engineering proceedings

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Proceeding Paper

Study of the Water-Resistant Properties of New Eco-Friendly Gypsum Composites with Additions from Single-Use Plastic Waste †

Alicia Zaragoza-Benzal [1,*], Daniel Ferrández [1], Paulo Santos [2] and Carlos Morón [1]

1 Departamento de Tecnología de la Edificación, Escuela Técnica Superior de Edificación, Universidad Politécnica de Madrid, Avda, Juan de Herrera, 6, 28040 Madrid, Spain; daniel.fvega@upm.es (D.F.); carlos.moron@upm.es (C.M.)
2 Department of Civil Engineering, ARISE, Institute for Sustainability and Innovation in Structural Engineering (ISISE), University of Coimbra, Rua Luís Reis Santos—Pólo II da Universidade, 3030-788 Coimbra, Portugal; pfsantos@dec.uc.pt
* Correspondence: alicia.zaragoza@upm.es; Tel.: +34-910675363
† Presented at the 1st International Online Conference on Buildings, 24–26 October 2023; Available online: https://iocbd2023.sciforum.net/.

Abstract: The main aim of this research is to study the water resistance properties of new eco-friendly gypsum composites made with low-density polyethylene (LDPE) waste additions in granular form. Three percentages of LDPE additions by weight have been used as partial replacement of the original gypsum material: 2.5%, 5.0%, and 7.5%. The results show that the addition of these recycled raw materials reduces the total water absorption of the gypsum composites. On the other hand, durability tests have been carried out against the repeated action of wet chamber cycles and water–stove cycles. After carrying out these accelerated ageing tests, it was concluded that all the composites produced in this research exceeded the minimum flexural and compressive strengths recommended by the EN 13279-2 standard. Thus, the gypsum composite materials produced are a sustainable alternative for recovering and revaluing plastic waste.

Keywords: plastic waste; gypsum composites; durability test; circular economy; sustainability

Citation: Zaragoza-Benzal, A.; Ferrández, D.; Santos, P.; Morón, C. Study of the Water-Resistant Properties of New Eco-Friendly Gypsum Composites with Additions from Single-Use Plastic Waste. *Eng. Proc.* **2023**, *53*, 26. https://doi.org/10.3390/IOCBD2023-15201

Academic Editor: Antonio Formisano

Published: 24 October 2023

1. Introduction

In recent decades, the production of plastics has increased more than any other material as a result of their growing number of industrial applications [1]. Expert predictions show that the consumption of plastic materials will double by the year 2050 [2], with 330 million metric tons of these products currently being generated, of which only 9% is recycled; among the remaining 91%, 12% is incinerated and 79% accumulates in landfills [3]. This alarming environmental situation has drawn the attention of governments and entrepreneurs to the adoption of circular economy criteria to reduce the generation of plastic waste, increase the useful life of products made from these materials, and commit to the preservation and care of the ecosystem [4].

On the other hand, the construction sector demands large amounts of raw materials annually, while at the same time it generates more solid waste than any other industrial activity in the European Union [5]. In this context, it is understood that the incorporation of plastic waste under circular economy criteria for the design of new ecofriendly materials is an alternative with high added value. Thus, gypsum composite materials represent a source of possibilities for the recovery and revalorisation of this solid waste [6]. In general terms, the incorporation of these plastic wastes makes it possible to lighten the weight of gypsum prefabricated products, improving their thermal resistance and reducing the consumption of original raw materials [7]. On the other hand, although there is a decrease in their mechanical properties; these usually exceed the minimum values required by EN 13279-2 [8], as shown in Figure 1.

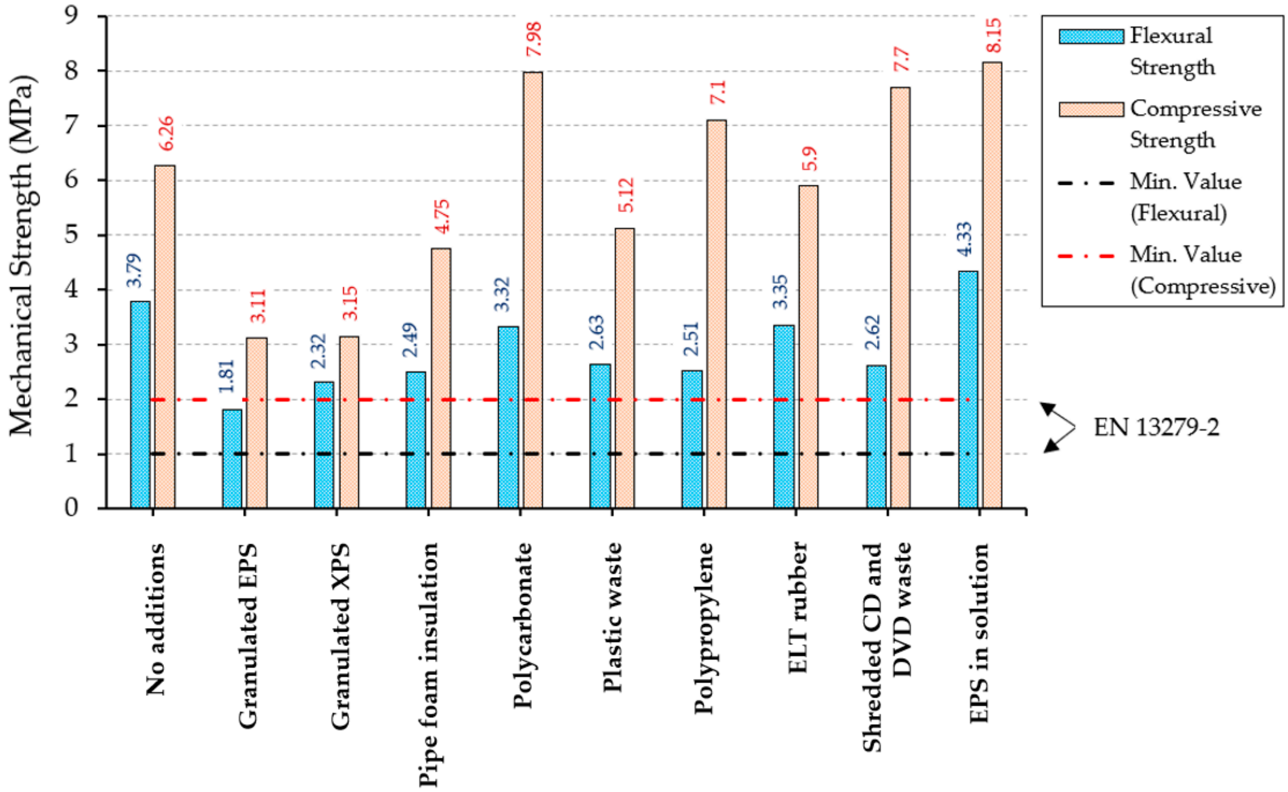


Figure 1. Mechanical properties of gypsum composites with additions of waste plastics. In the graph, the references are to the following additions: no additions [9]; granulated EPS [10]; granulated XPS [11]; pipe foam insulation [12]; polycarbonate [13]; plastic waste [14]; polypropylene [15]; end-of-life tire rubber (1–2 mm diameter) [16]; shredded CD and DVD waste [17]; EPS added in solution [18].

However, although the use of gypsum composites is mainly limited to residential interiors, they have serious disadvantages when used in wet environments, since the action of water has a negative impact on their mechanical properties and contributes to their loss of mass [19]. In this sense, several authors have tried to improve the water resistance of gypsum composites with the addition of reinforcement fibres [20], or even with the incorporation of plastic waste [21]. This is why, in this work, the aim is to study the performance against the action of water of novel ecofriendly gypsum composites produced under circular economy criteria.

For this reason, the main objective of this research is to evaluate the behaviour against wet chamber cycles and water–stove cycles of gypsum composite materials with the addition of granular LDPE plastic waste from single-use bags. In this way, it is intended to show the effect of accelerated ageing cycles on these materials with the addition of plastic waste. The paper is structured as follows: general introduction, methodology and materials used, most relevant results and discussion, and finally, conclusions.

2. Materials and Methods

This section describes both the materials and dosages used to produce the new ecofriendly gypsum composites, as well as the experimental programme proposed for this research work.

2.1. Materials and Dosages Used

The following raw materials have been used for the development of this work:

- Gypsum for construction has been selected as the binder material for this work. This material is known as B1 according to UNE-EN 13279-1 [22]. It is a binder with a purity of more than 75%, with setting time control and pH > 6.
- The water used for mixing was tap water from Canal de Isabel II (Madrid, Spain).
- LDPE waste in granular form has been added as secondary raw material. This waste from single-use bags has a diameter between 1–2 mm. Their main characteristics are as follows: tensile strength—30 MPa; elongation to failure—400%; bulk density—930 kg/m^3.

Regarding sample preparation, the recommendations of EN 13279-2 [8] were followed. For this purpose, a manual mixing process was used, previously dispersing the LDPE residues in a dry state in the conglomerate-forming material. Table 1 shows the mass proportions used to produce the gypsum composites designed in this research.

Table 1. Dosages used to produce the gypsum composites.

Sample	Gypsum (g)	Water (g)	LDPE (g)	Setting Time (min)
G0.65	1000.0	650.0	—	17.0
G0.65–2.5%	975.0	633.8	41.3	14.0
G0.65–5.0%	950.0	617.5	82.5	13.5
G0.65–7.5%	925.0	601.2	123.8	12.5

As shown in Table 1, the addition of LDPE wastes has been carried out as a partial substitution of the original material in percentages of 2.5%, 5.0%, and 7.5%, respectively. Thus, we are committed to the development of new, more sustainable construction products, decreasing the demand for natural resources and committed to a redesign of the manufacturing process that incorporates recycled materials with a slow degradation process.

2.2. Experimental Programme

This experimental campaign was carried out using a series of six $4 \times 4 \times 16$ cm test samples: a reference series, another series to be subjected to wet chamber cycles, and a final series to be subjected to water–stove cycles.

Wet chamber cycles: this is a non-standardised test that was designed by del Río Merino in his doctoral thesis [23]. For this, prismatic samples are subjected to constant humidity conditions for five days through a humid chamber (21 °C and relative humidity 90 ± 2%). They are then deposited for seven days in the laboratory at room temperature (21 °C and relative humidity 50 ± 2%). This cycle is carried out twice, and they are then tested for Shore C surface hardness and mechanical resistance to bending and compression.

Water–stove cycles: this is also a test designed by del Rio Merino in his doctoral thesis [23]. This test consists of placing the prismatic specimens in a container with water for two days and then drying them in an oven at 40 ± 5 °C for another two days. This cycle is repeated twice. The Shore C surface hardness, as well as the mechanical resistance to bending and compression are then evaluated.

The characterisation tests carried out once the specimens have been subjected to accelerated ageing cycles are shown in Table 2.

Table 2. Description of the characterisation tests conducted for the different gypsum composites.

Test	Standard	Description
Bulk density	EN 13279-2:2014 [8]	Ratio of mass to apparent volume, using a precision balance to three decimal places to obtain the mass of the compounds.
Total water absorption	EN 520:2004 [24]	The samples are weighed in the dried state and then immersed horizontally in water for 120 ± 2 min, allowing the water to penetrate through all sides. After this time, they are removed from the container and reweighed. The result is expressed as a percentage of water absorbed by each sample.
Surface hardness Shore C	UNE 102042:2013 [25]	Five measurements are taken on each of the plane-parallel faces of the sample in contact with the mould, separated by at least two centimetres from each other and from the ends of the sample tested.
Flexural and compressive strength	EN 13279-2:2014 [8]	Using an IBERTEST hydraulic press. The simple bending test is carried out with the sample supported on two points and the application of a point load in the centre (load speed of 10 N/s). The compression test is carried out in the same press on the semi-metrics generated in the bending test (load speed of 20 N/s).
Mass loss	—	Mass change after accelerated ageing tests expressed in percentages.

3. Results and Discussion

This section presents the main results derived from this research. Firstly, Table 3 shows the results obtained for the bulk density, the total water absorption coefficient and the mass losses obtained in each of the durability tests.

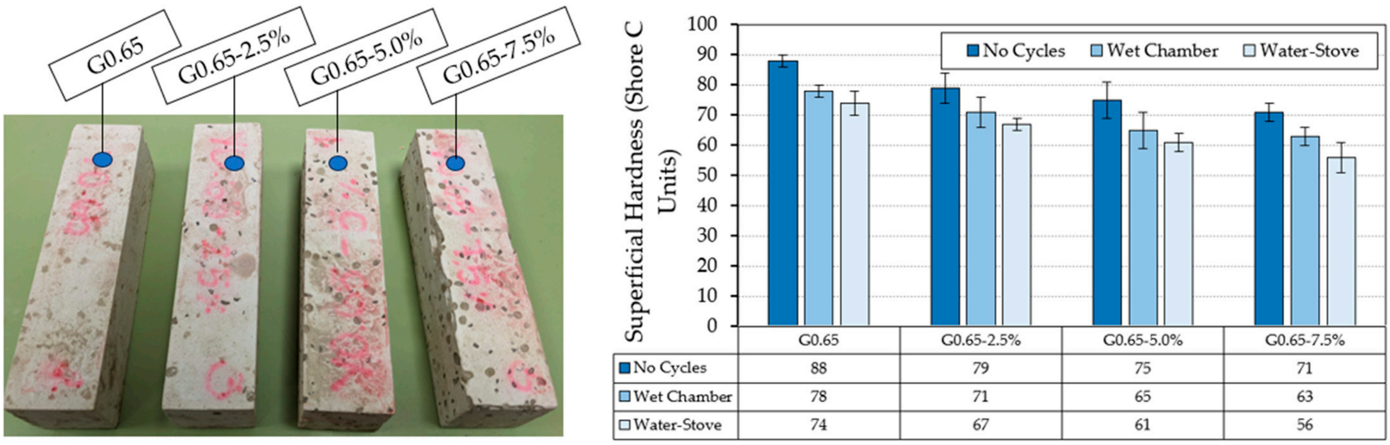
Table 3. Bulk density, total water absorption coefficient, and mass variation after durability tests.

Sample	G0.65	G0.65–2.5%	G0.65–5.0%	G0.65–7.5%
Bulk Density (kg/m^3)	1221 ± 15	1136 ± 11	1048 ± 17	974 ± 9
Total Water Absorption Coefficient (%)	42.0 ± 1.1	37.0 ± 1.8	34.3 ± 1.4	32.1 ± 0.4
∇ mass after Wet Chamber Cycles test (%)	4.3 ± 0.3	5.6 ± 0.6	5.4 ± 0.1	6.3 ± 1.0
∇ mass after Water–stove Cycles test (%)	4.5 ± 0.9	5.7 ± 0.3	5.8 ± 0.5	6.8 ± 0.6

As can be seen in Table 3, the gypsum composites with a higher content of LDPE wastes as secondary raw materials showed a lower bulk density. This effect is due to the higher porosity generated by these plastic wastes in the samples and is closely related to the increase in the total water absorption coefficient [14]. In addition, it can be observed how the samples with higher recycled material content presented a higher mass loss after the accelerated ageing tests, having presented a higher severity on average in the water–stove cycles test. Figure 2a shows the final state of the samples after wet chamber test.

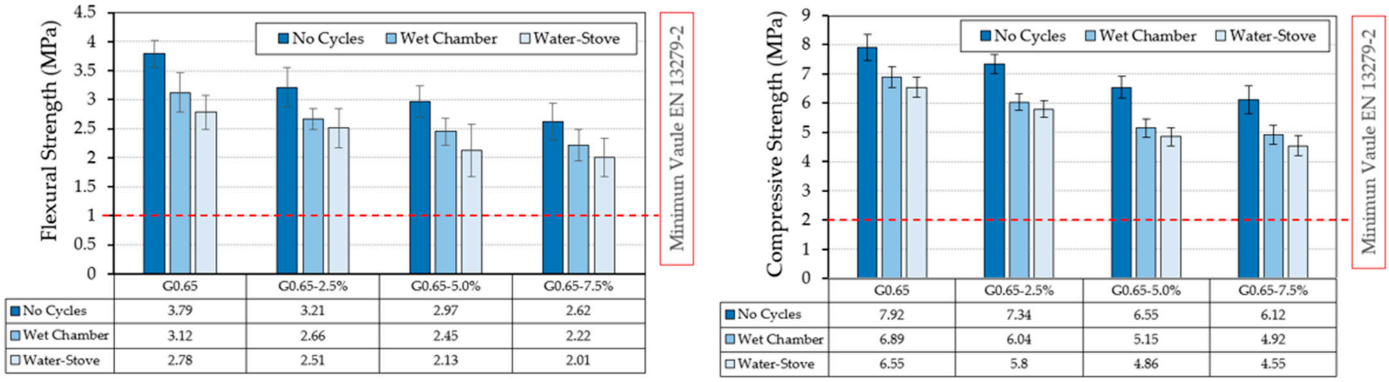
Next, Figures 2b and 3 show the results obtained for the mechanical tests of Shore C surface hardness and flexural and compressive strength, both for the reference samples and the composites subjected to durability test.

Figure 3 show that all mechanical properties were reduced in the samples subjected to accelerated ageing tests. Furthermore, in accordance with the higher mass loss experienced, the samples subjected to water–stove cycles presented worse mechanical performances in all the tests performed. It is observed that the mechanical strength decreases as the recycled plastic content added to the gypsum composites increases, in agreement with the results obtained by other researchers [10,15]. Furthermore, there is a direct relationship between the decrease in surface hardness and the flexural and compressive strengths. However, as shown in Figure 3, the minimum values of 1 MPa and 2 MPa set by EN 13279-2 for flexural and compressive strengths in gypsum composites were exceeded in all cases.



(a) (b)

Figure 2. (**a**) Condition of the gypsum composites after being subjected to water–stove cycles; (**b**) results of the Shore C surface hardness test.



(a) (b)

Figure 3. Results obtained for the tests of: (**a**) flexural strength and (**b**) compressive strength, for the three series of specimens tested (reference without cycles, subjected to wet chamber cycles and subjected to water–stove cycles).

4. Conclusions

In this research, new gypsum composites have been developed under circular economy criteria, which has made it possible to reintroduce LDPE waste into the manufacturing process of new sustainable construction materials. In this sense, the consumption of original raw materials has been reduced by up to 7.5% with respect to the original gypsum materials, in turn reducing the apparent density by 21%.

As an innovation, the behaviour and durability of these new materials has been tested under the action of wet chamber cycles and water–stove cycles. In all cases, it has been possible to verify how, despite the decrease in mechanical properties with respect to the original material, mechanical resistance and surface hardness obtained are much higher than those specified in the EN 13279-2 standard. In this way, the field of application of these new, more sustainable construction materials has been extended, demonstrating their technical viability for implementation in the development of new lightweight prefabricated materials for modular construction.

Author Contributions: Conceptualization, D.F., A.Z.-B., and P.S.; methodology, D.F. and A.Z.-B.; software, A.Z.-B.; validation, D.F., A.Z.-B., and P.S.; formal analysis, D.F. and A.Z.-B.; investigation, D.F. and A.Z.-B.; resources, P.S.; data curation, D.F. and A.Z.-B.; writing—original draft preparation, D.F. and A.Z.-B.; writing—review and editing, P.S.; visualization, P.S.; supervision, P.S. and C.M.;

project administration, P.S.; funding acquisition, P.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FEDER funds through the Competitivity Factors Operational Programme–COMPETE, and by national funds through FCT, Foundation for Science and Technology, within the scope of the project POCI-01-0145-FEDER-032061.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors are grateful to Ana Fonseca, (CEMMPRE) for providing the LDPE plastics used in this work. We would also like to thank Luisa Durães (University of Coimbra) for making it possible for the LDPE samples to arrive in Madrid.

Conflicts of Interest: The authors declare no conflict of interest.

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