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Adoquines de cemento aligerados con residuos poliméricos industriales
Cement cobblestones lightened with industrial polymeric waste

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Resumen-- **Se espera que el consumo mundial de recursos como la biomasa, los combustibles fósiles, los metales y los minerales se duplique en los próximos años (Organización para la Cooperación y el Desarrollo Económicos [OCDE], 2018), mientras que se prevé que la generación anual de residuos en Europa aumente un 70 % para 2050 (Kaza et al., 2018). Por ello, es necesaria una transición hacia un sistema económico y productivo sostenible como parte de las nuevas estrategias industriales. Estudios recientes estiman que la aplicación de los principios de la economía circular tiene el potencial de de mejorar los procedimientos de ingeniería creando nuevos puestos de trabajo cualificados. Más del 80% del impacto medioambiental de los materiales de construcción se determina en la fase de diseño (Comisión Europea, 2019). Muchos subproductos se descomponen demasiado rápido y no pueden reciclarse sin más, y muchos se fabrican para un solo uso. Junto con esta condición, las políticas de gestión proporcionan normas mundiales hacia la sostenibilidad de los materiales de construcción (Taurino, Bondioli, & Messori, 2023).**

Con el objetivo de caracterizar estos adoquines ecosostenibles, también se han realizado diferentes ensayos de durabilidad como congelación-descongelación y cristalización salina, estableciendo la resistencia a la compresión antes y después del ensayo, confirmando las propiedades idóneas para ser utilizados en diferentes ambientes exteriores.

Palabras clave— Sostenibilidad; economía circular; residuos de poliuretano; adoquines de mortero de cemento; prefabricados ligeros.

Abstract— **Global consumption of resources such as biomass, fossil fuels, metals and minerals is expected to double in the next years (Organisation for Economic Co-operation and Development [OECD], 2018), while annual waste generation in Europe is projected to increase by 70% by 2050 (Kaza et al., 2018). For this reason, it is necessary a transition to a sustainable economic and productive system as part of the new industrial strategies. Recent studies estimate that applying circular economy principles has the potential**

to improve the engineering procedures creating new qualified jobs. More than 80% of construction materials' environmental impacts are determined at the design phase (European Commission, 2019). Many by products break down too fast and cannot be simply recycled, and many are made for single use only. Together with this condition, the management policies provide world-wide standards towards construction materials sustainability (Taurino, Bondioli, & Messori, 2023).

With the aim of characterize this eco sustainable cobblestones, different durability tests have also been carried out as freeze-thaw and crystallization salt, establishing the compressive strength before and after the test, confirming the suitable properties to be used in different – outdoor – environments.

Index Terms— Sustainability; circular economy; polyurethane waste; cement mortar cobblestones; lightweight prefabricated.

I. Introduction

In order to reduce the current dependence on raw materials and revalue waste produced by various industries, institutions at global, European, national, and regional levels are increasingly focused on introducing guidelines and legislation to protect the environment and human health. These efforts highlight the importance of adopting effective waste management, recovery, and recycling techniques to alleviate resource pressure and enhance their efficient use (European

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Parliament and Council, 2008).

The construction sector accounts for 36% of global final energy consumption, nearly 40% of total direct and indirect CO2 emissions, and over 45% of waste generation (Institute of Construction Technology, n.d.). Consequently, incorporating new construction materials derived from recycled waste can significantly reduce life cycle impacts and lower the sector's reliance on natural resources.

This research aims to develop innovative construction products utilizing recycled materials from industrial waste in the automotive sector. By doing so, it contributes to a more sustainable planet and promotes a circular economy by minimizing the use of natural resources and transforming waste into valuable raw materials for prefabricated construction products.

II. Methods

The objective of this research is to develop lightweight prefabricated elements using waste materials from the automotive sector. This waste comprises the interior components of vehicle roofs that have reached the end of their life cycle, primarily made of polyurethane along with remnants of adhesives, cardboard, and other materials. To incorporate this waste, it is shredded and used as a partial replacement for the aggregate typically employed in cement mortars, enabling its application in both building and civil engineering. This approach reduces waste treatment costs and minimizes landfill disposal.

Using the described waste, prefabricated pavers are produced with a composition that includes cement, washed river sand, water, and an additive to enhance the material's properties. The cement-to-aggregate ratio is maintained at 1:3, with the aggregate progressively replaced by waste at levels of 20%, 40%, and 60%. An additive is included to improve matrix compaction, thereby enhancing mechanical strength and other critical properties.

Prefabricated cement mortar pavers are manufactured using these specified dosages, alongside a reference sample. The polyurethane waste is mixed with cement and aggregate, while water and the additive are combined separately. These components are then thoroughly mixed, kneaded, and poured into molds to create prefabricated elements. A compaction and vibration process follows, producing pavers with dimensions of 200x100x60 mm³, which comply with standard market dimensions.

Fig. 1. Prefabricated Pavers with 20% Dosage

The prefabricated elements are subjected to tests in accordance with European regulations. For this purpose, the necessary samples were produced to meet the standards required for the various tests, ensuring compliance with the criteria set forth in each regulation.

The pavers are tested after 28 days, with the samples stored under conditions specified by the relevant standards. Tests include determining the apparent density for different dosages and assessing surface hardness using the Shore C scale. Fire reaction tests classify the pavers as Class A1 without additional testing, as they meet external fire behaviour requirements. Mechanical strength tests were conducted following the EN 1338 standard, "Concrete Paving Blocks – Requirements and Test Methods."

III. Results

The results obtained from testing prefabricated pavers with different dosages, where aggregate is substituted with polyurethane waste, indicate that some properties are slightly reduced due to the waste's presence. However, all dosages comply with the current standard for pavers, UNE-EN 1338:2004, "Concrete Paving Blocks. Specifications and Test Methods."

Table 1 summarizes the results of analysing the physical properties of the pavers across the various dosages.

A. Density and Surface Hardness

The properties of both fresh and hardened pavers were measured for the specified dosages (Table 1). These tests followed the UNE-EN 1338:2004 standard, "Concrete Paving Blocks. Specifications and Test Methods."

The results (Figure 2) show a progressive decrease in density as the percentage of aggregate replaced by waste increases. This reduction is attributed to the lower density of the waste compared to the aggregate it replaces. Consequently, the prefabricated elements become lighter than conventional pavers

TABLE I
RESULTS OF TESTED PHYSICAL PROPERTIES

Dosages. Aggregate-Waste Substitutions	Apparent Density (kg/m³)	Shore C Hardness	Compressive Strength (MPa)
Reference	2317,13	93,08	4,80
20	2178,57	90,29	5,08
40	2152,17	85,71	4,33
60	2052,61	84,58	3,79

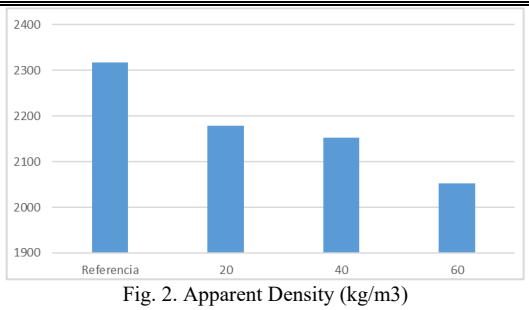

Fig. 2. Apparent Density (kg/m3)

currently available on the market, offering advantages such as reduced structural loads and improved workability during installation.

Shore C surface hardness (Fig. 3) also decreases with increasing aggregate replacement by waste. Despite this reduction, the hardness values remain consistently high, exceeding 84 in all cases.

A relationship between density and surface hardness (Figure 4) reveals that both properties decline as the waste substitution percentage increases. However, Shore C hardness remains high across all tested dosages, resulting in lightweight prefabricated elements with sufficient surface hardness for practical use.

B. Mechanical properties

The breaking strength of the pavers was determined through compression tests in accordance with UNE-EN 1338:2004, "Concrete Paving Blocks. Specifications and Test Methods." As per the standard, the characteristic breaking strength must be at least 3.6 MPa, with no individual value falling below 2.9 MPa or a breaking load of less than 250 N/mm of breaking length.

As illustrated in Figure 5, all tested dosages meet the standard, including the highest substitution level of 60% aggregate replacement with waste. At 28 days, this dosage achieved a breaking strength of 3.8 MPa. Notably, the 20% substitution dosage showed a slight increase in compression strength, likely due to the additive's effect. The additive reduces water demand during mixing, which in turn enhances the mixture's mechanical properties.

For higher substitution levels, compression strength decreases, but values consistently remain above the standard minimums.

A relationship between apparent density and compression strength demonstrates that incorporating waste produces lighter prefabricated elements without significantly compromising mechanical performance. Although mechanical properties diminish as waste content increases, all tested dosages maintain compliance with the standard, achieving breaking strengths above 3.6 MPa.

IV. Conclusions

This study analyzed prefabricated cement mortar pavers composed of cement, aggregate, water, an additive, and polymeric waste in varying percentages, where the waste partially replaces the aggregate by volume.

The results obtained demonstrate the viability of these prefabricated elements for use in construction, as they comply with the relevant standards regarding mechanical properties such as compressive strength. Furthermore, incorporating waste with a lower density than the aggregate results in prefabricated elements with reduced densities compared to conventional products used in the construction sector. This reduction in weight enhances transportation and installation efficiency.

Notably, the addition of waste does not compromise the shape or dimensions of the prefabricated product, nor does it lead to issues such as cracking or efflorescence. This ensures that the aesthetic and functional characteristics of the pavers meet the required standards for this type of product.

Additional tests are planned to complete the characterization of these pavers and confirm their compliance with all standard

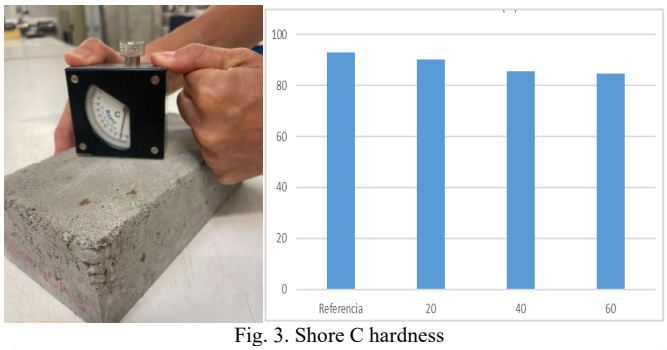

Fig. 3. Shore C hardness

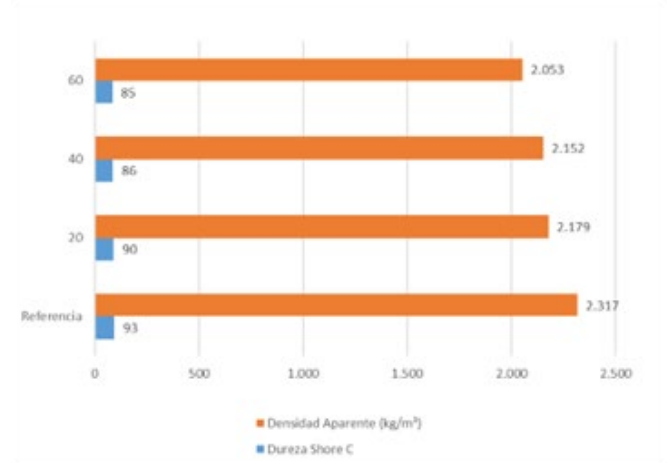

Fig. 4. Relationship Between Apparent Density and Shore C Hardness

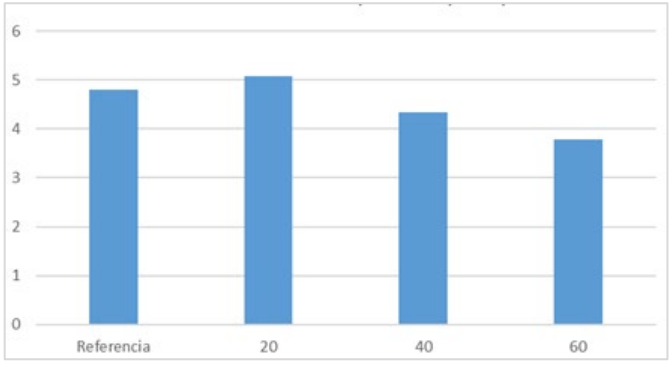

Fig. 5. Compressive strength

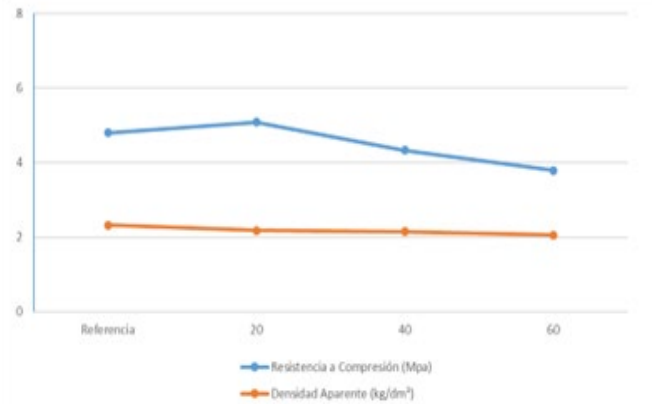

Fig. 6. Relationship Between Apparent Density and Compressive Strength

requirements. The use of these eco-friendly pavers contributes to a more sustainable economic and production system by repurposing waste as raw material, reducing landfill disposal, and conserving natural resources. Moreover, this approach lowers energy consumption and environmental impacts associated with traditional manufacturing processes, aligning with ongoing research efforts to promote sustainable development and a circular economy.

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