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Potential of mortars with PCR-PET for permeable pavements in sustainable urban drainage

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ABSTRACT
Objective - The study aims to investigate the potential of mortars containing PCR-PET (Post-Consumer Recycled Polyethylene Terephthalate) for constructing permeable pavements, focusing on sustainable urban drainage. The research seeks to demonstrate how partially replacing natural sand with PCR-PET influences the physical and mechanical properties of mortars, with an emphasis on permeability and environmental impact reduction.
Methodology - The scientific method involved formulating mortars with varying proportions of sand replaced by PCR-PET (0% to 40%). Physical and mechanical tests were conducted, including compressive strength, flexural tensile strength, water absorption by immersion, void index, capillary coefficient, water retention, air content, and density. Data were statistically analyzed using ANOVA and Tukey's test to assess significant differences between compositions.
Originality/Relevance - The study addresses the theoretical gap related to sustainable alternatives in civil construction, reducing reliance on natural resources and promoting plastic waste recycling. Academically, it is significant for integrating recycled materials into permeable pavements, contributing to the literature on green infrastructure and stormwater management.
Results - Key findings showed that: The addition of PCR-PET reduced mechanical strength (compressive and flexural) but increased porosity and permeability; Water absorption and void index increased with higher PCR-PET content, indicating improved water infiltration; Density and specific mass decreased, making the material lighter and suitable for low-traffic applications.
Theoretical/Methodological Contributions - The study provides empirical evidence on balancing mechanical strength and permeability in PCR-PET mortars, proposing a standardized methodology for evaluating such materials. The results contribute to the theoretical foundation on sustainable composites and permeable pavements.
Social and Environmental Contributions - Reduces plastic waste disposal and natural sand extraction, promoting a circular economy and ecosystem preservation; Enhances urban stormwater management, mitigating floods and heat islands while improving thermal comfort. Applications in low-traffic pavements (sidewalks, bike lanes) offer an affordable and sustainable solution for cities.

KEYWORDS: Permeable pavement. PCR-PET. Sustainable urban drainage.

Potencial de argamassas com PET-PCR para pavimentos permeáveis em drenagem urbana sustentável

RESUMO
Objetivo - O estudo tem como objetivo investigar o potencial de argamassas com PET-PCR (Polietileno Tereftalato pós-consumo reciclado) para a construção de pavimentos permeáveis, visando à drenagem urbana sustentável. A pesquisa busca demonstrar como a substituição parcial da areia natural por PET-PCR influencia as propriedades físicas e mecânicas das argamassas, com foco na permeabilidade e na redução de impactos ambientais.
Metodologia - O método científico empregado incluiu a formulação de argamassas com diferentes proporções de substituição de areia por PET-PCR (0% a 40%). Foram realizados ensaios físicos e mecânicos, como resistência à compressão, resistência à tração na flexão, absorção de água por imersão, índice de vazios, coeficiente de capilaridade, retenção de água, teor de ar incorporado e densidade. Os dados foram analisados estatisticamente utilizando ANOVA e teste de Tukey para avaliar diferenças significativas entre as composições.
Originalidade/relevância - O estudo insere-se no gap teórico relacionado à busca por alternativas sustentáveis para a construção civil, reduzindo a dependência de recursos naturais e promovendo a reciclagem de resíduos plásticos. A pesquisa é relevante academicamente por abordar a integração de materiais reciclados em pavimentos permeáveis, contribuindo para a literatura sobre infraestrutura verde e gestão de águas pluviais.
Resultados - Os principais resultados mostraram que: A adição de PET-PCR reduziu a resistência mecânica (compressão e tração na flexão), mas aumentou a porosidade e a permeabilidade; A absorção de água e o índice de

vazios aumentaram com a proporção de PET-PCR, indicando maior capacidade de infiltração; A densidade e a massa específica diminuíram, tornando o material mais leve e adequado para aplicações de tráfego leve.
Contribuições teóricas/metodológicas - O estudo fornece evidências empíricas sobre o equilíbrio entre resistência mecânica e permeabilidade em argamassas com PET-PCR, além de propor uma metodologia padronizada para avaliação desses materiais. Os resultados contribuem para a base teórica sobre compósitos sustentáveis e pavimentos permeáveis.
Contribuições sociais e ambientais - Redução do descarte de resíduos plásticos e da extração de areia natural, promovendo a economia circular e a preservação de ecossistemas; Melhoria na gestão de águas pluviais em áreas urbanas, reduzindo enchentes e ilhas de calor, e aumentando o conforto térmico. A aplicação em pavimentos de tráfego leve (calçadas, ciclovias) oferece uma solução acessível e sustentável para cidades.

PALAVRAS-CHAVE: Pavimentos permeáveis. PET-PCR. Drenagem urbana sustentável.

Potencial de morteros con PET-RPC para pavimentos permeables en drenaje urbano sostenible.

RESUMEN
Objetivo – El estudio tiene como objetivo investigar el potencial de morteros con PET-RPC (Polietileno Tereftalato reciclado post-consumo) para la construcción de pavimentos permeables, orientados al drenaje urbano sostenible. La investigación busca demostrar cómo la sustitución parcial de arena natural por PET-RPC influye en las propiedades físicas y mecánicas de los morteros, con enfoque en la permeabilidad y la reducción de impactos ambientales.
Metodología – El método científico empleado incluyó la formulación de morteros con diferentes proporciones de sustitución de arena por PET-RPC (0% a 40%). Se realizaron ensayos físicos y mecánicos, como resistencia a la compresión, resistencia a la tracción por flexión, absorción de agua por inmersión, índice de vacíos, coeficiente de capilaridad, retención de agua, contenido de aire incorporado y densidad. Los datos fueron analizados estadísticamente mediante ANOVA y prueba de Tukey para evaluar diferencias significativas entre las composiciones.
Originalidad/relevancia – El estudio se inserta en el vacío teórico relacionado con la búsqueda de alternativas sostenibles para la construcción civil, reduciendo la dependencia de recursos naturales y promoviendo el reciclaje de residuos plásticos. La investigación es relevante académicamente por abordar la integración de materiales reciclados en pavimentos permeables, contribuyendo a la literatura sobre infraestructura verde y gestión de aguas pluviales.
Resultados – Los principales resultados mostraron que: La adición de PET-RPC redujo la resistencia mecánica (compresión y tracción por flexión), pero aumentó la porosidad y la permeabilidad; La absorción de agua y el índice de vacíos aumentaron con la proporción de PET-RPC, indicando mayor capacidad de infiltración; La densidad y la masa específica disminuyeron, haciendo el material más ligero y adecuado para aplicaciones de tráfico ligero.
Contribuciones teóricas/metodológicas – El estudio proporciona evidencia empírica sobre el equilibrio entre resistencia mecánica y permeabilidad en morteros con PET-RPC, además de proponer una metodología estandarizada para la evaluación de estos materiales. Los resultados contribuyen a la base teórica sobre compuestos sostenibles y pavimentos permeables.
Contribuciones sociales y ambientales – Reducción del vertido de residuos plásticos y de la extracción de arena natural, promoviendo la economía circular y la preservación de ecosistemas; Mejora en la gestión de aguas pluviales en áreas urbanas, reduciendo inundaciones y islas de calor, y aumentando el confort térmico. La aplicación en pavimentos de tráfico ligero (aceras, ciclovías) ofrece una solución accesible y sostenible para ciudades.

PALABRAS CLAVE: Pavimentos permeables. PET- RPC. Drenaje urbano sostenible.

1 INTRODUCTION

Increasing urbanization and soil sealing has created significant challenges for urban drainage, such as increased risk of flooding, erosion and surface water pollution. Replacing impermeable surfaces with sustainable solutions, such as permeable pavements, is widely discussed in the literature as an effective approach to mitigating these problems, since these systems allow water to infiltrate the soil, reducing surface runoff and promoting groundwater recharge, as studies on green infrastructure point out (Muttuvelu *et al.,* 2015) and (Fletcher *et al.,* 2015).

However, the production of permeable pavements still depends considerably on natural materials, such as sand, whose large-scale extraction generates significant environmental impacts, including habitat degradation and biodiversity loss. Several authors, such as Peduzzi (2014), highlight the need to minimize the use of natural resources in engineering projects, seeking more sustainable alternatives.

In this context, the partial replacement of natural aggregates with recycled materials, such as post-consumer recycled polyethylene terephthalate (PCR-PET), has emerged as a promising option for reducing environmental impacts. As well as reducing the extraction of natural resources, the use of PCR-PET in permeable pavements contributes to the management of plastic waste, one of today's greatest environmental challenges (Hopewell, Dvorak and Kosior, 2009).

Studies indicate that the inclusion of recycled plastics in construction materials can not only reduce the accumulation of waste, but also improve certain mechanical and durability properties of composites (Silva *et al.*, 2019). Within this scenario, this study proposes the partial replacement of natural sand with PCR-PET in the development of mortars for permeable pavements, assessing its technical feasibility and its impact on sustainable urban drainage.

Replacing conventional aggregates with PCR-PET has the potential to increase the porosity of mortars, making the pavement more permeable and efficient at infiltrating rainwater. However, it is still necessary to investigate the effects of this incorporation on the durability and mechanical strength of the pavement, in order to assess its viability as a sustainable alternative for urban drainage systems using recycled plastic waste.

To achieve these objectives, mechanical tests of compressive strength and flexural tensile strength were carried out to assess the structural robustness of the pavement over time. In addition, various physical tests were carried out to characterize fundamental properties related to permeability, including water absorption by immersion, void index, capillarity coefficient, water retention, incorporated air content and mass density in the fresh stage. Determining the actual specific mass and apparent specific mass of the mortars complemented the analysis of the material's physical properties.

Evaluating these parameters is essential to understand the pavement's performance in terms of water absorption and drainage capacity, which directly impacts the efficiency of urban drainage systems. Thus, it is expected that sidewalks developed with PCR-PET will not only have satisfactory mechanical resistance, but also high permeability, favoring rainwater management and reducing surface runoff. Thus, pavements developed with PCR-PET are expected to exhibit not only satisfactory mechanical strength but also high permeability, promoting stormwater management and reducing surface runoff. This behavior contributes to sustainability in densely paved urban areas, supporting studies on the efficiency of permeable pavements in urban contexts (Menezes; Cabral, 2023). Thus, this study seeks to demonstrate that the incorporation of PCR-PET can enable an effective and environmentally responsible solution for sustainable urban drainage.

2 LITERATURE REVIEW

2.1 Permeable Pavements and Urban Sustainability

Growing urbanization has increased soil sealing in urban areas, generating a series of environmental problems, including intensified flooding, soil erosion and pollution of surface water bodies. To reduce these impacts, one of the most effective solutions has been the adoption of permeable pavements, which allow water to infiltrate the soil, reducing surface runoff and promoting groundwater recharge (Boogaard *et al.*, 2014).

Permeable pavements are characterized by a porous structure that facilitates the passage of water, and are considered a sustainable alternative for stormwater management in densely paved urban environments (Pratt *et al.*, 2017).

The use of these pavements is directly linked to the principles of green infrastructure, which aims to combine urban development with environmental sustainability practices, seeking to reduce the impact of human activities on the environment (Fletcher *et al.*, 2015).

In addition to control rainwater runoff, permeable pavements have shown benefits in terms of thermal control, as they help to reduce the heat island effect, which is very common in urban areas (Shafique *et al.,* 2018).

2.2 Replacement of Conventional Materials in Permeable Pavements

Permeable pavements are traditionally composed of mineral aggregates, including natural sand, which plays a crucial role in the composition of the mix and the permeability of the mixture. However, the extraction of natural sand has caused significant environmental impacts, such as the degradation of river habitats, erosion and imbalance in aquatic ecosystems (Peduzzi, 2014). For this reason, the search for sustainable alternatives that replace conventional materials with recycled options has been gaining momentum in the construction industry.

Among the most studied alternatives is the use of recycled plastic waste, such as PCR-PET (post-consumer recycled polyethylene terephthalate). This material, derived from the recycling of plastic bottles, has been explored for its mechanical properties and its potential to reduce dependence on natural resources in construction (Hopewell *et al.,* 2009).

The use of PCR-PET as a partial substitute for sand in permeable pavements mixes not only promotes sustainability through the reuse of plastic waste, but can also result in greater porosity and permeability of the sidewalk, improving its drainage capacity (Silva *et al.,* 2014).

2.3 Mechanical and Physical Properties of PCR-PET Pavements

Recent studies have investigated the impact of partially replacing sand with recycled plastics on the mechanical and physical properties of mortars used in permeable pavements. Research indicates that the use of PCR-PET can directly influence parameters such as compressive strength, water absorption, void index, capillarity coefficient, water retention and incorporated air content (Gesoglu *et al.*, 2014).

These parameters are essential for assessing the efficiency of permeable pavements, since an increase in porosity, for example, is directly related to the pavement's ability to allow water to flow through its structure. However, it is crucial that these properties are balanced with the mechanical strength of the material, ensuring that the sidewalk is able to withstand the loads imposed by urban traffic (Ahmad *et al.*, 2015).

Previous research indicates that the inclusion of PCR-PET can reduce sidewalk density, which can be advantageous in terms of structural lightness, but at the same time can compromise compressive strength compared to conventional materials. On the other hand, increased permeability and water absorption capacity make the use of recycled plastics a viable option for applications in areas where stormwater control is a priority (Shafique *et al.*, 2018).

2.4 Environmental Benefits of Using PCR-PET in Pavements

Incorporating PCR-PET into permeable pavements also has significant environmental benefits, as well as reducing the amount of plastic waste in landfills and oceans, the use of this material contributes to reducing the extraction of natural sand, helping to preserve river habitats and aquatic ecosystems (Thakur & Singha, 2017). Studies have shown that the inclusion of recycled plastic waste can contribute to the reduction of CO_2 emissions associated with the production of construction materials, making the process more sustainable (Silva *et al.*, 2014).

In addition, the development of paving technologies using PCR-PET can encourage the circular economy by promoting the reuse of plastic waste and reducing the demand for new materials. This type of approach is particularly relevant in urban contexts, where solid waste management and stormwater control represent major challenges for sustainability (PlasticsEurope, 2018).

2.5 PCR-PET Analysis of Permeable Pavements

The use of PCR-PET in permeable sidewalks is an emerging practice aimed at sustainability and efficiency in the management of rainwater in urban areas. Permeable sidewalks are designed to allow rainwater to infiltrate into the ground, reducing the amount of surface runoff and consequently minimizing urban flooding (Engenharia 360, 2022).

The use of PCR-PET in the manufacture of these sidewalks offers a viable and environmentally friendly alternative, since it makes use of a material that is often discarded and takes hundreds of years to decompose. Studies, such as those by Tripathy; Acharya (2023), show that incorporating recycled materials into concrete can not only enhance structural performance but also help reduce the environmental impact associated with the production of new materials.

In addition to the environmental benefits, analysis of the performance of PCR-PET in permeable sidewalks also considers technical aspects such as compressive strength and durability. According to research carried out by Ryu *et al.* (2020), permeable sidewalks made with PCR-PET showed mechanical strength comparable to conventional sidewalks, as well as having superior drainage properties. These studies indicate that the use of recycled PET does not compromise the quality of the sidewalk but, on the contrary, can improve important characteristics such as infiltration capacity and resistance to wear, increasing the useful life of the material.

3 METHODS

This chapter describes the methodology adopted to investigate the potential use of permeable pavements with partial replacement of natural sand with PCR-PET in sustainable urban drainage. The main objectives include formulating and characterizing the mortars, carrying out mechanical and physical tests, and analyzing the results obtained to validate the hypothesis that the inclusion of PCR-PET can increase the permeability of the pavements.

The chosen proportions of PCR-PET were also defined in previous studies by the authors in more detail, with the aim of this document being to present the experimental parameters used with performance within the appropriate standards.

3.1 Mortar Formulation

The following materials were used to make the mortars:

Portland cement CP-II E 32: used as a binder; natural sand: as a standard aggregate and of medium sand size; PCR-PET: as an artificial aggregate to replace the natural one, with medium sand granulometry and obtained from the recycling of plastic bottles; and water: used to hydrate the cement.

To formulate the mortar molds, five different compositions were defined in order to assess the impact of replacing natural sand with PCR-PET on the material's physical and mechanical properties. The compositions studied include:

Reference Mortar: This composition was prepared without the addition of PCR-PET, using only natural sand as fine aggregate. It serves as a parameter for comparing the properties of mortars containing PCR-PET.

Mortars with substitutions ranging from 10% up to 40% PCR-PET: In these compositions, the volume of natural sand was replaced by PCR-PET. This proportion was chosen to assess the initial effects of adding recycled material on the properties of the reference mortar.

Each of these compositions was prepared in at least three repetitions to ensure the reliability of the results. This approach allowed a detailed comparison between the effects of partially replacing natural sand with PCR-PET in different proportions, providing information on the feasibility of using plastic waste in the production of sustainable mortars.

3.2 Mold Preparation

The mortars were molded in steel molds of standardized dimensions, in accordance with the ABNT (Brazilian Association of Technical Standards) test standards. The molds were previously lubricated to facilitate demolding. After molding, the mortars were subjected to a curing process in a controlled environment, with constant temperature and humidity, for 28 days, following the recommendations for proper cement hydration.

3.3 Mortar Characterization Tests

Tests were carried out to characterize the mortars developed:

Compressive strength: The test was carried out in accordance with the ABNT NBR 13279 standard, so that the samples are subjected to compression in a hydraulic press until they fail, then the strength values are recorded.

Flexural tensile strength: As stipulated by ABNT NBR 13279, the test was carried out on samples molded to the appropriate dimensions and subjected to loading in a hydraulic press until rupture, allowing the flexural tensile strength to be obtained.

Water Absorption by Immersion: This test determines the amount of water that mortars can absorb in a 24-hour period, in accordance with the guidelines of ABNT NBR 9778.

Void Index: This is calculated based on the ratio between the pore volumes and the total volume of the sample, according to the proposed methodology.

Capillarity Coefficient: The test is conducted using a water column method, where the height of the rising water as a function of time is measured, allowing the capillarity coefficient of the mortars to be calculated.

Water retention: Water retention is measured as a function of time, considering the mass of the samples after saturation in water.

Incorporated Air Content: This parameter is assessed using an incorporated air meter, which provides a measure of the amount of air trapped in the mortar.

Bulk Density in the Hardened Stage: The density is determined by the ratio between the mass of the sample and the volume occupied.

Specific Gravity: The specific mass is measured using a pycnometer, which makes it possible to determine the density of the solids present in the mortar.

3.4 Data Analysis

The data obtained from the tests was statistically analyzed using tools such as analysis of variance (ANOVA) and Tukey's test to check for significant differences between the properties of the mortars formulated. In addition, a correlation analysis was carried out between the proportion of PCR-PET and the parameters of permeability and mechanical strength, in order to identify the relationship between these variables.

3.5 Ethical Considerations

This research respects the ethical guidelines related to scientific research, ensuring that the processes have been conducted rigorously and transparently. The use of recycled materials such as PCR-PET is carried out in such a way as to minimize environmental impacts and promote sustainability, in line with the objectives of sustainable development.

4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained from the tests carried out on the mortars developed with partial replacement of natural sand with PCR-PET, as well as a discussion on the significance of these results in relation to the study's objectives. The data is presented in tables and graphs to facilitate visualization and understanding of the mortars' mechanical and physical properties.

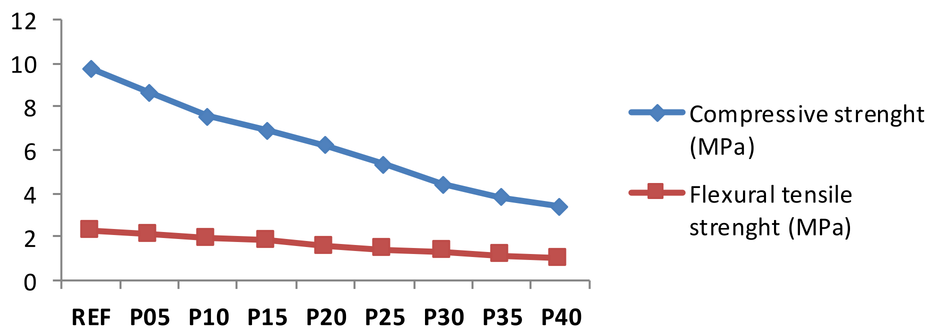
4.2 Results of the Mortar Characterization Tests

The results of the tests carried out on the mortar samples are presented below. The properties analyzed include compressive strength, flexural tensile strength, water absorption, void index, capillarity coefficient, water retention, incorporated air content and specific gravity in the fresh stage.

4.2.1 Compressive Strength and Tensile Flexural Strength

The tendency in the compressive and flexural tensile strength values of the mortars can be seen in Figure 1.

Figure 1 - Tendency graph of average values for mortar strength tests



Source: Autors (2024).

The compressive strength and flexural tensile strength data for the mortars in the study are shown in Table 1, showing the average for each proportion of PCR-PET that was studied.

Table 1 - Mortar mechanical strength tests

Sample	Compressive strenght (MPa)	Flexural tensile strenght (MPa)
REF	9,75	2,29
P05	8,65	2,10
P10	7,54	1,95
P15	6,88	1,82
P20	6,21	1,55
P25	5,33	1,42
P30	4,40	1,34
P35	3,82	1,17
P40	3,41	1,03

Source: Autors (2024).

The analysis shows that both strengths decrease as the proportion of PCR-PET increases, compared to the reference samples (100% natural sand). The results of the compressive strength and flexural tensile strength tests are essential for assessing the pavement's ability to withstand applied stresses, especially in high-traffic areas.

The data indicates that the addition of PCR-PET affects negatively these pavements properties, depending on the proportion used. This highlights the need to consider practical issues related to the durability of the material. In addition, it is essential to verify the technical feasibility of PCR-PET in different compositions, ensuring that the pavement meets the application requirements.

4.2.2 Water Absorption by Immersion, Void Index and Capillarity Coefficient

The results of the parameters of water absorption by immersion, void index and capillarity coefficient are shown in Table 2.

Table 2 - Water absorption, void index and capillarity coefficient tests

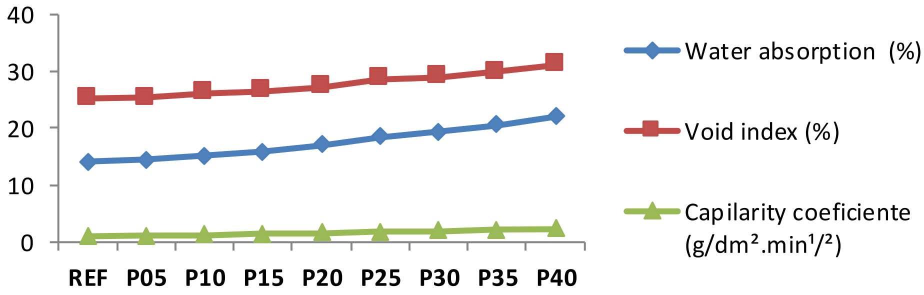
Sample	Water absorption (%)	Void index (%)	Capilarity coeficiente ($g/dm^2.min^1/^2$)
REF	14,17	25,26	1,03
P05	14,40	25,40	1,10
P10	15,20	26,24	1,23
P15	15,84	26,61	1,37
P20	17,05	27,23	1,60
P25	18,49	28,66	1,77
P30	19,39	29,12	1,90
P35	20,56	29,93	2,10
P40	22,06	31,11	2,27

Source: Autors (2024).

The results of the water absorption, void index and capillarity coefficient tests indicate that the progressive inclusion of PCR-PET in the mix results in an increase in the void index, which contributes to a greater capacity for water infiltration. This conclusion is confirmed by the increase observed in both immersion water absorption and the capillarity coefficient.

These results are fundamental to validating the hypothesis that partially replacing sand with PCR-PET can effectively promote greater permeability in the pavement. Note the tendecy of the values found in the research in the graph shown in Figure 2.

Figure 2 - Tendency graph of average values for mortar absoprtion tests



Source: Autors (2024).

4.2.3 Water Retention and Incorporated Air Content

The data on the water retention tests and the incorporated air content are shown in Table 3.

Table 3 - Water retention tests and incorporated air content

Sample	Incorporated air(%)	Water retention(%)
REF	10,1	97,38
P05	9,4	97,16
P10	8,6	96,94
P15	8,2	96,89
P20	7,7	96,61
P25	7,1	96,34
P30	6,8	96,17
P35	6,4	96,03
P40	6,1	95,90

Source: Autors (2024).

The table shows the test results indicating that, as the proportion of PCR-PET increases, both the water retention and the incorporated air content progressively decrease, corroborating the expected trend for this type of composition. Incorporated air content is a crucial factor for pavements durability, while water retention reflects the material's ability to remain hydrated in different climatic conditions, contributing to long-term performance.

The tendency of the water retention and incorporated air content test values can be seen in Figure 3.

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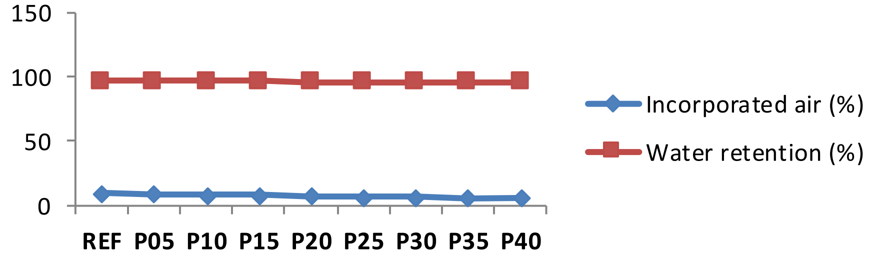
Figure 3 - Tendency graph of values for water retention tests and incorporated air content



Source: Autors (2024).

4.2.4 Bulk Density and Specific Gravity in Hardened Stage

The results for bulk density in the hardened stage and specific gravity are shown in Table 4. These results confirm the initial expectation of a reduction in values, since the artificial PCR-PET aggregate has a lower density than natural aggregate (sand), and the packing of the particles in the mixture increases porosity, resulting in a reduction in these parameters.

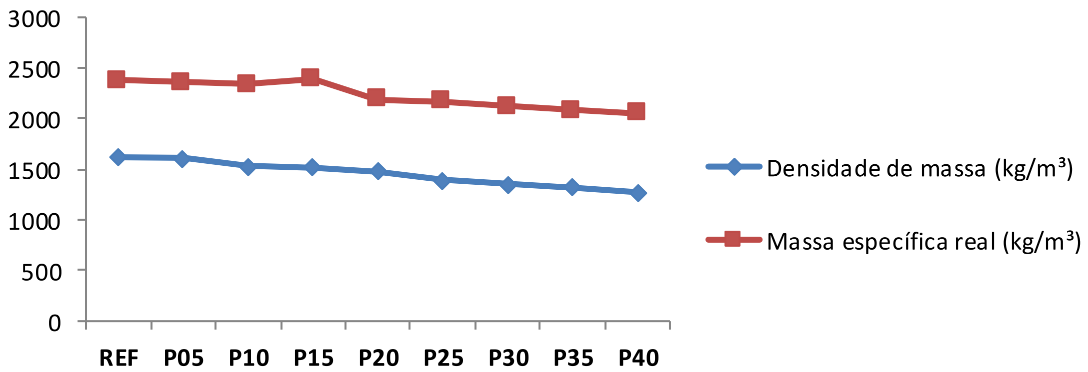
Table 4 - Values for bulk density in the hardened stage and specific gravity

Sample	Bulk density (kg/m³)	Specific gravity (kg/m³)
REF	1618	2380
P05	1606	2360
P10	1526	2340
P15	1518	2390
P20	1475	2190
P25	1396	2170
P30	1351	2120
P35	1321	2080
P40	1273	2050

Source: Autors (2024).

The tendency of the average values found in the bulk density tests in the hardened stage and the specific gravity can be seen in Figure 4.

Figure 4 - Tendency graph for bulk density in the hardened stage and specific gravity



Source: Autors (2024).

4.3 Considerations on the Results

The partial replacement of natural aggregates with PCR-PET in mortars has both advantages and disadvantages. The results showed that as the proportion of PCR-PET increased, there was a reduction in both compressive strength and flexural tensile strength, limiting the use of these mortars in applications requiring high structural resistance. This effect aligns with studies such as Ngayakamo (2025), which observed a similar impact when incorporating recycled plastics into construction materials.

On the other hand, regarding specific water absorption, void index, and capillary coefficient properties, the PCR-PET modified mortars demonstrated advantages in applications requiring permeability. These properties were enhanced by the increased porosity resulting from PCR-PET incorporation, confirming initial hypotheses and supporting previous studies such as Diniz *et al.* (2021), which highlight the role of porous pavements in water infiltration.

In aspects related to water absorption by immersion, void index, capillarity coefficient, water retention and incorporated air content, it was observed that, in applications with permeable mortar characteristics, the compositions proved to be advantageous (Führ *et al.*, 2021).

When the parameters of incorporated air content and water retention in the fresh stage of a mortar are higher, the tendency is for the absorption coefficient of the mortar to be lower. This is because the greater amount of incorporated air and water retention provide a more porous and saturated structure, which reduces the amount of water that can be absorbed later. This corroborates the research findings.

The higher air content creates air bubbles that act as voids in the mortar, which can limit water penetration. In addition, water retention in the fresh stage indicates that the mortar has a greater amount of water available for the curing process, resulting in a more compact and less permeable matrix after drying. Therefore, these combined factors generally contribute to a lower absorption coefficient.

Increasing the proportion of PCR-PET in the composite also resulted in significant improvements in all these parameters, making it more suitable for practical applications requiring greater permeability. As emphasized by Diniz *et al.* (2021), porous pavements exhibit superior potential for water infiltration - a critical aspect determining their effectiveness.

It can be seen that the lower density and mass values found in the compositions that use partial substitution of natural aggregate (sand) with artificial aggregate (PCR-PET) indicate better workability, especially in the assembly of permeable pavements, making the material lighter and easier to handle. As is widely recognized in the literature, density has a direct influence on the mechanical strength and overall performance of pavements, something that was proven by the values obtained in the aforementioned tests.

The results indicate that the addition of PCR-PET significantly increases the permeability of the pavement, especially the void index and the capillarity coefficient. This effect is comparable to the findings of Shafique *et al.* (2018), who observed an increase in the infiltration capacity of pavements with recycled materials. In practical terms, these higher permeability values make the pavement more suitable for application in light traffic areas, such as sidewalks and bike paths, where stormwater control is a priority but resistance demands are lower.

5 CONCLUSIONS

The advancement of permeable paving technologies, combined with the use of recycled materials such as PET, represents an important step towards more resilient and sustainable cities. Investments in research and development are essential for the dissemination of this technology, as well as for the creation of standards regulating the use of recycled materials in construction. With increased awareness of the importance of efficient rainwater management and waste reduction, PCR-PET presents itself as a promising solution, aligning innovation and environmental responsibility.

Based on the literature reviewed, the partial replacement of natural sand with PCR-PET in permeable pavements represents a promising solution for sustainable urban drainage. Although technical challenges related to mechanical strength still need to be overcome, the environmental benefits and increased permeability capacity of these pavements reinforce their relevance in green infrastructure and sustainable development strategies.

As expected and demonstrated in the research, the incorporation of PCR-PET as a partial substitute for natural aggregates results in a mortar with greater porosity, which becomes one of its main characteristics. This porosity is essential for applications in permeable pavements, as it allows water to infiltrate through the surface, helping to prevent flooding in urban areas, where impermeable surfaces are increasingly prevalent.

The use of PCR-PET promotes the recycling of plastic materials, helping to reduce the environmental impact caused by the improper disposal of this waste. Permeable pavements are often integrated into green infrastructure projects, in which sustainability is a central factor. Thus, the use of PCR-PET is perfectly aligned with these sustainable practices.

Although the incorporation of PCR-PET can negatively affect some of the mortar's mechanical properties, such as compressive strength and flexural tensile strength, these changes can be controlled and adjusted to meet the requirements of permeable pavements suitable for each application. This is especially relevant in situations that do not require such high strengths as conventional sidewalks, such as light or moderate traffic sidewalks, where the mechanical performance obtained with a higher proportion of artificial aggregate can be satisfactory.

On the other hand, the decrease in compressive strength and flexural tensile strength observed with PCR-PET proportions above 20% reinforces a limitation for use on high-traffic roads. To expand the applicability of these sidewalks, future formulations could include additives that strengthen the mortar without compromising permeability.

These findings indicate that PCR-PET is best suited to situations where mechanical strength is not the main requirement, but where water management is essential. In places where traffic is light, such as residential areas or pedestrian zones, these pavements can provide an economically and environmentally viable alternative, meeting green infrastructure guidelines and contributing to the reduction of flooding in urban areas.

Another advantage observed is that PCR-PET can give the mortar greater flexibility, which is beneficial in permeable sidewalks, as it allows the material to deform slightly without breaking, increasing its resistance to wear and mechanical fatigue. These characteristics are essential for structures subject to light and moderate traffic.

5.1 Final considerations and future research

The study showed that incorporating PCR-PET into permeable paving mortars is a promising approach for sustainable urban drainage. However, the drop in mechanical strength associated with increasing the proportion of PCR-PET highlights the need to adjust the formulation to meet different application requirements. It is therefore suggested that hybrid mixtures be developed, combining PCR-PET with other additives that can compensate for this loss of strength without compromising the material's permeability.

For practical implementation in urban projects, it is recommended that specific technical guidelines be created for the use of pavements with PCR-PET in light and moderate traffic areas, where resistance requirements are lower. In addition, tests in field conditions could verify the performance of these pavements in different climatic and usage conditions, guaranteeing the durability and efficiency of the solution.

Further research is recommended to explore the thermal properties of PCR-PCRPET mortars, especially their contribution to reducing the heat island effect in urban areas. Evaluating thermal behavior can consolidate PCR-PET as a viable solution for sidewalks in regions with high temperatures, increasing environmental comfort and reducing air conditioning costs.

Another relevant point for future studies is the analysis of other mortar properties, such as resistance to wear and fatigue under continuous traffic conditions. Exploring different contexts of use and optimizing the proportion of PCR-PET in mixtures will contribute to the development of technical standards and broaden the range of practical applications.

REFERENCES

AHMAD, S.; GHANI, A. N. A.; ADEWALE, P. Properties of sustainable permeable pavement. **Journal of Cleaner Production**, v. 112, p. 3157-3162, 2015.

ARQUITETURA PRO. Arquitetura sustentável e o uso de recursos naturais renováveis. **Arquitetura Pro**, 2025. Disponível em: https://arquiteturapro.com.br/arquitetura-sustentavel-e-o-uso-de-recursos-naturais-renovaveis/. Acesso em: 30 Março. 2024.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 9778: Argamassa e concreto endurecidos – Determinação da absorção de água, índice de vazios e massa específica**. Rio de Janeiro, 2009.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 13279: Argamassa para assentamento e revestimento de paredes e tetos – Determinação da resistência à tração na flexão e à compressão**. Rio de Janeiro, 2005.

BRANDÃO, R. S.; LIMA, J. A. P.; ALEXANDRE, J. Characterization and classification of mortars for underlayment with PCR-PET artificial aggregate in partial replacement of natural sand aggregate in the mix**. Revista Nacional de Gerenciamento de Cidades**, v. 12, n. 85, 2024. Disponível em: https://doi.org/10.17271/23188472128520245312.

DINIZ, M. I. L.; CAVALCANTI, A. B.; CLAUDINO, C. M. A.; SENA, T. S.; NASCIMENTO, R. F.; NUNES, C. G. L.; SILVA, D. C.; PEREIRA, P. H. S.; DELFINO, L. M.. Estudo da eficiência de pavimentos permeáveis: análise da permeabilidade e das propriedades mecânicas. **Revista Ibero Americana de Ciências Ambientais**, v.12, n.3, p.398-407, 2021. Disponível em: http://doi.org/10.6008/CBPC2179-6858.2021.003.0032

DOS SANTOS D. V. N.; PIRES G. C.; ROBERTO L. A. G. F. Análise do processo de construção de um ambiente constituído por garrafas PET. Periódico Eletrônico Fórum Ambiental da Alta Paulista, v. 9, n. 1, 2013. Disponível em: https://doi.org/10.17271/19800827912013594

ENGENHARIA 360. **Pavimentos permeáveis reduzem inundações.** [S. l.], [2022]. Disponível em: https://engenharia360.com/pavimentos-permeaveis-reduz-inundacoes/. Acesso em: 16 jul. 2024.

FLETCHER, T. D.; ANDRIEU, H.; HAMEL, P. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. **Advances in Water Resources**, v. 51, p. 261-279, 2015.

FÜHR, G.; MASUERO, A.; PAGNUSSAT, D.; BARRETO, M. Impact sound attenuation of subfloor mortars made with exfoliated vermiculite and chrome sawdust. **Applied Acoustics**, v. 174, 107725, 2021.

HOPEWELL, J.; DVORAK, R.; KOSIOR, E. Plastics recycling: challenges and opportunities. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 364, n. 1526, p. 2115-2126, 2009.

KONG, J.; JEONG, S.; LEE, J.; JEONG, S. **Permeable pavement blocks as a sustainable solution for managing microplastic pollution in urban stormwater.** *Science of The Total Environment*, v. 966, p. 178649, 2025. ISSN 0048-9697. Disponível em: https://doi.org/10.1016/j.scitotenv.2025.178649.

MENEZES, L. A. A.; CABRAL, J. J. S. P. Utilização de pavimento permeável como alternativa compensatória para drenagem urbana em Recife-PE. **Periódico Eletrônico Fórum Ambiental da Alta Paulista**, v. 19, n. 5, 2023. Disponível em: https://doi.org/10.17271/1980082719520233775

MUTTUVELU, D. V.; WYKE, S.; VOLLERTSEN, J. Are permeable pavements a sustainable solution? A qualitative study of the usage of permeable pavements. **Sustainability**, v. 14, n. 19, p. 12432, 2022. Disponível em: 10.3390/su141912432. Disponível em: https://doi.org/10.3390/su141912432.

NGAYAKAMO, B. H. Investigation of plastic-sand paving blocks: A sustainable solution using recycled plastic waste**. Hybrid Advances**, v. 10, p. 100492, 2025. ISSN 2773-207X. Disponível em: https://doi.org/10.1016/j.hybadv.2025.100492.

PEDUZZI, P. Sand, rarer than one thinks. **Environmental Development**, v. 11, p. 208-218, 2014.

PRATT, C.; MANTLE, J.; SCHOFIELD, P. UK research into the performance of permeable pavement, reservoir structures. **Water Science and Technology**, v. 32, n. 1, p. 63-69, 2017.

RYU, B.-H.; LEE, S.; CHANG, I. Pervious pavement blocks made from recycled polyethylene terephthalate (PET): fabrication and engineering properties. **Sustainability**, v. 12, n. 17, 6356, 2020. DOI: 10.3390/su12176356.

SHAFIQUE, M.; KIM, R.; RAFIQ, M. Use of recycled plastic in permeable pavement: a review. **Environmental Technology Reviews**, v. 7, n. 1, p. 19-30, 2018.

SILVA, R. V.; DE BRITO, J.; DHIR, R. K. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. **Construction and Building Materials**, v. 65, p. 201-217, 2014. DOI: https://doi.org/10.1016/j.conbuildmat.2014.04.117.

TRIPATHY, A.; ACHARYA, P. K. Ecological impact assessment of sustainable concrete paver blocks based on endpoint damage categories**. Materials Today***: Proceedings*, [S. l.], 2023. ISSN 2214-7853. Disponível em: https://doi.org/10.1016/j.matpr.2023.05.281

THAKUR, V. K.; SINGHA, A. S. **Green polymer composites from natural resources**. Cham: Springer International Publishing, 2017.

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CLARAÇÃO DE CONFLITOS DE INTERESSE

Nós, **Raul de Souza Brandão, Ramon Fernandes de Abreu e Jonas Alexandre**, declaramos que o manuscrito intitulado: **" Potencial de argamassas com PET-PCR para pavimentos permeáveis em drenagem urbana sustentável":**

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