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SUSTAINABLE SOLUTIONS FOR URBAN INFRASTRUCTURE: THE ENVIRONMENTAL AND ECONOMIC BENEFITS OF USING RECYCLED CONSTRUCTION AND DEMOLITION WASTE IN PERMEABLE PAVEMENTS

Eliomar Gotardi Pessoa

UFRJ -Universidade Federal do Rio de Janeiro- Rio de Janeiro-RJ, Brazil.

http://orcid.org/0009-0008-7713-4740

Email: eliomar.pessoa@coc.ufrj.br

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ABSTRACT

This study explores the economic and environmental implications of using recycled construction and demolition waste (CDW) in permeable pavements, presenting it as a viable solution for promoting sustainable urban development. As urbanization intensifies, both the volume of CDW and the demand for resilient, flood-mitigating infrastructure are rising. Permeable pavements made from recycled concrete, ceramic bricks, reclaimed asphalt, and industrial waste offer a dual benefit—minimizing environmental degradation and enhancing pavement performance. The findings from various studies indicate that these materials, when properly processed and chemically stabilized, can replace virgin aggregates in pavement base and subbase layers without compromising structural integrity. The paper highlights improvements in mechanical properties, stormwater infiltration, and pollutant removal when using permeable systems, even when recycled materials are incorporated. In particular, innovations such as the use of geopolymer concrete and secondary aluminum dross (SAD) fillers have shown to enhance compressive strength and moisture resistance in asphalt mixes containing RCA. Moreover, life cycle assessment (LCA) methods validate the environmental gains of these practices, from reduced carbon emissions to lower resource extraction rates. Despite these advantages, technical challenges such as pore clogging, leaching risks, and material variability persist. Addressing these through standardization, further field trials, and continued innovation will be key to expanding the adoption of CDW in permeable pavements. Ultimately, the integration of recycled materials into urban infrastructure emerges as a promising strategy to reduce construction waste, conserve natural resources, and build cities that are both sustainable and resilient.

I. INTRODUCTION

The growing urbanization has generated increasingly significant challenges for the management of construction and demolition (C&D) waste. These wastes, primarily composed of concrete, bricks, wood, metals, and asphalt, represent a significant portion of solid waste generated in urban areas. The reuse of these materials in the construction of permeable pavements offers an innovative and sustainable solution to two crucial problems: the growing amount of waste and the need for urban infrastructure that minimizes environmental impacts such as urban flooding and excessive stormwater runoff.

Permeable pavements, which allow rainwater infiltration into the soil, have increasingly been used as an ecological alternative to traditional asphalt, which contributes to the increase in urban land impermeability. When made from recycled demolition materials, such as recycled concrete, broken bricks, and reclaimed asphalt, these pavements not only play a vital role in urban drainage but also promote the circular economy by reintroducing materials that would otherwise be discarded. This process reduces the demand for new natural resources and decreases the need for waste disposal areas.

From an economic perspective, the reuse of demolition materials in permeable pavements offers several benefits. First, the use of recycled waste can significantly reduce the production cost of pavements, as recycled materials are often cheaper than new ones. Furthermore, disposal costs for demolition waste are reduced, as many of these materials can be directly reused in construction, minimizing the need for transportation and disposal in landfills. Another relevant economic benefit is the creation of new market opportunities and jobs, especially in the recycling sector and sustainable construction industry. The demand for technologies that improve C&D waste reuse, such as the chemical stabilization of recycled materials and innovation in construction methods, can generate new investments and stimulate the local economy. Additionally, by adopting sustainable practices, cities can attract investments related to green infrastructure, promoting long-term urban resilience.

From an environmental perspective, permeable pavements made from recycled materials contribute to the mitigation of significant environmental issues. The primary advantage of these pavements is the reduction in soil impermeabilization, which allows for better rainwater absorption, reducing the risk of urban flooding and the overload of drainage systems. Furthermore, by promoting the infiltration of rainwater, these pavements help recharge groundwater tables and reduce water pollution, as the water passing through them can be filtered of impurities. The reuse of demolition materials also plays an essential role in reducing the carbon footprint of the construction industry. The production of new construction materials, such as cement and asphalt, is an energy-intensive process that generates greenhouse gas emissions. By replacing these materials with recycled options, permeable pavements help reduce the demand for natural resources and the emission of pollutants, contributing to climate change mitigation.

However, the reuse of C&D materials also presents challenges, such as variations in the quality of recycled materials and the possibility of pore clogging in permeable pavements over time. These issues can be minimized through ongoing research to improve processing and stabilization methods for the waste, ensuring that these pavements are both durable and effective.

The reuse of demolition materials in the construction of permeable pavements is a promising solution that combines economic and environmental benefits. By adopting this practice, cities not only face the challenges of C&D waste management more effectively but also promote sustainability by improving urban infrastructure and the quality of life for their inhabitants. The continuous advancement of recycling technologies and the encouragement of sustainable practices are critical to the success of this approach, which could become an essential strategy for the future of more resilient and environmentally responsible cities.

II. THEORETICAL REFERENCE

The research conducted by [1] evaluates and contrasts the environmental and economic impacts of permeable bricks and concrete pavement bricks, focusing on China's "sponge city" initiative. By employing a life cycle assessment within a "cradle-to-gate" framework, the study identifies the primary environmental and cost implications of both materials. The results show that concrete pavement bricks have a lower environmental impact and economic cost when the water-saving benefits of permeable bricks are not factored in. Notable contributors to the environmental footprint of concrete bricks are basalt powder and cement, whereas permeable bricks primarily involve cement and crushed gravel. The study underscores the numerous advantages of permeable bricks, including groundwater preservation, reduced waterlogging, and cost savings on drainage system construction and maintenance. These insights are particularly valuable for shaping policies and strategies for sustainable urban development, such as the promotion of sponge cities.

In a similar vein, [2] examines the potential of reusing recycled construction and demolition (C&D) waste, specifically mortars, concrete, and ceramic bricks, as aggregates for making interlocking blocks. This study simulates the characteristics of conventional blocks used in civil construction. Six concrete load specimens were cast using varying proportions of coarse and fine aggregates—50% and 25%, respectively—following NBR 5738 standards. The findings reveal that interlocking pavements created from C&D waste significantly enhance land permeability, benefiting sidewalks and streets. Additionally, the study emphasizes that ordinary people can produce and apply these sustainable blocks in their homes, offering a practical and environmentally friendly solution for urban construction.

The research by [3] provides a thorough review of the use of recycled concrete aggregate (RCA), a major component of C&D waste, in base and subbase layers of pavements. The paper explores the impact of crushing RCA particles, particularly in terms of resilient modulus, permanent deformation, and the California Bearing Ratio. It also compares RCA with natural aggregate (NA) and discusses the consumption and disposal policies of these materials in various countries. The study highlights the environmental and economic benefits of using RCA, emphasizing that when processed correctly, RCA can perform as well as or better than virgin aggregates for many pavement applications. However, it is advised that full-scale tests be conducted to ensure the mechanical properties and durability of RCA before its widespread use. The findings offer valuable guidance for contractors and engineers seeking sustainable alternatives in construction while reducing the environmental impact of C&D waste.

The work of [4] addresses the global challenges associated with the increasing demand for non-renewable natural resources in the construction and maintenance of hot mix asphalt pavements. Simultaneously, the growing volume of C&D waste has raised significant environmental and economic concerns. However, the study suggests that C&D waste, once converted into raw materials, holds substantial potential in the market. Through an extensive literature review, the paper explores alternative methods for incorporating C&D waste in asphalt paving projects, aiming to encourage highway authorities to create new technical guidelines and specifications for CDW recycling. The review also stresses the importance of verifying the safety, effectiveness, and feasibility of using these materials by supporting larger-scale production and suitability testing. The research envisions a new era of economic innovation in pavement engineering, driven by the sustainable application of C&D waste.

Finally, [5] focuses on the recycling and reuse of Construction and Demolition Waste (CDW), which results from debris generated during the construction, renovation, and demolition of buildings, roads, and bridges. Recycling these materials is essential for achieving sustainability, particularly from an environmental standpoint. Despite the inclusion of recycled aggregates in some technical specifications, their widespread use is still hindered by a lack of knowledge about their technical applications. This paper consolidates the recommendations found in the "Catalogue of Road Pavements with Recycled Aggregates," supported by experimental sections. The study proposes various structural configurations for road pavements using recycled aggregates, aiming to encourage broader adoption of these sustainable materials in road construction projects.

III. METHODOLOGY

The methodology adopted for this study was based on an extensive bibliographic research in major scientific databases, aiming to collect relevant information on the use of recycled materials, such as construction and demolition waste, in permeable pavements. The research was conducted through consulting specialized journals, conference papers, theses and dissertations, as well as technical reports available in academic repositories. The sources consulted were selected based on their relevance and scientific quality, prioritizing studies that presented experimental analyses, literature reviews, or case studies applied to sustainable infrastructure projects.

In addition, databases such as Google Scholar, Scopus, Web of Science, and ScienceDirect were extensively used to ensure the breadth and quality of the gathered information. The publication selection process involved searching for specific keywords, such as "permeable pavements," "construction waste recycling," "recycled aggregates," and "environmental impact of pavements." Through reading abstracts and full articles, the main advancements in the use of recycled materials in paving were identified, along with the experimental methodologies employed in different geographical and climatic contexts.

Finally, the collected data were analyzed both qualitatively and quantitatively to identify patterns and trends in the results found. The bibliographic research allowed for an in-depth understanding of the techniques used, the challenges faced, and the solutions proposed to optimize the use of recycled materials in permeable pavements. This approach contributed to the development of a critical view on the environmental and economic impact of using these materials, providing a basis for recommendations and suggestions for future research in the field.

IV. RESULTS AND DISCUSSIONS

The research carried out by [6] delves into the advancement of permeable pavement systems (PPS), especially regarding their function in sustainable urban drainage systems (SUDS) for managing stormwater. Utilizing a bibliometric analysis and a systematic literature review of studies published between 2000 and 2021, the authors identified trends, knowledge gaps, and innovations in the field. Their findings suggest that small design modifications or the use of novel filtering layers can improve the removal of pollutants. However, factors such as low-permeability soils and inadequate pore sizes remain as primary challenges to infiltration efficiency. Additionally, the study emphasizes that combining different maintenance techniques can successfully address clogging—mostly occurring in the top 1.5–2.5 cm of the system. Although recycled aggregates improved permeability, they caused a slight reduction in compressive strength. The study provides useful directions for future innovations aimed at enhancing water quality and incorporating recycled materials into PPS designs.

In the study conducted by [7], the pressing issue of construction and demolition waste (CDW), which exceeds 10 billion tonnes annually, is addressed through the development of sustainable pavement solutions. The researchers assessed the use of CDW fines to create recycled cement, optimized with well-graded crushed stone (WGCS), for use in pavement base layers. The project included scaling up the methodology with materials from a local recycling plant and constructing pilot pavement sections to measure field performance. Results indicated that the CDW cement achieved substantial heat accumulation and compressive strength, while pavement sections using this cement exhibited unconfined compressive strength and resilient modulus values comparable to conventional alternatives. Deflections reduced over time due to pozzolanic reactions, proving the feasibility of CDW in creating sustainable, structurally sound pavements.

Focusing on sustainable construction, [8] explored the viability of reusing CDW materials—such as crushed concrete, asphalt mix, and ceramic waste aggregates—in the construction of pavement base layers. The research aimed to minimize landfill use and reduce dependence on natural aggregates. A field investigation tested pavement sections under actual traffic loads, confirming the structural adequacy of the recycled materials. The results demonstrated satisfactory load-bearing performance, reinforcing the potential for CDW to serve as a sustainable and technically sound alternative in road construction.

The investigation by [9] tackles the environmental consequences of urban development by proposing a novel approach combining pervious surfaces, recycled concrete aggregates (RCA), and industrial waste to produce pervious geopolymer concrete. With a target porosity of 15%, the study assessed the performance of pervious geopolymer recycled aggregate concrete (PGRAC) using two binder blends—slag:fly ash in 1:0 and 1:1 ratios—and varying RCA contents (0% and 100%). The concrete made with natural aggregates and a 1:0 binder blend delivered significantly higher compressive strength compared to its 1:1 counterpart. Although permeability remained relatively unchanged with binder variation, full RCA replacement reduced strength, while the 1:1 mix offered slightly better permeability. These findings support the potential use of PGRAC in sustainable pavement applications.

The study presented by [10] contributes to the ongoing efforts to mitigate environmental harm caused by the accumulation of industrial waste. By recycling materials like concrete, brick, and breeze blocks from demolished structures, the research explores their potential application in the base layers of flexible pavements. The mechanical behavior of these recycled materials was evaluated through experimental methods, revealing promising results. The use of such materials helps preserve natural resources, reduce transportation-related emissions, and lower energy consumption. This approach not only optimizes pavement design but also offers a cost-effective solution that avoids the use of expensive surface layers like bituminous concrete.

In research by [11], attention is drawn to the challenge of improving the performance of asphalt mixtures that incorporate recycled concrete aggregates (RCA). Given the limitations of RCA in traditional asphalt applications, this study investigates the use of secondary aluminum dross (SAD) as an alternative filler. SAD was substituted for limestone dust in varying proportions (10%, 20%, and 30%), and its effects on mixture properties were evaluated using the Marshall method, as well as tensile and compressive strength tests. Results showed that SAD enhanced mechanical performance, with 20% being identified as the most effective dosage. When applied to mixtures containing 25% RCA, this dosage significantly improved both the tensile strength ratio (TSR) and the index of retained strength (IRS). The findings underline the potential of industrial by-products to strengthen asphalt pavements while contributing to sustainable waste management.

Lastly, the work developed by [12] highlights the importance of integrating C&D waste into sustainable infrastructure practices, particularly in road construction. It addresses both the environmental burden caused by the excessive generation of waste and the depletion of natural aggregate resources by the transportation sector. The study promotes the use of recycled C&D materials in pavement layers, which not only reduces landfill volumes but also minimizes resource extraction. A life cycle assessment (LCA) was employed to evaluate the environmental performance of recycled aggregate use, considering risks related to chemical composition and leaching. The research advocates for broader adoption of C&D waste in roadworks, offering a viable pathway toward zero-waste construction and eco-efficient infrastructure development.

V. CONCLUSIONS

The reuse of construction and demolition waste (CDW) in permeable pavements presents a significant opportunity for integrating sustainability into urban infrastructure. This practice effectively addresses two of the most pressing challenges in civil construction: the growing volume of waste materials and the environmental impacts of impermeable surfaces in cities. By substituting traditional materials with recycled alternatives such as concrete, brick, and asphalt, permeable pavements contribute to improved urban drainage, reduced flood risks, and the circular use of resources that would otherwise burden landfills.

Moreover, the studies reviewed indicate that permeable pavements made with recycled materials not only meet technical performance standards but also offer tangible environmental and economic advantages. Benefits include enhanced water infiltration and quality, reduced greenhouse gas emissions from the manufacturing of virgin materials, and significant cost savings in waste disposal and raw material extraction. The inclusion of industrial by-products, such as secondary aluminum dross, further amplifies these benefits, offering a path toward more efficient and eco-friendly pavement technologies.

However, challenges remain. Variability in the quality of recycled aggregates, risks of pore clogging, and slight reductions in compressive strength demand further research and innovation. Standardization, long-term performance evaluations, and continued investment in recycling technologies are essential to fully realize the potential of CDW in permeable pavements. With proper policy support and technical refinement, this approach holds promise for transforming urban infrastructure into a more resilient, cost-effective, and environmentally responsible system.

VI. AUTHOR’S CONTRIBUTION

Conceptualization: Eliomar Gotardi Pessoa.
Methodology: Eliomar Gotardi Pessoa.
Investigation: Eliomar Gotardi Pessoa.
Discussion of results: Eliomar Gotardi Pessoa.
Writing – Original Draft: Eliomar Gotardi Pessoa.
Writing – Review and Editing: Eliomar Gotardi Pessoa.
Resources: Eliomar Gotardi Pessoa.
Supervision: Eliomar Gotardi Pessoa.
Approval of the final text: Eliomar Gotardi Pessoa.

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