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Mechanical characterization of plaster-based blends modified with high-density polyurethane wastes

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Abstract. This research applies a circular economy model by reusing polymer waste from a local company, promoting recycling and revaluing these materials with applications in the construction sector. The study focuses on a plaster-based composite material, which is incorporated with recycled high-density polyurethane (HDP) particles. Different samples were prepared with specific proportions of HDP in the plaster matrix. With the objective of evaluating the physical-mechanical properties of different compounds, the relationships among specific process variables, which affect their performance in constructive applications, have been analyzed. For this, a factorial experimental design (DOE) with 3 levels and 2 factors was implemented, which allowed analyzing the interactions between the mixing ratio (R) and the amount of HDP, and how these variables affect the density, flexural strength and compression of the compounds. The most relevant results indicate that an increment of R, especially the highest tested level (R=0.7), negatively influences both the resistance to bending and compression caused by porosity, due to the increasing amount of water. An optimal level of R, which ensures good material performance without compromising its mechanical properties, was, in the end, determined. For what concerns the content of HDP, its increasing concentration decreases the performance of the compound in terms of compression resistance, below the minimum standards required value of 2MPa, when HDP at 10% was tested.

Introduction

The need to reduce industrial residual loads of polymeric waste on the environment has led to the redesign of materials and products that are framed in a circular economic model, driving innovation in different sectors of the economy [1]. In this context, the revalorization of polymeric waste materials has become a priority and an environmentally friendly recycling strategy even for the rise of global production. Indeed, the growth of polymeric resins, due to technological advances in manufacturing and their wide field of industrial applications in a wide variety of sectors such as energy, automotive, aerospace, etc. [2,3], has led to much attention being paid to them [4]. One of the possibilities, where recycled polymers can be reused, is as aggregate in the construction sector, which offers the possibility of using polymeric waste as additives in plaster-based composite products. At the same time, these resins have been increasing significantly as waste to be disposed of [5]. Polymeric waste must be treated correctly in order to be reused as raw material [6]. However, in addition to the type of recycled polymeric resin, the stages of the mechanical recycling process are essential to achieve the desired yields. Various processes such as shredding, cutting and tearing are used to reduce the initial dimensions [7].

Polymer waste-reinforced plaster materials are innovative materials that offer great application potential due to their improved physical properties [8]. Thermal performance, acoustic absorption and fire resistance are some of the properties that can benefit from this mixture, making the obtained mixture a more efficient and sustainable solution suitable for construction with a large

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impact on the environment, reducing pollution [9-12]. These applications and characteristics provide an opportunity to seek innovative alternatives that can provide economic solutions with great social impact, designed to create new materials that use plaster-polymeric waste as raw material in adequate proportions to further improve products' physical-mechanical properties.

Researchers have delved into this topic by providing methods and procedures for the creation of materials with plaster matrix as the main element, improving it with aggregates of recycled and natural materials for applications such as lightweight panels. In [13], the authors proposed a production strategy that consists of progressively adding polyamide powder to a plaster mix, the one known as B1 type, which is recommended for this type of use according to European standard 13279-1 [14], obtaining a consistent mix according to EN 13279-2 [15].

In this direction, S. Gutiérrez-González [16] also analyzed the influence of polyamide-plaster composite materials resulting in a proposal that could have a great impact by reusing polymers to create new materials with special characteristics. Another interesting study in the same context was presented by [17]. Specifically, ecological composites, mainly used for thermal insulation in buildings, were experimentally analyzed, obtaining a composite of plaster and coffee waste mixed with the corresponding additions of water. The evaluation of the material revealed that the density, conductivity and thermal diffusivity decreased respectively when compared to the mixture containing only plaster. In another researcher, A. Asadi Ardebili [18] presented plaster-based materials incorporating wastes from the automotive industry, such as mixed wastes (containing polyurethane, cardboard and fiberglass) obtained during the production of automotive panels. They incorporated mixed wastes (2.5%, 6% and 11%), also varying the water/plaster ratio (w/g). In particular, w/g values of 0.5, 0.6 and 0.7 were tested. The waste particles were characterized by dimensions between 1 mm and 5 mm. The best mechanical behaviors were detected for compounds with a w/g value of at least 0.7, with waste additions below 6%. Anyway, the incorporation of wastes at 11% into the plaster was the recommended solution, because this is able to maintain good workability of the mixture and properties superior to the minimum values established by the legislation [18].

Different polymeric resins were mechanically recycled with the above discussed strategy. For example, an experimental study of plaster panels composed of various fractions of rubber (values of 30%, 40%, 50% and 60% with respect to the weight of plaster) mechanically crushed, was proposed in [19]. The particle sizes were divided into three groups (0-0.6 mm; 0.5-2.5 mm nominal; 2.5-4.0 mm) to analyze the physical, mechanical thermal and acoustic properties of the different blends.

In this research, an experimental procedure was implemented based on the mechanical recycling of high-density polyurethane (HDP), which is reused as aggregate material in plaster-based materials. The physical-mechanical characteristics of the prepared compound were evaluated in order to find the relationship and influences among specific process variables that provide better properties for applications in the field of the construction sector.

Experimental procedure

The experimental campaign was carried out by processing industrial waste HDP foam. The analysis begins with grinding these polyurethane parts ensuring the obtaining of particles with an average dimension less than 0.5 mm. Machined polymers (HDP) are reused as secondary aggregates in a brick mixture composed of plaster (P) and water (W). The sequence of tests carried out is shown in Fig.1.

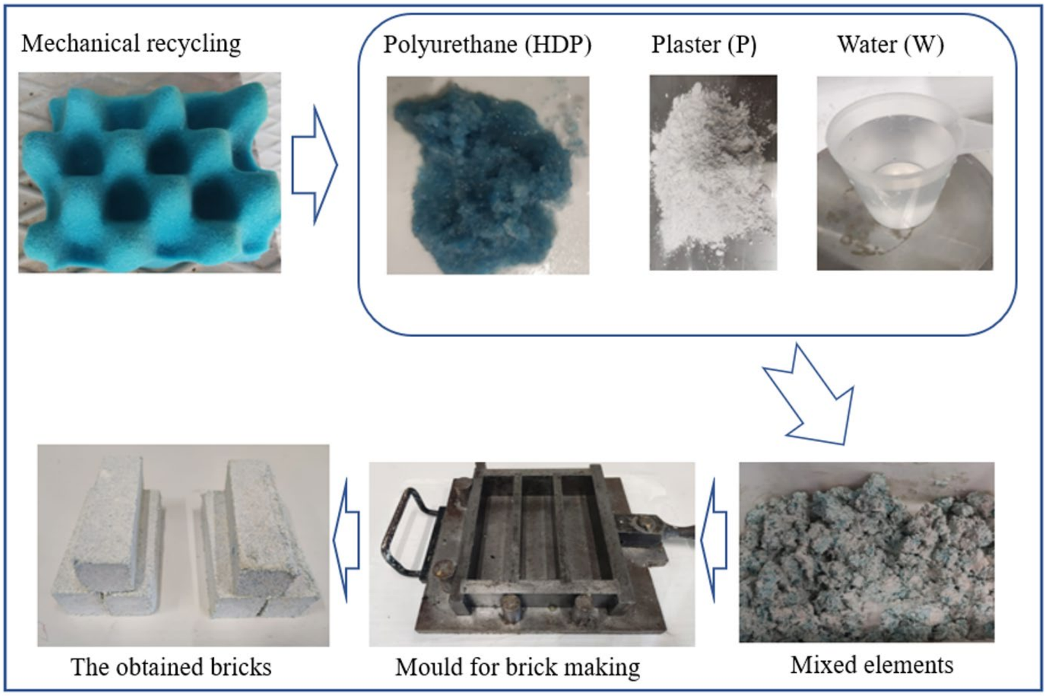

Figure 1 – Recycling steps of the polymeric wastes followed in the experiments

The bricks were produced using specific molds, ensuring controlled drying while respecting parameters such as temperature (23 ± 2) °C and humidity (50 ± 5) % for 28 days according to [12]. Homogeneous mixing was achieved for each volumetric configuration tested before the brick production phase, taking into account that at the end of each manufacturing stage the bricks obtained did not have visible defects to avoid alterations of the result due to surface irregularities. The water ratio (W) was determined using Eq.1.

$$R = \frac{W}{P+HDP}. \tag{1}$$

A complete factorial design was implemented to determine the interactions of R and HDP. Specifically, a complete factorial design of 3 levels and 2 factors was chosen to perform an in-depth analysis capable of achieving a consistent relationship between the investigated factors and their effects on one or more responses Table 1.

Table 1 – Design of experiments (Full factory design)

Factor	Name	Levels		
R	Mixing ratio	0.5	0.6	0.7
HDP	Polyurethane [%]	0	5	10

The determination of mechanical properties was carried out in accordance with the standards for this type of material. MTS-Criterion Model 42 test machines and an Instron 8501 model were used in the experimental tests carried out. The 3-point bending tests were carried out in accordance with the standard [12] and the dimensions used for the bricks were 160x40x40 mm (Fig. 2a). Flexural strength (σ_f) is a fundamental parameter to determine and represents the maximum stress that the material can withstand before failing due to bending measured in (MPa). It is decided according to Eq.2.

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$$\sigma_f = \frac{3}{2}\frac{FL}{bt^2}\,(\text{MPa}) \tag{2}$$

The applied force (F) is the point load placed on the center of the beam during the test, measured in Newton. Furthermore, L is the distance between the support points while b and t are respectively the width and the thickness of the sample. The tests were carried out with a loading increment of 0.05 N/s.

On the other hand, the dimensions of the bricks used for the compression test (Fig. 2b) are 40x40X40 mm according to [12]. The loading increment, for this type of test, was of 0.5 N/s. The compressive strength (σ) is the variable to be calculated according to Eq.3.

$$\sigma = \frac{F}{A}\,(\text{MPa}) \tag{3}$$

The force (F) is the external load, in Newton, distributed on the transversal area (A) of the specimen.

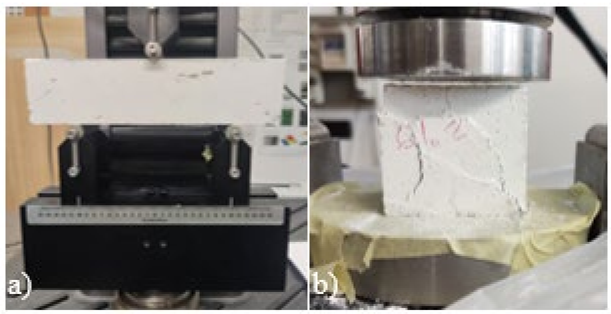

Figure 2 – Executed a) flexural and b) compression strength tests

Results Analysis

As regards the incorporation of polyurethane resins in the plaster mixture configurations (HDP 0%, HDP 5%, HDP 10%), the first one (HDP 0%) being a pure plaster configuration without polymer aggregate was tested as a reference case. The proportion of polyurethane volumetric aggregates was evaluated, doubling the percentage (HDP 5% and HDP 10%). The results indicate that the addition of polymers has a significant effect on both density (Fig.3 and Table 2) and mechanical properties of composite materials (Fig.5 and Table 3).

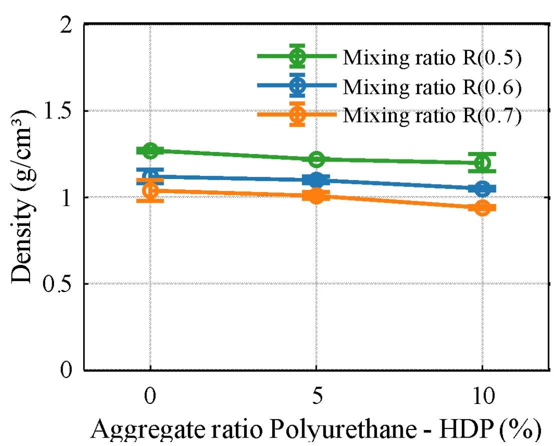

Figure 3 – Results of material density when changing the investigated factors

Table 2 – Density distribution at changing of investigated variables

Mixing ratio [R]	Density[g/cm3]					
	[HDP]0%	DEV_0%	[HDP]5%	DEV_5%	[HDP]10%	DEV_10 %
0.5	1.27	0.01	1.22	0.0033	1.20	0.05
0.6	1.12	0.04	1.10	0.02	1.05	0.01
0.7	1.09	0.06	1.01	0.02	0.94	0.01

The reduction in density, in the case of 0% HDP, is caused by the increase in the R factor. For higher values of R, the amount of water in the mixture increases, which, evaporating during the drying process, leaves pores inside the structure, thus reducing its weight. Fig.4 shows the porosity variation at changing of the R value.

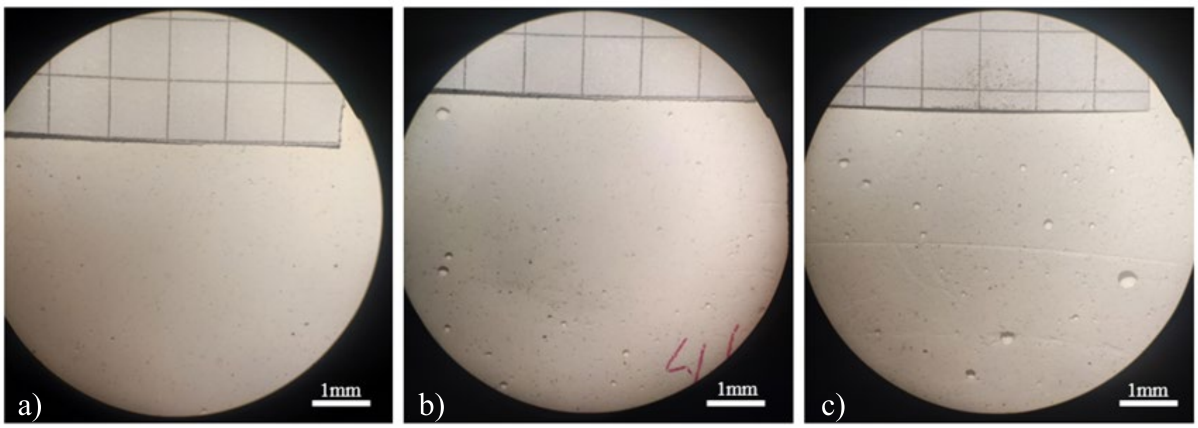

Figure 4 – Variation of the material porosity at changing of the R value: a) 0.5, b) 0.6 and c) 0.7

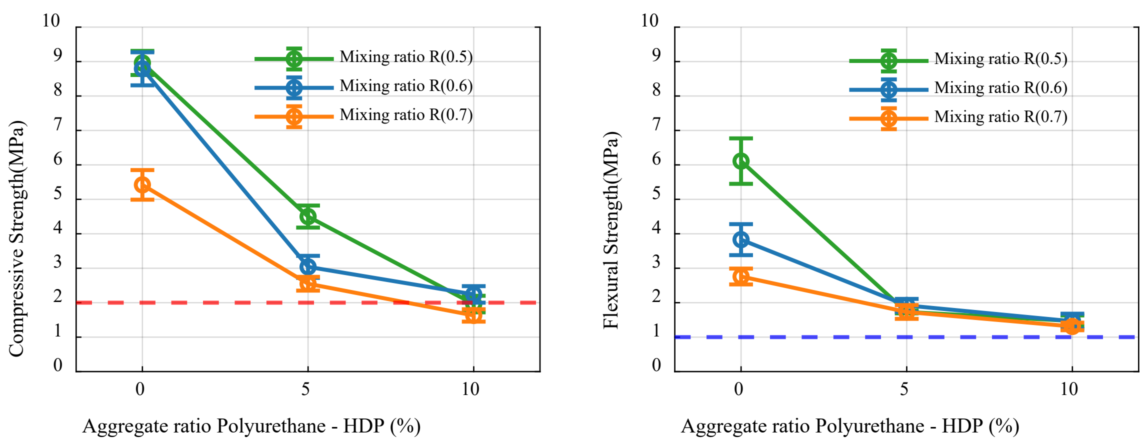

Figure 5 – Results of compressive-flexural strength at changing of the investigated factors

The mechanical properties of the analyzed samples are affected by the R values, with a decrease in both flexural and compressive strength for the highest values (R=0.7), due to the pores in the mixture. A HDP increment causes a constant decrease in the properties of the bending resistance to compression. A critical point in the compressive strength is related to the configuration with HDP=10%, since the strength decreases below the minimum value of 2 MPa needed for these materials to be suitable [12] for the whole tested R configurations.

Table 3 – Monitored mechanical performances at changing of investigated variables

Mixing ratio [R]	Compression Strength [MPa]					
	[HDP] 0%	DEV_0%	[HDP] 5%	DESV_5%	[HDP] 10%	DESV_10 %
0.5	8.96	0.35	4.50	0.32	1.96	0.24
0.6	8.79	0.49	3.04	0.20	2.24	0.22
0.7	5.42	0.43	2.55	0.21	1.63	0.18
Mixing ratio [R]	Flexural Strength [MPa]					
	[HDP] 0%	DEV_0%	[HDP] 5%	DESV_5%	[HDP] 10%	DESV_10 %
0.5	6.11	0.66	1.73	0.04	1.47	0.16
0.6	3.83	0.45	1.92	0.17	1.46	0.14
0.7	2.76	0.23	1.73	0.20	1.31	0.11

Conclusions

This study presents an innovative solution to the growing challenge of increasing polymer waste, using mechanical recycling to ensure crushed particles. The upgrading of these wastes as aggregates in plaster-based materials, widely used in the construction sector, is assessed against the minimum standards required to ensure their viability. It is essential to characterize the possible combinations and effects of two factors, namely R and HDP percentage, on the physical-mechanical properties of the produced compounds, allowing the identification of the best combinations. The factor R is the one that mainly affects the compound density because the increase in water that evaporates during the drying step, leaves pores within the material structure. It also decreases, even if more slightly, when the HDP percentage increases. According to that, it has to be highlighted that the HDP absorbs a water proportion, leaving a mixture in the production phase less fluid and, therefore, more difficult to be processed. The evaluation of the mechanical properties of the material showed that the HDP level is the most meaningful factor. Indeed, the compounds are close to exceed the limits required by the standards for both compressive and flexural strength when the HDP percentage of 10 is taken into account regardless of the R value.

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