Article

Characterization of Gypsum Composites Containing Cigarette Butt Waste for Building Applications

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Abstract: Cigarette butts are one of the most common waste on the planet and are not biodegradable, so they remain on the landscape for many years. Cigarette butt composition makes it suitable to be added during the manufacture of construction materials, so it can be considered a waste recovery material, helping to reduce the ecological footprint of the construction sector. This article shows the characterization of gypsum composites containing cigarette butt waste. Several gypsum specimens were prepared incorporating different percentages of cigarette butt waste (0.5%, 1.0%, 1.5%, 2.0% and 2.5%). Samples without waste additions were also prepared in order to compare the results obtained. Samples were tested for density, superficial hardness, flexural and compressive strength, bonding strength and acoustic performance. Results show that it is possible to add cigarette butts in a gypsum matrix, resulting in better mechanical behavior than traditional gypsiums.

Keywords: cigarette butts; gypsum; recycling; mechanical properties; physical properties

1. Introduction

Currently, humans are consuming more natural resources than the ones available in the Earth. The human ecological footprint exceeds the bio-capacity of the Earth in such way that in 2016 the global population needed about 1.6 Earths. This situation is expected to worsen, because the global population is destined to grow to about 9.8 billion people in 2050, with respect to the current 7.47 billion. In this sense, population growth is directly related to high amounts of waste production, which is currently poorly managed. Presently, more and more products are being manufactured due to the high demand of consumers and, once converted into waste, they are increasingly difficult to eliminate due to their composition, their size or their great amount [1]. According to the European official statistics, 4968 kg of waste/inhabitant/year were generated in Europe and only around half was recycled or reused and the remaining part was placed in landfill [2]. Thus, the waste quantities and their inadequate management have been identified as one of the main environmental problems nowadays.

In addition, the construction sector is one of the industries responsible for the highest environmental impact and ecological footprint, as it consumes great amounts of natural resources and generates vast quantities of waste [3,4]. In particular, about 923 million tons of construction and demolition waste were generated in Europe during 2016, representing around 34 % of the global European waste [5]. Therefore, an urgent shift within the construction sector is currently needed to improve this situation.

The negative environmental impact caused by the construction sector can be reduced by promoting waste recovery, using sustainable materials and renewable energy resources [6]. In this sense,
many research works have been conducted aiming to characterize building materials containing several wastes categories from different industries of society [7–9].

One of the largest wastes generated in our society are cigarette butts, which represent around 13% from total items collected in the international coastal cleanup (1,863,838 CB from 14,337,215 overall items collected) [10]. According to the Tobacco Atlas, approximately 6 billion cigarettes are smoked per year and the butt of three out of four cigarettes is thrown out inadequately [11], which means that 12.5 million cigarette butts are thrown every day [12]. In addition, the problem is not only the large amount generated, but also the difficulty of its collection and management. Smokers smoke anywhere and butts are very light, so they are easily spread and accumulated in most leisure places, such as beaches, sidewalks, etc., becoming a public health problem [13,14]. In addition, cigarette butts are not biodegradable, in the ground or in water, so they can take about ten years to degrade [15]. Few initiatives have tried to solve this situation and, therefore, other solutions to landfill are still needed [16].

For this reason, several researchers have explored the viability of incorporating cigarette butts in different composites for building construction [16]. Most of these studies incorporate cigarette butts in bitumen and asphalt mixtures in order to reduce their density. For instance, Mohajerani et al. (2017) [17] investigated the possibility of encapsulating cigarette butts and incorporating them into asphalt concrete for the manufacture of recycled pavement construction. Results from this study revealed that incorporating encapsulated cigarette butts increases the porosity, and thus the thermal conductivity decreases. More recently, Jin et al. (2019) [18] incorporated cigarette butts in pavements and the Marshall test and rutting test were performed. Results show that cigarette butts can be used as a modifier in asphalt mixture, as they improve the road performance and extend the service life of the road.

Other studies were conducted incorporating cigarette butts in concrete, such as the recent study conducted by Luo et al. (2019) [19]. This study incorporated cigarette butts in concrete and analyzed their influence. For this, several cubic samples were produced and tested, concluding that compression strengths were reduced continuously when the amount of cigarette butts increased. The minimum reduction (13%) of the compression strength was achieved when the cigarette content did not exceed 10kg/m³.

Furthermore, Mohajerani et al. (2016) [13] analyzed the viability of incorporating up to 10%wt of cigarette butts in fired clay bricks. Results showed a decrease in the density and compressive strength of the brick when cigarette butts were added. This article recommends bricks with 1%wt cigarette butt content, because it keeps the properties very similar to the reference. Furthermore, Sarani and Kadar (2014) [20] explored the thermal behavior of fired clay bricks with up to 5% wt of cigarette butts. The conclusions of this study revealed a reduction of the density and thermal conductivity of the samples.

Further studies were conducted with cellulose materials, such as the study of Maderuelo-Sanz et al. (2018) [21], which analyzed the properties and acoustic behavior of a cellulose acetate containing cigarette filters. The results show that cellulose containing cigarette butts performs very similar to the reference, and, therefore, it can be an alternative material to the cellulose currently commercialized.

In addition to the studies dealing with the mechanical properties of the compounds containing cigarette butts, specific studies exploring the acoustic behavior were also found. Gómez Escobar et al. (2019) [22] analyzed the potential for using cigarette butt waste—in different sizes and quality—as acoustic absorbent material. Results showed that the sound absorption coefficients were greater than 0.8 for frequencies over 2000 Hz. In addition, both the length and quality of the butts were found to be key factors influencing the sound absorption coefficient.

Despite a few research works having been conducted incorporating cigarette butts in building materials—mainly to improve the mechanical properties and reduce the weight—none of the research works incorporated cigarette butts in gypsum composites. In this sense, adding cigarette butt waste (CBW) in gypsum composites is still a research gap that needs to be further explored. Adding CBW in
gypsum composites will improve mechanical properties of the gypsum as well as reduce the amount of natural gypsum consumed, helping to remove large amounts of waste from our planet. Therefore, the main aim of this research is to characterize gypsum composites containing cigarette butt waste.

2. Materials and Methods

In order to characterize the gypsum composites containing cigarette butts, the materials were chosen first and samples were further prepared with different percentages of waste. Finally, tests were performed, and data were collected.

2.1. Materials

The materials used were:

- Gypsum E-35 (E): supplied by Placo Saint-Gobain [23] with the following characteristics: particle size 0–2 mm and flexural strength: 3.5 N/mm².
- Cigarette butt waste (CBW): The filter’s main material is cellulose acetate, which can be included in thermoplastic group. CBW were first submerged in water in order to eliminate the external dirtiness and then placed in the oven at 80° for 24 h (Figure 1a). Subsequently, cigarette butts were separated from the outer paper (Figure 1b) and were further stored in the desiccator and crushed into small fragments following the physical method followed in previous research works [16]. Cigarettes were crushed using a machine of 550 W power at 50 Hz, for three intervals of 3 min each (Figure 1c). The amount crushed each time was 6 g in order to obtain a homogeneous mixture. Density of CBW changes when they are crushed. Average density of collected CBW is 0.19 g/cm³ while average density of crushed CBW is 0.09 g/cm³.
- Water with the technical characteristics established by standard UNE EN 13279-2 [24]

![Figure 1.](image-url) (a) CBW were dried in the oven; (b) CBW separated from the outer paper; (c) CBW mixture.

2.2. Preparation of Test Samples

A total of five different composites were prepared following the regulation EN 13279-2 [24] with a water/gypsum (w/g-240/300 (g)) ratio of 0.8 and different percentages of CBW over the weight of gypsum: 0.5%, 1.0%, 1.5%, 2.0% and 2.5% (Table 1). The workability of the composite decreased when more than 2.5%wt was added; therefore, higher percentages of CBW will require either higher water quantities or the use of additives to ensure the same consistency. Furthermore, a reference sample (without CBW) was prepared in order to compare the results. Finally, the excess of compound was weighed once the cast was filled.

In all the samples, the CBW was mixed first with the gypsum and then it was all incorporated into the water (Figure 2a–c).

2.3. Tests for Mechanical and Physical Properties

The samples were kept for one week in the laboratory and were further dried in an oven at 40 ± 2 °C for 24 h before testing, following standard EN 13279-2 [24]. The laboratory conditions were temperature 23 ± 2 °C and humidity around 50% ± 5%.
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The following tests were conducted: density, superficial hardness, flexural and compression strength, bonding strength and acoustic behavior. For the density, superficial hardness and mechanical strength, several series of three specimens 40 × 40 × 160 mm³ were prepared with the different percentages of CBW and were further tested following the standard EN 13279-2 [24]. For the bonding strength test, the standard EN 13279-2 was followed and a Dynatest DTH 500 device was used to obtain the results [24]. The sound absorption test was done using the “two-microphone” or “transfer function” method, established by standard ASTM E1050 and ISO 10534-2 [25,26]. This test method uses a Kundt’s tube and two microphones. The test sample was mounted at one end of the impedance tube. Flat waves were generated in the tube by a sound source (white noise), and the sound pressures were measured at two positions near the sample. The complex acoustic transfer function of the signals in the two microphones was used to calculate the absorption coefficient for normal incidence. For the acoustic test, three test tubes of each compound containing different percentages of CBW were made (Figure 3a,b). In total, 0.5 CB samples were not performed for the acoustic test, because the small amount of CBW contained in that sample was not considered enough to provide conclusive sound absorption results.

Gypsum samples’ preparation for the acoustic test were particularly difficult to achieve, because samples must fit perfectly in the sample holder. In this sense, samples were made with a slightly smaller diameter (34.8 mm) than the inner diameter of the Kundt’s tube (34.9 mm). Petroleum jelly was used as a flexible seal around the circumference of the tube. The thickness of the sample is a significant variable in the measurement of sound absorption and the effect of the thickness of the
material on its sound absorbing capabilities is well known [27]. Therefore, all the samples had the same thickness (30 mm) in order to be able to analyze the results.

![Image](https://via.placeholder.com/150)

Figure 4. Testing for (a) density; (b) superficial hardness; (c) flexural strength; (d) compression strength, (e) bonding strength; and (f) sound absorption.

For each test (Figure 4a–f), the mean values were calculated and compared with the reference and with the minimum values set in the standards (Table 1). Finally, based on the results obtained, several building applications are proposed for the optimum compounds.

| Tests                  | Series of Samples | Samples Dimension | Compound | Percentage wt of CBW |
|------------------------|-------------------|-------------------|----------|----------------------|
| Superficial hardness   | SERIES 1          | 4 x 4 x 16 cm³    | REF      | 0%                   |
| Flexural strength      |                   |                   | CB0.5    | 0.5%                 |
|                        |                   |                   | CB1      | 1%                   |
|                        |                   |                   | CB1.5    | 1.5%                 |
|                        |                   |                   | CB2      | 2%                   |
|                        |                   |                   | CB2.5    | 2.5%                 |
| Compression strength   |                   |                   | REF      | 0%                   |
|                        |                   |                   | CB0.5    | 0.5%                 |
|                        |                   |                   | CB1      | 1%                   |
|                        |                   |                   | CB1.5    | 1.5%                 |
|                        |                   |                   | CB2      | 2%                   |
|                        |                   |                   | CB2.5    | 2.5%                 |
| Bonding strength       | SERIES 2          | Ø 50 mm/e = 10 mm | REF      | 0%                   |
|                        |                   |                   | CB0.5    | 0.5%                 |
|                        |                   |                   | CB1      | 1%                   |
|                        |                   |                   | CB1.5    | 1.5%                 |
|                        |                   |                   | CB2      | 2%                   |
|                        |                   |                   | CB2.5    | 2.5%                 |
| Sound absorption ¹     | SERIES 3          | Ø 34.8 mm/e = 30 mm| REF      | 0%                   |
|                        |                   |                   | CB1      | 1%                   |
|                        |                   |                   | CB1.5    | 1.5%                 |
|                        |                   |                   | CB2      | 2%                   |
|                        |                   |                   | CB2.5    | 2.5%                 |

¹ The proportion 0.5 was not considered because similar results were expected to the reference sample.

Finally, to analyze the amount of natural gypsum that can be saved, the amount of gypsum replaced or reduced was studied. The reduction of gypsum is explored and compared with the reference sample without additions. For this, the amounts of each material (gypsum, water and...
cigarette butt waste) used to produce the samples were recorded and used together with their weight after demolding.

3. Results

Table 2 shows the data from the tests carried out for each of the composites analyzed.

| Compound | Density $\text{g/cm}^3$ | Superficial Hardness Shore C | Flexural Strength MPa | Compression Strength MPa | Bonding Strength N/mm² |
|----------|------------------------|-----------------------------|----------------------|--------------------------|-----------------------|
| REF      | 0.983                  | 69.93                       | 4.20                 | 8.62                     | 0.130                 |
| CB0.5    | 0.986                  | 73.30                       | 4.26                 | 9.20                     | 0.083                 |
| CB1      | 0.996                  | 73.87                       | 4.41                 | 9.27                     | 0.098                 |
| CB1.5    | 0.997                  | 77.01                       | 4.53                 | 9.42                     | 0.111                 |
| CB2      | 1.013                  | 78.21                       | 4.61                 | 9.43                     | 0.100                 |
| CB2.5    | 1.030                  | 80.33                       | 4.63                 | 9.61                     | 0.116                 |

1 Sound absorption is showed in a separate table due the different kind of data. s: Standard deviation.

Firstly, sample tests were dried and weighed in order to know the density of different percentage gypsum compounds. Figure 5 shows that the density slightly increases as the amount of CBW increases. However, this density increase is not relevant and must be taken into account when analyzing the mechanical properties. The point is to study how mechanical properties improve in reference to density and how this improvement is related to the percentage of CBW.

![Figure 5](image_url)

**Figure 5.** Average density of different gypsum composite samples.

3.1. Series 1

3.1.1. Superficial Hardness

The average values of the superficial hardness obtained for the different samples are shown in Figure 6. These data are related to density, in order to know the relation between the superficial hardness and the density of the compounds.
These data mean that Shore C hardness increases as the CBW’s proportion increases. This result was expected since fibers generate an integrating net between gypsum particles, which greatly benefits the hardness. In addition, proportionally, greater increases are achieved with lower densities, which allow one to obtain good hardness with very low densities.

3.1.2. Flexural and Compression Strength

To verify the effect of CBW percentages on mechanical properties, a comparison was made between flexural and compression strength. The results are shown in Figures 7 and 8.

![Figure 6](image1.png)  
(a) Average superficial hardness. (b) Density and superficial hardness correlation.

These results showed superficial hardness increased up to 14.87% when CBW percentages were increased. In addition, all values remained above the sample reference and the minimum regulations. These data mean that Shore C hardness increases as the CBW’s proportion increases. This result was expected since fibers generate an integrating net between gypsum particles, which greatly benefits the hardness. In addition, proportionally, greater increases are achieved with lower densities, which allow one to obtain good hardness with very low densities.

3.1.2. Flexural and Compression Strength

To verify the effect of CBW percentages on mechanical properties, a comparison was made between flexural and compression strength. The results are shown in Figures 7 and 8.

![Figure 7](image2.png)  
(a) Average flexural strength. (b) Density and flexural strength correlation.

These results show that flexural and compression strengths increased around 10.24% and 11.48%, respectively. These results also conclude that a smaller density increase achieved greater mechanical strengths. The strength increase is pretty constant between different samples, but the largest increase happens in the lowest CBW proportions. In particular, flexural strength increase is around 7.86% between the reference sample and CB1.5. Regarding the compression strength, around 9.28% improvement was achieved with the same range of percentage (CB1.5).

This can be explained because the initial 0.8 water/gypsum ratio used to prepare the samples can be slightly reduced when more CDW is added. Mainly because the CBW can compete for the water with the gypsum and thus reduce the amount of water used to hydrate the gypsum. In addition, the increase in the mechanical properties can also be explained because the fracture of the samples keeps both sides of the sample strongly joined, due to the CBW fibers.
These results also conclude that a smaller density increase achieved greater water with the gypsum and thus reduce the amount of water used to hydrate the gypsum. In addition, samples CB0.5 and CB1 do not achieve the minimum 0.1 MPa set by the regulation (EN 13279-2) [25]. It is possible to observe a slight tendency to reduce as the amount of CDW increases. These results were expected due to the presence of higher amount of CBW which makes it more difficult to bond to the brick. A decrease in bonding strength was also observed in previous research works were fibers were added in a gypsum matrix [28].

3.3. Series 3: Sound Absorption

Table 3 and Figure 10 show the results obtained in the acoustic test performed for each of the composites analyzed. The data obtained are the absorption coefficient ($\alpha$) for each sample—calculated in each frequency—and the standard deviation ($s$), with both data in decibels. Table 3 gathers the main information of the acoustic samples and compares the sound absorption coefficient with standard deviation.
Table 3. Absorption coefficient “α” and standard deviation “s”.

| REF  | CB1    | CB1.5   | CB2    | CB2.5   |
|------|--------|---------|--------|---------|
|      | α      | s       | α      | s       | α      | s       | α      | s       | α      | s       |
| 100  | 0.08   | 0.001   | 0.06   | 0.014   | 0.07   | 0.041   | 0.07   | 0.019   | 0.07   | 0.023   |
| 125  | 0.18   | 0.005   | 0.18   | 0.002   | 0.12   | 0.064   | 0.17   | 0.001   | 0.17   | 0.005   |
| 160  | 0.11   | 0.004   | 0.12   | 0.003   | 0.08   | 0.054   | 0.12   | 0.006   | 0.11   | 0.003   |
|      |        |         |        |         |        |         |        |         |        |         |
| 200  | 0.02   | 0.001   | 0.03   | 0.002   | 0.02   | 0.006   | 0.02   | 0.002   | 0.02   | 0.003   |
| 250  | 0.00   | 0.000   | 0.00   | 0.002   | 0.02   | 0.024   | 0.00   | 0.000   | 0.00   | 0.001   |
| 315  | 0.00   | 0.000   | 0.00   | 0.001   | 0.02   | 0.027   | 0.00   | 0.000   | 0.00   | 0.000   |
| 400  | 0.02   | 0.000   | 0.03   | 0.003   | 0.03   | 0.006   | 0.03   | 0.001   | 0.03   | 0.000   |
| 500  | 0.04   | 0.000   | 0.05   | 0.002   | 0.04   | 0.007   | 0.04   | 0.001   | 0.04   | 0.001   |
| 630  | 0.02   | 0.001   | 0.02   | 0.003   | 0.02   | 0.001   | 0.02   | 0.001   | 0.02   | 0.000   |
| 800  | 0.01   | 0.002   | 0.02   | 0.002   | 0.02   | 0.001   | 0.02   | 0.001   | 0.02   | 0.001   |
| 1000 | 0.03   | 0.001   | 0.04   | 0.004   | 0.03   | 0.002   | 0.03   | 0.001   | 0.03   | 0.001   |
| 1250 | 0.03   | 0.001   | 0.04   | 0.003   | 0.04   | 0.001   | 0.04   | 0.001   | 0.04   | 0.001   |
| 1600 | 0.03   | 0.002   | 0.03   | 0.004   | 0.03   | 0.001   | 0.03   | 0.001   | 0.03   | 0.000   |
| 2000 | 0.02   | 0.001   | 0.03   | 0.004   | 0.03   | 0.003   | 0.03   | 0.001   | 0.03   | 0.001   |
| 2500 | 0.04   | 0.002   | 0.04   | 0.003   | 0.04   | 0.003   | 0.04   | 0.002   | 0.04   | 0.001   |
| 3150 | 0.07   | 0.001   | 0.07   | 0.002   | 0.08   | 0.005   | 0.07   | 0.002   | 0.07   | 0.001   |
| 4000 | 0.08   | 0.001   | 0.08   | 0.003   | 0.09   | 0.001   | 0.08   | 0.001   | 0.08   | 0.001   |
| 5000 | 0.06   | 0.001   | 0.07   | 0.002   | 0.07   | 0.007   | 0.07   | 0.002   | 0.07   | 0.001   |

Figure 10. Sound absorption coefficient from frequencies

As it can be seen, the values of the standard deviation are very small (three decimals are needed to notice it), giving an idea of how clustered the data are around the mean. The results show minimal differences between reference samples and samples with different percentages of CBW. This can be clearly appreciated in Figure 10. According to the Catalogue of constructive elements of the Código Técnico de la Edificación (CTE: Main Spanish Construction Regulation), it has obtained similar results from an average gypsum panel: 125 Hz: 0.10; 250 Hz: 0.10; 500 Hz: 0.05; 1000 Hz: 0.04; 2000 Hz: 0.07; 4000 Hz: 0.09. In the case of acoustic plaster plates, it is not possible to make an accurate comparison since the increase absorption in these panels comes from the perforations and not from the material.

The differences observed between different dosages are minimal and cannot be considered relevant. Note that the values in the low frequencies where the dosage called CB1.5, which differs slightly from the others, are precisely the values with a slightly higher standard deviation.
3.4. Analysis of Gypsum Replacement or Reduction

Table 4 shows the reduction of gypsum for each compound compared with the reference sample (gypsum without additions). The results show that incorporating CBW from 2% to 2.5% over the weight of gypsum, reduces the amount of raw gypsum consumed around 5.8% and 7.2%, respectively.

| Composite | Material | Content (wt %) | Per Sample | Quantities per m³ | Reduction of Raw Material per m³ (wt %) |
|-----------|----------|----------------|------------|-------------------|--------------------------------------|
| REF       | Gypsum   | 55.56          | 208.0      | 80.00             | -                                    |
|           | Water    | 44.44          | 166.4      | 166.4             | 0.68                                 |
|           | Waste    | 0.00           | 0.0        | 0                 | 0.00                                 |
|           | Total    | 100            | 374.40     | 246.40            | 1.00                                 |
| YG0.8 + 0.5% | Gypsum | 55.50          | 217.9      | 83.82             | 0.32                                 |
|           | Water    | 44.40          | 174.3      | 174.3             | 0.67                                 |
|           | Waste    | 0.09           | 0.4        | 4.00              | 0.02                                 |
|           | Total    | 100            | 392.63     | 262.17            | 1.00                                 |
| YG0.8 + 1% | Gypsum | 55.45          | 219.9      | 84.59             | 0.31                                 |
|           | Water    | 44.36          | 175.9      | 175.9             | 0.66                                 |
|           | Waste    | 0.18           | 0.7        | 8.08              | 0.03                                 |
|           | Total    | 100            | 396.60     | 268.61            | 1.00                                 |
| YG0.8 + 1.5% | Gypsum | 55.40          | 225.4      | 86.69             | 0.31                                 |
|           | Water    | 44.32          | 180.3      | 180.3             | 0.65                                 |
|           | Waste    | 0.28           | 1.1        | 12.42             | 0.04                                 |
|           | Total    | 100            | 406.83     | 279.42            | 1.00                                 |
| YG0.8 + 2% | Gypsum | 55.35          | 235.1      | 90.44             | 0.31                                 |
|           | Water    | 44.28          | 188.1      | 188.1             | 0.64                                 |
|           | Waste    | 0.37           | 1.6        | 17.28             | 0.06                                 |
|           | Total    | 100            | 424.81     | 295.82            | 1.00                                 |
| YG0.8 + 2.5% | Gypsum | 55.30          | 250.3      | 96.26             | 0.30                                 |
|           | Water    | 44.24          | 200.2      | 200.2             | 0.63                                 |
|           | Waste    | 0.46           | 2.1        | 22.99             | 0.07                                 |
|           | Total    | 100            | 452.59     | 319.48            | 1.00                                 |

* Densities used to obtain the volume: 0.09 g/cm³ (CBW); 2.6 g/cm³ (gypsum); 1 g/cm³ (water).

It is important to underline that the largest increase was achieved between samples with highest percentages. In this sense, the percentage of natural gypsum consumed would decrease because of the CBW addition, because more quantity of the compound can be made with the same water and gypsum quantities.

4. Discussion

This study demonstrates that the mechanical properties of gypsum are improved with CBW. Analyzing these results, the following steps should focus on the reduction of the gypsum within the mixture, because the best relationship between the physical properties and the density was achieved with the CBW1.5 compound.

Regarding the acoustic properties, the sound absorption does not improve with respect to the reference. The proportion of CBW is not enough to provide significant sound absorption improvements. The absorption capacity of the gypsum weighs more, as what happens in mechanical properties. The benefit of incorporating CBW should be achieved with higher proportions of CBW and reducing the gypsum to the minimum allowed. Therefore, for this specific use, more research works are needed to study alternative mixtures in which the amount of gypsum is reduced in more proportions.

Incorporating CBW in a gypsum matrix is a good way to save plaster, since the mechanical properties are kept similar and around 7.2% of gypsum can be saved when 2.5% wt of CBW is incorporated. It was announced, on the top of this section, that the best compound was CBW1.5, so in connecting this result with the results of gypsum savings we can conclude that CBW1.5 percentage...
can achieve a gypsum saving of around 4.4%. Therefore, this compound did not achieve the greatest saving but also achieved a good result.

In addition to the use of CBW in gypsum composites, future research directions may lead us to find out the minimum amount of gypsum needed to keep (or even improve) the mechanical properties of the reference. In this sense, the amount of water must also be taken into consideration in relation to the sound absorption. It was demonstrated that a reduction of the amount of gypsum used could be achieved by including CBW.

At this moment, this material would be suitable for the manufacture of precast panels, such as suspended ceiling plates or interior cladding walls, since the adherence on the ceramic support is not a feature that was improved, although it complies with the standard. The different types of panels currently commercialized can be manufactured with CBW, improving their properties, saving money and removing waste from our planet. In addition, this gypsum containing CBW can be used as interior moldings (just as regular plaster) and future research works should focus on the joints to the support, and further studies will be necessary to improve bonding strength. It is important to underline that future studies can focus on the porosity, water absorption behavior and workability, since that is a key property when industrializing precast products.

Any other construction element that is currently made from gypsum can be manufactured with CBW gypsum.

5. Conclusions

From the results obtained it is feasible to incorporate CBW in a gypsum matrix obtaining compounds with an improved performance compared to the reference gypsum.

- The addition of CBW improves mechanical behavior. In particular, adding CBW (up to 2.5% on the weight of the gypsum) increases the superficial hardness, mechanical strength and density of the reference without additions.
- The best results are achieved with the compound containing 2.5% of CBW. However, proportionally, the greatest increase happens when 1.5% over the weight of the plaster is added.
- No improvements in the bond strength have been observed. That is the main disadvantage found in terms of mechanical properties.
- Regarding the acoustic absorption, the results obtained in third-octave bands show that there are no significant differences in the sound absorption coefficient between the reference sample and the samples made with CBW percentages analyzed.
- The sound penetration suffers due to the high percentage of gypsum mortar in the samples. Gypsum does not allow air motion to generate enough friction, as higher percentages of CBW probably would have done.
- Therefore, these compounds are suitable for construction applications that require high surface hardness and/or mechanical resistance (such as precast panels) but are not to be bonded to a ceramic support.

Finally, in general, these compounds provide direct benefits to the industry, since the mechanical behavior of the gypsum is improved, while the consumption of raw materials is reduced.

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