UNIVERSIDADE ESTADUAL PAULISTA “JÚLIO DE MESQUITA FILHO”
FACULDADE DE ENGENHARIA
CÂMPUS DE ILHA SOLTEIRA

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“CEMENT REPLACEMENT IN PERVIOUS CONCRETE: Feasibility of Using Sugar cane ashes and Sand Considering the Overall Performance of the Material”

Ilha Solteira
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UNIVERSIDADE ESTADUAL PAULISTA
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RODRIGO GAROZI DA SILVA

"CEMENT REPLACEMENT IN PERVIOUS CONCRETE: Feasibility of Using Sugar cane ashes and Sand Considering the Overall Performance of the Material"

A thesis submitted to the Faculdade de Engenharia – Campus de Ilha Solteira/ UNESP, as part of the requirements for obtaining the degree of Doctor in Materials Science.
Area of knowledge: Materials Science and Engineering.

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Mauro Mitsuuchi Tashima

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Potential impact of this research

This research focused on the study of pervious concrete mixtures with partial replacement of Portland cement. Pervious concrete can be used as a coating on pervious pavements to help reduce the runoff of rainwater and increase water infiltration into the soil. The study to expand the use of this technology can bring several social and environmental benefits, mainly in urban centers, such as the mitigation of flooding, which consequently reduces problems of garbage and pollutants carried by water, in addition to improving the recharge of groundwater. So, social issues can be improved, such as greater comfort and safety on pavements due to the reduction of water runoff, lower risk of disease proliferation caused by contaminated flood waters, etc. In addition to the benefits of using pervious concrete to increase permeable areas, the research seeks to reduce the amount of Portland cement in the mixtures, replacing it with a waste or even a material with less environmental impact. Portland cement is responsible for a massive portion of the greenhouse gases emissions, so the use of concrete with less cement can help achieve a more sustainable society. All these approaches make this research meet the Sustainable Development Goals (SDGs) 11, 12 and 13, which move towards a better quality of life for future generations.

Impacto potencial desta pesquisa

Esta pesquisa focou no estudo de misturas de concreto permeável com substituição parcial de cimento Portland. O concreto permeável pode ser utilizado como revestimento em pavimentos permeáveis para colaborar com a redução de escoamento superficial de águas pluviais e aumento de infiltração de água no solo. O estudo para ampliar o uso dessa tecnologia pode trazer diversos benefícios sociais e ambientais principalmente em centros urbanos, como a mitigação de alagamentos, o que consequentemente reduz problemas de lixo e poluentes carreados pela água, além de melhorar a recarga de lençóis freáticos. Com isso, questões sociais podem ser melhoradas, como maior conforto e segurança em pavimentos pela redução de escoamento de água, menor risco de proliferação de doenças causadas por águas de alagamento contaminadas, etc. Além dos benefícios do uso do concreto permeável para o aumento das áreas permeáveis, a pesquisa busca reduzir a quantidade de cimento Portland na mistura, substituindo-o por um resíduo ou mesmo um material de menor impacto ambiental. O cimento Portland é responsável por considerável parcela de emissão dos gases causadores do efeito estufa, portanto a utilização de concretos com menos cimento pode colaborar para uma sociedade mais sustentável. Todas essas abordagens alinham essa pesquisa aos Objetivos de Desenvolvimento Sustentável (ODSs) 11, 12 e 13 que buscam refletir em melhor qualidade de vida para gerações futuras.

CERTIFICADO DE APROVAÇÃO

TÍTULO DA TESE: CEMENT REPLACEMENT IN PERVIOUS CONCRETE: Feasibility of Using Sugarcane ashes and Sand Considering the Overall Performance of the Material

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DEDICATION

I dedicate this thesis primarily to God, and to all my family who always supported me in all my decisions.

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“Mathematics is the language in which God has written the universe.”

Galileu Galilei

ABSTRACT

Pervious concrete (PC) is a material with interconnected macropores (approximately 15-35% porosity) that allows water to drain through its structure, generally used in pervious pavements. It is made with coarse aggregates bonded by a cementitious paste, and generally with little or no incorporation of fine aggregate, which guarantees interconnected porosity. Due to the absence of fines and high porosity, this material may require a greater amount of cement and achieves lower mechanical performances than conventional concrete. Considering the environmental and cost issues associated with the production of Portland cement, this work focused on the use of supplementary cementitious materials and fine aggregate replacing Portland cement in pervious concretes. Sugar cane bagasse ash (SCBA) and sugar cane straw ash (SCSA) were incorporated by replacing 10 to 25 wt.% of Portland cement in PC mixtures with aggregate to binder ratio of 3.5 to 5.0. The results demonstrated that mixtures with a smaller amount of cement (e.g. aggregate to binder 5.0), compressive strength was enhanced when compared to their respective control sample. Furthermore, the greatest compressive strength was achieved for 10 wt.% of both sugar cane wastes, reaching about 13.2 MPa for 10% SCBA and for 10% SCSA about 12 MPa. On the other hand, sand was used as fine aggregate replacing 15% to 59% of the cement paste, in PC mixtures with design porosities set at 25%, 30% and 35%. The results demonstrated that up to 38% of sand can be incorporated by replacing cement paste, without causing a reduction in hydraulic and mechanical properties and without significantly altering the porosity compared to control mixtures (100% Portland cement). This could represent savings of about 100 kg/m³ of cement compared with ordinary PC reported in the literature. Furthermore, life-cycle assessment demonstrated a reduction in environmental impact when sand replaced paste volume by up to about 38% while economic cost analysis predicted that cost savings in materials could be around 10-25%. Finally, the multi-criteria performance evaluation demonstrated that ideal paste volume replacement could be influencied by the size of coarse aggregate. Therefore, the well-planned partial replacement of Portland cement or cement paste could represent more functional, efficient and sustainable pervious concretes.

Keywords: pervious concrete; sugar cane wastes; fine aggregate; cement replacement.

RESUMO

O concreto permeável (PC) é um material com macroporos interligados (aprox. 15-35% de porosidade) que permite o escoamento da água pela sua estrutura, geralmente utilizado em pavimentos permeáveis. É elaborado com agregados graúdos unidos por pasta cimentícia e geralmente com pouca ou nenhuma incorporação de agregado miúdo, o que garante porosidade interconectada. Devido à ausência de finos e à elevada porosidade, este material pode necessitar de maior quantidade de cimento e atingir desempenhos mecânicos inferiores aos do concreto convencional. Considerando as questões ambientais e de custos associadas à produção de cimento Portland, este trabalho focou na utilização de materiais cimentícios suplementares e agregados finos em substituição ao cimento Portland em concretos permeáveis. Cinza de bagaço de cana-de-açúcar (SCBA) e cinza de palha de cana-de-açúcar (SCSA) foram incorporadas substituindo 10 a 25% em peso de cimento Portland em misturas de PC com relação agregado/ligante de 3,5 a 5,0. Os resultados demonstraram que em misturas com menor quantidade de cimento (ex. agregado/ligante 5.0), a resistência à compressão foi melhorada quando comparada com a respectiva amostra controle. Além disso, a maior resistência à compressão foi alcançada para 10% em ambos os resíduos de cana-de-açúcar, atingindo cerca de 13,2 MPa para 10% SCBA e para 10% SCSA cerca de 12 MPa. Já a areia foi utilizada como agregado fino em substituição de 15% a 59% da pasta de cimento, em misturas de PC com porosidades de projeto fixadas em 25%, 30% e 35%. Os resultados demonstraram que até 38% de areia pode ser incorporada em substituição à pasta de cimento, sem causar redução nas propriedades hidráulicas e mecânicas e sem alterar significativamente a porosidade em comparação às misturas controle (100% cimento Portland). Isto poderia representar uma economia de cerca de 100 kg/m³ de cimento em comparação com o PC comum relatado na literatura. Além disso, uma avaliação do ciclo de vida demonstrou uma redução no impacto ambiental quando a areia substituiu volume de pasta em até 38%, enquanto a análise de custos econômicos previu que a redução de custos em materiais poderia ser de cerca de 10-25%. Finalmente, a avaliação de desempenho multicritério demonstrou que a substituição ideal do volume de pasta pode ser influenciada pelo tamanho do agregado graúdo. Portanto, a substituição parcial bem planejada do cimento Portland ou da pasta de cimento podem proporcionar concretos permeáveis mais funcionais, eficientes e sustentáveis.

Palavras-chave: concreto permeável; resíduos da cana-de-açucar; agregado fino; substituição de cimento.

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CHAPTER 1 - INTRODUCTION

Pervious concrete is a type of concrete widely used as a drainage management tool. Its structural skeleton contains interconnected macropores that allow water infiltration while preserving mechanical properties necessary for some types of low-traffic paving.

The use of pervious pavements specially applying pervious concretes contributes to several social and environmental issues, mainly focused at reducing flooding and excessive water runoff. These characteristics make the use of pervious concrete meets with the low-impact development (LID) practices [1].

Furthermore, in 2015, the United Nations General Assembly (UNGA) proposed the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs) [2]. These goals seek to promote the peacefull development of humanity, reducing inequalities and caring for the planet. In this context, the rainwater management capability makes pervious concrete a useful tool to achieve some of the SDGs [3,4], especially the SDG 11: Sustainable cities and communities.

The most commonly used binder in pervious concrete mix designs is the Portland cement. Taking into account environmental issues arising from the significant emission of pollutants that occur in the process of obtaining clinker, the main component of Portland cement, several recent studies seek to obtain pervious concrete mixtures with high mechanical and hydraulic efficiency while at the same time reducing the amount of cement required.

In this context, the replacement of portland cement by supplementary cementitious materials (SCMs) has been strongly presented as a way to make pervious concrete more sustainable and environmentally friendly while maintaining its properties. The practice of reducing the use of clinker reusing wastes, such as agro-industrial by-products, also contributes strongly to achieving the SDGs proposed in the 2030 Agenda. This approach can help reduce climate change and advance in the circular and sustainable production. This emcompasses SDG 12: Responsible consumption and production and SDG 13: Climate action [4].

This work presents a global scope of the use of alternative materials used as a partial replacement of Portland cement, as well as the use of agro-industrial ashes from sugar cane production named sugar cane bagasse ash (SCBA) and sugar cane straw ash (SCSA), both partially replacing Portland cement. Furthermore, it addresses an optimization of mix design to use sand in pervious concrete, replacing cement.

1.1 RESEARSH SIGNIFICANCE

One of the major global challenges is reducing the use of Portland cement in the global construction industry. In 2022, 4.16 billion tons of cement were produced, and it is expected to reach 4.28 billion tons by the end of 2024 [5]. This robust industry represents a high energy consumption that reaches approximately 12%–15% of energy consumption by global industrial activities [6]. Considering sustainability issues, this large energy consumption reflects the need for fuels and resources. To produce clinker, the raw material needs to be calcined to temperatures around 1450 ºC, which is achieved in conventional processes through the burning of fossil fuels such as coal [6]. This energy requirement also brings other concerns, such as the high greenhouse gas emissions associated with this process. In 2022, approximately 1.61 billion tons of CO_2 were emitted from the cement industry, which represents around 5% of CO_2 emissions worldwide [6,7]. All these issues reinforce the need to reduce the use of Portland cement and replace it with materials with lower costs, low-carbon emissions and good technical efficiency, such as wastes, for example.

Annual sugar cane harvest exceeds 1.8 billion tons worldwide in the last 10 years [8]. Brazil is the largest producer of sugarcane in the world, with harvests exceeding 700 million tons per year in the last 10 years. The harvesting and processing of sugar cane for the production of sugar and ethanol generate by-products of interesting calorific value: sugar cane straw and sugar cane bagasse. These by-products can be burned for energy generation, and the ashes remained are valuable for use in cementitious compounds [9,10]. In this way, the partial replacement of cement by SCBA and SCSA in pervious concrete mixtures was approached in this work, as a viable alternative to reduce cement consumption.

River sand is used in pervious concrete, generally as an addition or replacement to coarse aggregates. However, this material has an intermediate grain size, between Portland cement and coarse aggregates, sometimes being much smaller than coarse aggregates, which could make it feasible to replace cement by sand, to form a mortar capable of efficiently binding the coarse aggregates, achieving satisfactory hydraulic and mechanical properties. Therefore, this research addressed the use of sand as partial substitute for Portland cement, seeking to make mixtures more efficient and less environmentally impactful by reducing the use of Portland cement.

1.2 OBJECTIVES

The main objective of this thesis was to propose a technical and environmental improvement on pervious concrete mixtures through the partial replacement of Portland cement by sugar cane wastes and river sand.

In this sense, the specific objectives were:

a) Assess the viability of incorporating SCBA, SCSA and sand in pervious concrete, replacing part of the binder.

b) Evaluate the mechanical and hydraulic effects of partial replacement of cement by SCBA, SCSA and sand as well as finding optimal replacement amounts;

c) Measure the environmental impact of conventional pervious concrete mixtures in relation to mixtures with cement replacement by sand, in order to find solutions with low impact on the environment.

1.3 THESIS STRUCTURE

This thesis was divided into 7 chapters organized in order to achieve the proposed objectives.

Chapter 1 comprises the introduction in which the thesis' object of study is presented.

Chapter 2 presents a review of the literature in which the main characteristics of pervious concrete are presented, as well as the main studies on replacement of cement by different materials to pervious concrete.

Chapter 3 comprises the methodology adopted to obtain, present and discuss the results.

Chapter 4, presented in the form of paper, addresses the study with the partial replacement of cement by SCBA and SCSA, encompassing introduction, methodology, results and discussions and conclusion.

Chapter 5, presented in the form of paper, addresses the study with the partial replacement of cement paste by sand, encompassing introduction, methodology, results and discussions and conclusion.

In Chapter 6, the global conclusions were presented about the obtained findings.

And finally in Chapter 7, proposals for future research on the topic is recommended.

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CHAPTER 2 – LITERATURE REVIEW

This chapter presents a brief description of the main characteristics of pervious concrete mixtures. Furthermore, studies are presented on the partial replacement of Portland cement by alternative materials, as a way to improve pervious concrete mixtures. Figure 2.1 schematically represents a summary of the content covered in the chapter.

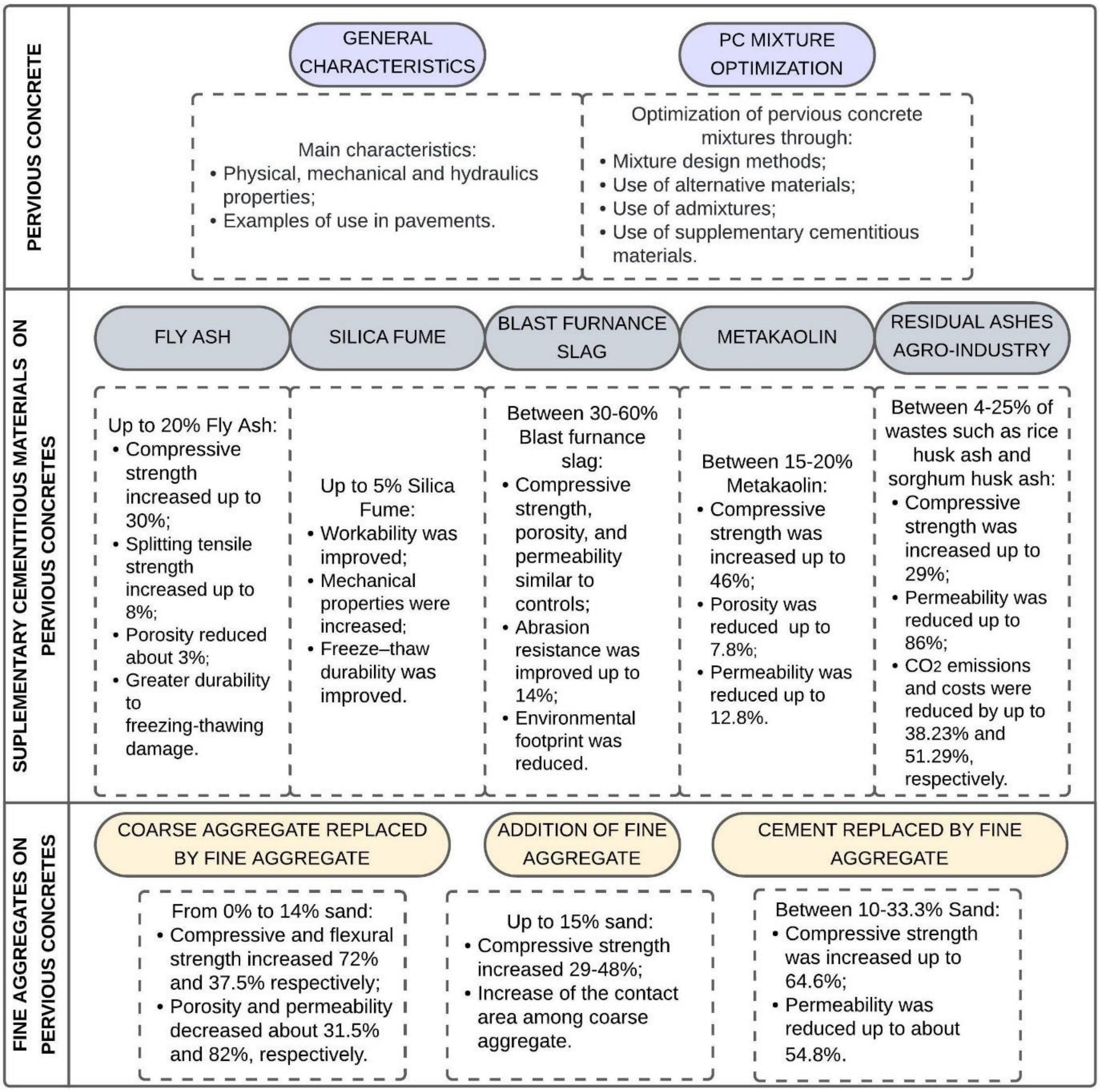

Figure 2.1 - Schematic representation of the topics covered in the chapter and summary of the main results presented from literature.

2.1 PERVIOUS CONCRETE

2.1.1 GENERAL CHARACTERISTICS

Pervious concrete (PC) is a relevant building material, due to its draining capacity, associated with the existence of interconnected pores. It can be classified as a low-impact development practice due to its hydraulic and structural performance. When applied in low-traffic pavements, it can be used to infiltrate and store water for progressive infiltration to the soil or drainage system [1]. Figure 2.2 presents a schematic representation of PC as pavement.

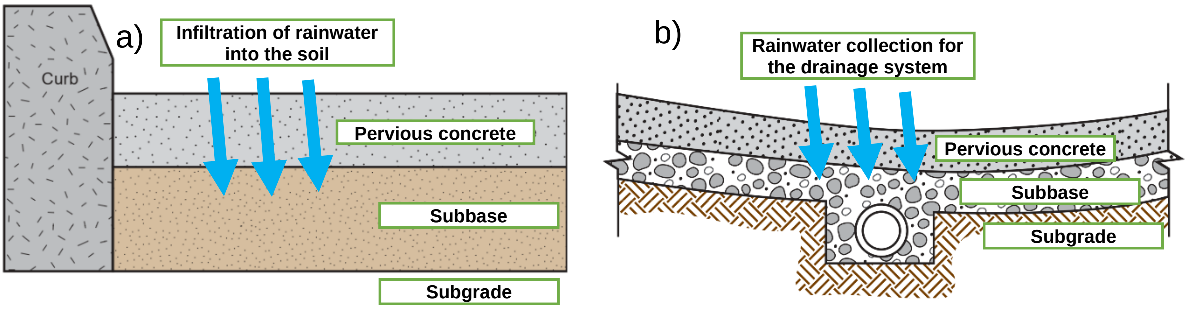

Figure 2.2 - Example of cross-sections of drainage arrangements with pervious concrete: a) Infiltration of rainwater into the soil; b) Rainwater collection for the drainage system (Adapted from Tennis et al. [2]).

The environmental benefits associated to infiltration of rainwater to soil includes the reduction of flooding and transport of pollutants, and the contribution to the recharge of groundwater. Furthermore, it can reduce the phenomenon of heat island and road noise and improve the road adhesion [1–3]. PC porosity (15-35%) is achieved through the use of coarse aggregate well-proportioned with a cementitious material such as Portland cement and the use of fine aggregates is reduced or even avoided [2,4,5]. This can provide a compressive strength ranging from approximately 3 to 28 MPa and an infiltration rate from approximately 0.003 to 3.3 cm/s [5].

2.1.2 PC MIXTURE OPTIMIZATION

In recent years extensive research has focused on optimizing PC mixtures, aiming to improve the environmental, mechanical and hydraulic characteristics [1,6-12]. To reach this goal, some research work on improve the mixture design methods.

Several methodologies have been tested and applied to achieve a balance between hydraulic and mechanical properties, to efficiently meet the mechanical and hydraulic requirements of each project [6–10].

On the other hand, it is possible to optimize PC mixtures through the use of materials with lower cost and greater technical and/or environmental efficiency [1]. Natural coarse aggregates are often replaced or combined with recycled waste aggregates and according to literature, the mechanical and hydraulic properties can be increased or decreased depending on the aggregate used [11,12]. It happens because the type, size and shape of the aggregate are strongly related with the entire porous structure and consequently to the total porosity of the PC [12,13]. Wang et al. [11] found that replacing basaltic coarse aggregates with steel slag aggregates promoted a progressive increase in compressive strength up to 34.3% for 100% steel slag aggregates. The authors associated this behavior to an improvement on interfacial transition zone (ITZ) through to the better development of hydrates in the interface of steel slag aggregates (when compared to natural basaltic coarse aggregates) which improves the mechanical performance. Conversely, Yap et al. [12] observed that natural granite aggregates replaced from 20 to 100% by recycled coarse aggregates (RCA) from construction and demolition wastes have lower mechanical properties, resulting in up to 48% lower compressive strength with full RCA replacement. However, in the mixture with 100% RCA, greenhouse gas (GHG) emissions could be reduced by up to 24%.

Admixtures (superplasticizers, high-range water-reducing, air-entraining, viscosity modifying, etc.) can also improve the efficiency of PCs mainly by interfering with the hydration of Portland cement [14–16]. Dai et al. [14] found that water-reducing agent added 2.5‰ to cement paste, increased compressive strength by approximately 26% compared to control PC samples. Furthermore, Lima et al. [15] states that superplasticizer based on naphthalene sulfonate (0.6 wt.% cement) could improve the fluidity of the paste, which provided better coverage of the aggregates while Hydroxypropyl Methylcellulose (0.05 wt.% total dry materials) admixture could improve the viscosity of the cement paste, which improved the paste-aggregate adhesion. This contributed to strengthening ITZ, and consequently improved mechanical properties of pervious concrete with natural and recycled aggregates. On the other hand, Strieder et al. [16] incorporated an rheology-modifying admixture specially produced for pervious concrete (V-MAR VSC 500) into PC mixes made with recycled concrete coarse aggregates to improve the paste rheology. The fresh properties were improved, and better workability and molding process were achieved. This led to a reduction in porosity and consequently in permeability of up to 55%. However, the mechanical properties were not improved.

The use of supplementary cementitious materials (SCMs) on PC is often adopted to reach more efficient mixtures. The most commonly SCMs incorporated into PC that are discussed in the literature are fly ash (FA), silica fume (SF), blast furnace slag (BFS), metakaolin (MK), residual ashes from agroindustry and other fine materials that could have a positive effect on binding properties [17–22]. These materials can generate different effects on PC mixtures depending on their chemical and mineralogical composition, morphology and granulometric distribution. It can contribute to improving material properties (physical, mechanical, etc.) and reducing Portland cement consumption [22], which is responsible for about 7% of greenhouse gas (GHG) emissions [23].

Another relevant issue on PC is the use of fine aggregates that are generally absent, or incorporated in small amounts as an addition or replacement of coarse aggregates [24–26]. Its use is often encouraged, due to the mainly mechanical benefits it can provide, but there should be a limitation, as it contributes to the reduction of interconnected porosity, which can reduce the infiltration rate [24,25,27,28]. Alternatively, fine aggregates can be used to partially replace Portland cement in pervious concrete, but limited studies were found in the literature [29–31] and there is difficulty with controlling porosity, which can directly influence the engineering properties that govern the use of pervious concrete. The use of this technique can be interesting due to the reduction in the amount of cement, which is replaced by a material with better environmental and economical characteristics [32,33].

Considering the benefits associated with the reduction of Portland cement consumption through incorporation of SCMs and fine aggregates, this work aimed to present and discuss the replacement of Portland cement in PC through the use of SCMs (i.e., SCBA and SCSA), and also by fine aggregate (siliceous river sand). It was intended to expand knowledge about increasing the efficiency of PC mixtures, to achieve the reduction of costs, improvement of physical-mechanical properties and environmentally friendly mixtures.

To support this issue, in the next items will be presented some of the main studies found on the literature that address this topic. For clarification, some terms used in this chapter may be different but with similar meaning, depending on the type of test performed and depending on the author. In this thesis, density is treated as the ratio of total mass per total volume of pervious concrete as specified by the ISO 17785-2, [34] standard. However, in this chapter, sometimes the term “unit weight” has been used according to the nomenclature adopted by some authors. Similarly, the terms “porosity” or “total porosity” are used by us representing the percentage in total volume of voids in relation to the total volume of pervious concrete. The literature may address this term as "void content". Finally, the hydraulic properties of the pervious concrete covered in this work were treated as "infiltration rate", which measures the volume that flows per area per time, according to tests carried out following the ISO 17785-1 [35]. Depending on the method in which this test is performed, the term "permeability" is often used and appears in this chapter on literature review.

2.2 SUPLEMENTARY CEMENTITIOUS MATERIALS INCORPORATED ON PERVIOUS CONCRETES AND THEIR EFFECTS

The SCMs can be divided firstly, according to their origin. Natural SCMs are materials extracted through mining and may require prior processing such as grinding to be used. We can mention limestone fillers, volcanic ash, diatomaceous earth, etc. SCMs can also be by-products or wastes from industrial processes that present interesting characteristics when applied to cement matrices. Examples include fly ash, silica fume, blast furnace slag and agro-industrial ash [36,37].

Different effects can be observed in cementitious matrices depending on the characteristics of the SCM used, which could collaborate to improve some properties of the mixture. The chemical effects occur when a material has the ability to react with other components present in the cement matrix, to generate hydrated products related to increased strength, while physical effects concern the improvement of the properties of the matrix due to physical characteristics of the particles, such as size, shape, etc.

Encompassing the chemical effects, the SCMs can present pozzolanic properties when they contain amorphous siliceous or silicoaluminous source components. The pozzolanic reaction occurs when an amorphous siliceous or silicoaluminous material react with calcium hydroxide (hydrated lime, or calcium hydroxide released by other cementitious materials, such as Portland cement) in the presence of water [36]. This reaction generates aluminate and silicate hydrates similar to those which are found upon hydration of Portland cement, contributing to increasing the mechanical strength of the matrices [36]. Several materials can have pozzolanic properties, such as fly ash, silica fume and some agro-industrial ashes.

Furthermore, some SCMs could collaborate through hydraulic reaction, that is, they can form hydrated products when in contact with water, which contribute to increasing strength, similar to Portland cement reactions [36]. Blast furnace slag (BFS) is the most common hydraulic material used as SCM. Combined with Porland cement, BFS can contribute to formation of aluminate and silicate hydrates, which contributes to improving the properties of the matrix.

Physical effects may also be responsible for improving the mechanical performance of matrices containing SCMs. When fine materials (generally finer than Portland cement grains) are incorporated, the empty spaces between the grains can be filled, which may be responsible for the increase in mechanical strength by reducing the porosity of the matrix. This is known as the filer effect and can happen even with non-reactive SCMs.

Furthermore, when fine materials are incorporated into matrices, some of the hydrates that are formed during the hydration of reactive particles, such as cement, may migrate to the surface of nearby adjacent particles. This is known as the nucleation effect and can help the binder particles to be better hydrated, since cement particles surface can be available for contact with water.

Dilution effect can also collaborate to better hydration of cement particles. When small particles that do not participate in the hydration process partially replace the cement, they leave more water available for the reaction of the particles that need to be hydrated, since the amount of water is maintained. It results in an increase in the water to cement ratio [38]. This could contribute to greater hydrate formation, which provides a positive effect on the mixture.

Below are listed the main SCMs that can present these effects as well as their application on PCs.

2.2.1 FLY ASH (FA)

FA is obtained from the burning of coal in power plants to generate electricity. The high temperatures reached make some mineral components melt and when quickly cooled they turn into small spherical glass particles [36]. As the particles formed are very small, their collection usually occurs by electrostatic or mechanical precipitation from flue gas [39]. There are two main types of FA (Classes F and C) related primarily by their chemical composition. Class F fly ash (siliceous) commonly has the sum of major oxides SiO_2, Al_2O_3 and Fe_2O_3 exceeding 70%. On the other hand, Class C (calcareous) fly ash presents the sum of this oxides exceeding 50%, with a higher total calcium content [36]. Rapid cooling during fly ash formation favors the generation of a strongly amorphous structure, enabling pozzolanic reaction processes with calcium hydroxide released during Portland cement hydration.

Fly ash is a widely studied material in cement matrices capable of improving the performance of cement-based materials [40,41]. In pervious concrete, its use is associated with the improvement of compressive strength and reduction of porosity [40]. Wang et al. [40] found that the replacement of up to 20 wt.% of Portland cement with FA in mixtures with coarse aggregate to binder ratio (a/b) of 4.54 and water to binder (w/b) of 0.31 was able to increase more than 30% compressive strength, 8% splitting tensile strength with a small decrease in porosity (less than 3%) and permeability compared to control pervious concrete. Above 20% replacement, both compressive and splitting tensile strength significantly decreased, as depicted in Figure 2.3

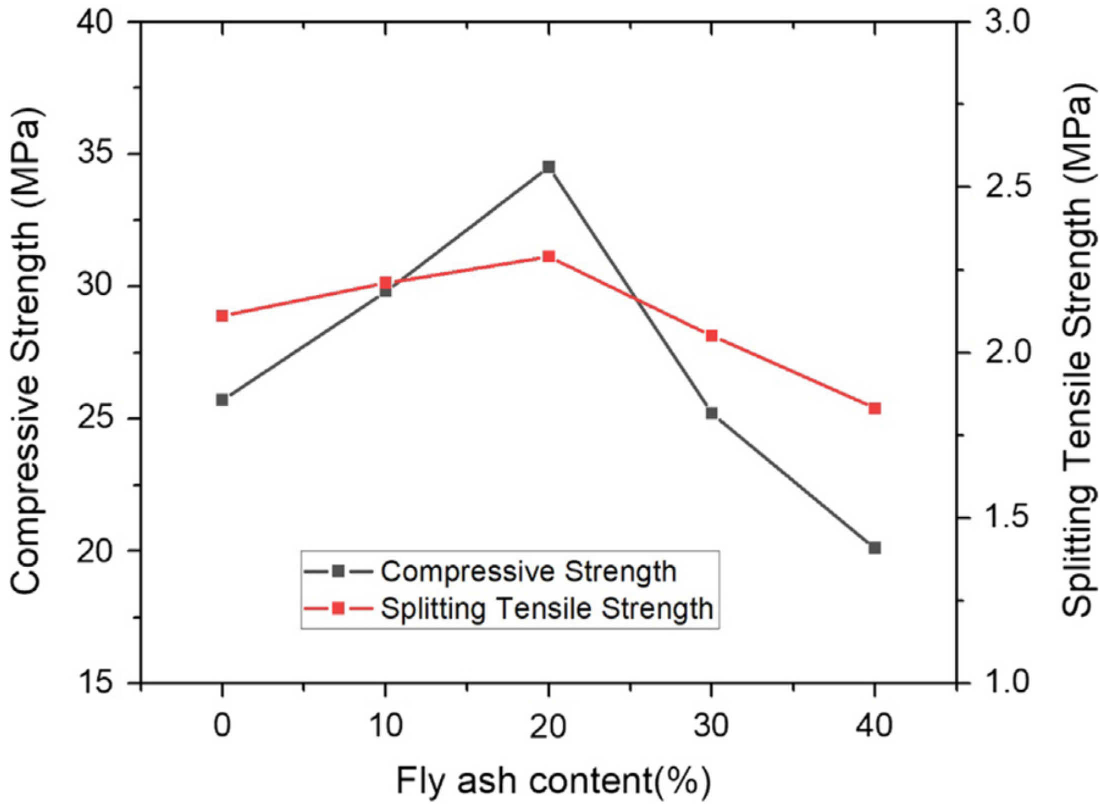

Figure 2.3 - Compressive and splitting tensile strength of pervious concrete with a/b = 4.54 and w/b = 0.31 replacing Portland cement from 0 to 40 wt.% by FA (Wang et al. [40]).

Furthermore, FA could improve the durability of pervious concrete. Anderson and Dewoolkar [41] investigated the freezing-thawing and salt exposure in a field-representative environment of pervious concretes mixtures with a/b of 4.43 and w/b of 0.35 with incorporation of air-entraining agent (AEA), high-range water-reducing admixture (HRWRA), viscosity modifying admixture (VMA), and hydration-controlling admixture (HCA). Four different mixtures were prepared with cement replacement by FA with 0, 10, 20, and 30 wt.%. Samples were subjected to a single-day freezing-and-thawing cycle for up to 100 days in cycles included 16 hours at –20°C, and 8 hours at 25°C. Additionally the samples were submerged in sodium chloride solution at concentrations of 2, 4, 8 and 12% for the last hour of the thawing segment, then removed to drain. The measured mass loss results demonstrated that 10 and 20 wt.% FA replacement provided greater durability to freezing-thawing damage, including the use of salt solutions as presented in Figure 2.4. The most harmful salt solutions were at 4 and 8% concentrations, while the least harmful solutions were at 0 and 12%.

Excessive salt concentration by 12% probably increased freeze time and decreased absorption rate which reduces damage to samples submitted to this solution.

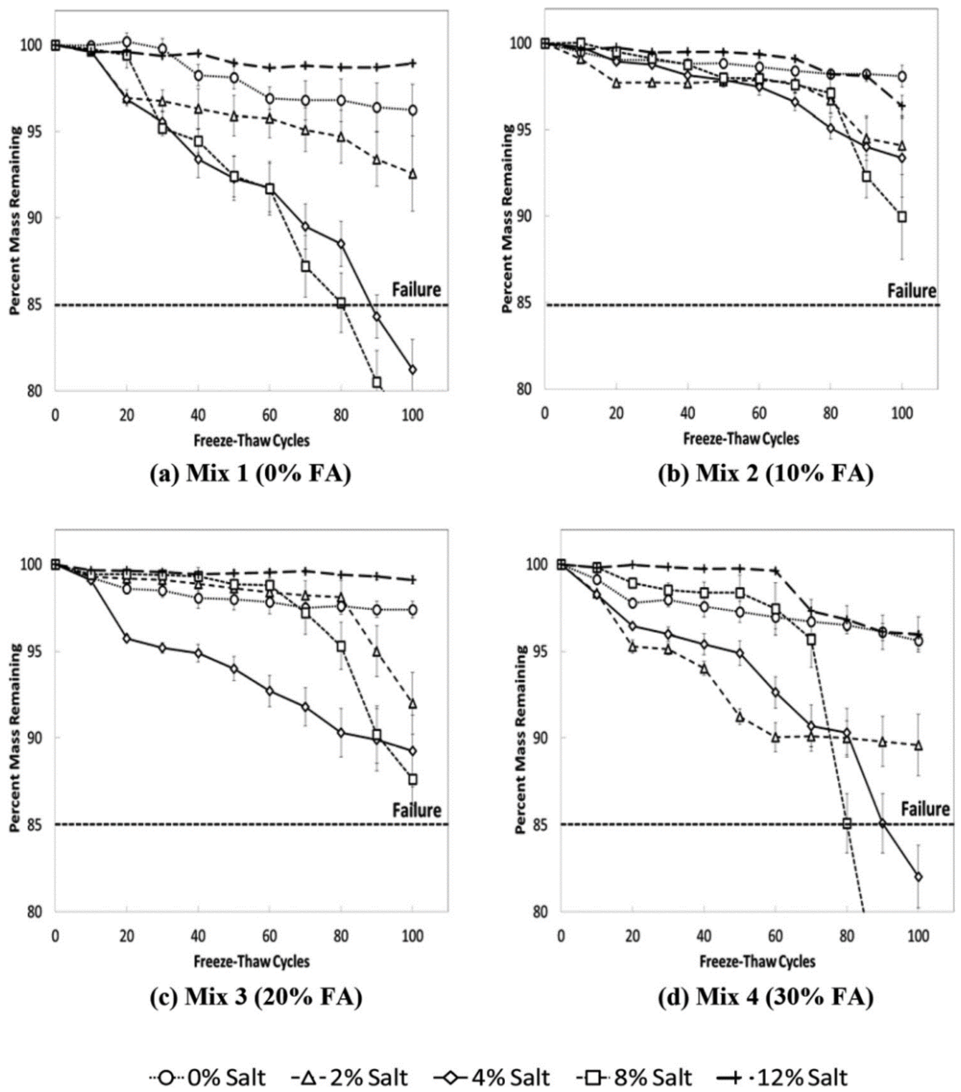

Figure 2.4 - Percent mass remaining of pervious concrete submitted to freezing-thawing and salt solutions cycles with: a) 0% FA; b) 10% FA; c) 20% FA; d) 30% FA (Dewoolkar [41]).

2.2.2 SILICA FUME (SF)

Silica fume, also called “microsilica”, “condensed silica fume” and “volatilised silica” is obtained from the manufacturing process of silicon metal and ferrosilicon alloys in an electric arc furnace. Temperatures of up to 2000ºC reduce quartz to gaseous SiO, which is transported by combustion gases to lower temperature zones.

SiO is then oxidized by air and condenses in the form of small particles of SiO_2. SF particles are spherical, with a high specific surface area and due to rapid cooling, their structure is predominantly amorphous, presenting high pozzolanic reactivity [36].

Studies involving the use of SF in pervious concrete are associated with the improvement of the cementitious matrix, densifying the microstructure and improving mechanical properties [18,42,43]. The literature reports [18] that the use of 5 wt.% silica fume could improve the workability measured in rheological tests, and further improve strength and freeze–thaw durability of pervious concretes. It was attributed to a reduction in void content and to the improvement in the ITZ, which enhanced paste-to-aggregate bonding. Above 5% SF, the mixtures became sticky, resulting in an increase on void content (See Figure 2.5), and consequently leading to a decrease in mechanical strength and durability (See Figure 2.6). The authors indicate that to solve this problem, admixture amount will need to be increased, since the specific surface area of SF is high.

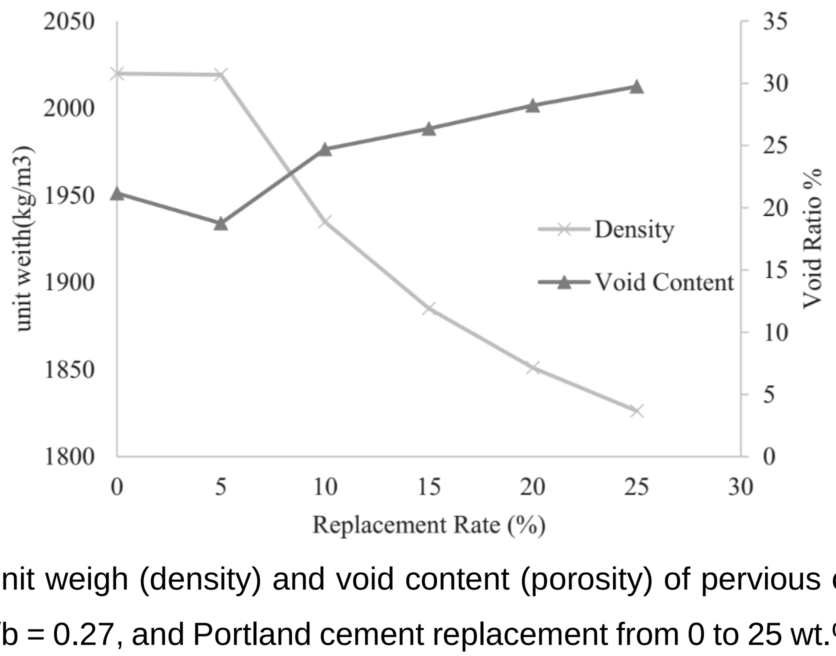

Figure 2.5 -Unit weigh (density) and void content (porosity) of pervious concrete with a/b = 4.45, w/b = 0.27, and Portland cement replacement from 0 to 25 wt.% by SF (Adil et al. [18]).

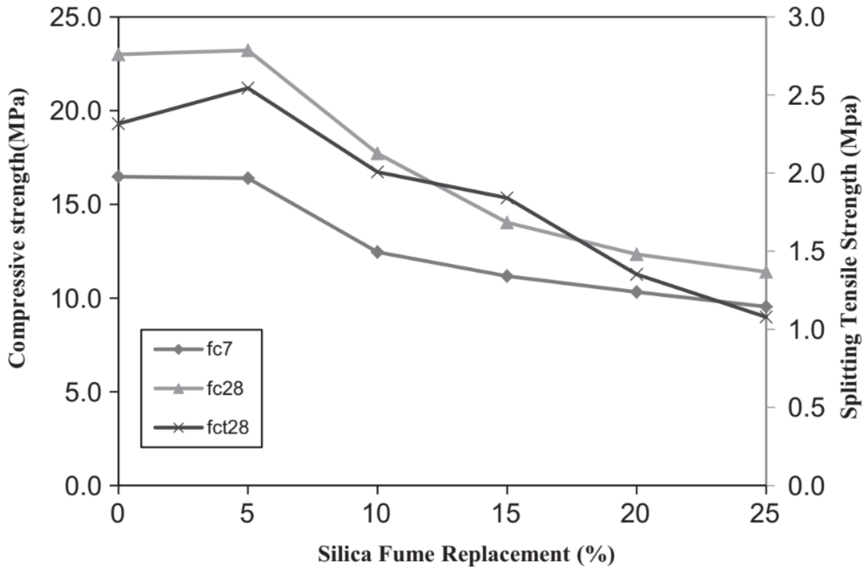

Figure 2.6 - Compressive strength at 7 curing days (fc7) and 28 curing days (fc28) and splitting tensile strength at 28 curing days (fct28) of pervious concrete with a/b = 4.45, w/b = 0.27, and Portland cement replacement from 0 to 25%wt by SF (Adil et al. [18]).

2.2.3 BLAST FURNANCE SLAG (BFS)

BFS is obtained by processing iron in furnaces where iron oxide ore is reduced by means of coke to metallic iron, while the silica and alumina constituents of the ore combine with the lime and magnesia to form a molten slag. Depending on the processes, BFS with different characteristics can be formed, for example air-cooled blast furnace slag and blast furnace slag pellets, which are normally used as aggregate in concrete. The granulated blast furnace slag has a rapid water-cooling process, which solidifies it as a glassy granulated mass. Granulated BFS is commonly ground and is employed as a cementitious material, even to replace Portland cement, with significant amounts of CaO, SiO_2, Al_2O_3, MgO and Fe_2O_3 [36].

In pervious concrete, BFS has been extensively used as an alkaline-activated binder [44–46] or as a substitute for Portland cement [19,47,48]. The combination of 60 wt.% BFS with 40 wt.% cement in PC can result in similar compressive strength, porosity, and permeability of PC mixtures with 100% cement (approx. 20-25 MPa), according to Oinam et al. [49]. Zhang et al. [47] replace Portland cement by 16 wt.% BFS and achieved an increase of more than 20% in the compressive strength of the matrix binder paste used to produce pervious concrete. Probably due to the different rheology of the binder paste, although the matrix achieved better mechanical strength, the pervious concrete with BFS matrix incorporated (a/b of 4.55) reached an increase of porosity compared to the control mixture with 100% Portland cement (20% porosity for control compared with 35% porosity to BFS incorporation), which reduced the compressive strength of the PC. However, Gaedicke et al. [19] claimed that the use of BFS could be able to effectively replace up to 30% of cement to improve abrasion resistance of pervious concrete cores by impact abrasion. After 500 revolutions on abrasion machine the mass loss was reduced by 13% and 14% in pervious concrete with limestone and recycled concrete (RCAB) coarse aggregates, respectively, both containing BFS, as depicted in Figure 2.7. Furthermore, El-Hassan and Kianmehr [48] observed that the use of 50% BFS replacing cement could reduce the environmental footprint of pervious concrete leading to a reduction on carbon emissions by up to 54%.

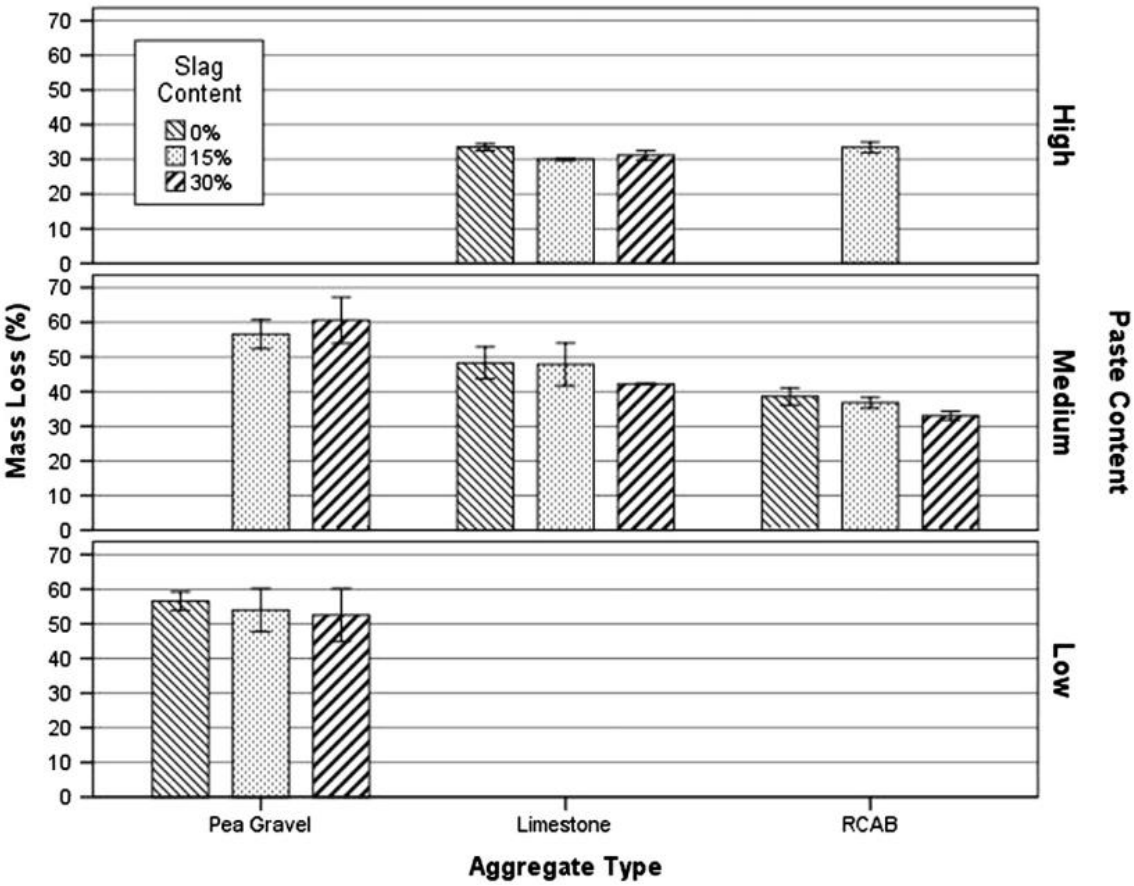

Figure 2.7 - Mass loss according to procedures of ASTM C1747 for different aggregate types (Pea gravel, limestone and RCAB) and different levels of slag, and paste content measured after 500 revolutions. High: a/b = 4.5; Medium: a/b = 5.2; Low: a/b = 6.0 (Gaedicke et al. [19]).

2.2.4 METAKAOLIN (MK)

MK is a type of artificial pozzolan produced by heat treating kaolinite clay composed mainly of silica and alumina. The clay is subjected to temperatures between 650 °C and 800 °C that break the crystalline network of minerals. A higher reactivity of MK will depend on a predominantly amorphous structure [36].

The use of MK on pervious concrete combined with cement was able to improve mechanical properties up to approximately 15 to 20% replacement [20,50,51]. Singh et al. [50] obtained up to 46% increased compressive strength (cured at 90 days) of a pervious concrete with 20 wt.% MK (a/b = 4.5 and w/b = 0.38). Bright Singh and Murugan [20] observed that the replacement of up to 20 wt.% of cement by MK in pervious concrete with a/b of 3.54 and using coarse aggregates of nominal size of 12.5 mm and 20 mm, reduced the porosity progressively from 17.21% to 15.86% (12.5 mm coarse aggregate) and 22.30% to 21.00% (20 mm coarse aggregate). Consequently, as showed in Figure 2.8, the permeability also reduced up to 12.8%. The authors attributed the densification of pervious concrete mixtures to the filler effect combined with the pozzolanic activity provided by MK. On the other hand, this strengthening in the cement paste matrix, yielded improved mechanical properties, regarding compressive, split tensile, and flexural strength. Up to 15 wt.% MK provided an increase on compressive strength of up to 39.25% and 43.41% in pervious concretes with 12.5 mm and 20 mm coarse aggregates, respectively, as indicated in Figure 2.9. Above 15 wt.% mechanical performance was reduced, probably due to the lower amount of cement, which is responsible for the formation of portlandite responsible by the synergistic effect of MK.

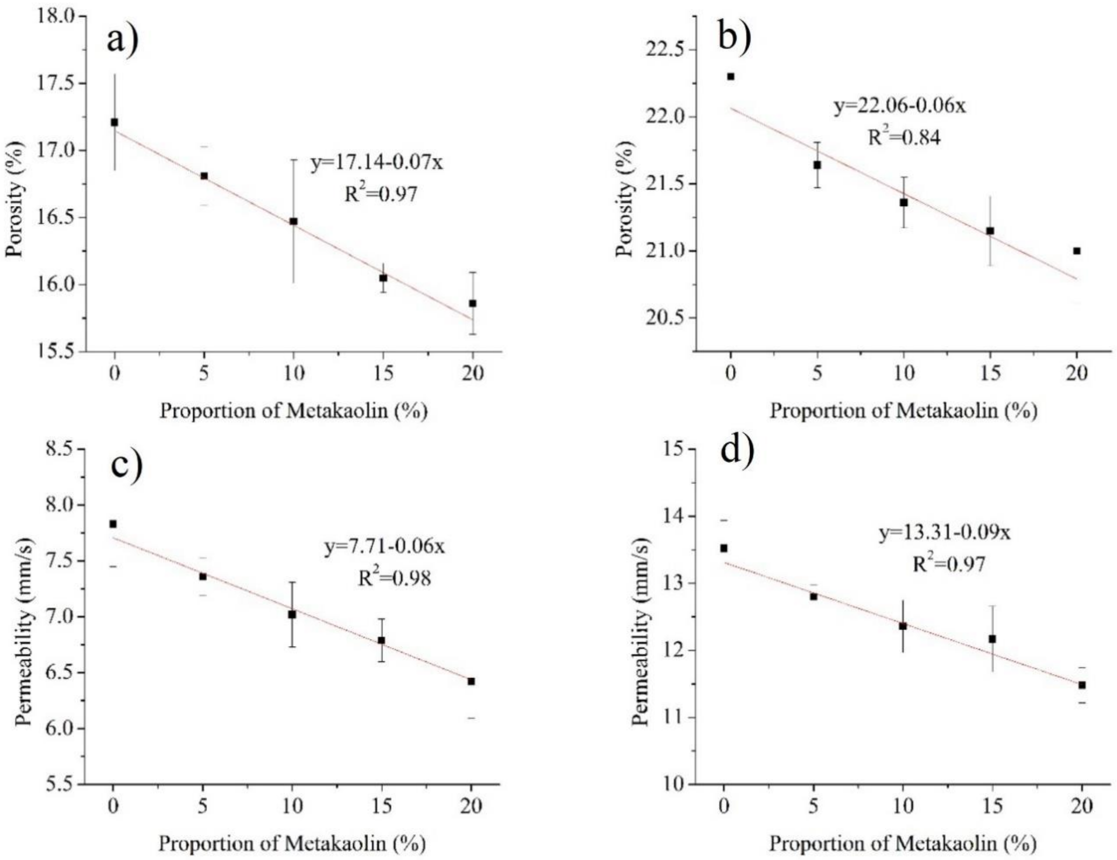

Figure 2.8 - Pervious concrete with a/b = 3.54: a) Porosity of PC with 12.5 mm aggregates; b) Porosity of PC with 20 mm aggregates; c) Permeability of PC with 12.5 mm aggregates; d) Permeability of PC with 20 mm aggregates (Adapted from Bright Singh and Murugan [20]).

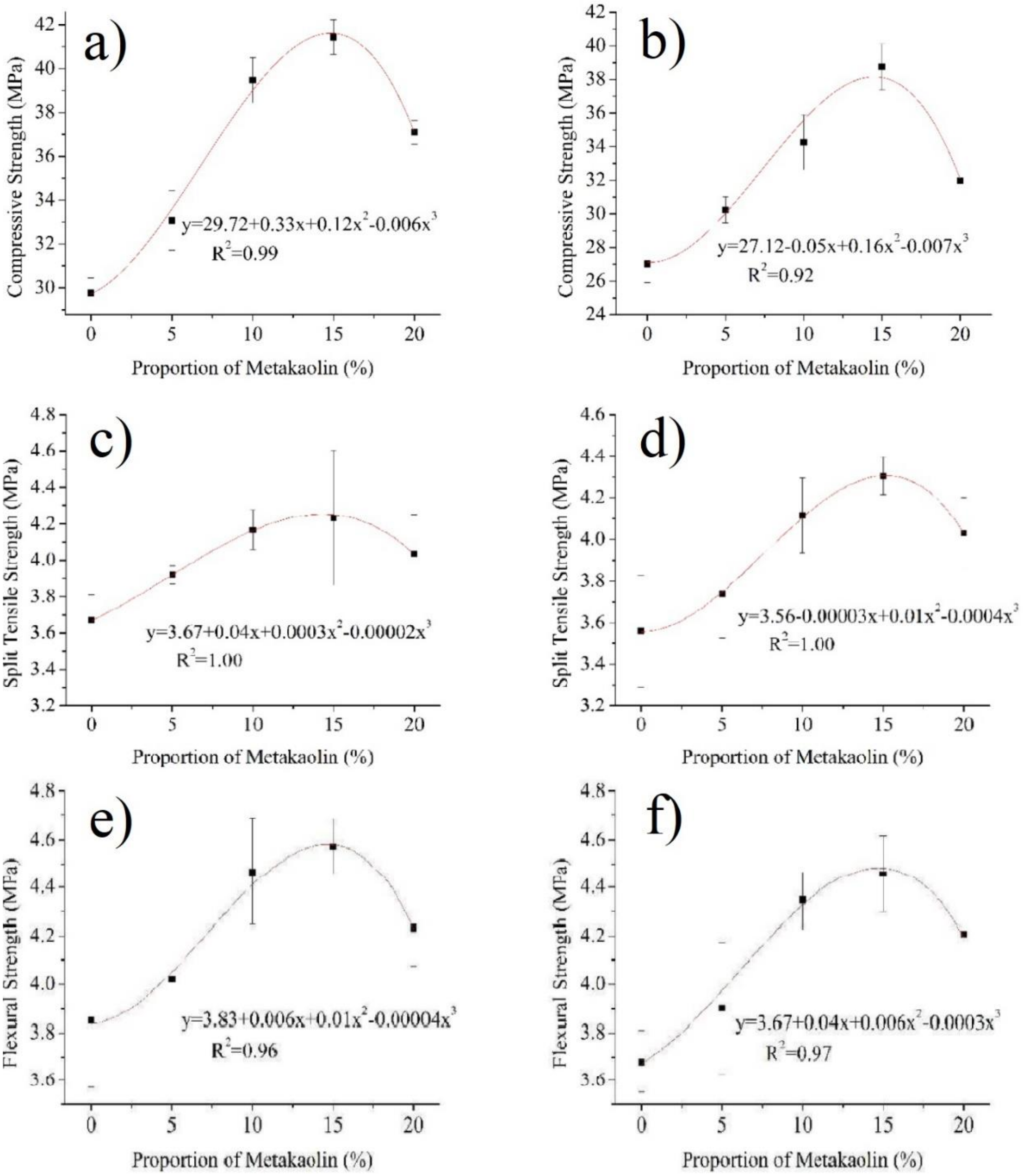

Figure 2.9 - Pervious concrete with a/b = 3.54: a) Compressive strength of PC with 12.5 mm aggregates; b) Compressive strength of PC with 20 mm aggregates; c) Split tensile strength of PC with 12.5 mm aggregates; d) Split tensile strength of PC with 20 mm aggregates; e) Flexural strength of PC with 12.5 mm aggregates; f) Flexural strength of PC with 20 mm aggregates (Adapted from Bright Singh and Murugan [20]).

2.2.5 RESIDUAL ASHES FROM AGROINDUSTRY

On global scale, the agroindustry is responsible for disposing of a large amount of crop residues that are often discarded, generating air and land pollution [52]. These residues can be valued in some applications, such as using at bio-fertilizers as an alternative to chemical fertilizers and used as biomass fuel, which can replace coal, for example [52]. Even after burning, secondary by-products are formed, in this case the ashes, that can be used in various applications. Rice husk ash (RHA) for example, could be used as an absorbent, catalyst, abrasive agent, among others, while sugarcane bagasse ash (SCBA) could be useful in the rubber industry as a replacement for commercial silica, as a filter and in soil stabilization [52]. Furthermore, these agricultural wastes can be valuable for use as SCMs, due to their proven efficiency.

Studies reported that rice husk ash, palm oil fuel ash, bamboo leaf ash, corn cob ash, wood waste ash, and sugar cane bagasse ash were suitable to be used in cementitious mixtures, representing a viable solution for sustainable construction which is important to the environment and society [53].

2.2.5.1 Rice husk ash (RHA)

RHA is worldwide studied as SCM due to its efficiency as a pozzolanic material and wide availability due to the large rice crops around the world [54]. It is obtained by calcining rice husk, which generates an ash with a high silica content (>80% silica). Burning conditions can influence the pozzolanic activity of RHA, since it influence the formation of amorphous and also crystalline phases, such as quartz and cristobalite, which can appear in significant amounts [36].

RHA could efficiently replace Portland cement in pervious concrete mixtures. Hesami Ahmadi and Nematzadeh [55] found that 8 wt.% of RHA replacing Portland cement, could provide 29% increase in compressive strength compared to PC mixture without RHA. Above 8% RHA, there was a decrease in mechanical properties, as shown in Figure 2.10. Subramaniam and Sathiparan [56] prepared mixtures with a/b of 2.5 varying the w/b from 0.30 to 0.45 with the incorporation of up to 20 wt.% of RHA replacing Portland cement. The use of RHA reduced the porosity of the mixtures, culminating in a negative effect on the permeability, however the compressive strength could be improved from approximately 17.5 MPa to 19.92 MPa with the incorporation of 5% of RHA and w/b of 0.35. Mixtures with w/c above 0.35 were not suitable for use as measured permeability was too low or zero. Furthermore, the authors stated that RHA decreased total embodied energy, the production cost, and CO_2 emissions.

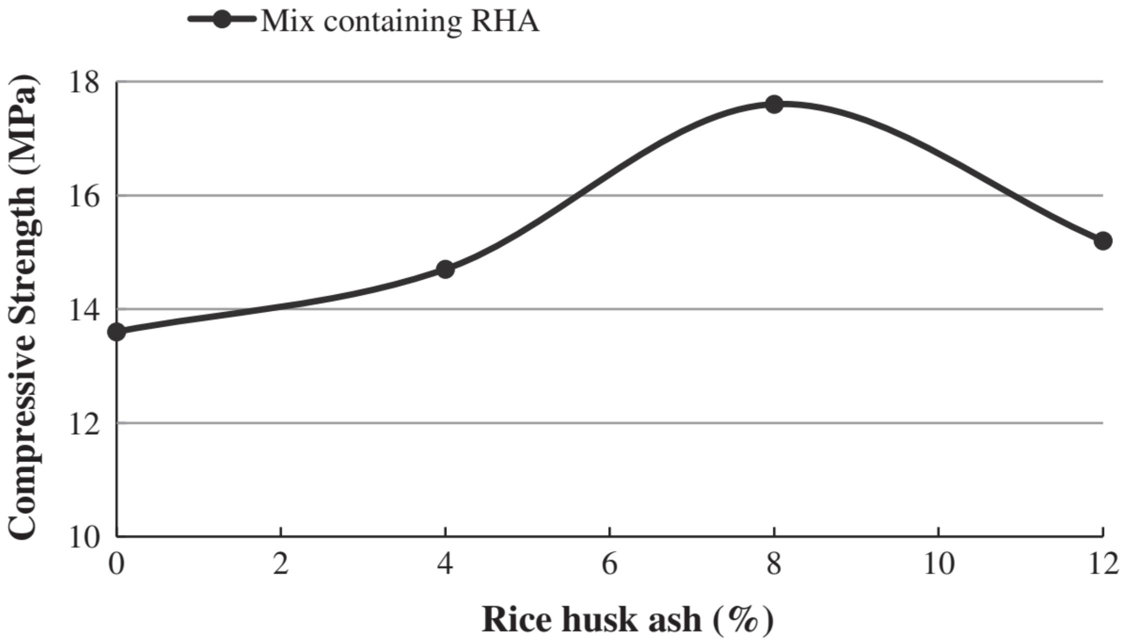

Figure 2.10 - Compressive strength at 28d of pervious concrete with a/b = 4.10 and w/b = 0.27 replacing Portland cement from 0 to 12 wt.% by RHA (Hesami Ahmadi and Nematzadeh [55]).

2.2.5.2 Sugar cane wastes

The large worldwide generation of sugarcane wastes has been a motivation for numerous studies, mainly applying it as building material. In the last 10 years the world sugarcane harvest reached about 1.8-1.9 billion tonnes annually, which leads to a large volume of waste after sugarcane processing [57]. Two main wastes can be generated: sugarcane bagasse which is equivalent to approximately 30–34 wt.% of sugarcane in natura [58] and sugarcane straw, basically composed of the leaves and the top of the plant, which may represent about 14% of harvested sugarcane [59]. Both residual biomasses can become attractive as fuel in cogeneration processes and from them, new co-residues are generated, the sugarcane bagasse ash (SCBA) which corresponds to approximately 2–3 wt.% from sugarcane bagasse [58] and sugarcane straw ash (SCSA) which represents approximately 3–5.5 wt.% from sugarcane straw [59].

Sugar cane bagasse ash (SCBA)

SCBA has been widely studied as a component in cementitious materials. There are studies that addressed its application in alkali-activated materials or even partially replacing Portland cement [58,60]. SCBA generally has high amounts of SiO_2, Al_2O_3 and Fe_2O_3 in the range of approximately 60.46%–76.52% of total composition, which enables pozzolanic reactivity when in contact with calcium hydroxide from Portland cement hydration [58]. The pozzolanic reactivity is related to the presence of SiO_2 in the amorphous phase, and this is strongly dependent on the burning conditions of the bagasse. The ideal temperature range usually varies between 600 to 800 ºC [58]. Much lower burning temperatures generally do not guarantee efficient carbon removal, resulting in high loss on ignition (LOI), which results in less percentage available of amorphous silica [58]. On the other hand, excessively high temperatures can favor the formation of crystalline silica that does not react efficiently to form hydrated cementitious compounds, such as hydrated calcium silicates (C-S-H) [61]. Through Scanning Electron Microscopy (SEM) images of SCBA obtained by auto combustion [62], it was possible to observe that the particles present irregular morphology as shown in Figures 2.11a and 2.11b. Even after 50 min ball milling process, the particles maintained the irregular particle morphology (Figures 2.11c and 2.11d), however there was a reduction in size, which could improve the pozzolanic activity.

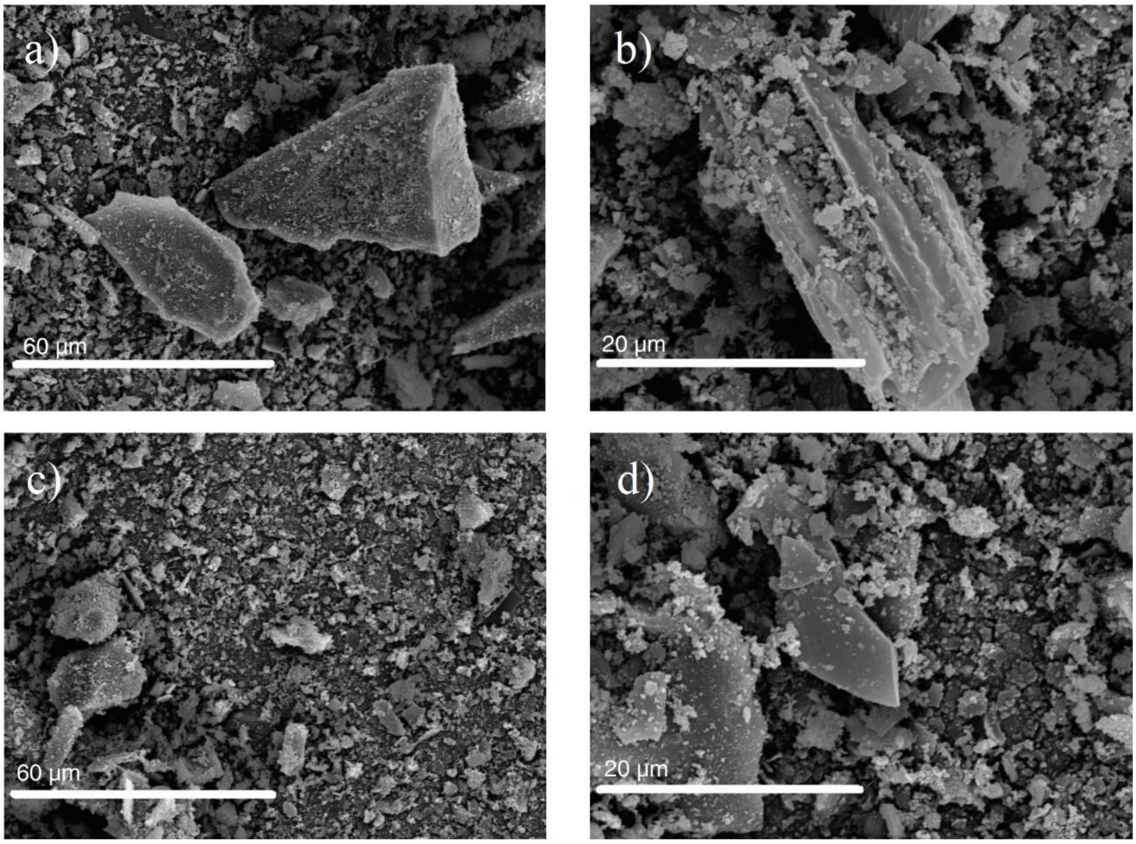

Figure 2.11 - SEM images of obtained SCBA: a) and b) before milling; c) and d) after 50 min milling process (Pereira et al. [62]).

Although no relevant research was found using SCBA in pervious concrete, several studies prove the effectiveness of SCBA in cementitious matrices such as SCM. Wu et al. [63] studied ultra-high performance concrete (UHPC) mortars combining Portland cement, silica fume, silica sand, quartz powder and superplasticizer with 0 to 60 wt.% SCBA replacing cement. SCBA was obtained from a local power plant, and due to incomplete combustion, it had an LOI of 26.04%. To reduce the amount of carbon, a calcination process was carried out in a muffle, at 600 °C for 60 min, which reduced the LOI to 2.23%. SCBA was then ball-milled to reach a median particle size d50 of 12 µm for then be used on UHPC. Compressive and flexural strength were virtually constant with the incorporation of up to 40% SCBA at 28 curing days and slightly improved at 91 curing days for compressive strength as presented in Figure 2.12. Above 40% both mechanical properties were reduced, indicating a limitation in replacement quantity. However, the authors observed that up to 60% SCBA replacement rate, autogenous shrinkage could be reduced by up to 30.25%

(Figure 2.13), indicating that the progressive incorporation of SCBA had a positive effect on this property.

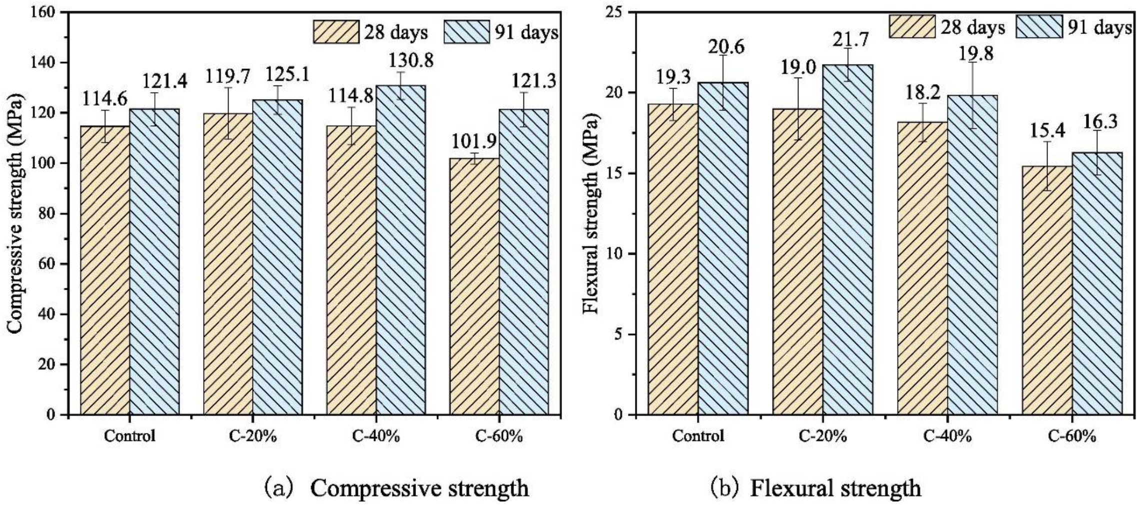

Figure 2.12 - a) Compressive strength and; b) Flexural strength of UHPC with SCBA replacement rate of 0 to 60 wt.% at 28 and 91 curing days (Wu et al. [63]).

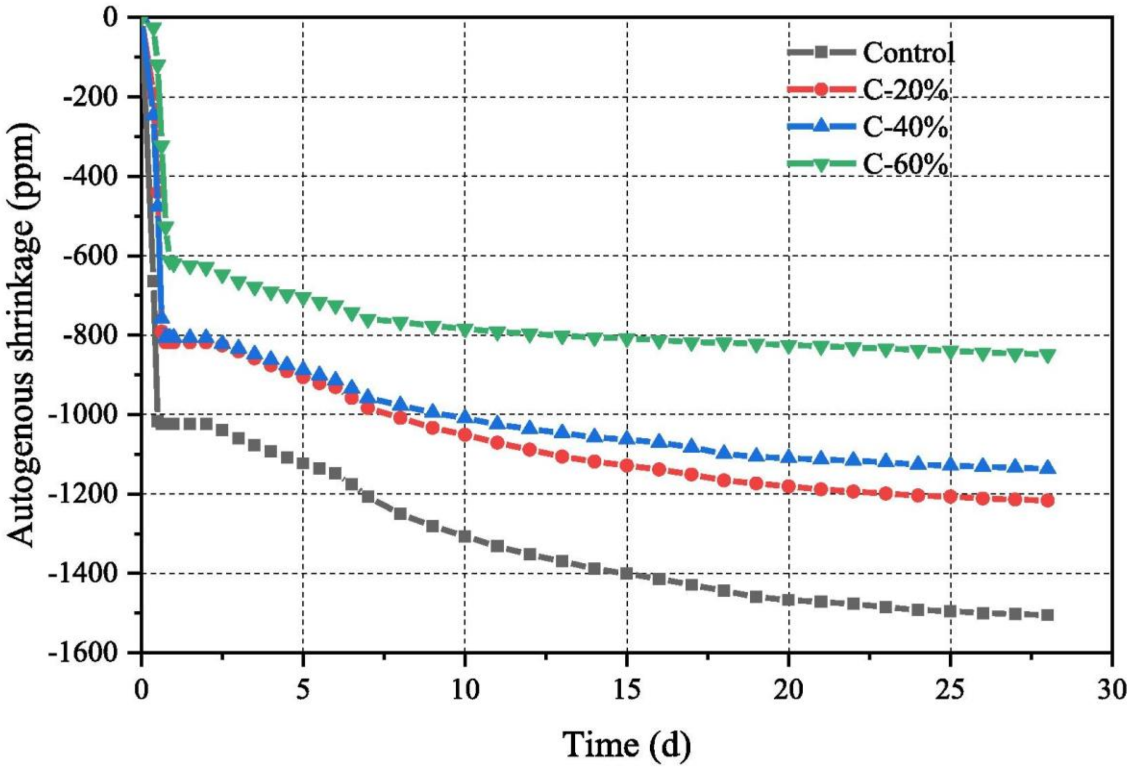

Figure 2.13 - Autogenous shrinkage of UHPC with SCBA replacement rate of 0 to 60 wt.% over time up to 30 days (Wu et al. [63]).

On the other hand, Joshaghani and Moeini [61] combined nanosilica with SCBA (produced by burning the bagasse at 800 ºC for 30 min), replacing Portland cement in mortars. The results demonstrated that the incorporation of SCBA can improve mechanical strength mainly at long ages. 15 wt.% SCBA replacing Portland cement could provide an increase of 11.8% on compressive strength compared to control at 90 curing days. Furthermore, when the cement was replaced by 6 wt.% nanosilica mixed with 15 wt.% SCBA, compressive strength increased 33.3% in relation to control while chloride penetration resistance was enhanced by 497% compared to the control at 90 curing days. The improvement in the properties was attributed to the release of SiO_2 which reacts with $Ca(OH)_2$ favoring the densification of the microstructure due to the greater volume of C-S-H gel mainly on later ages.

Sugar cane straw ash (SCSA)

Similar to SCBA, literature has not reported relevant research on the use of SCSA in pervious concretes, however it has been efficiently employed in cementitious matrices [59,64]. The calcination temperature could also interfere with the pozzolanic properties of SCSA. Guzmán et al. [65] tested 3 different calcination processes for sugar cane straw: 2 hours of incineration at a maximum temperature of 590 ºC; 2 hours of incineration at a maximum temperature of 700ºC; and pre-treatment with controlled combustion at 427 ºC for subsequent incineration at 700 ºC. Through the alkaline solubility test, it was observed that direct calcination at 700 ºC increased the amount of amorphous silica content by 13.5%, while the methodology applying pre-treatment followed by calcination at 700 ºC, improved the amount of amorphous silica by 54.0%, both in relation to straw calcined at 590 ºC. On the other hand, Frías et al. [66] calcined sugar cane straw at different temperatures: 800 ºC and 1000 ºC, both for 20 min. However, these authors did not observe significant differences in pozzolanic activity, measured through combination with saturated lime solution (lime fixation). Literature [59] reports that after SCSA calcination it presents irregular morphology, however, as shown in Figure 2.14 after being milled for 50 min in a ball mill in order to increase pozzolanic activity, the reduced particles could present a relatively more regular morphology.

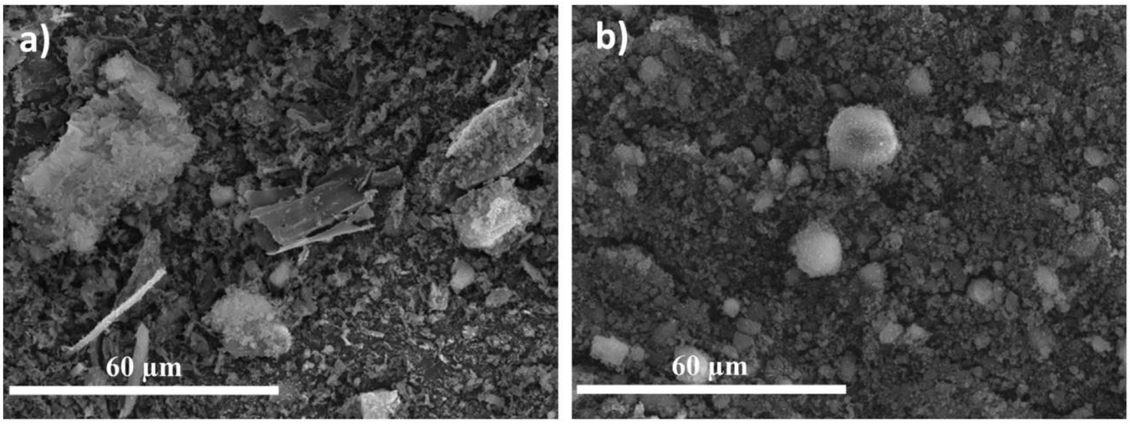

Figure 2.14 - SEM images of SCSA: (a) before milling; (b) after 50 min of milling (Moraes et al. [59]).

Due to the observed pozzolanic properties, SCSA has been successfully used as a cement substitute in cementitious matrices. Moraes et al. [59] tested replace cement by 0 to 30 wt.% SCSA in mortars samples with w/c of 0.50, and the ratio of sand to cementitious material of 2.5. SCSA was obtained by auto-combustion during 6h. The maximum temperature during the burning reached 700 ºC. SCSA could be incorporated up to 30 wt.% without causing a significant difference in compressive strength compared to the sample with 100% Portland cement at 3 to 90 curing days. In addition, the authors calculated the compressive strength gain (SG) which relates the compressive strength of the mixtures including SCSA with the compressive strength of the control mixture (100% cement), corrected on the equation by the rate of cement mass and total binder mass (cement + SCSA). According to the results depicted in Figure 2.15, the SCSA incorporation had a positive effect on (SG) of up to 30% considering all ages tested, indicating high activity of the SCSA as a pozzolan.

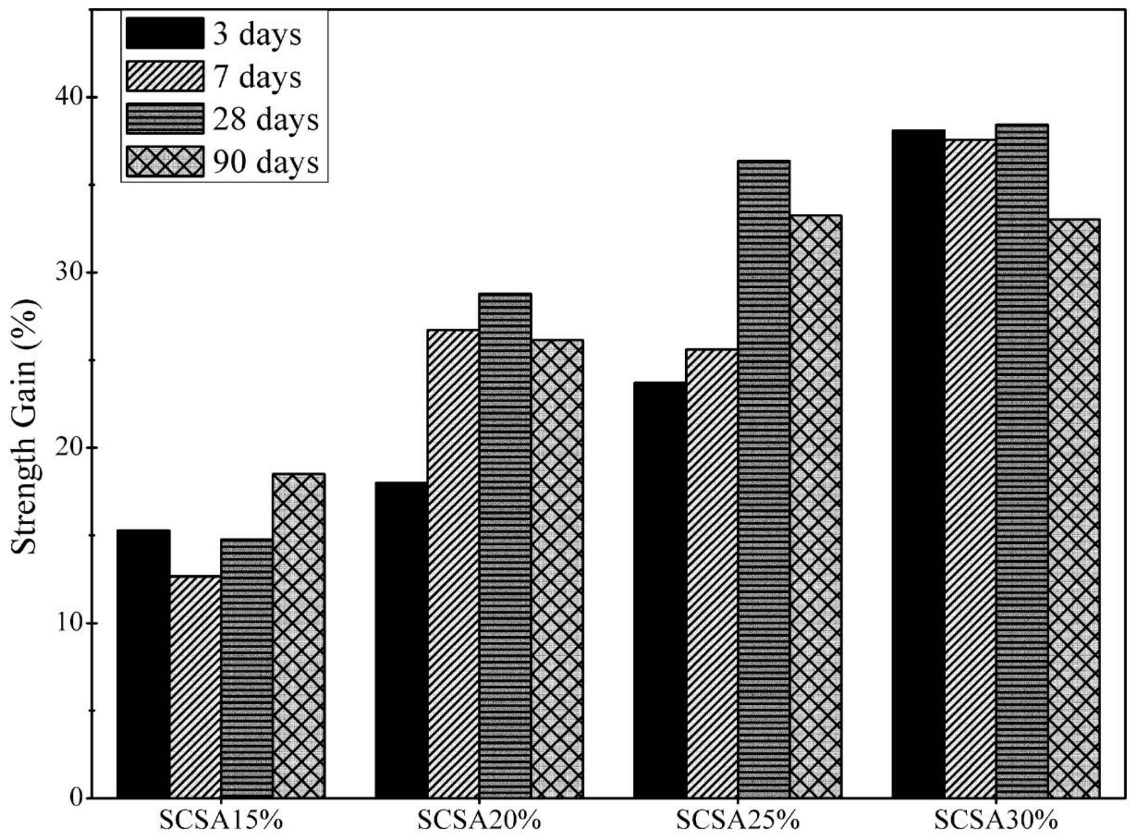

Figure 2.15 - Strength gain (SG) for mortars containing 15 to 30% SCSA at 3, 7, 28, and 90 curing days (Moraes et al. [59]).

Similarly, Calligaris et al. [64] investigated the effects of incorporating 20 wt.% SCSA burned at 700 ºC for 3h in Portland cement pastes to evaluate the pozzolanic reaction, using synchrotron X-ray diffraction data and quantification of phases by Rietfield method. The authors concluded that SCSA can cause a delay in the cement setting time (hardness process), in addition to causing a significant increase of ettringite formation up to 47% and reduce the Alite consumption. However, these mixtures provided higher concentration (two times) of calcite (a more strength compound) in which could achieved similar mechanical strength as mixtures with 100% Portland cement, corroborating the results reported by Moraes et al. [59]. Consequently, it can be inferred that the use of SCSA can be a good option to reduce the usage of Portland cement towards more sustainable binders.

2.2.5.3 Other residual ashes

In addition to RHA, SCBA and SCSA, several other ashes from agroindustry, which are rich in reactive or amorphous silica, are successfully used as SCMs. These other types of residues arising from biomass burning could be efficiently used in the PC. Tijani et al. [67] showed a trend of reduction in density and increase in porosity and hydraulic conductivity (up to 86%), in PC replacing up to 25 wt.% cement by sorghum husk ash (SHA) with a/b of 4 and w/b of 0.4 mixtures. SHA was produced by calcining sorghum husk in an electric furnace at about 600–700 ºC. Compressive strength increased slightly to 5 wt.% SHA incorporation compared to control (0% SHA) at 7, 28, and 56 curing days and then decreased as the amount of SHA increased. In addition, the use of SHA reduced CO_2 emissions and economical cost by up to 38.23% and 51.29% respectively, for mixtures with 25% SHA combined with 100% RCA.

Another experimental investigation was developed by Khankhaje et al. [68] who used palm oil fuel ash (POFA) obtained from the burning of oil palm shells and fibers to produce electricity in palm oil industry. POFA was incorporated replacing 0 to 40 wt.% of cement in PC with a/b of 3.87, w/b of 0.32 and addition of 11% of sand in relation to the coarse aggregate for all mixtures. Through Figure 2.16 it was possible to observe a slightly and gradual increase in void content of up to 32%, as the POFA content increases up to 40 wt.% POFA, while water permeability increased gradually from 28% to 132% at 10 to 40 wt.% POFA in relation to control mixture without POFA. In contrast, the mechanical properties were reduced to both 7 and 28 curing days as depicted in Figure 2.17. 28 days compressive strength decreased from 9% to 49% compared to control for 10 to 40 wt.% POFA, while splitting tensile strength reduced 1% for 10 wt.% POFA, and then reached up to 34% decrease for 40 wt.% POFA compared to control mixture. Even though the mechanical properties experienced reduction, the authors consider that up to 20 wt.% POFA could be determined as optimum replacement range.

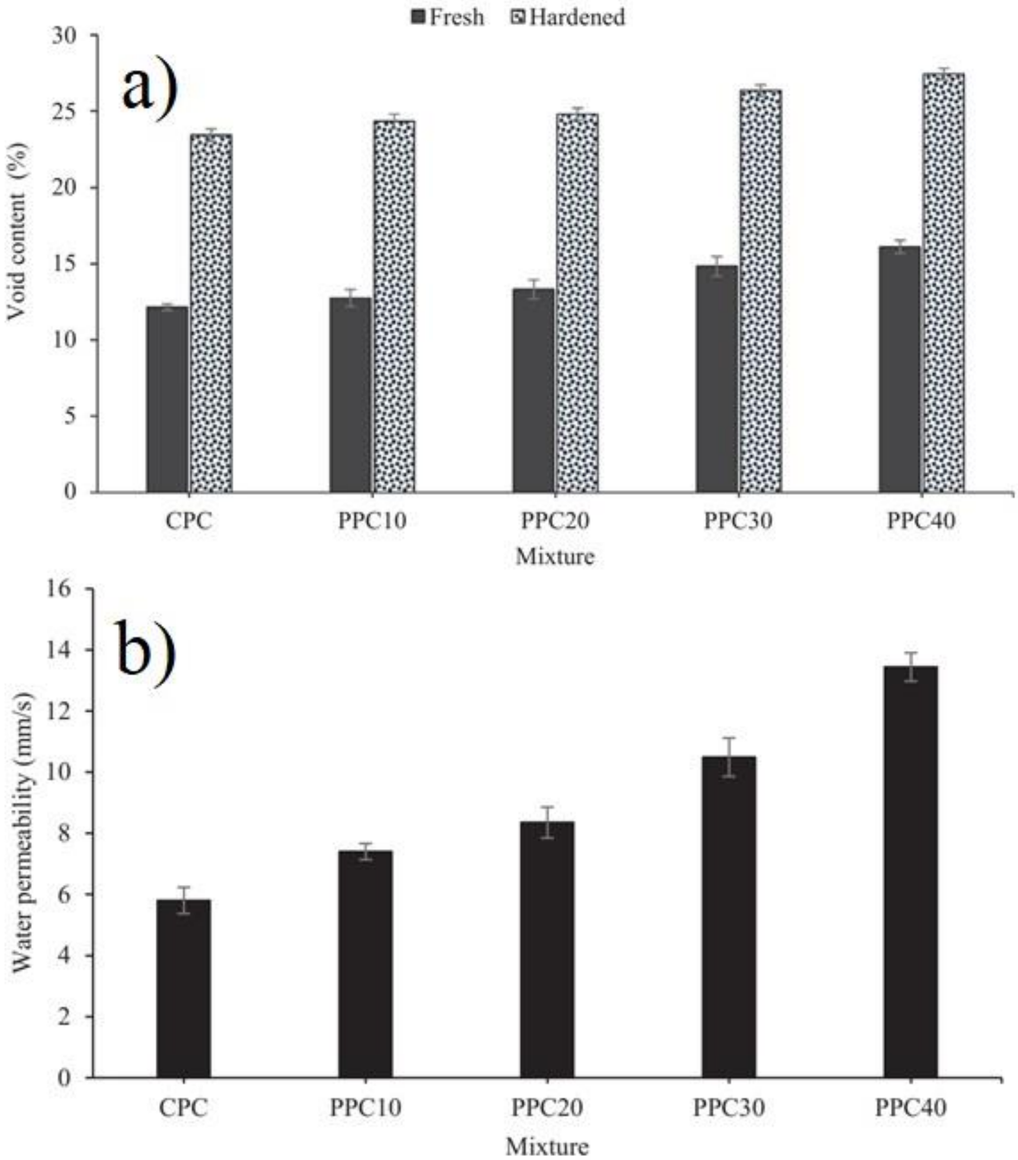

Figure 2.16 - Void content (a) and water permeability (b) of pervious concrete with a/b = 3.87 and w/b = 0.32 replacing Portland cement from 0 to 40 wt.% by POFA (Adapted from Khankhaje et al. [68]).

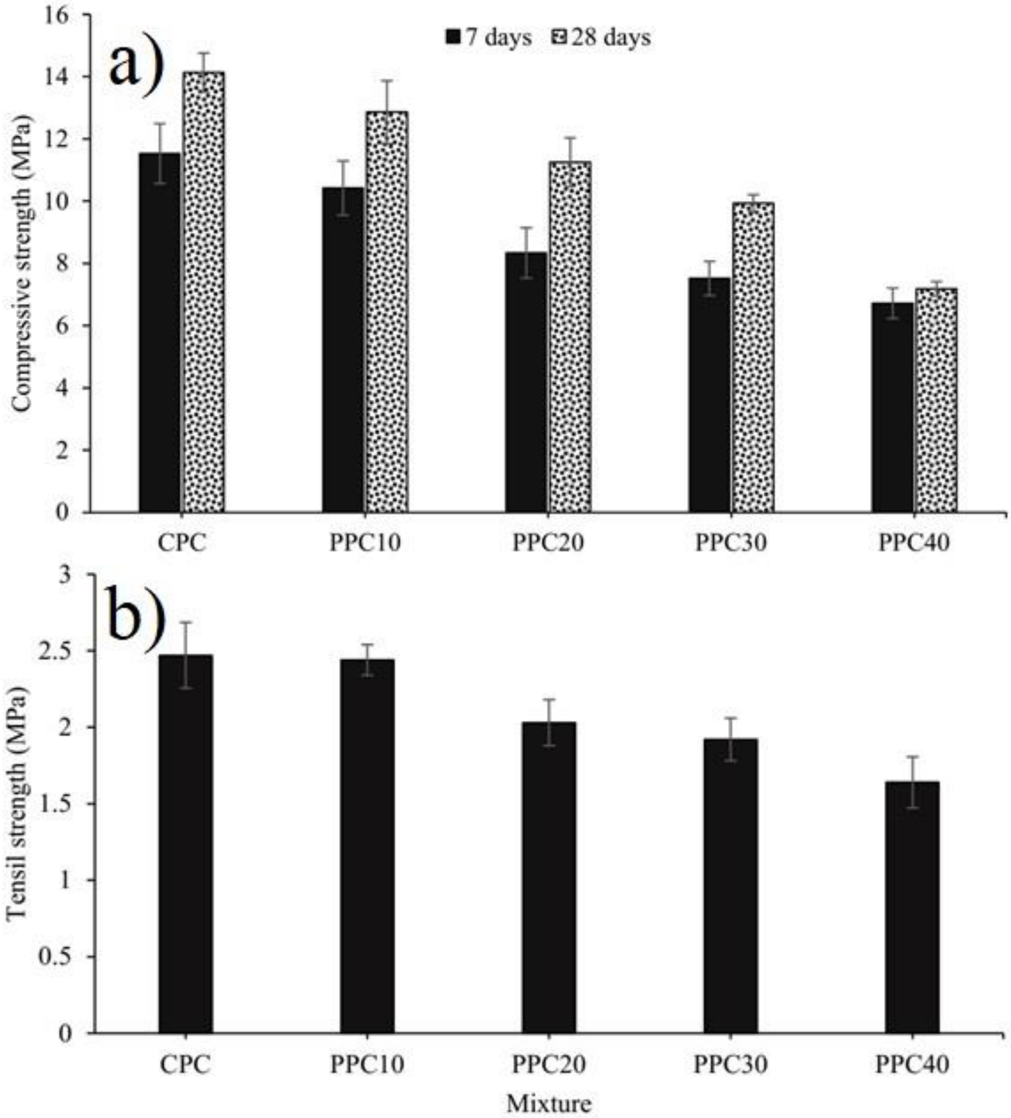

Figure 2.17 - Compressive strength (a) and splitting tensile strength (b) at 7 and 28 curing days of pervious concrete with a/b = 3.87 and w/b = 0.32 replacing Portland cement from 0 to 40 wt.% by POFA (Adapted from Khankhaje et al. [68]).

The study conducted by Abhinaya et al. [69] demonstrated that palm flower biochar (obtained by means of torrefaction procedure carried out at 200 °C for 2 h), could be useful to improve PC properties. Permeability and water purification ability were increased without compromising the compressive strength when the palm flower biochar was incorporated replacing up to 1% of Portland cement in mixtures with a/b of 4 and w/b of 0.40.

Therefore, different types of ash obtained from the agroindustry appear to have strong potential for designing more environmental-friendly solutions for PC. Observing the gaps in the literature, special attention should be given to sugar cane wastes, due to the positive effect observed in cement matrices. The lack of relevant works that deal with the incorporation of sugar cane wastes into pervious concrete, combined with the positive synergistic effect of both ashes in combination with Portland cement, make this topic interesting to explore, since pervious concrete generally requires a higher consumption of cement and deliver lower mechanical performances due to the interconnected porosity provided by the absence of fines.

2.3 FINE AGGREGATES ON PERVIOUS CONCRETES

Fine aggregates are classified by ABNT NBR 7211 [70] as those whose particles are smaller than 4.75 mm. The partial replacement of coarse aggregates by fine aggregates has been extensively addressed in the literature for PC. Bonicelli et al. [24] studied PC with a/b ratio of 5.0, and w/b from 0.27 to 0.33 and observed that the coarse limestone aggregate replaced by sand up to 10 wt.% provided an improvement of up to 70% in tensile strength, 35% in stiffness and reduced the raveling up to 40% (Cantabro Loss Index), although they cause a slight decrease in porosity and infiltration rate. The incorporation of fine aggregates replacing coarse aggregates provides an increase in mechanical strength, but it should be balanced with the permeability of pervious concretes. It was observed by Taheri et al. [27] that an increase in the amount of coarse aggregate replacement by sand from 0% to 14% promoted an increase of up to 72% and 37.5% in compressive and flexural strength respectively, while the porosity and permeability experimented a decrease of about 31.5% and 82%, respectively. As concluded by the authors, attention should also be paid to reduced permeability.

As indicated on literature, most authors who replace coarse aggregates by sand by weight, observed a decrease in porosity and, consequently, a decrease in the infiltration rate [24,25,27,28]. This happens because coarse aggregate, which is the skeleton that provides the internal voids, is removed and sand is incorporated, which occupies a part of the remaining internal voids, reducing porosity. The addition of fine aggregates of 1/6 to 1/10 of the size of the coarse aggregate fill the voids between the particles, not changing the packing of coarse aggregate, but filling the voids [26].

Similar behavior occurred when fine aggregates were added. According to Xu et al. [26], the addition of 15 wt.% (related to aggregates) of fine aggregate (artificial calcareous sand) provided an increase in the range of 29-48% in compressive strength compared to control samples (no fine aggregates).

A different approach to the use fine aggregates in pervious concretes can be their incorporation in order to replace cement in the mixture, as observed in literature [29–31]. However, it has been reported that although the mechanical properties have increased, there is a reduction in the infiltration rate associated with a reduction in porosity, when cement is replaced by up to 33.3 wt.% sand [29–31]. Elizondo-Martínez et al. [31] tested to replace cement by sand in 33.3 wt.% and 50 wt.% with the objective of to make a stronger matrix. The authors observed that 33.3 wt.% of replacement presented a gain in compressive strength and stiffness modulus up to 64.6% and 70.3%, respectively, compared to control with a slight decrease of permeability. Similarly, Beddaa et al., [30] reported an increase in compressive strength conditioned by a reduction of up to 54.8% in the permeability coefficient in pervious concretes with cement replaced by sandy and fine sediments at 10%.

Ibrahim et al. [29] incorporated recycled fine aggregates (RFA) and sand in pervious concrete, both in 10 wt.% replacing cement for different w/b (0.30, 0.35, 0.40). It was observed that 10 wt.% sand provided improvement of up to 36% and 57% for compressive strength and splitting tensile strength, respectively, compared with no-fines concrete, while 10% RFA increased compressive strength and splitting tensile strength up to 7% and 37%, respectively, at 28 curing days, as depicted in Figure 2.18. However, in both cases a reduction in total porosity was observed when compared to no-fines concrete mixtures.

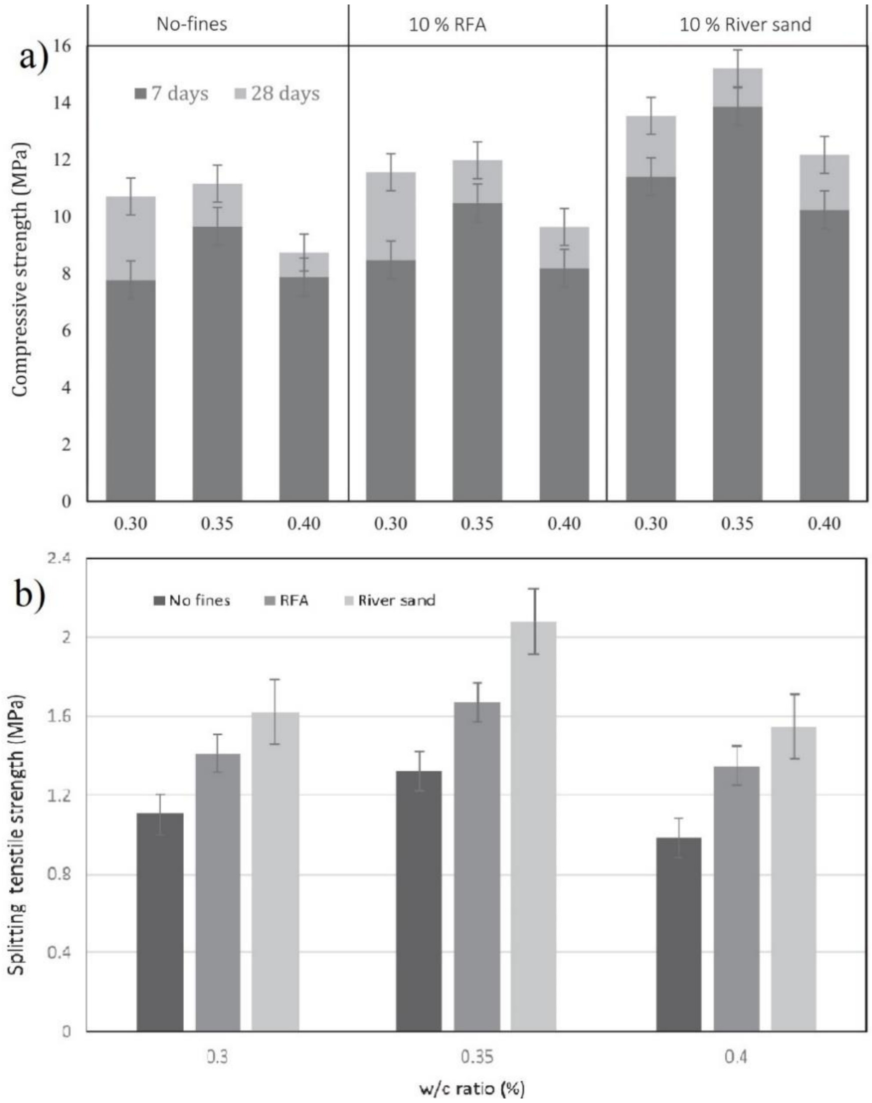

Figure 2.18 - Compressive strength at 7 and 28 curing days (a) and splitting tensile strength at 28 curing days (b) of pervious concrete with a/b = 2.77 replacing Portland cement at 10 wt.% by RFA and river sand (Adapted from Ibrahim et al. [29])

Considering the various possibilities and specificities of the use of fine aggregates in pervious concrete addressed by the literature, it could be inferred that there are some aspects that have not yet been properly addressed in the literature. Most studies that promote the incorporation of sand demonstrate changes in mechanical and hydraulic properties, however porosity is also modified. It could limit understanding of the topic due to the influence of both: the incorporation of sand and the change in porosity. As these two factors can influence the properties of the PC, it is difficult to understand the real influence of each one separately. Therefore, there is a broad field of research on this topic, in order to improve the efficiency of PC mixtures through the optimized use of materials.

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CHAPTER 3 – RESEARCH METHODOLOGY

This chapter presents a brief description of the research methodology applied to the experimental part of this thesis.

3.1 USE OF SUGAR CANE WASTES REPLACING CEMENT

The part of the research related to the study of the use of sugar cane wastes incorporated into pervious concrete was carried out in the laboratory and presented in chapter 4, structured as a paper entitled "Effect of wastes from sugar cane industry on the mechanical and hydraulic properties of pervious concrete".

Chapter 4 was divided into introduction, materials and methods, results and discussions and conclusions. The work began with the establishment of the objectives that should be achieved in relation to the use of both sugar cane wastes: sugar cane bagasse ash and sugar cane straw ash.

An experimental approach was then outlined in order to construct the sequence of analyses that would be carried out. At this stage, it was decided to partially replace Portland cement with both sugar cane wastes and comparatively use conventional SCMs, e.g., densified silica fume and rice husk ash. In the methodological part, the influence of 10% of cement replacement by SCMs in different binder:aggregate mass ratio (1:3.5, 1:4.0, 1:4.5 and 1:5.0) was first tested, and then, from a fixed mixture ratio, the cement was replaced by the sugar cane wastes from 0 to 25%, in mass. To test PC mixtures, the physical properties were then taken in the laboratory, through density and total porosity tests. The mechanical properties were tested through compressive strength test and, Infiltration rate tests were carried out to understand the interference of ashes in the hydraulic behavior.

To conclude this part of the study, a comprehensive evaluation of the data obtained was finally carried out to obtain the final results. A correlation between the results was performed for a better understanding, in addition to a grounded discussion with the literature. Then, the main effects of incorporation of wastes and their comparison with conventional SCMs were demonstrated. At the end, the main contributions found were presented, based on the objectives proposed at the beginning of the study. The flowchart presented in Figure 3.1 summarizes the structured methodology.

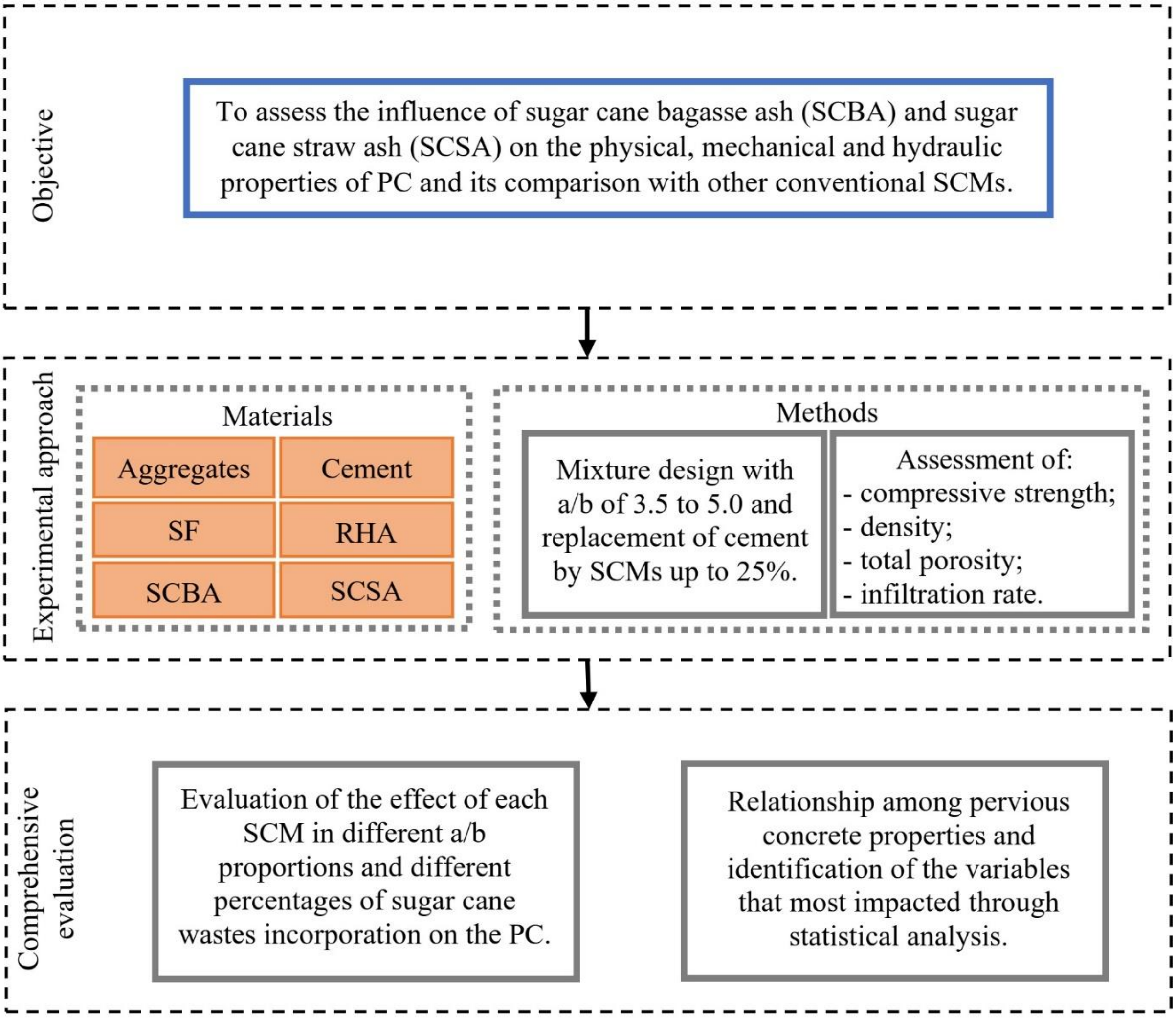

Figure 3.1 - Structured methodology to assess the effect of the use of sugar cane wastes incorporated into PC.

3.2 USE OF FINE AGGREGATES REPLACING CEMENT PASTE

The part of the research related to experiment the use of fine aggregates replacing cement paste was carried out in the laboratory and presented in chapter 5, structured as a paper entitled "New insights on the development of sustainable pervious concrete using sand replacing paste volume".

Chapter 5 was divided into introduction, experimental program, results and discussion and conclusions. In the first part of this study, the objectives to be followed were also proposed, to delimit the scope of the research. The main focus was to replace up to 59% of the Portland cement paste volume by fine aggregate (sand) in pervious concretes with fixed porosities.

The experimental approach was then designed and applied, as well as the incorporation strategies of fine aggregate (river sand) replacing cement paste (the replacement ranged from 0 to 59% in paste volume). Physical, mechanical and hydraulic tests were then performed. Towards a broader assessment, environmental analysis of the alternative proposed by the authors through the life cycle assessment (LCA) methodology was conducted, in addition to the cost analysis of all tested samples. The performance of mixtures with sand were then evaluated using a multi-criteria performance analysis to assist in decision making to find the most appropriate sand replacement content in PC mixtures.

Through a comprehensive evaluation, the collected data was then discussed based on the findings in the literature. The life cycle assessment and economical cost were presented and discussed, mainly highlighting the positive and negative effects of the use of fine aggregate replacing cement paste volume. Then, the multi-criteria performance analysis was used to assist in decision making to find the most appropriate sand replacement content in PC mixtures.

This approach made it possible to understand the main findings of the work, based on the proposed objectives in order to contribute to the improvement of pervious concrete. Figure 3.2 presented a flowchart that summarizes the structured methodology for the topic studied.

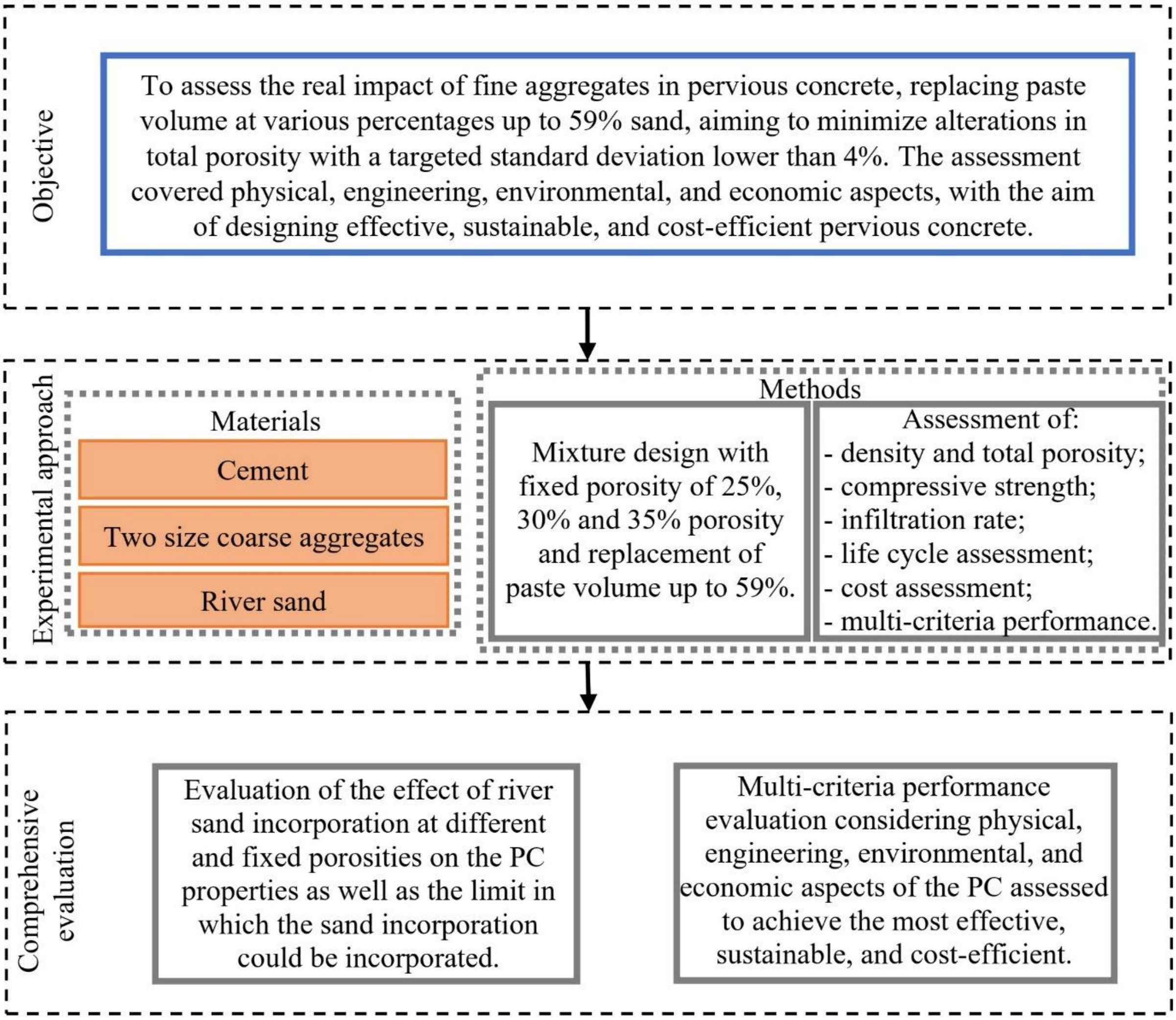

Figure 3.2 - Structured methodology to assess the effect the of fine aggregates replacing cement paste volume.

CHAPTER 4 – EFFECT OF WASTES FROM SUGAR CANE INDUSTRY ON THE MECHANICAL AND HYDRAULIC PROPERTIES OF PERVIOUS CONCRETE

This chapter presents the article entitled as "*Effect of wastes from sugar cane industry on the mechanical and hydraulic properties of pervious concrete*" co-authored by R. G. da Silva, M. Bortoletto, S. A. M. Bigotto, J. L. Akasaki, L. Soriano and M. M. Tashima, published in the journal **Road Materials and Pavement Design**, vol. 23, issue 9, p. 1981-1998, (2022) DOI: 10.1080/14680629.2021.1927156

Abstract: Pervious concrete is a construction material widely used in pervious pavements. Pozzolanic materials replacing partially Portland cement can improve mechanical and hydraulic issues associated with the use of pervious concrete. This paper reports the use of wastes from the sugar cane industry (sugar cane bagasse ash and sugar cane straw ash) and their influence on the mechanical and hydraulic properties of pervious concrete for different binder:aggregate mass ratio (1:3.5, 1:4.0, 1:4.5, 1:5.0). The assessed pervious concrete achieved a compressive strength in the range 7.4–14.2 MPa, a total porosity between 26.4 and 32.4% and an infiltration rate of 0.6–1.3 cm/s.

Keywords: Pervious concrete; pozzolans; sugar cane bagasse ash; sugar cane straw ash

4.1 INTRODUCTION

Pervious concrete is a type of concrete developed to reduce the environmental problems associated with uncontrolled growth in urban areas. This technology can contribute to the flood´s mitigation and reduce the damage caused by heavy rains. In the same way, it can provide a reduction in heat islands of urban environments, assist in recharging the groundwater by infiltration of rainwater and collaborate to reduce the pollution of water bodies [1–3]. Hence, it is expected an increment in the use of pervious concrete due to technical safety and environmental benefits, which are in agreement with sustainable development [4]. The typical properties for pervious concrete found in the literature are compressive strength in the range 1–28 MPa [3,5–7], about 15–35% of total porosity [4,5,8], and an infiltration rate between 0.1 and 2.0 cm/s [3,9–13].

This type of concrete is composed of a mixture of binding material (usually Portland cement), water, coarse aggregates, and, in some cases, small amounts of fine aggregates. Moreover, some supplementary cementitious materials and/or chemical additives can be used to improve their properties [14,15]. Several factors can influence the properties of pervious concrete: type and particle size distribution of aggregates, Portland cement consumption, the water/binder (w/b) ratio, the compaction process, etc. [1,3,5,16].

Similar to conventional concrete, the use of alternative materials replacing partially Portland cement emerges as an environmental-friendly alternative in the production of pervious concrete [7,17–27].

In the literature are reported several studies using pozzolanic materials in different percentages, yielding in most cases improvements in the mechanical strength, decrease in the total porosity, increment on the density around 10%, and reduction in the infiltration rate around 10–60%when compared to reference samples [7,18,19,23,24,27].

Chen et al. [20] evaluated engineering properties and environmental impact of pervious concrete mixtures with replacement of 15% cement by FA and 25% by BFS. According to the authors, pervious concrete based on Portland cement presented slightly enhanced properties than concretes containing 15% FA and 25% BFS: compressive strength in the range 7–14 MPa, hydraulic permeability about 0.045–0.058 cm/s.

Similarly, Peng et al. [25] studied pervious concrete using 20 and 30% of FA and BFS. The authors yielded 7–9 MPa in compression and total porosities of 27–28.5%. Studies performed by Ramkrishnan et al. [26] using FA and BFS suggested similar mechanical performance with an increment in the durability of pervious concrete compared to control.

Shafabakhsh and Ahmadi [18] assessed the use of RHA on the mechanical strength of pervious concrete. The compressive strength, tensile strength, and flexural strength reached the highest values for 8% RHA, increasing 41%, 42%, and 29%,respectively, compared to the control sample [18]. The total porosity was reduced by 24% to 15% of voids, and the infiltration rate was diminished from 0.27 to 0.19 cm/s [18]. In pervious concrete, it was found that up to 10% RHA replacing Portland cement, the mechanical strength can be improved [18,23].

Considering the large-scale production of sugar cane worldwide (about 1.907 billion tonnes in 2018), about 11 million tonnes of sugar cane bagasse ash (SCBA) and 14 million tonnes of sugar cane straw ash (SCSA) could be generated annually. Brazil is the most important producer of sugar cane (about 650 million tonnes in 2019/2020) and responsible for 39% of worldwide production in 2018 (Figure 4.1).

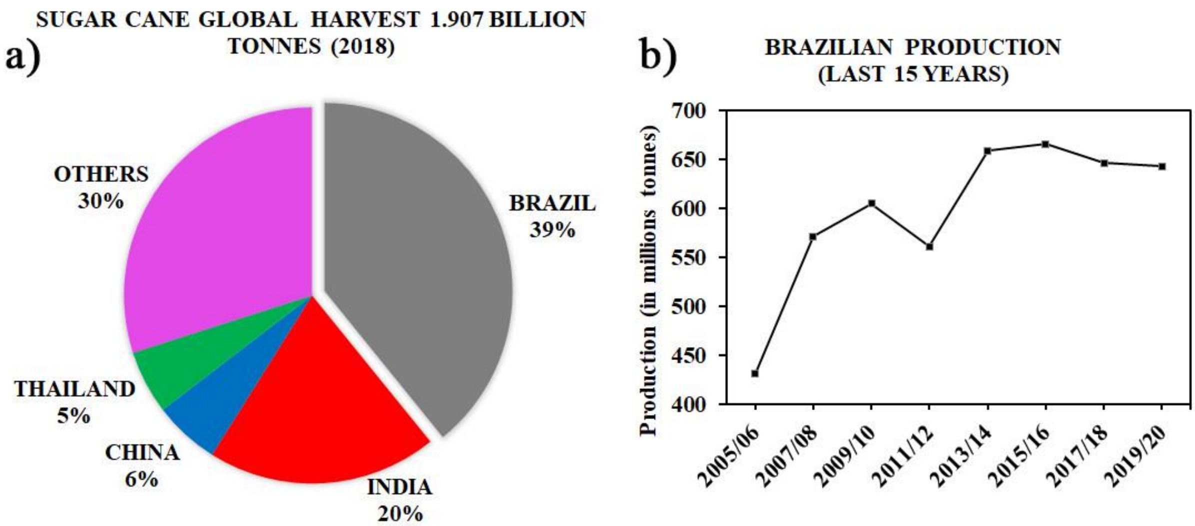

Figure 4.1 - Sugar cane production: (a) global harvest in 2018 (FAOSTAT [28]); (b) Brazilian harvest in the period 2005–2020 (CONAB [29]).

The use of wastes from the sugar cane industry has been assessed in civil construction [30–33]. Nevertheless, in the literature was not found any study related to the use of wastes from the sugar cane industry in the production of pervious concrete.

Hence, this study aims to assess, on a laboratory scale, the influence of sugar cane bagasse ash (SCBA) and sugar cane straw ash (SCSA) on the properties (compressive strength, density, total porosity, and infiltration rate) of pervious concrete. The large-scale worldwide availability of wastes from the sugar cane industry could contribute to its industrial application and the widespread use of pervious concrete.

4.2 MATERIALS AND METHODS

4.2.1 MATERIALS

A basaltic aggregate with a maximum particle size of 12.5 mm and apparent specific gravity of 2.84 g/cm^3, supplied by Mineração Grandes Lagos located in Itapura city, São Paulo – Brazil, was used in the production of pervious concrete. This aggregate presents a coefficient of uniformity equal to 1.89. This coefficient represents the ratio of D_{60} and D_{10} and, values lower than 2.0 indicates that the material shows a uniform distribution. This fact is essential in the development of pervious concrete (Figure 4.2). In the production of pervious concrete, the aggregate was used in saturated-surface-dry condition (SSD).

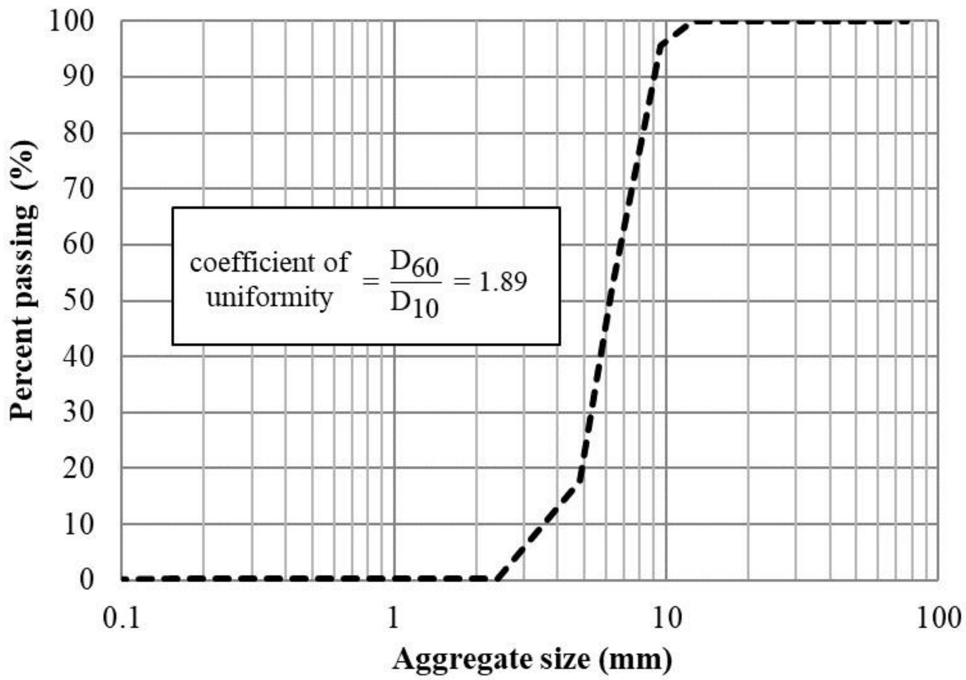

Figure 4.2 - Gradation curve of basaltic aggregate.

A Brazilian Portland cement type V – CPV ARI according to Brazilian standard NBR 16697 [34] was used as binding material. This cement contains more than 90% of clinker and has no pozzolanic addition to its composition. This type of cement was selected to assess the effect of wastes from sugar cane industry, avoiding the synergic effect caused by the supplementary cementitious materials, which can be added to the other types of Portland cement. Table 4.1 is presented the chemical composition of Portland cement, and its XRD pattern is depicted in Figure 4.3. To maintain fixed the water/binder ratio (binder is the sum of Portland cement and pozzolanic materials) for all assessed mix proportions, water reducing admixture based on polycarboxylate was used, when necessary.

Table 4.1 - Chemical composition (determined by X-ray fluorescence) of Portland cement and pozzolanic materials (wt.%).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SO_3	MgO	P_2O_5	Cl	Others	LOI
Cement	20.8	4.6	4.8	65.6	0.1	1.0	1.7	1.2	-	-	0.2	-
SF	91.7	0.3	0.1	0.4	-	-	0.5	0.4	-	-	6.6	-
RHA	92.8	2.5	0.1	1.6	0.3	2.0	-	0.6	-	-	-	0.1
SCBA	78.6	4.5	4.9	1.3	0.2	2.4	0.7	1.0	-	0.1	1.9	4.4
SCSA	36.5	2.8	3.4	16.4	0.2	7.9	4.4	7.3	4.0	0.4	1.2	15.5

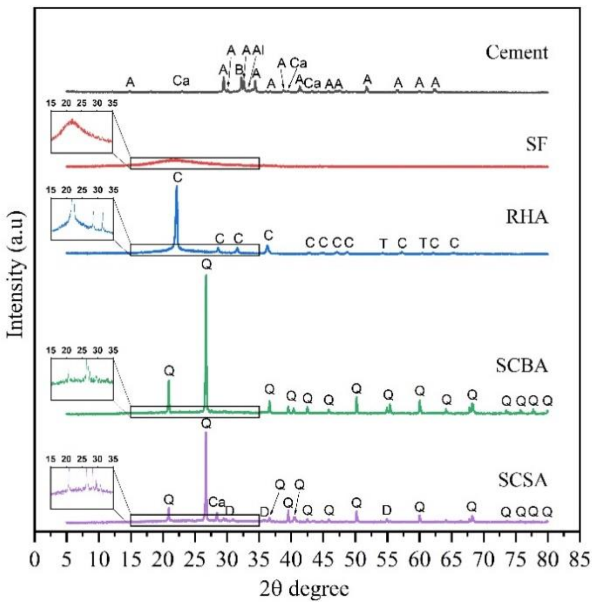

Figure 4.3 - DRX patterns of cement and pozzolanic materials. Key: A – Alite (C_3S); Al – Tricalcium Aluminate (C_3A); B – Belite (C_2S); C – Cristobalite (SiO_2); Ca – Calcite ($CaCO_3$); D – Diopside (SiO_2); Q – Quartz (SiO_2); T – Tridymite (SiO_2).

Densified silica fume (SF) and rice husk ash (RHA), both commercial pozzolanic materials in Brazil, were used as references in this study. Their chemical composition is presented in Table 4.1 and, Table 4.2 are shown both their density and granulometric parameters (obtained by laser diffraction granulometry). The assessed wastes from the sugar cane industry (SCBA and SCSA) were generated through an auto combustion process of sugar cane bagasse and sugar cane straw collected from a sugar cane producer near Ilha Solteira city (São Paulo – Brazil). After the burning process, both SCBA and SCSA were milled for 50 min [33,35]. The chemical composition, density and granulometry of SCBA and SCSA are depicted in Tables 4.1 and 4.2, respectively.

Table 4.2 - Density (g/cm^3) and granulometric parameters (determined by laser diffraction granulometry, μm) for Portland cement and pozzolanic materials.

Material	**Density**	**d(0.1)**	**d(0.5)**	**d(0.9)**	**Mean diameter**
Cement	2.99	3.40	10.02	22.20	11.52
SF	2.28	3.61	18.49	42.66	23.25
RHA	2.19	3.40	16.80	50.40	22.40
SCBA	2.22	2.16	25.11	82.35	34.60
SCSA	2.25	1.82	10.58	46.18	18.16

The Portland cement presents high amounts of CaO and SiO_2. XRD analysis could detect the typical compounds found in a Portland cement: Alite (#PDF Card 42-551), Belite (#PDF Card 6-476), Tricalcium Aluminate (#PDF Card 1-1060) and Calcite (#PDF Card 5-586) (Figure 4.3). SF and RHA are considered siliceous pozzolan due to the high SiO_2 content (> 90 wt.%) and, according to the XRD pattern, both SF and RHA are amorphous material verified by the baseline deviation in the range of 15–35° on the diffractogram (Figure 4.3). SCBA has a high content of silicon dioxide and low percentages of Al_2O_3 and Fe_2O_3 (the sum of these three oxides is 88%), and they can contribute to the pozzolanic reaction, as reported in a previous study [35]. Similarly, the XRD pattern of SCBA presents a baseline deviation at 15–35°, and the presence of some peaks indicates the presence of quartz (#PDF Card 33-1161) as an impurity. Indeed, it is due to the presence of contaminants (soil) in the sugar cane bagasse. Moreover, SCSA presents a low SiO_2, Al_2O_3 and Fe_2O_3 content of 36.5%, 2.8% and 3.4%, respectively, and high total alkali content (K_2O + Na_2O). The baseline deviation at 15–35° is also present for SCSA, and crystalline forms such as quartz (#PDF Card 33-1161), calcite (#PDF Card 5-586) and diopside (#PDF Card 11-654) are also found (Figure 4.3). A previous study also reported the pozzolanic reactivity of SCSA [32].

Related to the density, all assessed materials present a similar density. SF, RHA and SCSA have similar particle size parameters, with most particles ranging from approximately 3–50 µm and similar mean diameter (see Table 4.2 and Figure 4.4). Otherwise, SCBA was the material with well-graded particle size distribution with d(0.1), d(0.5) and d(0.9) of 2.16, 25.11 and 82.35 µm, respectively, resulting in the largest mean diameter (34.60 µm).

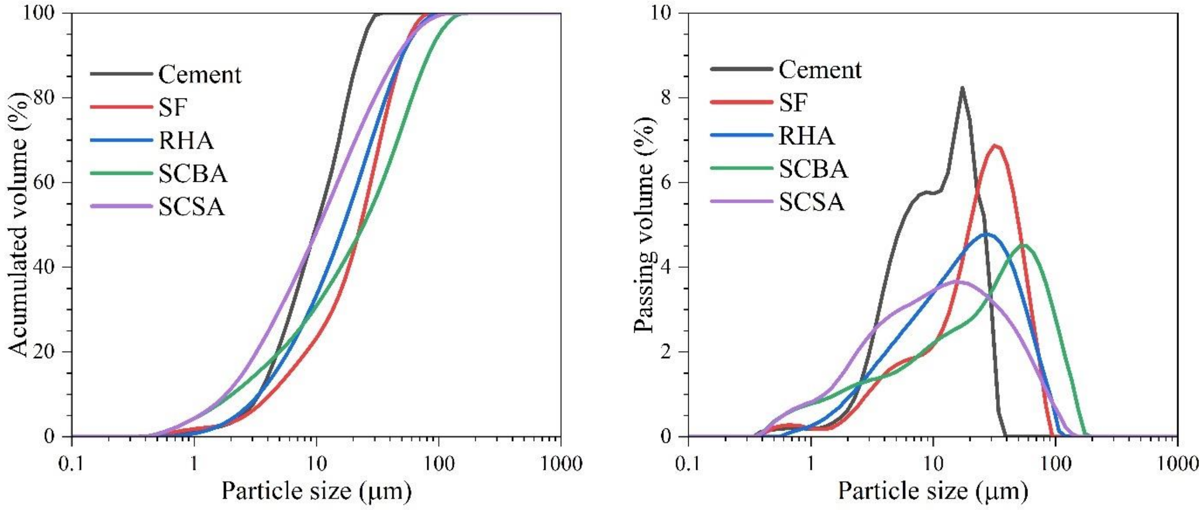

Figure 4.4 - Particle size distribution of binding materials.

4.2.2 METHODS

This study was performed in three steps. In the first step, the influence of 10% of wastes from the sugar cane industry for different binder:aggregate mass ratio (1:3.5, 1:4.0, 1:4.5 and 1:5.0) on the mechanical and hydraulic properties of pervious concrete was assessed (see section 4.2.2.1). In the second step, the influence of the percentage (0, 10, 15 and 25%, in mass) of wastes from the sugar cane industry (SCBA and SCSA) replacing Portland cement were analysed just for the pervious concrete that yielded the most significant enhancement in the first step of this study. Finally, a relationship among all assessed properties (compressive strength, density, total porosity and infiltration rate) was established using a statistical model for pervious concrete containing wastes from the sugar cane industry.

4.2.2.1 Influence of wastes from sugar cane industry for different binder:aggregate mass ratio

Table 4.3 summarises the mix proportions assessed on the first step of this study where the influence of binder:aggregate mass ratio was assessed for pervious concrete containing 10% of pozzolanic materials. For all cases, the water/binder ratio was fixed at 0.26 and, the amount of pozzolanic material replacing Portland cement was fixed in 10%, in mass. According to the literature, Portland cement replacements close to 10% seems to enhance the mechanical properties without promoting severe changes on the hydraulic properties of pervious concrete [18,23]. For each tested pozzolanic material (SF, RHA, SCBA, SCSA), four mixing proportions were designed varying the binder:aggregate mass ratio (1:3.5; 1:4; 1:4.5 and 1:5), where the binder is the sum of Portland cement and pozzolanic material.

Pervious concrete prepared using only Portland cement as the binder (control sample) yielded the ideal consistency for this type of concrete using a water/binder ratio of 0.26. The ideal consistency was determined experimentally according to Kia et al. [5] and Tennis et al. [3]: paste which covers the aggregates has a shiny appearance, not being drying (affecting the hydration process of Portland cement) nor very fluid (causing the clogging of pores). Hence the water/binder ratio was fixed in 0.26 for all assessed pervious concrete and, only for pervious concrete containing 10% SF, an addition of polycarboxylate superplaticiser was necessary in 0.27% (related to the binder mass) to maintain the ideal consistency.

Pervious concretes were mixed using a mechanical drum mixer. All aggregate was added with half of the total amount of water and mixed for 30 s. After that, the binder was added with the rest of the water and mixed for 150 s. The fresh mixture was poured into cylindrical moulds (100 × 200 mm). The compaction process was performed manually in two layers, with 25 blows of steel rod per layer. After 24 h, the demoulded process was performed and, all specimens were cured at room temperature with high relative humidity (RH ~ 100%). For each mix proportion, eight specimens were prepared: five of them were used for compressive strength test, and the others (three specimens) were employed on the density, total porosity, and infiltration rate tests. All tests were performed after 28 days of curing. It is important to state that the production of pervious concrete was performed in the laboratory at 27°C and relative humidity around 65%.

Table 4.3 - Mix proportions of pervious concrete (%, in mass).

ID	w/b	Binder:aggr	Binder				
			Portland Cement	Pozzolanic Material (%)			
				SF	RHA	SCBA	SCSA
Control	0.26	1:3.5	100	-	-	-	-
10% SF			90	10	-	-	-
10% RHA			90	-	10	-	-
10% SCBA			90	-	-	10	-
10% SCSA			90	-	-	-	10
Control	0.26	1:4.0	100	-	-	-	-
10% SF			90	10	-	-	-
10% RHA			90	-	10	-	-
10% SCBA			90	-	-	10	-
10% SCSA			90	-	-	-	10
Control	0.26	1:4.5	100	-	-	-	-
10% SF			90	10	-	-	-
10% RHA			90	-	10	-	-
10% SCBA			90	-	-	10	-
10% SCSA			90	-	-	-	10
Control	0.26	1:5.0	100	-	-	-	-
10% SF			90	10	-	-	-
10% RHA			90	-	10	-	-
10% SCBA			90	-	-	10	-
10% SCSA			90	-	-	-	10

4.2.2.2 Influence of the percentage of wastes from the sugar cane industry

The effect of different percentages of wastes from the sugar cane industry and, consequently, the optimum percentage of pozzolanic materials was analysed considering the binder:aggregate mass ratio that yielded the most significant enhancement on the mechanical strength in the first step. The percentages of SCBA and SCSA replacing Portland cement tested were: 0, 10, 15 and 25% replacing

Portland cement in mass. All experimental procedures adopted in this step are similar to those used in the first step of this study.

4.2.2.3 Relationship among pervious concrete properties

The relationship among mechanical strength, percentage of waste, density, total porosity, and infiltration rate was determined using a multiple regression analysis with a confidence level of 95%. A linear least-squares regression equation was defined to predict the compressive strength of pervious concrete based on the above-mentioned parameters. In this case, the linear regression model takes the following form:

$$y(x_1, x_2, x_3) = a_1 \times x_1 + a_2 \times x_2 + a_3 \times x_3 + a_4 \times x_4 + \beta_0 \quad (1)$$

where $y(x_1, x_2, x_3, x_4)$ is the predicted compressive strength, the independent variables are the percentage of waste (x_1), density (x_2), total porosity (x_3) and infiltration rate (x_4) and, the regression coefficients are a_1, a_2, a_3 and a_4.

4.2.2.4 Tests performed

Compressive strength test: The compressive strength test was performed on a universal test machine (maximum capacity of 200 tonnes) following the recommendations of NBR 5739 [36]. The test was performed using a load rate of 0.45 MPa/s.

Density and total porosity: Density and total porosity were assessed using ASTM C1754 [37] specifications. After the infiltration rate tests, the specimens were dried in an oven at a temperature of 110 ± 5°C until mass constancy. The samples were then weighed and submerged in water for 30 min for later measurement of submerged mass. With the dry and submerged masses, density and porosity were calculated according to Equations (2) and (3), respectively, where K is the conversion factor (1273240 in SI), A is the dry mass of the specimen (g), D is the average diameter of the specimen (mm), L is the average length of the specimen (mm), B is submerged mass of the specimen (g), and ρw is the density of water at the temperature of the water bath (kg/m^3).

$$Density = \frac{K\,.A}{D^2.L} \quad (2)$$

$$Void\ content = \left[1 - \left(\frac{K\,.(A-B)}{\rho_w\,.D^2.L}\right)\right].100 \quad (3)$$

Infiltration rate: The infiltration rate is a critical parameter to measure the efficiency of pervious concrete. The specimens were wrapped with plastic film in three layers along its entire length, just on the underside and leaving a 50 mm lip above the top to maintain a head during the test. The wrap was heated with a heat gun to adjust plastic film to the surface of the sample length to prevent water from percolating between the wrap and the external surface of the sample. For the test, the specimen was placed in a funnel so that the bottom face remained free for the passage of water. So, water was poured on the upper surface to maintain a head of approximately 20 mm, and the time to pour all the water was monitored. The infiltration rate was determined using the required time for 2000 ml (0.002 m^3) of water to percolate through the sample, following the recommendation of ISO 17785-1 [38]. The infiltration rate (k) can be calculated according to Equation (4). 'W' is the volume of water poured, 'A' is the cross-sectional area of the specimen, and 't' is the time required for the measured volume of water to infiltrate the concrete. Figure 4.5 presents a schematic of the infiltration test.

$$k = \frac{W}{A\,.t} \quad (4)$$

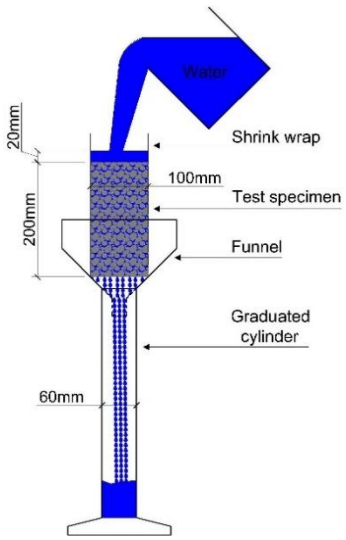

Figure 4.5 - Schematic representation of the infiltration rate test.

4.3 RESULTS AND DISCUSSION

4.3.1 INFLUENCE OF WASTES FROM SUGAR CANE INDUSTRY FOR DIFFERENT BINDER:AGGREGATE MASS RATIO

4.3.1.1 Compressive strength tests

The 28-days compressive strength for pervious concrete containing different binder:aggregate ratios are presented in Figure 4.6. As it was expected, for control samples, the reduction in the Portland cement consumption promotes a diminishing on the compressive strength of pervious concrete from 15.4 MPa to 10.6 MPa for the binder:aggregate ratio of 1:3.5 and 1:5.0, respectively. It represents a reduction of 31% of this mechanical property, which is proportional to the reduction in the Portland cement consumption (about 27.5% of reduction) when the mix proportion was changed from 1:3.5–1:5.0.

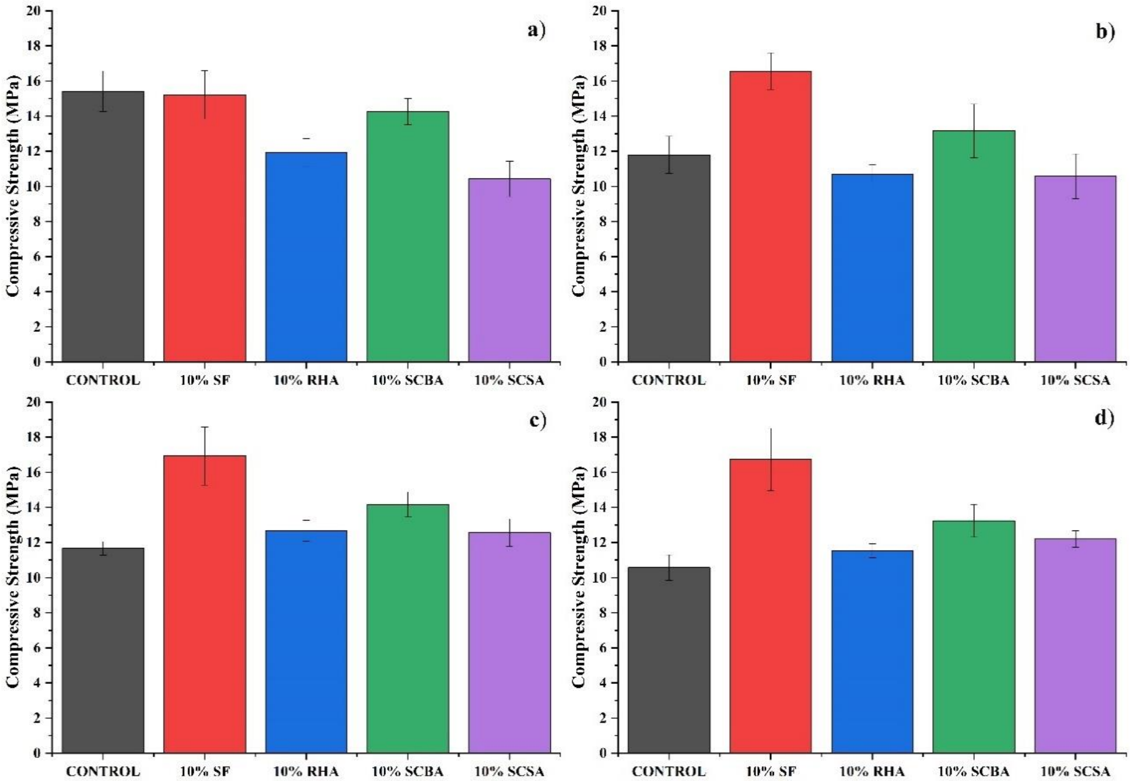

Figure 4.6 - 28-days compressive strength for different binder:aggregate ratio: (a) 1:3.5; (b) 1:4.0; (c) 1:4.5; (d) 1:5.0.

For pervious concrete containing 10% SCBA, the compressive strength was in the range 13.2–14.2 MPa, demonstrating less influence of binder:aggregate ratio for this type of concrete compared to control samples. Similar results were obtained for pervious concrete containing 10% SCSA, where compressive strength in the range 10.4–12.6 MPa were yielded. It indicates that the replacement of Portland cement by wastes from the sugar cane industry does not show a negative effect on the compressive strength. Moreover, for pervious concrete containing lower amounts of binder material, it means for the binder:aggregate mass ratio of 1:4.5 and 1:5.0, the compressive strength of pervious concrete containing both 10% SCBA and 10% SCSA are higher than control concrete. This behaviour can be justified by the improvement of the interfacial transition zone (ITZ) of blended pervious concrete caused both by the pozzolanic reaction and/or by their filler effect [15,39].

Comparing the effect of SCBA and SCSA, it was noticed that, for all binder:aggregate ratio, enhanced compressive strength was obtained for pervious concrete containing 10% SCBA. This fact can be observed for all binder:aggregate mass ratio assessed. Probably, it is due to the combined effect of its pozzolanic reactivity and due to its filler effect, demonstrated by well-graded particle size distribution of SCBA (see Table 4.2 and Figure 4.4). In general terms, the reduction in binder amount provides less compressive strength. Nevertheless, in some cases, the data presented reveal slight compressive strength gain. This fact could be assigned to the experimental variations, always presented in concrete, especially in pervious concrete [20,40]. Hence, it is important to take into account the standard deviation in the analysis.

The compressive strength of pervious concrete containing 10% RHA is depicted in Figure 4.6. The compressive strength of 10% RHA was in the range 10.7–12.7 MPa. The higher compressive strength was obtained for the binder:aggregate 1:4.5, yielding an increment of 8.6% compared to the control sample. Similar behaviour was observed by Shafabakhsh and Ahmadi [18], where the authors achieved an increment of 10% for concrete containing 10% RHA using a binder:aggregate ratio of 1:4.4. Comparing the compressive strength of pervious concrete 10% RHA with pervious concrete containing wastes from sugar cane industry, it is noticed that pervious concrete containing 10% RHA presented a similar behaviour to 10% SCSA.

For pervious concrete containing 10% SF, it was observed an improvement for almost all binder:aggregate ratios when compared to control concrete. 10% SF concrete yielded 15.2–16.9 MPa for 28-days compressive strength. This behaviour could be associated with the pozzolanic reactivity of silica fume and/or the use of superplasticiser, which improve the densification of the matrix and, consequently, its compressive strength [15,39]. For binder:aggregate 1:4.0, an increase of 40.41% on compressive strength was observed. Mondal and Biligiri [7] replaced Portland cement by up to 6% of SF and observed an increase of approximately 20–25% on compressive strength of 1:4.0 pervious concrete mixtures with three different aggregate sizes.

4.3.1.2 Density and total porosity

For the control samples, a modification on the binder:aggregate mass ratio (from 1:3.5–1:5.0) causes a linear decrease in density for the control mixtures yielding a minimum of 1909 kg/m^3 for a binder:aggregate ratio of 1:5.0 (Figure 4.7). For pervious concrete containing 10% SCBA, the reduction on the density is softened, where high density (1994 kg/m^3) was obtained for 1:3.5 binder:aggregate mass ratio and the lowest density was achieved by binder:aggregate mass ratio of 1:5.0 (1964 kg/m^3). Similar behaviour was observed for pervious concrete containing 10% SCSA and 10% RHA: in these cases, the obtained density values were slightly lower than those obtained for 10% SCBA. Otherwise, pervious concrete containing 10% SF presented the highest density value yielding up to 2044 kg/m^3 for the binder:aggregate ratio of 1:3.5.

For high consumption of Portland cement (binder:aggregate 1:3.5 and 1:4.0), only 10% SF and 10% SCBA presented higher values of density than control samples. In the case of 10% SCBA, it can be explained by the well-graded distribution of SCBA particles, providing an improvement on the packing and, consequently, an increment in the density. Otherwise, 10% SF present higher density values probably due to the packing effect of particle provided by both the SF and the action of superplasticiser [14,15,39]. For 10% SCSA, the density is similar to that obtained for the control sample yielding about 2080 and 2045 kg/m^3 for the binder:aggregate mass ratio of 1:3.5 and 1:4.0, respectively. Pervious concrete containing 10% RHA, due to the lower density of RHA (2.19 g/cm^3), achieved the lowest density for both binder:aggregate mass ratio of 1:3.5 and 1:4.0.

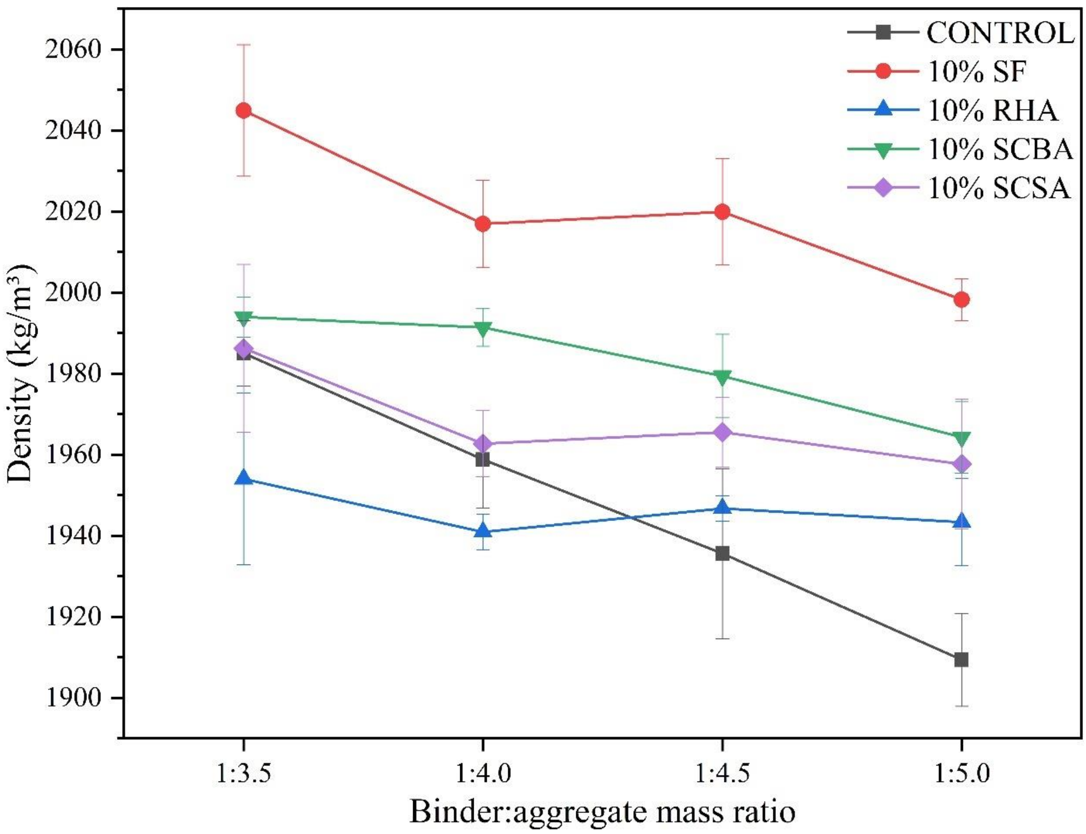

Figure 4.7 - 28-days density for different binder:aggregate ratio.

For lower Portland cement consumption assessed (binder:aggregate 1:4.5 and 1:5.0), all pervious concrete containing pozzolanic materials presented higher density values than the control sample. It is probably due to the better accommodation of the particles when pozzolanic materials are present that densified the microstructure in pervious concrete.

Total porosity is an essential factor in pervious concretes, as water leaks through it. Figure 4.8 shows the porosity for all mix proportions assessed. A trend very similar to density was observed for porosity. For control samples, a linear increment on the total porosity is observed when the Portland cement consumption is reduced from 1:3.5 to 1:5.0, yielding values from 27.1% to 31.5%, respectively. The obtained values are similar to those found in the literature [5,7,27].

The addition of a pozzolanic material reduces the total porosity, as can be seen in Figure 4.8. Concrete containing 10% SF presented the lowest percentages of total porosity in the range 23.8% and 26.7%, depending on the binder:aggregate ratio. The low porosity is directly associated with the high density of concrete, which is attributed to the increment in the thickness of ITZ due to the pozzolanic reaction [14,15,18,23].

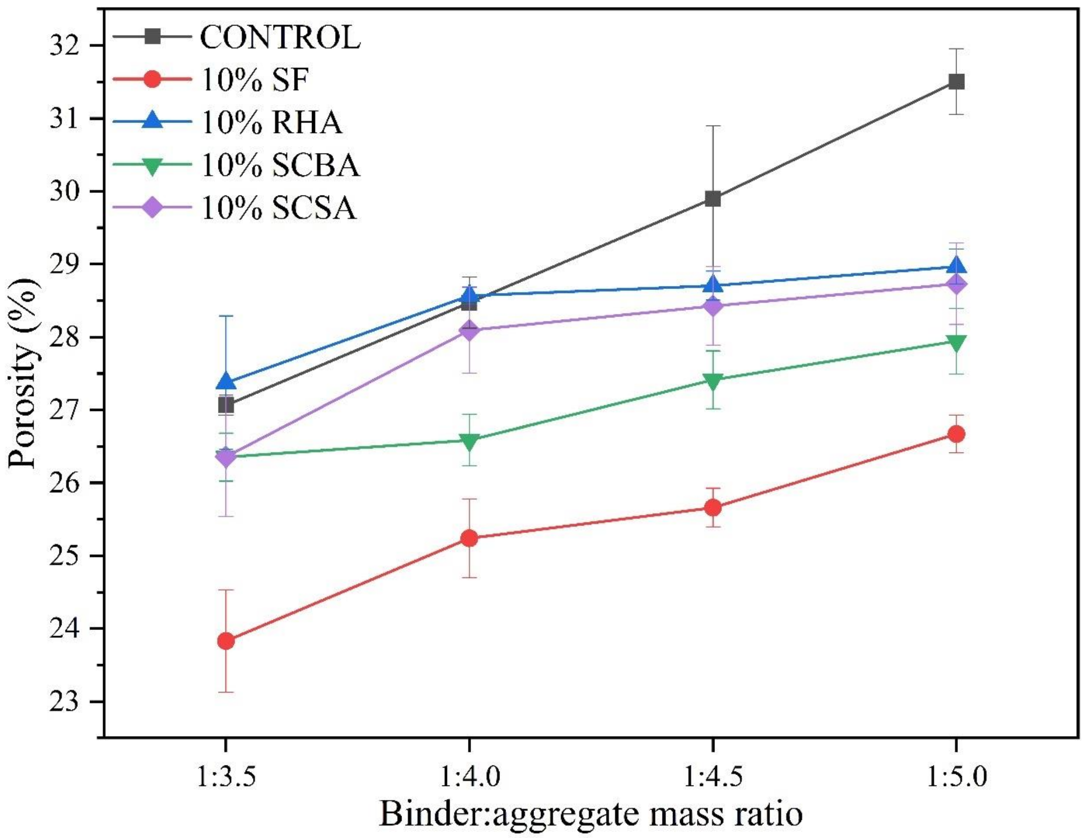

Figure 4.8 - 28-days porosity for different binder:aggregate ratio.

For pervious concrete containing wastes from the sugar cane industry, the obtained total porosity was similar to those found for 10% RHA, indicating the possibility of using both SCBA and SCSA to produce pervious concrete. For pervious concrete containing 10% SCSA, the total porosity is 26.36–28.73%. This value is about 5% lower than that obtained for control. In the same way, concrete containing 10% SCBA presented about 8% lower total porosity than control. These results indicate that 10% SCBA present a better packing effect on pervious concrete when compared to SCSA. Probably, it can be attributed to both the pozzolanic reactivity and the well graded particle distribution of SCBA.

4.3.1.3 Infiltration rate

NBR 16416 [41] recommends that pervious pavements have an infiltration rate of at least 0.1 cm/s. The drainability efficiency of the pervious concretes was measured by the infiltration rate tests. For all mixtures, an increase in the infiltration rate was observed for mixtures containing lower amounts of binding material. The highest infiltration rates were observed for control mixtures in all mixing proportions compared to mixtures with pozzolanic material incorporation, as seen in Figure 4.9.

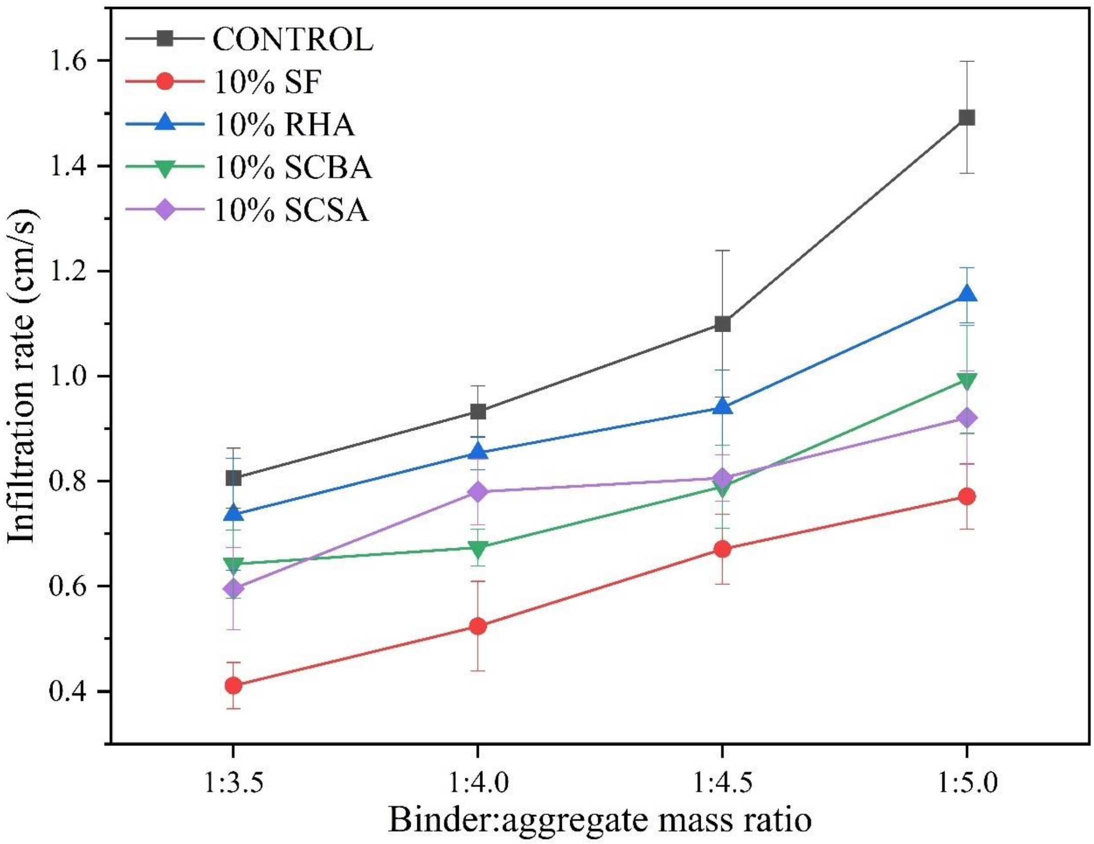

Figure 4.9 - Twenty-eight days infiltration rate for different binder:aggregate ratio.

The infiltration rate ranged from 0.81–1.49 cm/s for the control samples, with a decrease in binder content. 10% SF yielded 0.41–0.77 cm/s infiltration rates, the lowest values observed for the tested concrete. In any case, the obtained values are suitable according to both the recommendation of NBR 16416 [41] and data found in the literature [2,7,15]. The lowest values were expected for 10% SF due to the higher density and less porosity of these samples. The incorporation of RHA generated 0.74–1.15 cm/s infiltration rates. As observed on the porosity, infiltration rates remained close to the control for the binder:aggregate mass ratio of 1:3.5 and 1:4 and were relatively smaller than the control 1:4.5 and 1:5.0.

Both pervious concretes incorporating wastes from the sugar cane industry achieved similar behaviour, reaching 0.60–0.99 cm/s with the increase of binder content. In general, the infiltration rate was consistent with the porosity of the samples, being slightly lower for mixtures with incorporated materials.

According to the obtained results related to de influence of wastes from the sugar cane industry for different binder:aggregate mass ratio in pervious concrete, the enhanced performance compared to control sample was observed for lower amounts of binder, it means, for the binder:aggregate mass ratio of 1:4.5 and 1:5.0. Hence, in the next step of this study, the binder:aggregate mass ratio was fixed in 1:5.0, and the influence of different percentage of SCBA and SCSA replacing partially Portland cement (0, 10, 15, 25%, in mass) is assessed.

4.3.2 INFLUENCE OF THE PERCENTAGE OF WASTES FROM THE SUGAR CANE INDUSTRY

Figure 4.10 summarises the effect of different percentages of SCBA and SCSA on the mechanical and hydraulic properties of pervious concrete.

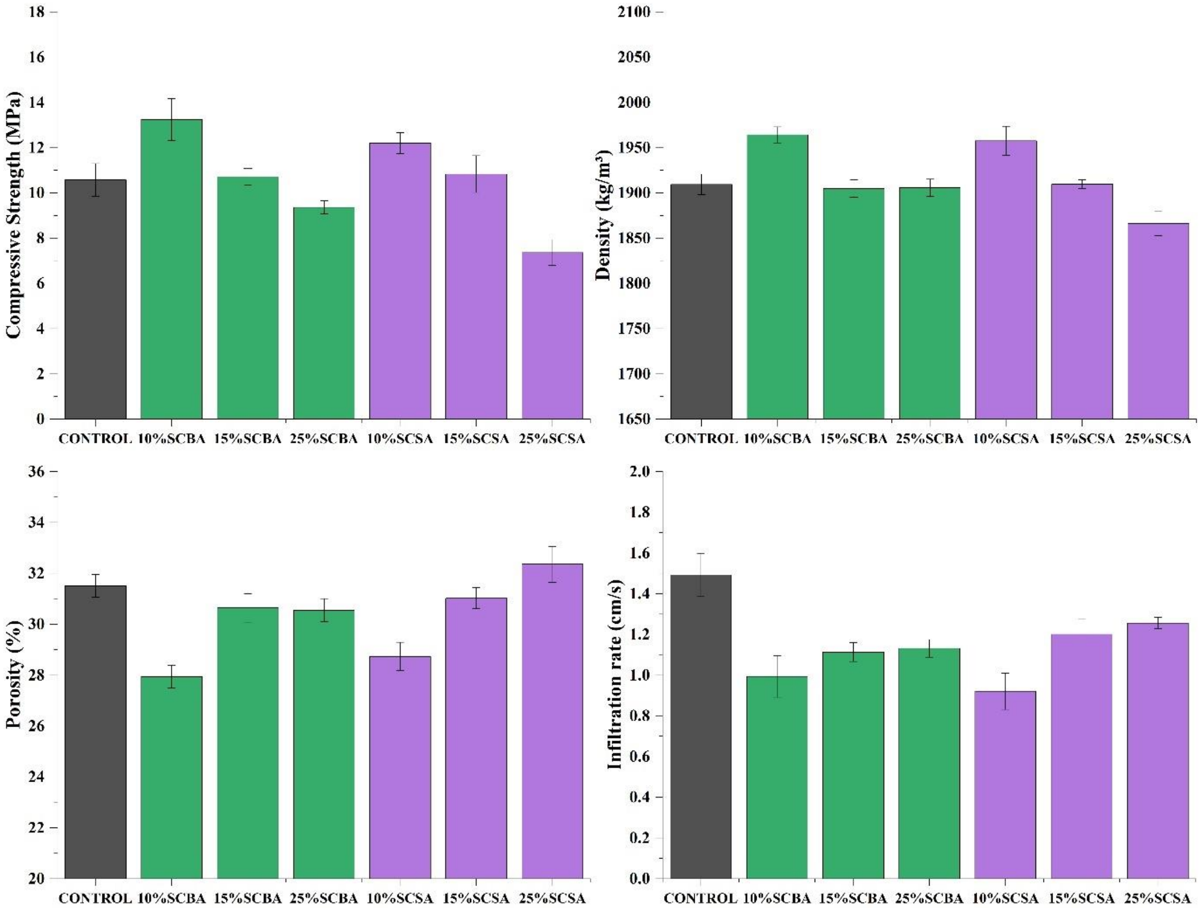

Figure 4.10 - Effect of percentage of SCBA and SCSA on the properties of pervious concrete.

Pervious concrete containing 10% SCBA and 10% SCSA presented increased compressive strength compared to Portland cement due to both filler and chemical effect (pozzolanic reaction). For 15% replacement, both SCBA and SCSA provided compressive strength similar to the control (10.6 MPa): 10.7, 10.8, respectively. For 25% replacement, both wastes reduce compressive strength to values of 9.4 and 7.4 MPa, respectively. For increased amounts of pozzolanic materials replacing Portland cement, the compressive strength was affected negatively due to the reduction in the Portland cement consumption.

The density of concretes with 10% of both SCBA and SCSA was higher than control. With 15% and 25% of these wastes, the density was very close to the control, indicating little influence on these substitution amounts. In terms of total porosity, an increment in the amount of SCBA and SCSA causes a growth in the total porosity yielding similar values to those obtained by the control sample (about 30.0%).

As already mentioned, 10% of the sugar cane wastes collaborate to reduce the infiltration rate compared to the control. For 15 and 25% of both residues, the average infiltration rate value is slightly lower than the control, with a more significant decrease for SCBA. Even so, these values are satisfactory for pervious concretes [3,9–13].

4.3.3 RELATIONSHIP AMONG PERVIOUS CONCRETE PROPERTIES

The relationship among compressive strength, density, and porosity is usually linear or exponential for pervious concretes studied in the literature, in which an increase in density results in an increase in the compressive strength and an increase in the total porosity results in a decrease in the compressive strength [18,19,27,42–45]. Similarly, the infiltration rate tends to increase with decreasing density and increasing the total porosity, either linearly or exponentially [13,42,45–47]. To clarify the influence of SCBA and SCSA on the pervious concrete behaviour, it is shown in Figure 4.11 the relationship between compressive strength, density, total porosity, and infiltration rate for 1:5.0 mixtures: control and containing the sugar cane wastes.

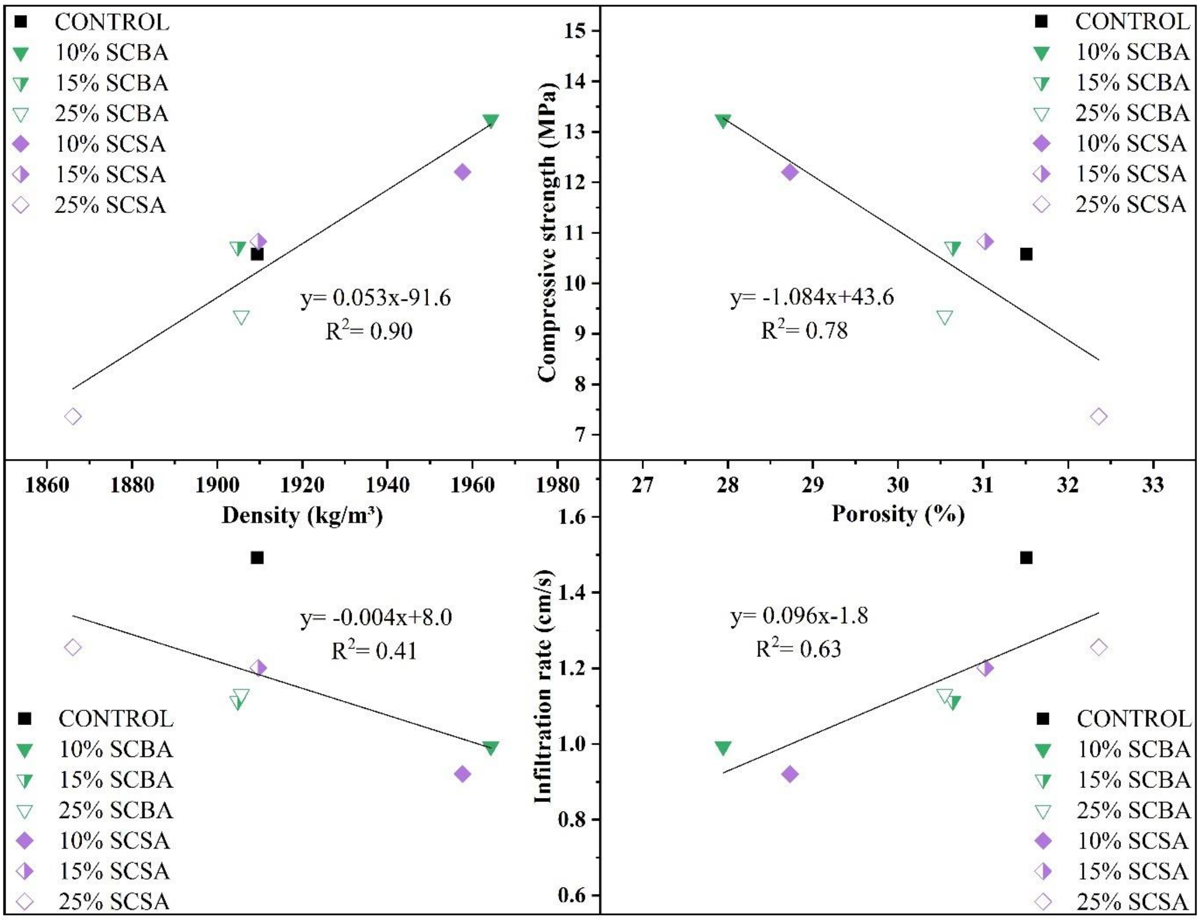

Figure 4.11 - Relationship between compressive strength, density, total porosity and infiltration rate for pervious concrete with a binder:aggregate mass ratio of 1:5.0.

The compressive strength and density presented a linear relationship yielding an R^2 equal to 0.90. The incorporation of 10% SCBA and 10%SCSA promoted an increment in the density and, consequently, an enhancement on the compressive strength of pervious concrete. The other percentages of replacement do not affect significantly the density and the compressive strength, achieving similar results to the control sample. Associating compressive strength and total porosity, a linear fit was established, achieving an R^2 of 0.78. Nevertheless, when a linear fit is proposed for total porosity vs infiltration rate and density vs infiltration rate, a low R^2 correlation is obtained: 0.63 and 0.41, respectively.

To establish a correlation among compressive strength, percentage of wastes from sugar cane industry, density, total porosity and infiltration rate, a multiple regression model was performed using a statistical program (Statgraphics Centurion). This analysis, using the linear regression model (Equation (1)), allows finding which parameter (percentage of waste, density, total porosity and infiltration rate) affect more significantly the compressive strength of assessed pervious concrete. In this analysis were used only the obtained data for pervious concrete with a binder:aggregate mass ratio of 1:5.0.

Table 4.4 summarises the obtained values of the coefficients a_1 (percentage of waste) a_2 (density), a_3 (porosity), a_4 (infiltration rate) and β_o (intercept), and significance p-values, with a 95% confidence level. The variance analysis (ANOVA) indicates a statistically significant relationship between the assessed parameters, with a 95% confidence level.

Table 4.4 - Brief of the results of the multiple regression model that considers the dependence of compressive strength to percentage of waste, porosity, density and infiltration rate.

	Coefficients (SCBA)	p-value (SCBA)	Coefficients (SCSA)	p-value (SCSA)
ANOVA	-	0.000	-	0.000
R^2	0.98	-	0.93	-
Intercept (βo)	117.42	0.075	-81.26	0.134
% of waste (a_1)	-0.13	0.000	-0.01	0.840
Density (a_2)	-0.03	0.184	0.05	0.056
Porosity (a_3)	-1.27	0.039	-0.14	0.643
Infiltration rate (a_4)	-2.45	0.102	1.75	0.619

For pervious concrete containing SCBA, the multiple regression model showed that the percentage of the waste is the most important parameter which affects the compressive strength of pervious concrete containing SCBA. Nevertheless, the total porosity is also a variable with a strong influence on the regression model (p-value of .039).

In the case of pervious concrete containing SCSA, the density is the unique variable which affects the compressive strength (p-value of .056). All other parameters (percentage of waste, total porosity and infiltration rate) presented a p-value higher than .60, indicating their low influence on the compressive strength of pervious concrete containing SCSA.

Figure 4.12 shows the relationship between the values of predicted compressive strength using the multiple regression model and experimental data. For both SCBA and SCSA, a linear fit was achieved with an R^2 above 0.90.

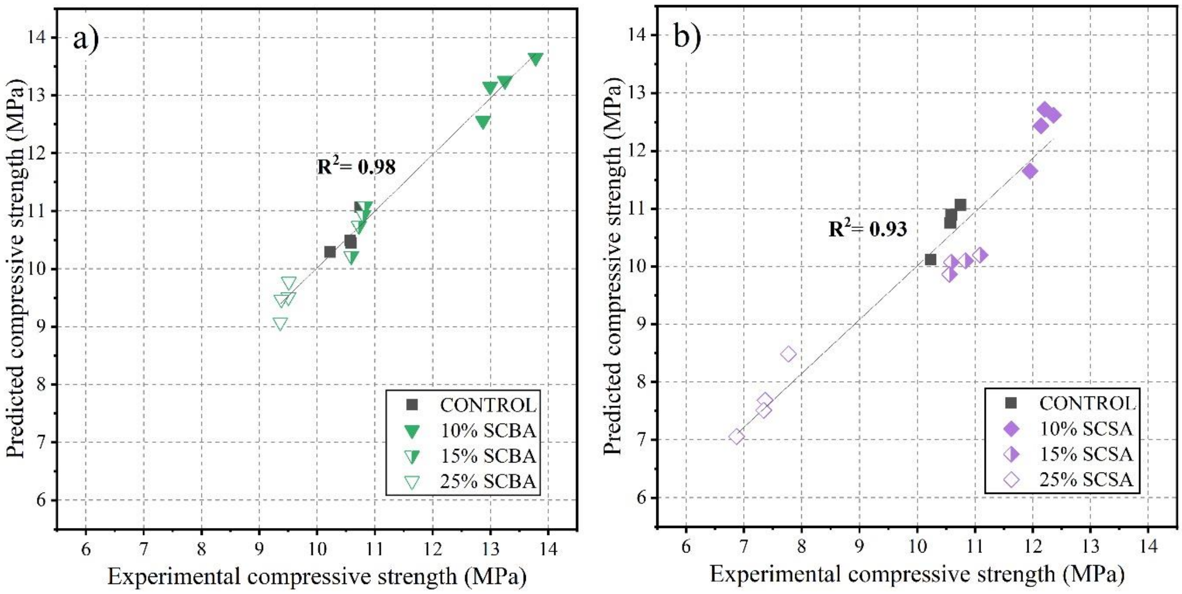

Figure 4.12 - Prediction results of multiple regression model versus experimental data for compressive strength of pervious concrete: (a) SCBA; (b) SCSA.

4.4 CONCLUSIONS

This study aimed to analyse the mechanical and hydraulic behaviour of pervious concrete containing SCBA and SCSA in different mix proportion and compare their behaviour to traditional pozzolanic materials (RHA and SF). Besides, the incorporation of 0%, 10%, 15% and 25% of both sugar cane wastes were also assessed. Based on the results, the following conclusions can be drawn:

- The use of 10% of pozzolanic material in pervious concrete with different binder:aggregate mass ratio showed that for lower amounts of binder, the compressive strength is enhanced when compared to their respective control sample.
- 10% SCSA presented similar mechanical strength and slight lower infiltration rate when compared to pervious concrete containing 10% RHA.
- Pervious concrete containing 10% SCBA presented higher compressive strength and similar infiltration rate when compared to 10% SCSA, yielding 13.2 MPa for a binder:aggregate mass ratio of 1:5.0.

- The use of 10% SF presented the best results in terms of mechanical strength, associated with the lowest infiltration rate. Probably, it was due to synergic effect of silica fume (pozzolanic reaction) and the use of superplasticiser (dispersion of binder). The superplasticiser was necessary specifically for pervious concrete containing 10% SF (high water demand proportioned by SF).
- Comparing the influence of different percentages of SCBA and SCSA for a fixed binder:aggregate mass ratio (1:5.0), the best results in compression were yielded for pervious concrete containing 10% SCBA (about 13.2 MPa) and for 10% SCSA (about 12 MPa).
- The increment in the amount of wastes from the sugar cane industry causes a reduction in the compressive strength, an increment in the total porosity (from 27.9% to 32.4%) and, consequently, a slight increment in the infiltration rate (from 0.92 to 1.26 cm/s).
- According to the multiple regression model, a linear least-squares regression equation was defined. For pervious concrete containing SCBA, the parameter that most influence its compressive strength is the percentage of waste.
- Similarly, for pervious concrete containing SCSA, the parameter that most influence its compressive strength is the density.
- The regression model fit well with experimental data yielding an R2 above 0.90 both for pervious concrete containing SCBA and SCSA.

In general, the use of pervious concrete is an environmental-friendly alternative for use as pervious pavement. The addition of agroindustrial such as wastes from the sugar cane industry (a massive industry) on the composition of concrete can contribute the sustainable development, mainly in developing countries.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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CHAPTER 5 – NEW INSIGHTS ON THE DEVELOPMENT OF SUSTAINABLE PERVIOUS CONCRETE USING SAND REPLACING PASTE VOLUME

This chapter presents the manuscript entitled as "*New insights on the development of sustainable pervious concrete using sand replacing paste volume*" co-authored by R.G. da Silva, K.H. Arcolezi, G.P. Lyra, J.L. Akasaki, L. Soriano, M.V. Borrachero, J. Payá and M.M. Tashima, submitted to the journal **Construction and building materials**.

Abstract: Studies in the literature concerning the use of fine aggregates in pervious concrete indicate changes in total porosity, which directly affect both compressive strength and infiltration rate. In fact, up to now, the real effect of fine aggregates on these properties of pervious concrete is uncertain. In this paper, pervious concrete with minimal alterations in the total porosity were produced, allowing a thorough assessment of the effect of fine aggregate replacing cement paste volume. Physical, engineering, environmental and economic aspects of these pervious concretes were evaluated. The results suggest that the use of fine aggregates limited to 38% replacing paste volume, present physical and engineering properties similar to mixtures without sand incorporation. This substitution could lead to a reduction in cement consumption by approximately 100 kg/m^3 and up to 25% in total costs of mixtures. Additionally, there is potential for a reduction of up to 30.7% in greenhouse gas emissions. Moreover, in the multi-criteria performance analysis, it was observed that when the particle size of coarse aggregate increases the optimal amount of sand incorporation to achieve the highest overall performance is also increased.

Keywords: Pervious concrete; fine aggregate; paste replacement; controlled porosity

5.1 INTRODUCTION

In the last decades, the growth of the world population associated with technological development has promoted substantial changes in society. The necessity for houses, buildings, and basic infrastructure construction connected to environmental concerns to protect the planet can be considered one of the biggest existing challenges nowadays. The development of efficient pavements using pervious concrete technology to contribute to drainage management can be viewed as an environmentally friendly solution [1]. This technology can reduce flood problems, transport pollutants, and allow groundwater recharge, minimizing the urban heat island due to its open-pore structure and consequent water infiltration capacity [2–6]. Nevertheless, some adjustments associated with the materials selection in pervious concrete production should be performed to achieve a more sustainable material. For example, Portland cement is the component associated with the largest portion of greenhouse gas (GHG) emissions and energy consumption, comprising about 97-99% and 90-96%, respectively, of the total amount in the production of pervious concrete [7–9]. As reported in the literature, pervious concrete is associated with high consumption of Portland cement (about 300-400 kg/m^3) [10–13].

Regarding the engineering properties, some crucial issues, such as increasing pavement friction and reducing road noise, are reported in the literature when pervious concrete is used [2,5,14]. The open-pore structure of pervious concrete is responsible for compressive strength values generally in the range of 10-15 MPa [10–13]. Moreover, the total porosity in the range of 10-35% is responsible for the capability of water infiltration in this type of pavement [2,4,6,15–21]. The variability in physical and mechanical properties depends on the proportion of materials, coarse aggregate type and characteristics (mineralogy, gradation, shape, angularity, etc.), and the compaction process employed [2–4,6,15].

Most studies on enhancing compressive strength use supplementary cementitious materials [7,21–23] or fine aggregates [5,10,16,17,24–28] to modify the granular skeleton of pervious concrete. In the literature, the use of fine aggregates in pervious concrete can be found replacing coarse aggregates [10,17,24,25,27], as addition in pervious concrete [29], or replacing Portland cement [26,30,31]. Table 5.1 summarizes some of the main fidings on the fine aggregates incorporation to pervious concrete reported in the literature. Besides, Figure 5.1 presents the schematic structures of the pervious concrete by incorporating fine aggregates and the respective effect on the physical properties based on results reported in the literature.

Table 5.1 - Summary of the main results on the fine aggregates incorporation to pervious concrete concerning to physical, mechanical and hydraulic properties reported by literature.

Authors	**How fine aggregates were incorporated**	**Main results related to the use of fine aggregates**
Taheri and Ramezanianpour [25]	Sand was used in pervious concretes replacing coarse aggregates at 5 wt.%, 7 wt.%, 10 wt.% and 14 wt.% e compared to control mixture (no fine aggregates).	Up to 14 wt.% sand: Compressive strength increased up to 72% compared to control; Flexural strength increased up to 37.5% compared to control; Total porosity reduced up to 31.5% compared to control; Infiltration rate reduced up to 82% compared to control.
Xu et al. [29]	15 wt.% (related to aggregates) of fine aggregate (artificial calcareous sand) was added to the pervious concrete and compared to control (no fine aggregates).	Compressive strength increased in the range of 29-48% when compared to the pervious concrete prepared only with coarse aggregate.
Ibrahim et al. [26]	Cement paste was replaced by river sand at 10% on pervious concrete mixtures and compared to control (no fine aggregates).	Compressive strength increased up to 36% compared to control; Total porosity reduced up to about 12% compared to control; Permeability coefficient reduced up to about 40% compared to control.
Beddaa et al. [30]	Cement was replaced by sandy and fine sediments at 10% on pervious concrete mixtures and compared to control (no fine aggregates).	Compressive strength increased up to 32% compared to control; Total porosity reduced up to about 24% compared to control; Permeability coefficient reduced up to about 54.8% compared to control.
Elizondo-Martinez et al. [31]	Cement was replaced by sand at 33 wt.% and 50 wt.% on pervious concrete mixtures and compared to control (no fine aggregates).	The best results related to strength was obtained for 33 wt.% sand: Compressive strength increased up to 64.6% compared to control; Stiffness modulus increased up to 70.3% compared to control; Infiltration rate reduced up to 38.6% compared to control.

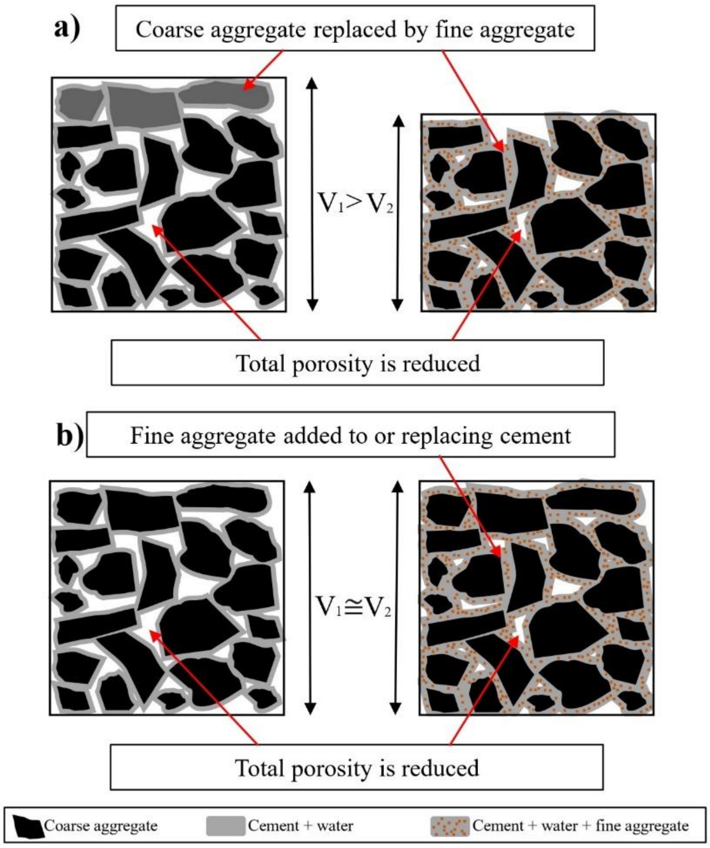

Figure 5.1 - Schematic structure of pervious concrete by incorporating fine aggregates in different ways: a) fine aggregate replaces partially coarse aggregate; b) fine aggregate added to mixture or replacing cement.

In the case of fine aggregates replacing partially coarse aggregates (as depicted in Figure 5.1a), the unit volume of concrete is reduced (V1>V2). This fact increases the thickness of the paste with a consequent reduction of total porosity, which can positively affect compressive strength [10,17,24,25,27]. According to Taheri and Ramezanianpour [25], percentages of sand replacing coarse aggregates up to 14wt.% promoted increments of 72% in the compressive strength, while the total porosity and the infiltration rate presented reductions of 31.5% and 82%, respectively.

When fine aggregate is added to pervious concrete or replaced with Portland cement in the mixture, the unit volume is maintained similarly (V1≅V2), and the paste thickness is increased, as depicted in Figure 5.1b. Consequently, enhancement in the compressive strength and reduction in the total porosity and infiltration rate could be observed in the literature when percentages up to 35wt.% of fine aggregate were incorporated [5,26,29–31].

According to Xu et al. [29], when 15% of fine aggregate (artificial calcareous sand) was added to the pervious concrete, an increment in the compressive strength in the range of 29-48% is observed when compared to the pervious concrete prepared only with coarse aggregate.

When fine aggregate replaced cement at 33wt.%, the compressive strength and stiffness modulus increased to 64.6% and 70.3%, respectively, associated with a reduced infiltration rate of up to 38.6% [31]. According to Beddaa et al. [30], the increment in the compressive strength when fine aggregate replaces cement is associated with the reduction of the total porosity with consequent enhancement in the bond strength among coarse aggregates. Similar results were achieved by Ibrahim et al. [26], which observed variations in the total porosity when fine aggregate replaced Portland cement.

In summary, numerous studies in the literature examining the incorporation of fine aggregate into pervious concrete have consistently demonstrated changes in the total porosity. These alterations generally lead to enhanced mechanical properties and decreased infiltration rates. As a result, the impact of fine aggregate on pervious concrete concerning these properties remains uncertain.

Hence, this study aims to assess the performance impact of fine aggregates in pervious concrete. Pervious concrete mixtures were developed with fine aggregates replacing paste volume at various percentages up to 59%, aiming to minimize alterations in total porosity with a targeted standard deviation lower than 4%. Besides, from this approach it was possible to assess sand incorporation limits, in which porosity can be controlled, in addition to understanding what consequences the excess of sand could have on the properties of the mixtures considering the limit of 59% of sand incorporation replacing paste volume. The assessment covered physical, engineering, environmental, and economic aspects, with the aim of designing effective, sustainable, and cost-efficient pervious concrete. The use of fine aggregate was evaluated alongside two different sizes of coarse aggregate, while total porosity was pre-established. Furthermore, a multi-criteria assessment was conducted, considering factors such as compressive strength, infiltration rate, greenhouse gas (GHG) emissions, and relative cost (derived from cost assessment), to determine the most efficient percentage of fine aggregate replacing paste volume. This comprehensive approach aimed to identify the optimal proportion of fine aggregate for achieving effective and sustainable pervious concrete mixtures.

5.2 EXPERIMENTAL PROGRAM

Experimental tests and analysis were conducted to assess the effects induced by incorporating fine aggregate (sand) partially replacing the paste volume. A flowchart of experimental tests is shown in Figure 5.2, showing an overview of the process.

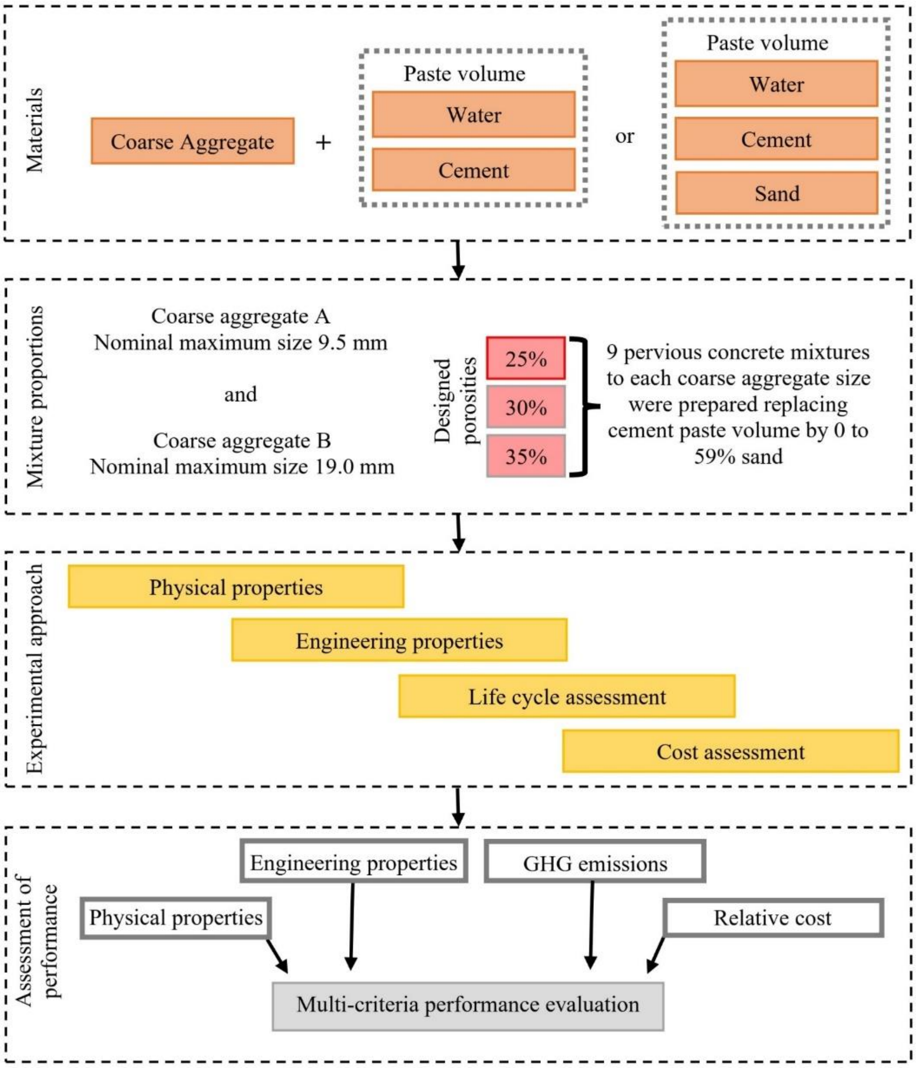

Figure 5.2 - Flowchart of experimental tests and analysis conducted.

5.2.1 MATERIALS

A Brazilian Portland cement type V – CPV ARI (equivalent to type III in Standard ASTM C150 [32]) with a specific gravity of 2.99 was employed in this study. The chemical composition (wt.%, in oxides), determined by X-ray fluorescence, is depicted in Table 5.2.

Table 5.2 - Chemical composition of Portland cement (wt.%).

SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SO_3	MgO	Others	LOI
19.9	4.4	4.6	62.8	0.1	1.0	1.6	1.1	0.2	4.3

Locally available basaltic coarse aggregates with two granulometric ranges were selected (A and B). The aggregates present a uniform distribution indicated by their low uniformity coefficient (UC = D_{60}/D_{10}), 1.50 and 1.57, respectively. A siliceous sand with a nominal maximum size of 1.18 mm was used as fine aggregate. Table 5.3 presents the physical properties of coarse and fine aggregates, and Figure 5.3 depicts the particle size distribution of all assessed materials.

Table 5.3 - Physical properties of aggregates.

Properties	**Coarse aggregates**		**Sand**	**Standard**
	A	**B**		
Nominal maximum size (mm)	9.50	19.00	1.18	NBR 17054 [33]
Fineness module	5.90	6.69	1.84	
Water absorption (%)	2.31	1.97	0.55	ASTM C127 [34]
Specific gravity	3.04	3.03	2.62	
Specific gravity OD	2.84	2.86	2.58	
Specific gravity SSD	2.91	2.92	2.60	
Unit weight (kg/m³)*	1683.86	1693.33	-	ASTM C29 [35]
Void content (%)*	44.63	44.11	-	

* Determined using the same compaction process for producing pervious concrete (see section 2.3).

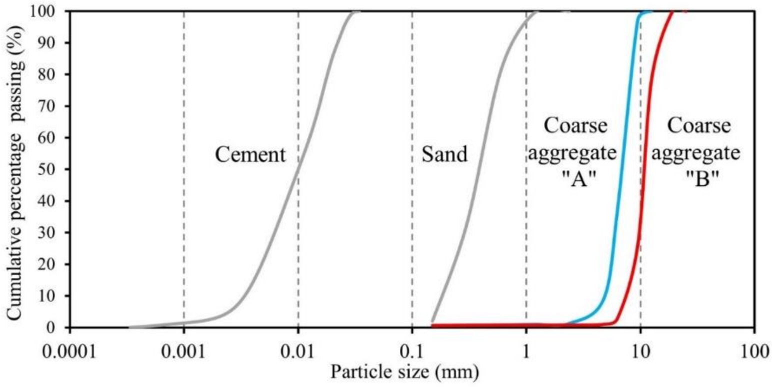

Figure 5.3 - Particle size distribution of the materials.

5.2.2 EXPERIMENTAL DESIGN

The impact of sand replacing paste volume was evaluated in pervious concrete up to 59%. The replacement of paste volume was adopted in order to maintain the total porosities of mixtures prepared with sand similar to those without sand incorporation, as illustrated in Figure 5.4. This approach was adopted to evaluate the real effect of sand, minimizing the effects of porosity change. Three different desired total porosities (25, 30, and 35%) for two sizes of coarse aggregates (A and B) were chosen using a fixed water/cement ratio of 0.26. All aggregates were used in saturated surface dry condition (SSD). The water/cement ratio was determined in previous studies following the literature recommendations related to the amount of paste to cover the coarse aggregates and their shiny appearance [2,4,6]. In total, 18 mix proportions were prepared, varying the percentage of sand replacing paste volume (see Table 5.4). The identification (ID) of mixtures was performed as follows "XYZ^{W}", where "X" is the desired total porosity (25, 30, or 35%), "Y" is related to the size of the coarse aggregate (A or B), and "Z" is associated to the sand percentage replacing paste volume (0-59%). The letter "W" represents the coarse aggregate/cement mass ratio (4.1, 4.4, 6.6, or 7.5), and it is indicated *only for mixtures containing similar values*. Considering that coarse aggregate/cement mass ratio is a key parameter on the mechanical and hydraulic properties of pervious concrete, a complementary comparative analysis among these pervious concrete are performed (e.g., $35A0^{7.5}$, $30A42^{7.5}$, and $25A59^{7.5}$).

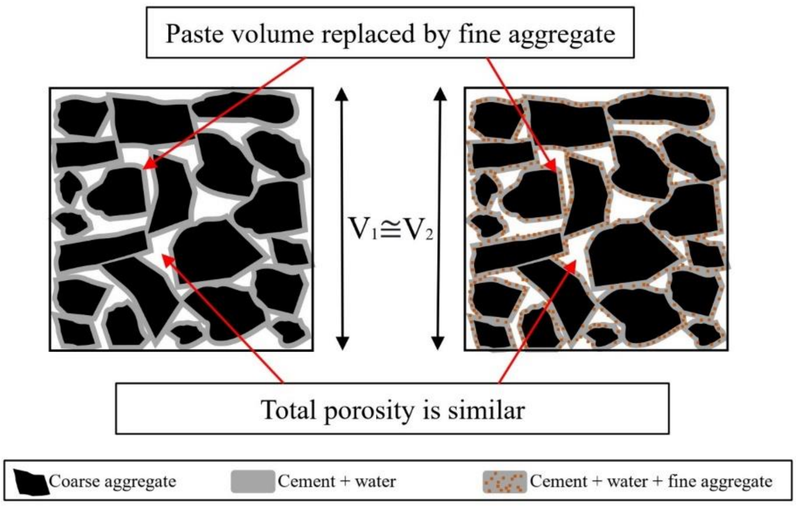

Figure 5.4 - Schematic structure of pervious concrete by the incorporation of fine aggregates replacing paste volume.

The mix design adopted in this study is based on a volumetric mix design methodology proposed by Deo and Neithalath [36]. According to these authors, a desired total porosity ($ø_{desired}$) can be fixed for each mix proportion. Considering this value and the void content of coarse aggregate ($μ_{agg}$), a paste volume (p_{vol}) is calculated following the equation proposed by Deo and Neithalath [36]:

$$p_{vol} = \mu_{agg} - ø_{desired} \tag{1}$$

According to the literature, the experimental values obtained for total porosity ($ø_{exp}$) could be higher than the theoretical values due to the different arrangement of the particles when the increment of paste reduces the porosity in a volume unit [36–38]. The incorporation of increased paste volume promotes the bulking of coarse aggregate particles, slightly reducing its mass per volume unit [39]. According to the literature, an additional paste volume (p_{vol+}) in the 2.0-4.5% range should be added to minimize this difference [36–38].

In our study, the paste volume (p_{vol}) is composed of Portland cement, water, and eventually siliceous sand, and the additional paste volume (p_{vol+}) was experimentally determined for each coarse aggregate, yielding values between 2.0-6.0%.

Table 5.4 - Mix proportions of designed pervious concrete.

Mix ID	$ø_{desired}$	**Sand replacing paste volume**	**Coarse Aggregate to cement ratio**	**Coarse aggregates (kg/m³)**		**Sand (kg/m³)**	**Cement (kg/m³)**	**Water (kg/m³)**
				A	**B**			
25A0	25%	0%	3.1	1482.2	-	0	482.5	125.5
25A15		15%	3.6	1482.2	-	84.6	410.2	106.6
25A29.5$^{4.4}$		29.5%	4.4	1482.2	-	166.4	340.2	88.5
25A35		35%	4.7	1482.2	-	197.5	313.7	81.5
25A59$^{7.5}$		59%	7.5	1482.2	-	332.8	197.8	51.4
30A0$^{4.4}$	30%	0%	4.4	1525.8	-	0	349.5	90.9
30A15		15%	5.1	1525.8	-	61.3	297.1	77.2
30A42$^{7.5}$		42%	7.5	1525.8	-	171.6	202.7	52.7
35A0$^{7.5}$	35%	0%	7.5	1569.4	-	0	208.1	54.1

25B0		0%	3.0	-	1497.7	0	501.4	130.4
25B15		15%	3.5	-	1497.7	87.9	426.4	110.8
25B27.5[4.1]	25%	27.5%	4.1	-	1497.7	161.2	363.5	94.5
25B35		35%	4.6	-	1497.7	205.2	325.9	84.7
25B55[6.6]		55%	6.6	-	1497.7	322.4	225.6	58.7
30B0[4.1]		0%	4.1	-	1545.3	0	374.5	97.4
30B15	30%	15%	4.9	-	1545.3	65.7	318.4	82.8
30B38[6.6]		38%	6.6	-	1545.3	166.4	232.2	60.4
35B0[6.6]	35%	0%	6.6	-	1592.9	0	238.9	62.1

5.2.3 SAMPLE PREPARATION AND CURING

The production of pervious concrete was performed in a drum mixer. At first, all the aggregates (coarse and fine if necessary) were added to a mechanical drum mixer with half of the water and mixed for 30 seconds. Then, the cement was added with the remaining water and mixed for another 120 seconds. After mixing, eight cylindrical samples (Ø10x20 cm) were molded to determine physical and mechanical properties. The molding process was performed in two layers using a steel rod and a vibrating table. Each layer was vibrated for 15 seconds. In the first 10 seconds, 10 strokes were manually applied simultaneously to the vibration process with the steel rod (approx. 1 per second), and finally, five additional seconds on the vibrating table were performed. The samples were demolded after 24h and then subjected to curing at room temperature with high relative humidity (RH ~ 100%) for 28 days for further testing. It is important to mention that the pervious concrete was prepared in the laboratory with controlled conditions, at 27°C and relative humidity around 65%.

5.2.4 TOTAL POROSITY AND DENSITY

Total porosity ($ø_{exp}$) and density were determined following the recommendations of ISO 17785-2 [40]. After the curing process, the samples were dry-oven until constant mass, and the dry mass (M_d) in kg was recorded. Then, the samples were submerged in water for 30 min, and their mass (M_s) in kg was noted. Considering the sample volume (V_s) in m^3 and the density of water at the temperature of the water bath (ρ_w) in kg/m^3, the total porosity ($ø_{exp}$) and density (D) were determined according to Equations (2) and (3).

$$ø_{\text{exp}}\ (\%) = \left[1 - \left(\frac{(M_d - M_s)/\rho_w}{V_s}\right)\right] \times 100 \qquad (2)$$

$$D\ (kg/m^3) = \frac{M_d}{V_s} \qquad (3)$$

5.2.5 COMPRESSIVE STRENGTH TEST

Four cylindrical samples (Ø10x20 cm) were tested in a universal test machine (maximum capacity of 200 tonnes) according to NBR 5739 [41], with a load rate of 0.45 MPa/s.

5.2.6 INFILTRATION RATE

The hydraulic characteristics of pervious concrete were measured through an infiltration rate test indicated by ISO 17785-1 [42]. The infiltration rate "k" (cm/s) is obtained through the required time "T" (s) for 2,000 cm^3 of water flow through a cylindrical sample with a cross-sectional area "S" (cm^2), according to Equation 4:

$$k\ (cm/s) = \frac{W}{S.T} \qquad (4)$$

5.2.7 LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

The attributional life cycle assessment (LCA) was conducted to assess the potential environmental impacts of pervious concrete designed with sand replacing paste volume. The LCA was performed with the 18 different formulations using the GaBi 6 software and the ecoinvent 3.8 database, following the methodology established by the standards NBR ISO 14040 [43] and NBR ISO 14044 [44] and by the ILCD System of IBICT – Brazilian Institute of Information in Science and Technology [45].

The reference flows encompass the necessary amount of raw material (by mass) to develop a functional unit, established as 1 MPa of compressive strength in 1 m³ of pervious concrete at 28 days. The reference flows analyzed in this life cycle assessment are presented in Table 5.5. The cradle-to-gate system boundaries were adopted, encompassing the extraction and transportation of raw materials, production and transportation of materials (cement, aggregates, etc.), and production of pervious concrete.

Table 5.5 - Reference flows for pervious concrete mixtures.

Mixture ID	Materials					
	Coarse aggregates (kg/MPa.m³)		Sand (kg/MPa.m³)	Cement (kg/MPa.m³)	Water (kg/MPa.m³)	Total (kg/MPa.m³)
	A	B				
25A0	71.0	0.0	0.0	23.1	6.0	100.2
25A15	65.8	0.0	3.8	18.2	4.7	92.4
25A29.5[4.4]	74.4	0.0	8.3	17.1	4.5	104.2
25A35	87.0	0.0	11.6	18.4	4.8	121.7
25A59[7.5]	170.6	0.0	38.3	22.8	5.9	237.6
30A0[4.4]	114.1	0.0	0.0	26.2	6.8	147.1
30A15	101.0	0.0	4.1	19.7	5.1	129.9
30A42[7.5]	152.9	0.0	17.2	20.3	5.3	195.7
35A0[7.5]	179.8	0.0	0.0	23.8	6.2	209.8
25B0	0.0	78.0	0.0	26.1	6.8	110.9
25B15	0.0	70.4	4.1	20.1	5.2	99.8
25B27.5[4.1]	0.0	74.9	8.1	18.1	4.7	105.8
25B35	0.0	80.0	10.9	17.4	4.5	112.8
25B55[6.6]	0.0	165.8	35.7	25.0	6.5	233.0
30B0[4.1]	0.0	113.4	0.0	27.5	7.1	148.0
30B15	0.0	107.1	4.6	22.1	5.7	139.5
30B38[6.6]	0.0	133.9	14.4	20.1	5.2	173.6
35B0[6.6]	0.0	251.3	0.0	37.7	9.8	298.8

The transport of materials was carried out on highways using trucks, and the transportation distance was adopted as an average distance from the place of extraction/production of the material to the final consumer. In the case of coarse aggregates and river sand, average transport distances of 50 km [46] and 70 km [47] were adopted, both covered by 45 t trucks. Due to the large territorial extension of Brazil, the average distance adopted for transporting cement from the cement plants to the final consumer was 500 km, covered by 32 t trucks [48]. To prepare pervious concrete, a mechanical drum mixer with 400 L capacity, with an electric motor of 1.5 kW, was considered [49].

Environmental data concerning materials, processes, and transport were obtained from the GaBi 6 software and Ecoinvent 3.8 and Ecoinvent 3.7.1 database with data of Brazilian origin. The ReCiPe 2016 Cycle Impact Assessment (LCIA) methodology (based on the midpoint method) was used to assess the potential environmental impacts of different scenarios through a hierarchical approach [50]. This methodology was chosen because it is one of the most recent, in addition to being a set that provides greater representation.

The results obtained in the LCA stage were classified and calculated and then transformed into graphs for better visualization and interpretation. The environmental impact categories analyzed were GHG emissions (in kg CO_2 eq.), photochemical ozone formation [ecosystems] (in kg NOx eq.), land use (in m^2.a), terrestrial ecotoxicity, and freshwater ecotoxicity (both in kg 1,4-DB eq.). The selection of environmental impact categories for this study was based on the materials and their potential environmental impact reported in the literature. It is important to mention that the category GHG emissions encompass emissions associated with carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are the three major gases responsible for the greenhouse effect [51]. Emissions were converted into CO_2 equivalent using the conversion factors for CH_4 and N_2O of 25 and 298, respectively.

5.2.8 COST ASSESSMENT OF PERVIOUS CONCRETE

A cost assessment was carried out, considering only the costs of the materials used in the mixture to understand the effect of sand replacing Portland cement paste volume in the final cost of pervious concrete. Fees associated with labor, transport, application, and maintenance of concrete were not computed [7] since they did not interfere with the analysis. They will be assumed the same for all concrete independently of paste volume replacement. The unit cost for raw materials (Portland cement, sand, coarse aggregate A and coarse aggregate B) were obtained by considering the current market value from local retailers in Ilha Solteira city – São Paulo, Brazil. The approximate price of water was calculated according to the local tariff of the water distribution company in Ilha Solteira city – São Paulo, Brazil.

5.2.9 MULTI-CRITERIA PERFORMANCE EVALUATION

A multi-criteria performance analysis was conducted to assist in decision making to establish the most appropriate sand replacement content in pervious concrete mixtures [7,23,52,53]. The performance of mixtures with sand were evaluated considering engineering properties, represented by compressive strength and infiltration rate besides to encompass environmental and economic aspects, represented by the GHG emissions and relative cost (RC). The multi-criteria performance analysis was conducted by the internal normalization method, as presented in Equations 5 and 6, to maintain the same scale analysis to all properties assessed. The area covered by the data on a radar chart was used to quantify overall performance of the mixtures [7,23]. For the compressive strength and infiltration rate, where increased values are desirable for better performance, the Equation 5 was employed, while for the RC and GHG emissions, where lower values represent increased performance, the Equation 6 was applied [7,23]. Both Equations are intended to normalize all data from 0 to 1, and higher normalization values reflect better performance mixtures. For example, higher normalization values will be obtained for higher compressive strength and infiltration rate (Equation 5) and for lower RC and GHG emissions (Equation 6). In both Equations, N_{ij}^{Int} represents normalization values results, a_{ij} is the performance of each measured property and $Max_i(a_{ij})$ or $Min_i(a_{ij})$ are the maximum or minimum performance observed to each group assessed [7,23]. The analysis was carried out separately for mixtures with $ø_{desired}$ of 25% and 30%, to compare mixtures.

$$N_{ij}^{Int} = \frac{a_{ij}}{Max_i(a_{ij})} \quad (5)$$

$$N_{ij}^{Int} = \frac{Min_i(a_{ij})}{a_{ij}} \quad (6)$$

5.3 RESULTS AND DISCUSSION

5.3.1 TOTAL POROSITY AND DENSITY

Figure 5.5 presents the average total porosity and density obtained according to ISO 17785-2 [40] for all pervious concrete. In this work, cement paste is replaced by sand up to 59%. However, a restrict variation of ±4% in the $ø_{exp}$ respect to the $ø_{desired}$ was adopted for this physical property in order to assess the real effect of sand replacing paste volume minimizing the influence of variation in porosity. For example, pervious concretes with 25% $ø_{desired}$ must present average $ø_{exp}$ results of 24% to 26% (variation of ±4% respect to $ø_{desired}$). Mixtures that eventually exceeded this limit were also presented in this work and their divergent behavior was properly discussed.

As seen in Figures 5.5a and 5.5b, considering the maximum established variation of 4%, the $ø_{exp}$ was considered similar to the $ø_{desired}$ for mixtures up to 38% of sand replacing paste volume, independent on the size of coarse aggregate. However, mixtures containing above 38% of sand replacing paste volume exceeded the established limit. Mixture 25A59$^{7.5}$ achieved the maximum difference, resulting to an increase in porosity of 13.6% in relation to $ø_{desired}$ of 25%. These pervious concretes do not contribute to assess the real effect of sand replacing paste volume due to the significant variation in the total porosity and, consequently, on the engineering properties such as compressive strength and infiltration rate [30]. Similar results were found in the literature [31], performing total porosity about 14% higher than reference samples when 50% sand was incorporated.

The density of pervious concrete was very similar for the mixtures with the similar total porosity, and all values were in accordance with those reported in the literature for pervious concrete [1,2,4,5]. As seen in Figure 5.5c and 5.5d, the mixtures prepared with both coarse aggregates with 25%, 30%, and 35% of total porosity, had an average density of approximately 2050 kg/m³, 1955 kg/m³, and 1850 kg/m³, respectively. The exceptions were the mixtures with the replacement of paste volume by sand above 38% (25A59$^{7.5}$, 30A42$^{7.5}$ and 25B55$^{6.6}$), which, due to their higher total porosity (exceed the fixed variation value of 4%), had a lower average density than the other mixtures. Otherwise, literature [17] reports that when sand occupies the voids instead of replacing the paste, porosity decreases and density increases, since excess sand combined with cement paste, produces a thicker coating of the aggregates, which can occupy partially voids, reducing their size. Therefore, the concept of sand incorporation (up to 38%) applied on this work allowed that both porosity and density remained constant to all mixtures tested.

In general, independently on the size of coarse aggregate, all mixtures containing above 38% of sand replacing paste volume presented significant variations, therefore being the maximum replacement limit that ensures similar porosity to the respective controls. Probably, it can be justified by the difference in particle size and specific gravity of Portland cement and siliceous sand (sand has relatively larger particles than Portland cement). Increased amounts compromise the packing of the particles, increasing the voids in the paste and impairing the bond between the coarse aggregate particles, causing an increase in porosity and a decrease in the density of pervious concrete. Similar behavior was reported in the literature for pervious concrete produced using 50% sand replacing Portland cement [31].

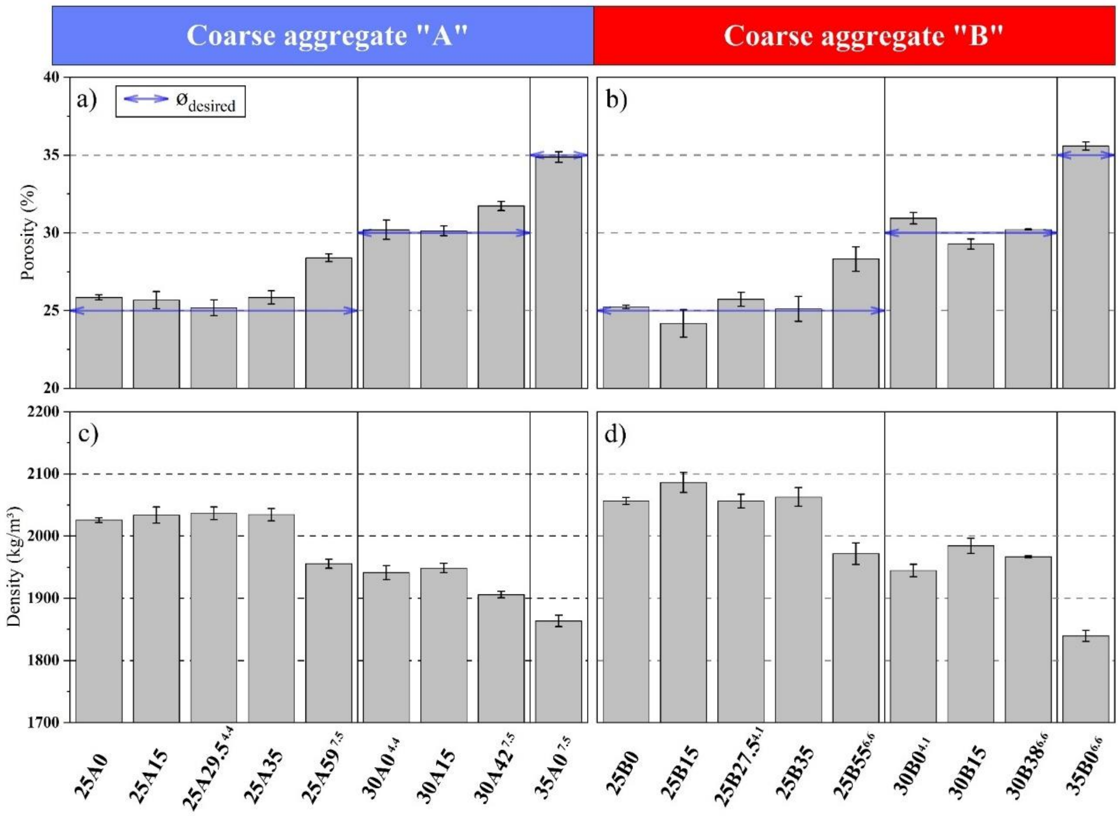

Figure 5.5 - Total porosity and density for pervious concrete: a) total porosity of mixtures using coarse aggregate “A”; b) total porosity of mixtures using coarse aggregate “B”; c) density of mixtures using coarse aggregate “A”; d) density of mixtures using coarse aggregate “B”.

5.3.2 COMPRESSIVE STRENGTH

Figure 5.6a and Figure 5.6b present the average compressive strength for all pervious concrete mixtures made with coarse aggregates A and B. For a given similar total porosity, aggregate size does not significantly influence the compressive strength of pervious concrete without sand replacing paste volume achieving about 20.0 MPa and 15.0 MPa for a $ø_{desired}$ of 25% and 30%, respectively. Only for a $ø_{desired}$ of 35% a difference of 27.4% on the compressive strength could be detected. Similar behavior was reported by Zhong and Wille [54], where the authors justified the lower compressive strength of larger coarse aggregates to the presence of a lower number of pores with increased size, with a consequent reduction in the contact area per unit volume.

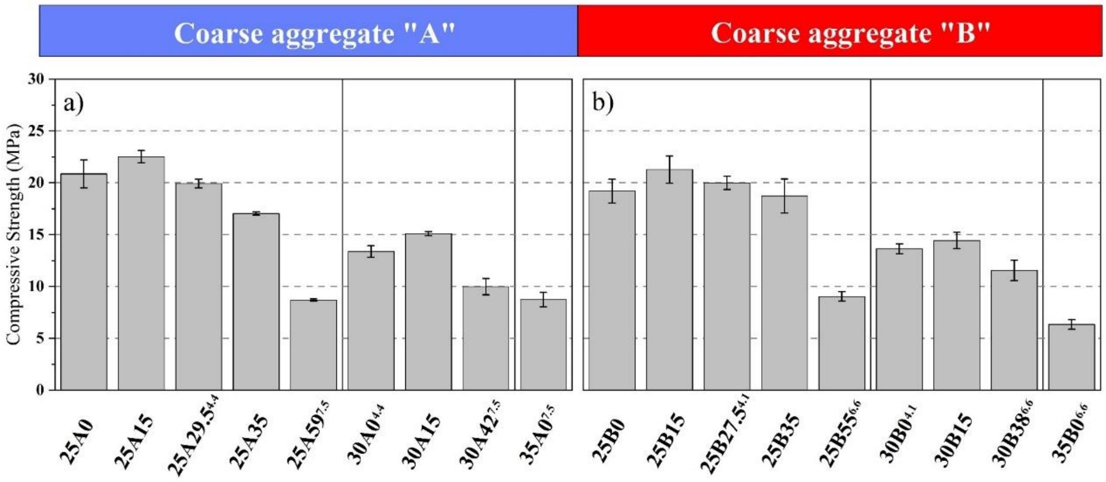

Figure 5.6 - 28-days average compressive strength for pervious concrete: a) using coarse aggregate “A”; b) using coarse aggregate “B”.

In general, compressive strength remained similar to the respective controls, for mixtures containing coarse aggregate A, with sand replacing paste volume up to 29.5% and for coarse aggregate B with sand replacing paste volume up to 38%, for a fixed $ø_{desired}$ (25 % and 30%) even presenting significant lower Portland cement consumption. This fact could be justified by the contribution of fine aggregates on the Portland cement hydration, reducing the capillary pores and contributing to the densification and the strengthening of the matrix [31,55,56]. Coarse aggregate A seems to be more sensitive to high percentages of sand replacing cement paste. For 35% sand replacement it was observed a slight reduction in compressive strength (from 20.9 to 17.0 MPa) when compared to its reference 25A0. This reduction was negligible for coarse aggregate “B” (from 19.2 to 18.7 MPa). This behavior could be explained by the larger pore size of pervious concrete using coarse aggregate “B”, which allows an improved arrangement of a high volume of sand [36].

In the literature, pervious concrete with 10% replacement of paste volume by sand presented increments up to 36% in compression. Nevertheless, this increment is probably associated with the reduction in the total porosity (about 12%), and due to the enhancement of the bonding and interlocking of the aggregates promoted by the increased paste thickness [26]. This enhanced behavior was not observed in our study because no significant changes on the total porosity (variation of $ø_{desired}$ respect to $ø_{exp}$) were observed up to 38% sand incorporation (see Figure 5.5a and Figure 5.5b).

Increased replacement levels higher than 38% of sand, besides exceeded the $ø_{desired}$, were also associated with diminishing in compressive strength, even for coarse aggregate “B”. Although it has been possible to prepare such mixtures, the literature and results demonstrated that compressive strength could be reduced up to 27% when 50% sand replaced Portland cement [31] while this decrease reached 58.3% for the $25A59^{7.5}$ mixture (59% sand replacing paste volume) compared to the respective control mixture. It could be explained by the reduction of the binder/aggregate ratio in the mixture which could weaken the cement paste and, consequently, the coarse aggregate bonds [57].

As mentioned in section 2.2., a complementary analysis can be performed for mixtures containing similar coarse aggregate/Portland cement mass ratio (“W” values). For a similar “W”, the 28-day compressive strength for all mixtures containing sand were similar or even higher than their respective reference sample. As observed, $25B55^{6.6}$ and $30B38^{6.6}$ mixtures, even presenting similar Portland cement consumption to mixture $35B0^{6.6}$, these mixtures showed an increment in the compressive strength of 42.4% and 81.9%, respectively. This fact indicates that for a similar coarse aggregate/cement mass ratio, the incorporation of fine aggregate enhances the compressive strength of pervious concrete. Furthermore, this demonstrates that when the incorporation of sand promotes the reduction of porosity, mechanical properties consequently increase, which is also reported in the literature [30,58,59].

5.3.3 INFILTRATION RATE

Figure 5.7a and Figure 5.7b are depicted the infiltration rate results for all assessed pervious concrete. In general, for a similar $ø_{desired}$, pervious concrete containing coarse aggregate "B" presented an increased infiltration rate with respect to pervious concrete with coarse aggregate "A". This difference is more notable for higher $ø_{desired}$, yielding a 63.1% increment comparing the mixture $35B0^{6.6}$ to $35A0^{7.5}$. The increased pores size can explain it with consequent enhanced pore-connectivity for pervious concretes with the largest coarse aggregate [37,60].

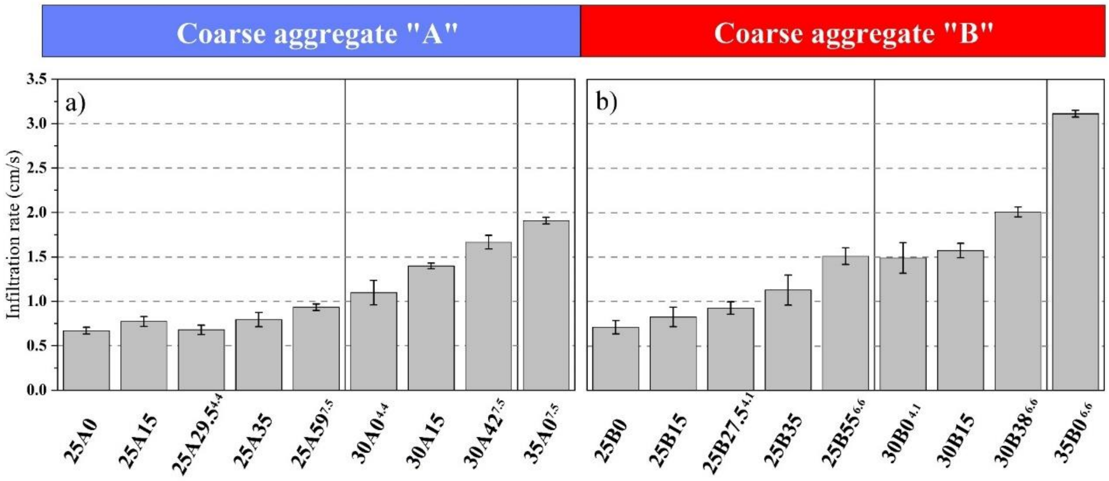

Figure 5.7 - 28-days average infiltration rate for pervious concrete: a) using coarse aggregate "A"; b) using coarse aggregate "B".

In general, the use of sand replacing paste volume seems to contribute to a slight increase in the average infiltration rate for pervious concrete prepared with A and B coarse aggregates. This behavior is more pronounced for increased sand replacing paste volume and higher total porosity of pervious concrete for both aggregates. It is probably due to the changes in the pore-structure, caused probably by the lack of cement in the mixture, which generates changes in the bonding among the particles.

It is reported in the literature that the incorporation of fine aggregates (up to 33.3%) replacing Portland cement leads to a reduction in the infiltration rate between approximately 10 to 54% in relation to not containing fine aggregate mixtures [26,30,31]. However, this behavior is associated with the total porosity reduction reported by the authors (up to 20% reduction). This different approach reported in the literature demonstrates that the pore structure is modified differently. When cement paste is not removed from the mixture, the insertion of sand contributes to the increase in paste volume that involves the aggregates and occupies more spaces between the aggregates and therefore contacts between particles increase, reducing infiltration rate [61,62]. As shown in Figure 5.5, mixtures with up to 38% replacement of paste volume by sand did not show a significant decrease in porosity, which reflected in hydraulic performance different from that observed in the literature. Therefore, the way in which fine aggregates are incorporated leads to different changes in the porous structure of the mixtures [63].

Mixtures that exceeded porosity due to sand incorporation (above 38% sand replacing paste volume) had the infiltration rate increased as porosity increased. Literature demonstrated that for 50% sand replacing Portland cement, infiltration rate could increase up to 45.5% [31], similar to increase observed to mixture $25A59^{7.5}$(39.4%), while it increased twice for the $25B55^{6.6}$ mixture (55% sand replacing paste volume) in relation to the respective control. This behavior is associated with the direct relationship between infiltration rate and total porosity widely observed in the literature [37,60,62].

As expected, the mixtures containing similar coarse aggregate/Portland cement mass ratio (“W”) presented expressive variations in their infiltration rate when sand is incorporated. For example, a significant reduction from 1.097 to 0.679 cm/s was observed for mixture $25A29.5^{4.4}$ compared to $30A0^{4.4}$. This value represents 38.1% of reduction due to the sand incorporation. It is essential to state that all assessed mixtures, even presenting a reduction in the infiltration rate, achieved similar values to those found in the literature (0.7-2.0 cm/s) and higher than the minimum established in the Brazilian standard [6,26,64].

5.3.4 CEMENT CONSUMPTION ANALYSIS

The optimization of pervious concrete mixture design is an issue that has been addressed due to its importance, mainly to obtaining functional mixtures in terms of applicability, economy, and sustainability [36,39,57,65–67]. The consumption of cement from pervious concrete is sometimes higher than that from conventional concrete depending on the required mechanical properties. This occurs precisely to compensate the absence of fines that guarantees the interconnected porosity. As addressed in the previous sections, the partial replacement of paste volume by sand in pervious concretes could be suitable for maintaining the mechanical properties with no significant changes on the hydraulic properties. Cement is associated with most of the concrete production costs and emissions of polluting gases [68–70]. Therefore, a reduction in the Portland cement consumption is desired as long as mechanical and hydraulic properties are maintained.

The efficiency of replacing paste volume by sand can be evaluated by observing the consumption of cement per cubic meter of pervious concrete produced in relation to the mechanical strength obtained without causing damage to hydraulic properties. Figure 5.8 presents a graphical comparison between cement consumption, compressive strength, and infiltration rate at 28 days of a selection of literature-reported pervious concretes without incorporating supplementary materials. Additionally, in the same Figure (Figure 5.8), the results from our study are depicted: the pervious concrete controls (25A0, $30A0^{4.4}$, $35A0^{7.5}$, 25B0, $30B0^{4.1,}$ and $35B0^{6.6}$) and the pervious concrete evaluated in this research with the incorporation of sand replacing paste volume up to 38%, it means, pervious concrete with ø$_{exp}$ similar to the ø$_{desired}$ (variation lower than 4%). The mechanical data obtained from the literature includes conventional pervious concrete with porosities between 16.8% to 31%.

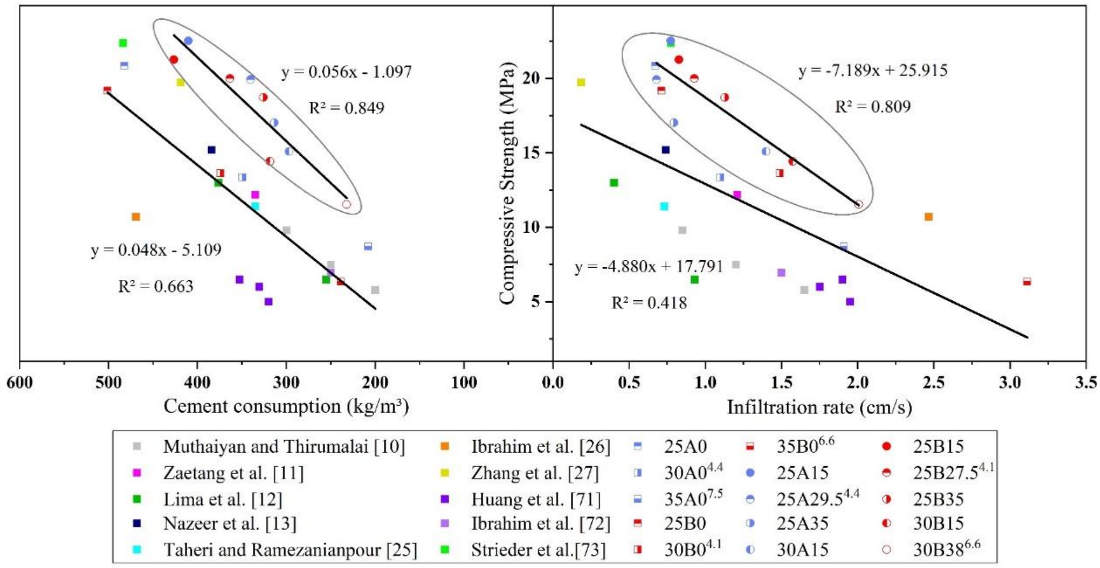

Figure 5.8 - Comparison of cement consumption with compressive strength (left) and with infiltration rate (right) for 28 days literature-reported pervious concretes (without sand or other supplementary materials) and obtained results from this research.

A linear fit was drawn for the conventional pervious concrete reported in the literature relating cement consumption with compressive strength (R^2=0.663) and infiltration rate with compressive strength (R^2=0.418). The significant scattering data of literature can be assigned to the different materials, mix designs, compaction process used by each author.

Otherwise, almost all mixtures with sand up to 38% of paste volume replacement (obtained in this study) remained above the literature-reported mixtures, and a linear fits with R^2>0.8 was obtained from the data. In Figure 5.8, is shown that cement consumption is strongly related to mechanical performance. Comparing the linear regression parameter (both linear and angular coefficient) of literature-reported mixtures with the obtained data for pervious concrete using up to 38% of sand replacing paste volume, it is possible to estimate an increment in the compressive strength in the range 6-8 MPa for pervious concrete containing sand. Moreover, more than 100 kg/m^3 of cement can be saved for a similar compressive strength.

As the infiltration rate can be more sensitive to several parameters such as porosity, type, shape, size of aggregate, connectivity, and tortuosity of pores, etc. [2,3,6], in practice, the infiltration rate shows greater dispersion. Nevertheless, for a similar compressive strength, an increment on the infiltration rate for pervious concrete containing sand could be detected. This fact is relevant on the design of pervious concrete pavements.

5.3.5 LIFE CYCLE ASSESSMENT (LCA)

This section of the research presents life cycle assessments and a comparative analysis of the different formulations for concrete designed with sand replacing paste volume. The method used was ReCiPe 2016 methodology (midpoint method) with a hierarchical approach [50].

Figures 5.9a and 5.9b present the results of all pervious concretes for the GHG emissions impact category. The results are presented in kg CO_2 eq. per functional unit (MPa.m^3). Portland cement was the component material that most contributed to the emission of CO_2 eq., representing 83.9% to 93.5% of the impacts, considering all the 18 mixtures designed. The results were similar to those reported by the literature [7–9]. The most significant contribution of Portland cement is attributed to clinker production, where approximately 0.9 kg of CO_2 is emitted for each kg of cement [74]. The reduction in GHG emissions was significant since the other items used for preparation (coarse aggregates, sand, water, and electricity) have much lower GHG emissions than Portland cement. The emissions generated from these components are mainly associated with collection/extraction/transport, which are fewer polluting processes in relation to clinker production [75].

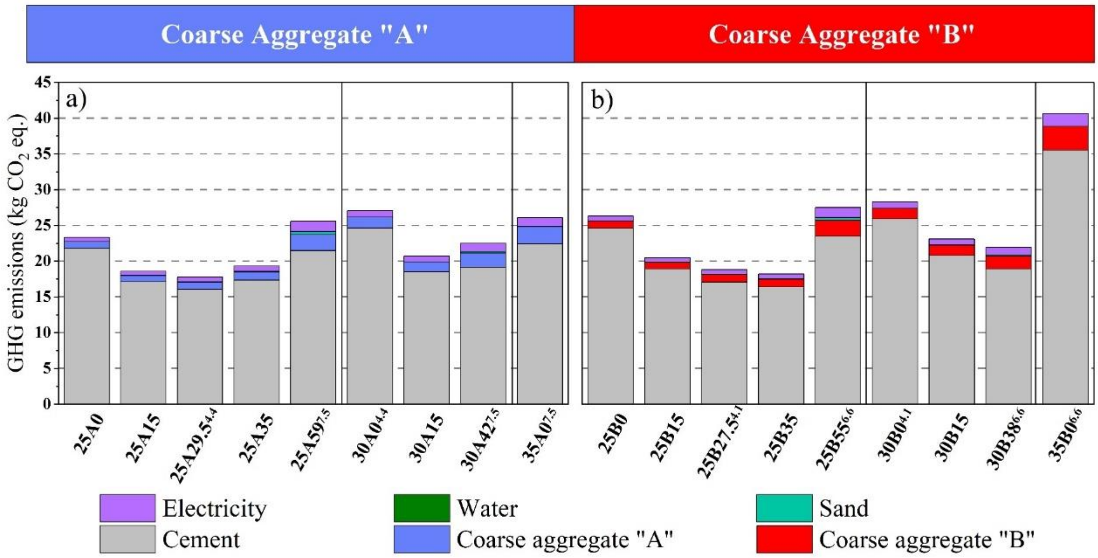

Figure 5.9 - Environmental impact contribution to the GHG emissions category, including biogenic carbon, for pervious concretes with: a) coarse aggregate “A” and b) coarse aggregate “B”.

As expected, coarse aggregate A or B and the $ø_{exp}$ did not significantly influence the total CO_2 equivalent emissions. It seemed to be more sensitive to the replacement of paste volume by sand. Mechanical strength was considered an important parameter, since the lower the mechanical strength, the greater amount of material will be necessary to reach an established efficiency, e.g., $35B0^{6.6}$ that reached the lowest compressive strength and was responsible for the highest equivalent CO_2 emissions per MPa yielded (40.6 Kg CO_2 eq./MPa.m^3). For both A and B coarse aggregates used, the replacement of paste volume by sand demonstrated a reduction of 16.7% to 30.7% in CO_2 equivalent emissions for mixtures with 15% to 42% replacing paste volume by sand compared to the respective controls (25A0, $30A0^{4.4}$, 25B0 and $30B0^{4.1}$). The combined and balanced effect of reducing the amount of Portland cement with no or little reduction in mechanical strength reduced GHG emissions, making the mixtures more environmentally efficient. From the analysis, partial incorporation of fine aggregate is strongly advised for more efficient mixture designs, since CO_2 emissions can cause various effects across the planet, due to climate change, such as species extinction, loss of biodiversity, melting glaciers with a consequent rise in sea level, fires, human health problems, among others [50]. Chen et al. [23] reported the reduction of GHG emissions by replacing cement in pervious concrete. In this case, cement was replaced by fly ash and blast furnace slag (15wt.% and 25wt.%, respectively), reducing 14% and 22% in GHG emissions, respectively. In our study, although sand is a raw material, the replacement of paste volume by sand could efficiently contribute to the reduction of emissions, when properly incorporated into pervious concrete (percentages lower than 42%).

Only mixtures above 42% sand were more polluting than the respective controls due to the low mechanical strength caused by the large amount of binder replaced by sand with consequent modification in the total porosity. This demonstrated that even though the incorporation of more sand reduces cement consumption, the internal structural changes could modify the key properties of pervious concretes [63], making this mixture less environmentally friendly.

In addition, the environmental impacts associated with Photochemical Ozone Formation (P.O.F.) [Ecosystems], Land use, terrestrial ecotoxicity, and freshwater ecotoxicity were measured and are presented per functional unit (MPa.m^3) in Figure 5.10. Portland cement was the main responsible for the environmental impacts assessed, with global impact ranging from 36.4% to 84.1% considering all categories depicted in Figure 5.10.

The production and transport of clinker contribute to the emission of several NMVOCs (non-methane volatile organic compounds). Among them, nitrogen oxides (NOx) are the main contributors to Photochemical Ozone Formation (P.O.F.). As the emission is mainly associated with the burning of fossil fuels [76], the use of both A or B coarse aggregates also contributed significantly to the emission of NOx (from 17.5% to 34.6%) since all extraction, crushing, and transport processes require fossil fuel. Sand, water, and electricity did not significantly contribute to the photochemical ozone formation in relation to cement and coarse aggregates, as they require less use of fossil fuels in their processes.

Since Portland cement strongly contributes to NOx emissions, the replacement of paste volume by sand provided a reduction in photochemical ozone formation. The results were similar to those obtained for GHG emissions, achieving a decrease of 6.6% to 25.6% in NOx emission when 15% to 42% of paste volume was replaced by sand for both A and B aggregates. It was caused due to less contribution of sand to the NOx emissions rate than cement. For higher replacement contents, above 42% sand, emissions were up to 30.2% higher than the respective controls. This worsening was caused due to an accentuated decrease in mechanical strength, as total porosity did not meet $ø_{desired}$. Reducing NOx emissions is vital since ozone can be inhaled by the human population or absorbed by plants, leading to increased human mortality, harmful effects on plant species, and ultimate damage to human health and ecosystems [50].

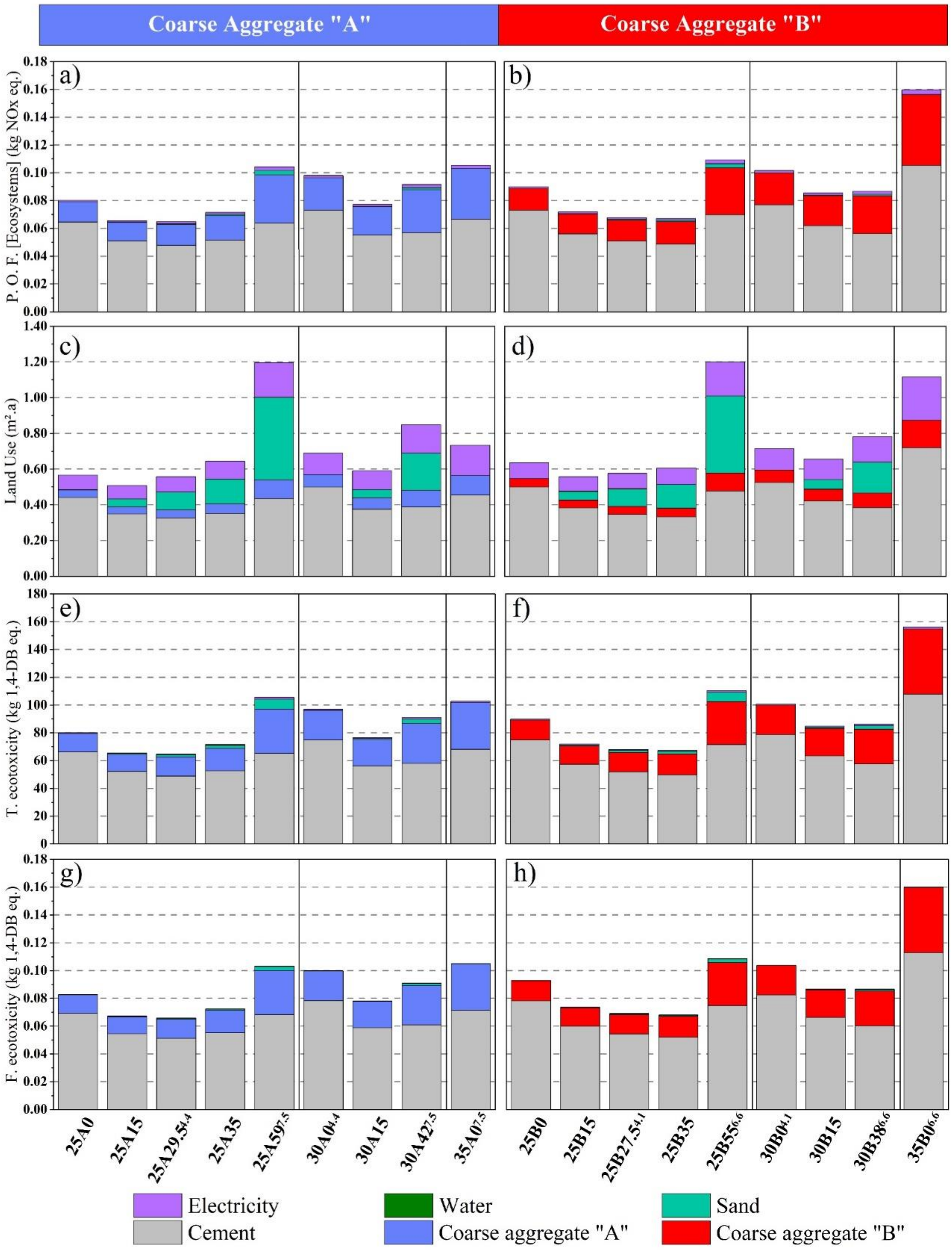

Figure 5.10 - Environmental impact contribution for pervious concretes to: a) P.O.F. [Ecosystems] with coarse aggregate “A”; b) P.O.F. [Ecosystems] with coarse aggregate “B”; c) Land use with coarse aggregate “A”; d) Land use with coarse aggregate “B”; e) Terrestrial ecotoxicity with coarse aggregate “A”; f) Terrestrial ecotoxicity with coarse aggregate “B”; g) Freshwater ecotoxicity with coarse aggregate “A”; h) Freshwater ecotoxicity with coarse aggregate “B”.

Both cement and sand strongly contribute to the land use category when used in significant amounts (sand contributed up to 38.8%). The significant impact on land use, expressed in area time (m^2.a) in Figures 5.10c and 5.10d, is justified by the extraction of raw material for the manufacture of cement, such as limestone and clay, as well as for sand, which promotes occupation and transformation of the soil. Special attention should be given mainly to the impact caused by limestone mining processes for cement production, which may be responsible for the release of chemicals, causing negative impacts on the environment and reaching local, regional or even global scales [77]. Electricity also contributed significantly, accounting for 14.2% to 23.3% of land use impact. In Brazil, a significant amount of electricity comes from hydroelectric power plants. Land use is strongly impacted due to the large areas occupied for its construction and operation [78]. Coarse aggregates demonstrate a low contribution to land use (7.4% to 14.9%) but without significantly influencing the different mixtures since their use is fixed. Water practically did not affect land use.

Although cement and sand contribute significantly to land use impact, the replacement of 15% to 29.5% proved beneficial in mixtures with both coarse aggregates. Land use reduction reached 14.0% for the 30A15 mixture. Considering that the abovementioned mixtures present similar mechanical strength, the enhanced environmental performance can be associated with the larger environmental impact of Portland cement compared to sand for a similar amount (approximately 34% higher). Above 35% replacement, the mixtures were more impactful in terms of land use. This impact category must be considered because it mainly affects the balance of ecosystems and may be associated with the extinction of several species [50].

Environmental impacts for both terrestrial (See Figures 5.10e and 5.10f) and freshwater ecotoxicity (See Figures 5.10g and 5.10h) categories were expressed in kg 1,4-dichlorobenzene equivalents (1,4-DB). Coarse aggregates were the most responsible after cement for the impact in both categories, contributing from 15.7% to 32.6%. Substances responsible for terrestrial ecotoxicity are emitted mainly from the exhaustion of burning fossil fuels [79] necessary for the extraction, transport, and crushing of coarse aggregates and the raw material required for the manufacture of clinker, as well as the calcination process [80]. Sand, water, and electricity did not contribute significantly to the impact in both categories (less than 3.2%).

The replacement of paste volume by sand from 15% to 42% efficiently reduced 6.2% to 26.8% of terrestrial and freshwater ecotoxicity impact caused by the control mixtures. As already observed for the other categories, the decrease in mechanical strength in mixtures with higher levels of sand incorporation caused a loss of environmental efficiency, increasing the impact up to 32.0%, as observed for mixture $25A59^{7.5}$ in the terrestrial ecotoxicity category, corroborated by the $35B0^{6.6}$ mixture, which showed low mechanical strength and was the mixture with the highest impact on both terrestrial and freshwater ecotoxicity. Although terrestrial ecotoxicity was more pronounced than freshwater for pervious concrete mixtures, the analysis was relevant since both categories are mainly associated with the damage to some species arising from toxic substances emitted into the water, air, and soil, thus affecting the balance of the ecosystem [50].

5.3.6 COST ASSESSMENT OF PERVIOUS CONCRETE

Table 5.6 presents the cost composition of each material constituting the concrete per cubic meter for all pervious concrete mixtures.

Table 5.6 - Cost of pervious concrete materials per cubic meter.

Mix ID	Coarse aggregates ($/m³)		Sand ($/m³)	Cement ($/m³)	Water ($/m³)	Total ($/m³)
	A	B				
25A0	25.69	-	0	85.84	0.14	111.67
25A15	25.69	-	0.98	72.98	0.12	99.76
$25A29.5^{4.4}$	25.69	-	1.92	60.53	0.10	88.23
25A35	25.69	-	2.28	55.81	0.09	83.87
$25A59^{7.5}$	25.69	-	3.84	35.19	0.06	64.78
$30A0^{4.4}$	26.44	-	0	62.18	0.10	88.72
30A15	26.44	-	0.71	52.86	0.09	80.09
$30A42^{7.5}$	26.44	-	1.98	36.06	0.06	64.54
$35A0^{7.5}$	27.20	-	0	37.02	0.06	64.28
25B0	-	25.79	0	89.20	0.14	115.14
25B15	-	25.79	1.02	75.86	0.12	102.79
$25B27.5^{4.1}$	-	25.79	1.86	64.67	0.10	92.43
25B35	-	25.79	2.37	57.98	0.09	86.24
$25B55^{6.6}$	-	25.79	3.72	40.14	0.07	69.72
$30B0^{4.1}$	-	26.61	0	66.63	0.11	93.35

30B15	-	26.61	0.76	56.65	0.09	84.11
30B38$^{6.6}$	-	26.61	1.92	41.31	0.07	69.91
35B0$^{6.6}$	-	27.43	0	42.50	0.07	70.00

The pervious concrete mixtures evaluated in this research presented relatively low material costs since the typical material cost for preparing conventional Portland cement pervious concretes ranges from approximately 140 to 425 \$/m³, according to the literature [81]. Portland cement is the most expensive material constituent of conventional pervious concrete. Mixtures with more paste volume, which are less porous, were the most expensive. For both aggregates, the control mixtures with 25% porosity cost approximately \$110-115, while the mixtures with 30% and 35% porosity had a cost reduction of approximately 20% and 40% respectively. Although very economical and more permeable, it must be taken into account that mixtures with reduced paste volume present lower mechanical efficiency [6].

The production cost of pervious concrete associated with the materials used appears to be substantially reduced by replacing paste volume by sand maintaining the same total porosity. For both A and B coarse aggregate used, replacing paste volume by sand up to 38% provided cost savings in materials of approximately \$8.60 to \$28.90, depending on the amount of sand used. It represents a reduction of approximately 10-25% in the cost of materials used to produce concretes with similar characteristics. It can be inferred that sand incorporation contributed to this reduction in Portland cement consumption through optimization between binder and fine aggregate.

The cost reduction was even more significant, above 38% sand replacement (in the case of mixtures 30A42$^{7.5}$, 25A59$^{7.5}$, and 25B55$^{6.6}$), achieving savings of up to 42% for 25A59$^{7.5}$. However, these mixtures did not reach the desired porosity due to excess replacement of paste volume by sand, and experienced a decrease in mechanical resistance of up to 58.3%. This could result in less efficient mixtures depending on the application desired.

Another way of evaluating the efficiency of replacing paste volume by sand is through the relative cost (RC), defined by the ratio of the total economic cost of material per m³ to the compressive strength reached by each mixture. Figures 5.11a and 5.11b show calculated RC values for all samples.

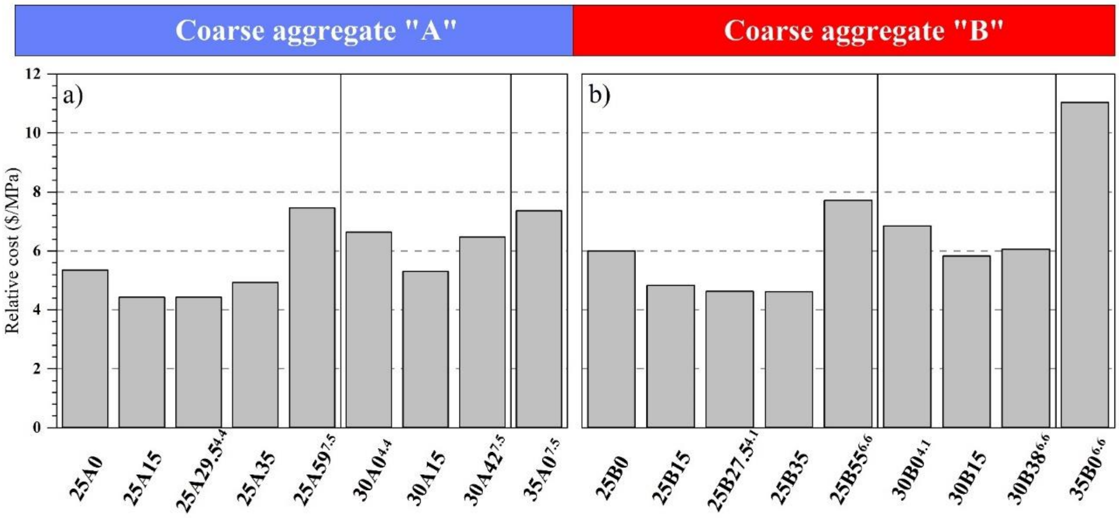

Figure 5.11 - Relative cost calculated for pervious concrete mixtures: a) coarse aggregate “A”; b) coarse aggregate “B”.

Although production costs are lower for mixtures with higher porosity, compressive strength is either highly sensitive to porosity. So, the decrease in compressive strength by increasing porosity increases the RC even in the control samples. 25A0 and 25B0 reached similar RC of 5.35 and 5.99 $/MPa, while 35A0$^{7.5}$ and 35B0$^{6.6}$ increased to 7.37 and 11.04 $/MPa, respectively.

The incorporation of sand significantly reduced the RC of the mixtures in relation to the control mixtures. Samples with 25% porosity achieved the lowest cost efficiency, reaching the minimum of 4.43 $/MPa for 25A15 and 25A29.5$^{4.4}$, representing a decrease of 17.3% in relation to the respective control 25A0. All 25% porosity samples for both A and B groups achieved RC lower than 5.00 $/MPa when sand was replaced from 15 to 35%.

The mixtures with 30% porosity presented RC higher than 25% porosity, although the replacement of paste volume by sand also improved the economic cost. 30A15 and 30B15 reached 5.31 and 5.83 $/MPa, values 20.1% and 14.9% lower than the respective 30A0$^{4.4}$ and 30B0$^{4.1}$ controls. Similarly, 30B38$^{6.6}$ achieved RC 11.6% lower than the control. The decreased RC is provided due to the lower cost of sand compared to cement [82] and the satisfactory mechanical performance obtained through replacing paste volume with sand up to a limited percentage (up to 38%).

Above 38% of sand, apparently RC is increased. 30A42$^{7.5}$ had a similar RC to the respective control, while the 25A59$^{7.5}$ and 25B55$^{6.6}$ presented an increase of 39.2%

and 28.7%, respectively, to the 25% porosity controls due to reduced compressive strength.

5.3.7 MULTI-CRITERIA PERFORMANCE EVALUATION

A multi-criteria analysis was carried out to evaluate the best performances, considering the incorporation of sand. In this performance analysis porosity was considered a fixed parameter, so only mixtures presenting similar total porosity (variation of ±4% respect to $ø_{desired}$ considering 25% and 30% porosity) were included. The multi-criteria analysis was performed using the compressive strength, infiltration rate, GHG emissions, and the relative cost. The results are shown in the radar chart in Figure 5.12. The best overall performance of pervious concrete is represented by the larger area covered on the radar chart [7,23]. The obtained area for each mixture was calculated and these values are shown in Table 5.7.

For all cases analyzed, all mixtures containing sand outperformed the respective controls (without sand) with an increase of at least 12.9% in the area on the radar chart. Interestingly, for coarse aggregate A (finer grain size), the mixtures that achieved better performance had 15% sand replacing cement paste volume, achieving coverage areas of 1.93 and 2 for 25% and 30% of total porosity, respectively. It represents an increase in area covered up to 53.2% (30A15). Otherwise, around 35-38% of the replacement of cement paste volume by sand achieved the best overall performance for coarse aggregate B. The areas covered on the radar chart were 1.88 and 1.76 for mixtures 25B35 and 30B38$^{6.6}$, respectively, representing a maximum increase of 70.2% (25B35).

The results have demonstrated that the changes in the structure and arrangement of the pores, due to the particle size of coarse aggregates, can influence the ideal percentage of sand replacing paste volume to achieve the best balance among assessed properties [83]. A coarse aggregate with larger grains appears to support a greater amount of sand without significantly weakening its properties. For example, through the radar chart, it was visualized that the compressive strength of mixtures with around 35% of sand replacing cement was more strongly reduced for coarse aggregate A, compared to B, contributing to the reduction of the area covered by the radar chart. So, it can be inferred that the specificities of each mixture will determine the ideal amount of sand incorporated to obtain the most technically, environmentally, and economically efficient mixture.

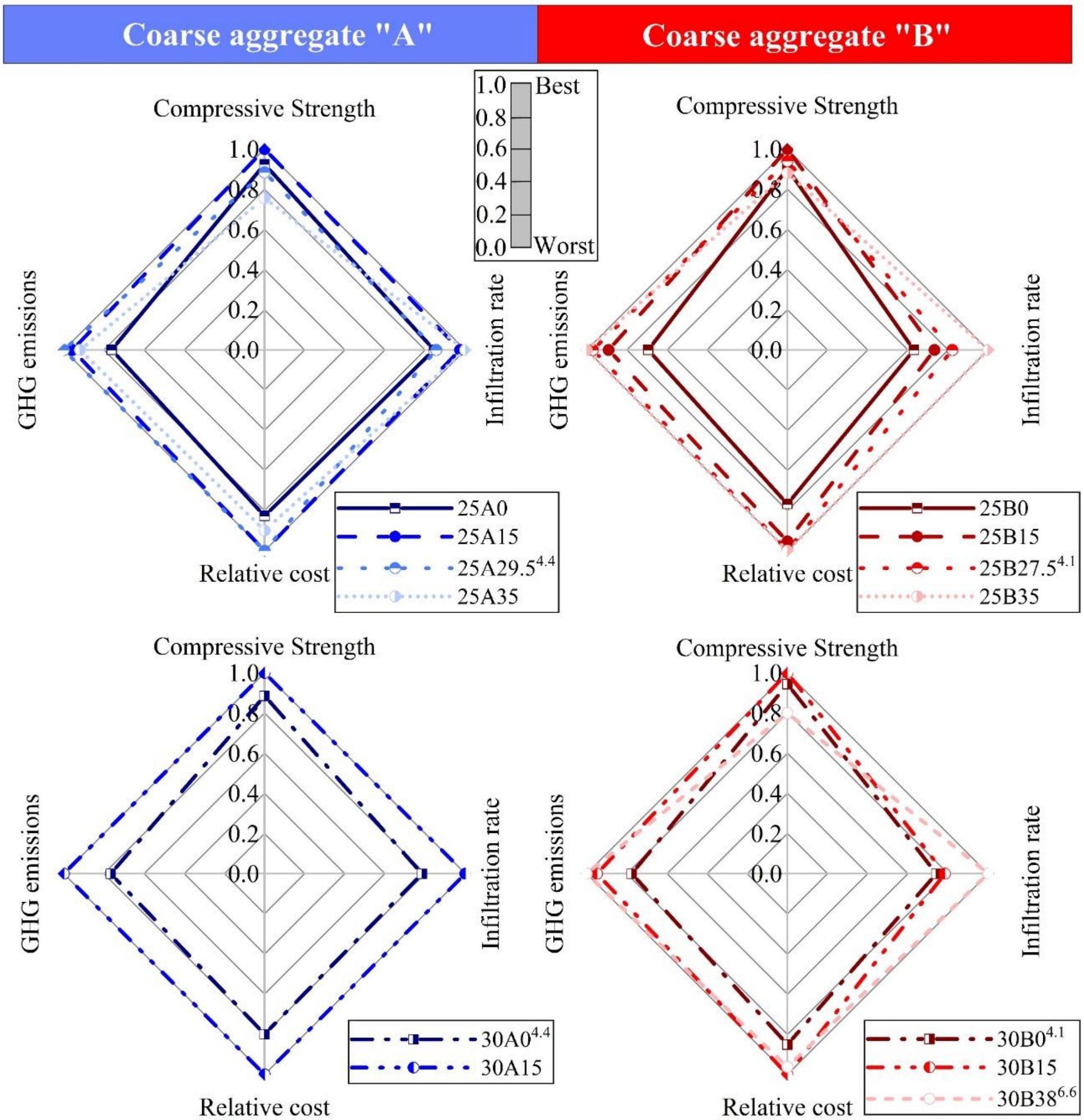

Figure 5.12 - Multi-criteria performance evaluation for pervious concrete mixtures replacing cement paste volume by sand at 25% and 30% porosity represented by radar chart.

Table 5.7 - Area calculated for each mixture assessed on the multi-criteria performance evaluation.

Coarse aggregate A			Coarse aggregate B		
Mixture ID	**Area**	**% increased***	**Mixture ID**	**Area**	**% increased***
25A0	1.41	Reference	25B0	1.11	Reference
25A15	1.93	37.2	25B15	1.58	43.4
25A29.5[4.4]	1.75	24.4	25B27.5[4.1]	1.73	56.9
25A35	1.59	12.9	25B35	1.88	70.2
30A0[4.4]	1.31	Reference	30B0[4.1]	1.36	Reference
30A15	2.00	53.2	30B15	1.73	27.2
-	-	-	30B38[6.6]	1.76	29.4

* Percentage increased in relation to respective control mixture

5.4 CONCLUSIONS

The replacement of paste volume by sand was tested in different percentages up to 59% for pervious concrete. Physical and engineering properties, environmental issues, and cost analysis were assessed. From this study it can be concluded that:

- Incorporating sand up to 38% of replacement to the paste volume does not significantly interfere with the total porosity and density of pervious concrete mixtures (total porosity deviated less than 4%). It is therefore suggested that there is a limit replacement (in this case, approximately 38%) at which the packing of the particles is compromised, increasing the voids in the mixture, causing an increase in total porosity and a decrease in the density.
- The results demonstrated that sand could replace paste volume by up to 38% without significantly losing mechanical and hydraulic properties. Although it is possible to prepare mixtures with more than 38% sand replacing the paste volume, there was a reduction in compressive strength and an increased infiltration rate, probably associated with the low amount of binder, compromising the bond between the particles and the increase in the total

porosity of the mixtures. So, the real effect of sand became compromised by these others factors.

- Partial replacement of paste volume by sand up to 38% could increase the compressive strength (approximately 6-8 MPa) for the same cement consumption. From another perspective, it means about 100 kg/m³ of Portland cement could be saved without changes in the compressive strength, compared with ordinary pervious concrete reported in the literature. In the same way, for a similar compressive strength, enhanced infiltration rate was achieved for proposed concretes.
- The life cycle assessment showed that Portland cement was primarily responsible for environmental impacts, contributing up to 93.5% of CO_2 emissions. All assessed categories recorded a reduced environmental impact when sand replaced paste volume by up to 29.5%. Even for the land use category, in which sand promotes a significant impact, a reduction of up to 14.1% was observed. Furthermore, GHG emissions could be reduced by up to 30.7%. Additionally, replacing paste volume with sand in percentages up to 38% provided cost savings in materials around 10-25% and a reduction on RC up to 20.1% compared to the respective control mixture.
- Through multi-criteria performance evaluation, it can be observed that 15% sand replacing paste volume for coarse aggregate A led to the best overall performance. In contrast, this value was around 38% for coarse aggregate B. This demonstrates that the ideal incorporation of fine aggregate replacing paste volume depends on the materials used and their structural arrangement.

The obtained results in this experimental study demonstrates that pervious concrete with minimal alterations in the total porosity can be produced, allowing a thorough assessment of the real effect of fine aggregate replacing cement paste volume. However, there is a limit of replacement, after which the porosity undergoes significant changes, influencing the other properties of the pervious concrete. The results indicate that fine aggregates are strongly recommended to optimize the efficiency of pervious concretes and its incorporation up to 38% is recommended in producing sustainable pervious concrete. Besides providing economic and environmental-friendly benefits for pervious concrete, the use of fine aggregates does not affect mechanical and hydraulic properties. The mix design methodology used in this study presents an accurate performance for producing pervious concrete using sand replacing paste volume without significant changes in the total porosity. Considering that the ideal amount of sand is influenced by the grain size of the coarse aggregate, future studies encompassing different types of coarse aggregates and different grain sizes of fine aggregate could be performed to extend the use of fine aggregates, in order to optimize pervious concrete mixtures and promote the dissemination of its application.

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CHAPTER 6 – GENERAL CONCLUSIONS

This study evaluated the replacement of Portland cement in pervious concrete by SCMs from sugar cane wastes and by fine aggregate and the following general conclusions can be drawn:

- The replacement of 10 wt.% of cement by SCBA showed similar or even better mechanical behavior than samples with 100% Portland cement (control groups). For a binder:aggregate mass ratio of 1:5.0 was reached 13.2 MPa on compressive strength compared to 10.6 MPa for respective control group. Although slightly inferior to SCBA, SCSA could be efficient in mixtures with lower binder:aggregate ratio when incorporated at 10 wt.%, similar to the effect caused by the incorporation of RHA (about 12.2 MPa).
- The incorporation of both SCBA and SCSA, without compromising the mechanical properties, should be associated with a limit, which in this case was 10-15 wt.%, for tests with binder:aggregate mass ratio of 1:5.0. Different materials, binder:aggregate mass ratio or even mixture design concept could change this optimal range to provide better performance.
- Similarly, the use of fine aggregates could substantially reduce the amount of Portland cement to produce previous concrete. Up to about 38% sand could be incorporated replacing cement paste volume, without causing significant reduction in mechanical and hydraulic properties. A systematic comparison with conventional pervious concretes obtained in the literature demonstrated that cement consumption can be reduced by up to 100 kg/m^3 in concretes with similar mechanical and hydraulic properties. Excessive amount of sand (above 38%) represents low amount of binder, which compromises the bond between the particles, causing a reduction in density, increased porosity, which leads to a decrease in mechanical properties.
- The environmental analysis of the material, obtained through LCA, demonstrated that the sand incorporation replacing cement paste led to lower environmental impact when compared to mixtures with only Portland cement at all categories assessed. The analysis demonstrated that the impact categories GHG emissions, Photochemical Ozone Formation (P.O.F.) [Ecosystems], terrestrial ecotoxicity, and freshwater ecotoxicity benefited when it was replaced

from 15 to 42%, reaching a range of 6.2 to 30.7% less impact than control samples (100% Portland cement). Land use was the category in which the use of sand caused the most impact, however, small amounts (15%) could reduce the impact by up to 14.0%, when compared to mixtures with 100% Portland cement.

- Economic cost analysis demonstrated that sand incorporation could provide savings of up to 20.1% in relative cost. Furthermore, multi-criteria performance evaluation demonstrated that the size of the coarse aggregate could influence the ideal amount of fine aggregate that makes the mixtures more efficient. All the parameters together - mechanical and hydraulic properties; environmental issues; and economic cost - corroborated the conclusion that the use of fine aggregates incorporated as a partial replacement for Portland cement could provide optimization of pervious concrete mixtures.

Therefore, alternatives to reduce the amount of Portland cement by incorporating other materials with a lower environmental footprint and low cost could be valuable in order to achieve pervious concrete with greater efficiency. Furthermore, an adequate mixture design should consider the particularities of the materials used, contributing to sustainability in the field of building materials.

CHAPTER 7 – PROPOSALS FOR FUTURE RESEARCH

The use of sugar cane wastes proved to be an interesting alternative for incorporation in pervious concrete due to its proven effectiveness as a SCM. In this way, more detailed studies regarding the behavior of the PC, mainly regarding durability, with the incorporation of both SCBA and SCSA could be valuable. Due to the exposure of this material to severe environments in paving, the resistance to chemical attacks, severe climatic conditions, in addition to the long-term mechanical behavior could be areas of interesting exploration.

Concerning to incorporation of fine aggregates into pervious concrete, it was observed that it was possible to reduce the environmental impact and costs of PC with the partial replacement of cement by sand without impairing the mechanical and hydraulic properties. Future studies can be carried out in assessment of the incorporation of fine aggregates of different sizes and granulometric ranges, and how it could interfere in the paste in relation to the amount incorporated.