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

RODRIGO GAROZI DA SILVA

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

Ilha Solteira
2024

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PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DOS MATERIAIS

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.

Supervisor:
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/m^3 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.

TABLE OF CONTENTS

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 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.