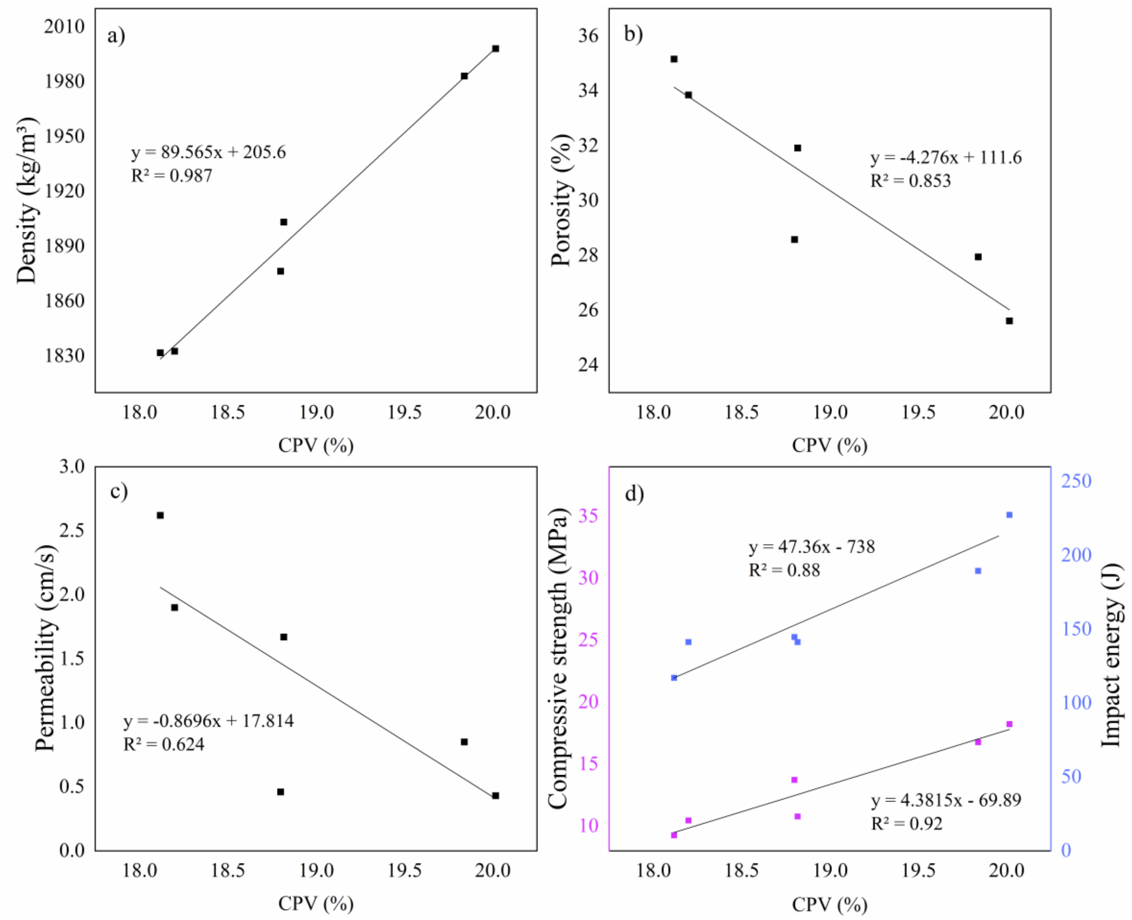


Figure 4.16 - Correlations between CPV and a) density, b) porosity, c) permeability, d) compressive strength and impact energy.

The compressive strength and impact strength of pervious concretes increase linearly with increasing CPV (R^2=0.92 and R^2=0.88 respectively). This demonstrates that the increase in CPV positively influences the mechanical properties of pervious concrete. However, it is important to note that the increase in CPV is slight (18.12 to 20.02%), while the mechanical strength significantly increases to almost 2 times both in compressive strength and in impact strength. It was observed by [45], that the increase in the amount of paste slightly improves the mechanical strength, but the authors find that the total porosity of the pervious concrete has a greater influence. This means that for mixtures with fixed aggregate to binder ratio, the mechanical properties are greatly influenced by the properties of coarse aggregates, such as aggregate size, particle packing, etc.

4.4.3.2 Statistical analysis

A multiple regression model was performed using a statistical program (Statgraphics Centurion) to establish a correlation between compressive strength, impact energy, density, void content, and aggregate size. Through the linear regression model (Equation 6), this analysis allows finding which parameters (density, porosity, and aggregate size) most significantly affect the compressive strength and impact energy of assessed PC mixtures.

Table 4.6 summarizes the values obtained by the coefficients a_1 (density), a_2 (porosity), a_3 (aggregate size), and β_0 (interception), p-values significance, and analysis of variance (ANOVA) with a confidence level of 95%. According to ANOVA, there is a statistically significant relationship between the assessed parameters (p-value < 0.05). Regarding the statistical analysis for compressive strength, the multiple regression model showed that density is the most crucial parameter that affects the compressive strength of pervious concrete (p-value 0.014). However, the aggregate size is also a variable with a strong influence in the regression model (p-value 0.056). On the other hand, when impact energy is the dependent variable, all variables strongly influence the regression model with p-values below 0.05. Although all variables have influence, density and aggregate size are the prominent influencers. For both compressive strength and impact resistance, density is the main influencing variable followed by aggregate size.

Table 4.6 - Summary of the results of the multiple regression model that considers the dependence of compressive strength and impact energy to density, porosity, and aggregate size.

	Coefficients		ρ-value	
	Compressive strength	Impact energy	Compressive strength	Impact energy
ANOVA	-	-	0.000	0.000
R^2	0.95	0.86	-	-
Intercept (β_0)	-118.831	-4299.440	0.058	0.003
Density (a_1)	0.071	2.095	0.014	0.001
Porosity (a_2)	0.043	19.981	0.910	0.022
Aggregate size (a_3)	-0.987	-38.692	0.056	0.001

The predicted values of compressive strength and impact resistance were associated with the experimental data obtained (Figure 4.17). Both models showed a good linear fit between predicted values and experimental data with $R^2 = 0.95$ for compressive strength and $R^2 = 0.86$ for impact strength.

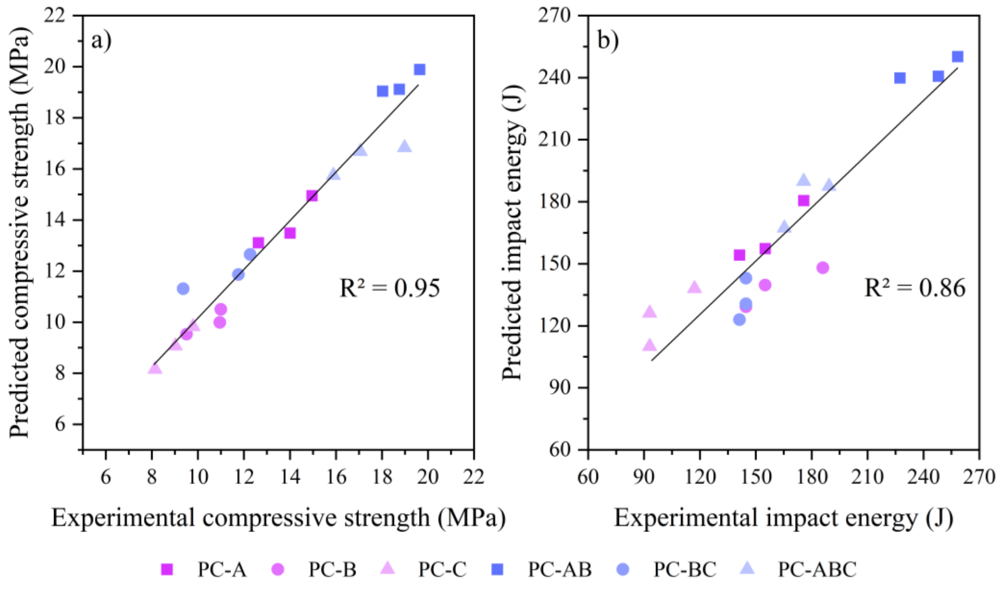


Figure 4.17 - Prediction results of multiple regression model versus experimental data of pervious concrete: a) compressive strength; b) impact energy.

4.5 CONCLUSIONS

This study aimed to analyze the influence of packing aggregates using the maximum density methodology to enhance pervious concrete properties. Based on the experimental findings, it can be concluded that:

- Density and porosity of pervious concrete are related to void content and unit weight of aggregates: Packed aggregates contributed to the increment of density and porosity of PC, yielding values of total porosity in the range 25.6 – 31.9%;
- Coarser aggregates presented higher infiltration rate (up to 2.6 cm/s). Packed aggregates reduce the porosity of PC and, consequently reduce the infiltration rate of PC. The finer aggregates drive the infiltration rate;
- Finer aggregates provide enhanced compressive strength for PC due to the lower porosity and the improvement in the bonding structure of PC. PC prepared using packed aggregates presented higher compressive than those produced using narrow-size aggregates (up to 18 MPa was obtained);

- Pervious concrete containing finer aggregates presented enhanced drop-weight impact resistance. Packed aggregates can improve this property due to the improvement on the bonding structure of PC;
- The pore characterization by image analysis presented some interesting and significant findings related to PC's performance: the use of finer aggregates increases the amounts of total pores. However, it reduces the average pore diameter and the average pore area. In the same way, the use of packed aggregates contributes to this statement, enhancing the PC mechanical properties.
- The multiple regression model indicates that while compressive strength is more influenced by density and aggregate size, drop-weight impact resistance is influenced by density, porosity, and aggregate size.

Hence, the use of packed aggregates emerges as a viable technical solution for PC use in pavements, maintaining the infiltration rate and enhancing the mechanical properties. Moreover, its use could prevent environmental problems associated with flooding of stormwater, contributing to the sustainable development.

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Conflict of interest

Authors do not present conflict of interest.

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5 GENERAL CONCLUSIONS

The use of pervious concrete can prevent environmental problems associated with the flooding of rainwater, contributing to sustainable development. Moreover, packaged aggregates proved to be a technical and viable solution for using pervious concrete in pavements, maintaining the adequate infiltration rate, and improving the mechanical properties.

Thus, answering the research question, it is possible to improve the mechanical strength of pervious concrete without significantly affecting the permeability from the study of granulometric combinations that enhance the properties of pervious concrete.

Based on the experimental results, it can be concluded that the aggregates size and packing greatly influence the concrete matrix's mechanical properties and pore characteristics.

Density and porosity are directly related to the unit mass of packed aggregates. The more packed they are, the denser and less porous the concrete.

Pervious concretes made with larger aggregate had higher porosities and higher infiltration rates. On the other hand, they presented lower mechanical performance since the porosity, and compressive strength properties are inversely proportional.

On the other hand, smaller aggregates provide greater mechanical strength (compression and impact) for pervious concrete due to the lower porosity and the improvement in the connection structure of pervious concrete.

The study of pore characterization by image analysis showed some points related to the performance of pervious concrete. The use of smaller aggregates increases the number of total pores, and on the other hand, the average diameter and pore area are reduced.

The multiple regression model indicates that both properties analyzed present statistically significant differences. On the one hand, the compressive strength is more influenced by the density and size of the aggregate. On the other hand, the impact resistance is influenced by the aggregate's density, porosity, and size.

6 PROPOSALS FOR FUTURE WORKS

The present master's dissertation aimed to improve the properties of pervious concrete using different sizes and combinations of aggregates. Thus, as proposals for future work, there are:

- Analyze other granulometric combinations and aggregate dimensions for a wider range of results. These tests can indicate mixing ratios that can also improve the mechanical properties of pervious concrete.
- Realization of different methodologies both in the dosage and in the compaction of the samples, since this is a very diverse subject in the literature and can bring different results. Some methodologies frequently presented are, for example, the use of proctor, rod, and press.
- Another point that can be analyzed and compared with other methods is the permeability test. The regulations and authors present different methodologies on a laboratory scale (variable load and constant load) and field tests. Both have different flow regimes and can influence the magnitude of permeability.
- Due to the lack of regularity in the pervious concrete surfaces, for the image analysis test, it is recommended to search for better surface regularization when photographing the images so that the software has more clarity when performing the analysis of the pores and to reduce discrepancies in the reading of the results.