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Lightweight recycled gypsum with residues of expanded polystyrene and cellulose fiber to improve thermal properties of gypsum

K.A. de Oliveira ✉, C.A.B. Oliveira, J.C. Molina

Department of Mechanical Engineering, UNESP - São Paulo State University (Guaratinguetá/SP, Brazil)
✉ kari.oliveira@outlook.com

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ABSTRACT: In this study, different proportions of gypsum composite reinforced with recycled cellulose fibers and expanded polystyrene were produced to study the properties of thermal conductivity, density, and flexural strength to be used as sealing plates to improve the thermal comfort of buildings. Different gypsum matrix composites were produced with varied proportions of cellulose fiber and expanded polystyrene, to analyze the influence of residues on the properties of the material. The thermal conductivity obtained for composites with greater amounts of expanded polystyrene was 0.18 W/mK, a 48% reduction in relation to plasterboard, improving thermal performance. The flexural strength was also analyzed, which met the minimum strength requirement for use as gypsum composites, however, it is not enough to be used in places that require mechanical resistance, thus it is indicated for sealing plates applications, improving the thermal performance of places where only plasterboard is used.

KEYWORDS: Thermal insulation; Cellulose fiber; Composites; Gypsum; Expanded polystyrene.

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RESUMEN: *Yeso reciclado con residuos de poliestireno expandido y fibra de celulosa para mejorar las propiedades térmicas del yeso* . En este estudio, se produjeron diferentes proporciones de compuesto de yeso reforzado con fibras de celulosa recicladas y poliestireno expandido para estudiar las propiedades de conductividad térmica, densidad y resistencia a la flexión. Se produjeron diferentes composites de matriz de yeso con variadas proporciones de fibra de celulosa y poliestireno expandido, para analizar la influencia de los residuos en las propiedades del material. La conductividad térmica obtenida para los composites con mayores cantidades de poliestireno expandido fue de 0,18 W/mK, una reducción del 48% con relación a las placas de yeso, mejorando el rendimiento térmico. También se analizó la resistencia a la flexión, la cual cumplió con el requisito de resistencia mínima para su uso como compuestos de yeso, sin embargo, no es suficiente para ser utilizado en lugares que requieran resistencia mecánica, por lo que está indicado para aplicaciones de placas de sellado, mejorando el rendimiento térmico de los lugares donde solo se utiliza placa de yeso.

PALABRAS CLAVE: Aislamiento térmico; Fibra de celulosa; Composicion; Yeso; Poliestireno expandido.

1. INTRODUCTION

The construction industry is one of the most important areas for the economic and social development of the world, and the concern for thermal comfort is a major item in today's constructions. Proper thermal insulation provides energy efficiency benefits in buildings and is essential for the sensation of well-being, mood and effectiveness of its users activities.

For many years, the thermal comfort of buildings was provided by artificial ventilation and air conditioning systems, operated based on electricity consumption. For Lamberts *et al.* (1), the buildings are responsible for 42% of electricity consumption, where much of it is by air conditioning systems. For this reason, it is important to know the thermal properties of building materials, because the choice of a suitable sealing material can reduce the solar thermal charge transmitted to the interior of the dwellings.

The construction industry is one of the largest consumers of natural resources, most non-renewable, and one of the largest waste generators in Brazil, accounting for 40 to 60% of urban solid waste, usually referred to as debris, such as bricks, concrete, rocks, soils, gypsum, mortar, and other materials (2, 3).

With the growing global concern for the environment and in order to reduce the thermal load in buildings using insulating materials, the civil sector has been looking for sustainable materials that can replace conventional materials, reducing the use of natural resources and the amount of waste that needs disposal, thus generating savings.

In a survey carried out by the Civil Construction Union (SINDUSCON) with civil construction companies in Brazil, it was observed that only 20% of the companies separate and reuse the construction waste generated by the buildings, in which plaster is the most difficult material to handle and reuse, according to 40% of the companies analyzed (4).

However, although the sector finds it difficult to reuse this material, plaster recycling is possible provided that contaminants incorporated in the waste generation process are removed, since the plaster still has the chemical characteristics of its raw material, gypsum, which allow removing this material using a simple recycling process by grinding and calcining the material (5, 6).

The reuse of this combined material with various composite waste can generate a lighter material with better properties than conventional gypsum, such as acoustic and thermal insulation, elasticity, compression strength, generating a material that can be used in partition panels, false ceilings, and others (7).

There are several studies focused on developing gypsum matrix composites with residues, as highlighted below:

1. Macedo *et al*. (8) studied the production of composites based on plaster and expanded polystyrene in the compositions (1.5:1), (1:1) and (1:1.5) in order to replace traditional ceramic bricks. The thermal conductivity tests showed that the higher proportion of Styrofoam provided better thermal comfort to the studied material but decreased its mechanical strength.
2. Serna *et al.* (9) studied the use of tire rubber particles in gypsum composite in different compositions to improve the elastic behavior of the plaster, reducing the likelihood of cracking after hardening. The results obtained showed that the addition of rubber particles led to a decrease in the mechanical properties of plaster resistance to flexion and compression, however the values obtained comply with the conditions specified in EN 13279-1. And, despite increasing the elastic modulus of the material, the addition of rubber decreased the toughness, worsening the resistance to crack generation.
3. Cunha *et al.* (10) studied the production of a plaster composite with vegetable fiber reinforcement (*Cocos nucifera*) for use as a sealing panel. The results obtained showed advantages over the standard panel used, as it presented less thermal conductivity, providing greater thermal insulation capacity, in addition to greater lightness and material savings.
4. San-António-Gonzalez *et al.* (11) studied the incorporation of different percentages of extruded polystyrene into a plaster matrix for use as light building material. The results obtained showed that increasing the percentage of extruded polystyrene in the mixture improves the thermal resistance of the material but decreases its mechanical strength and density.
5. San-Antonio-Gonzalez *et al.* (12) studied the production of composites based on gypsum and expanded polystyrene incorporating different additives (latex, binding additive, plasticizers) and fibers (glass fiber and polypropylene fiber). Density, resistance to flexion and compression, and thermal conductivity were tested. The results obtained showed that it is possible to produce a light material with excellent thermal behavior and good mechanical and density properties.
6. Alameda *et al.* (13) produced gypsum composite with polyurethane waste and polypropylene fibers testing various properties such as density,

surface hardness, thermal properties, and flexural strength. The results obtained showed that increasing the amount of polyurethane residues improved the thermal insulation capacity, but reduced the mechanical resistance of the material and its surface hardness, while increasing the amount of polypropylene fibers improved the mechanical performance.

7. Azevedo (14) studied the production of plaster composite with vermiculite for use as thermal insulation material in constructions, where different compositions of vermiculite (5, 10, 15 and 20%) were used in the plaster matrix. The results obtained indicated that the composite showed lower density and greater thermal insulation capacity, resulting in a material that provides better thermal energy conservation in buildings.
8. Del Rio Merino *et al.* (15) studied the production of a plaster composite with extruded polystyrene and expanded polystyrene for use in buildings, replacing composites produced with perlite and vermiculite. Density, hardness, mechanical strength, and thermal behavior tests were carried out. The results obtained showed that the addition of polystyrene in the plaster matrix improved the properties studied when compared to the composites with vermiculite and perlite, which can be used as partition panels and interior ceilings, providing good thermal performance to buildings.

There are various wastes used for the development of light plaster composites, and the use of expanded polystyrene is one of the most studied because, in addition to generating a light material with good insulating properties, it helps in managing this waste that causes environmental problems because it is not easy to recycle and it generates considerable storage, transportation and disposal costs for the industry (11, 12, 16).

But, as observed in the works cited, they generally revealed that the incorporation of polystyrene residues in the plaster improves the thermal and acoustic properties but reduces the mechanical resistance of the material. For this reason, the inclusion of other materials, such as wood fibers, is being studied in order to maintain the good insulation of the material and improve the resistance properties.

Therefore, the present study was developed using residues of expanded polystyrene and cellulose fibers in a plaster matrix for the production of a lightweight composite in order to study the feasibility of using the composite in civil constructions as sealing plates with thermal properties, also promoting the sustainable management of raw materials.

2. MATERIALS AND METHODS

2.1 Materials

The cellulose fiber used in this study came from the effluent generated by the alkaline extraction and bleaching steps and donated by a pulp and paper company in the city of Itapeva, State of São Paulo, Brazil. The expanded polystyrene and the plasterboard were collected at construction sites in the city that resulted from plasterboard cuttings when they were installed in the buildings.

The gypsum recycling was performed by calcination at 180ºC according to the methodology described by Bardella and Camarini (17). According to Savi (18), recycled gypsum presents flexural strength values between 0.7 and 3.5 MPa, but studies show that the use of cellulose fiber and expanded polystyrene in the recycled gypsum matrix results in flexural strength values below 0.7 MPa (19). For this reason, a mixture of commercial gypsum and recycled gypsum was used in a ratio of 1:1.

Five types of gypsum matrix composites with different amounts of waste were produced, and two using only gypsum as a control sample, one with commercial gypsum (Control 1) and one with a mixture of commercial and recycled gypsum (Control 2). Table 1 shows the percentages for common gypsum (G), recycled gypsum (RG), expanded polystyrene (EPS) and cellulose fiber (CF). The amount of water for hydration of the gypsum used in the production of the composites was in a ratio of 1:1.

Table 1 shows that the percentage of gypsum used in the composite production was maintained at 40% (20% of common gypsum and 20% of recycled gypsum) in all studied traits, this quantity was implemented because preliminary studies showed that the use of a lower percentage of gypsum was not enough for the homogenization and binding of the mixture, resulting in brittle samples. Only the percentages of the expanded polystyrene (EPS) and cellulose fiber (CF) residues were varied to produce the composites.

For the production of the composite, the EPS underwent a crushing process using a MARCONI brand chipper, as the material was in the form of plates, which required particle reduction with dimensions ranging from 2 mm to 3 mm to allow mixing with other materials. The EPS was then manually mixed with the cellulose fiber, gypsum, and water, until a homogeneous paste was formed, which was then transferred to the molds and kept at room temperature for 6 days for drying.

For thermal conductivity tests, samples of 50 mm in diameter and 20 mm in thickness were molded as

Table 1. Percentages of materials used in the production of composites.

Composite	Gypsum (%)	Recycled Gypsum (%)	Expanded Polystyrene (%)	Cellulose Fiber (%)
Control 1	100	-	-	-
Control 2	50	50	-	-
C1	20	20	30	30
C2	20	20	45	15
C3	20	20	15	45
C4	20	20	60	-
C5	20	20	-	60

specified by the ASTM E1530 standard (20). And for resistance tests, samples of 300 x 400 x 15 mm dimensions were molded, following specifications of NBR 14715-2 (21). The tests were performed using the samples with the gypsum in a hardened state.

2.2 Methods

After 6 days of drying, with the gypsum in a hardened state, the density of the studied composites was determined, calculating the division of the sample mass by its volume.

The thermal conductivity test, according to ASTM E1530 (20), was performed using the Thermal Conductivity Tester DTC-300 (Discovery, USA) which operates with steady-state heat flow meters in descending heat flow. For the measurements, the samples (Figure 1a), in hardened state, were impregnated with high thermal conductivity paste, used to decrease the thermal resistance between the surface of the sample and the equipment (Figure 1b).

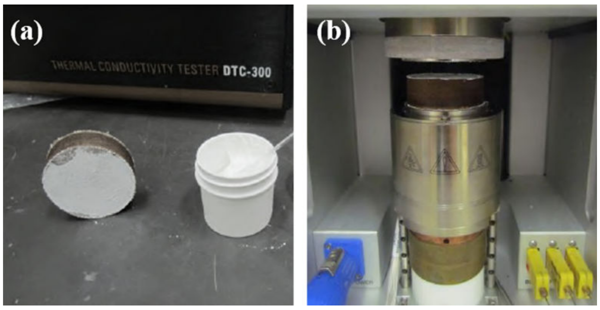

Figure 1. Sample with thermal paste (a) and equipment ready for test (b).

The thermal resistance of a material is defined as the capacity it has in opposing the heat flow due to a temperature difference. In other words, in a material heat transfer can occur by conduction, convection or thermal radiation.

In this work, the most relevant mechanism was heat conduction, governed by the Fourier Law, where the thermal conductivity (k) was equivalent to the amount of heat transmitted by a time interval through a thickness, in a normal direction to the surface area, due to temperature variation.

The bending and compression strength test was performed according to ABNT NBR 14715-2 (21), using the universal EMIC test machine, where the sample (Figure 2a) was placed on two parallel bases with 350 mm spacing. A load was applied in the central part of the sample at a speed of 250±10 N/min until failure of the element (Figure 2b) for the quantification of burst load and strength.

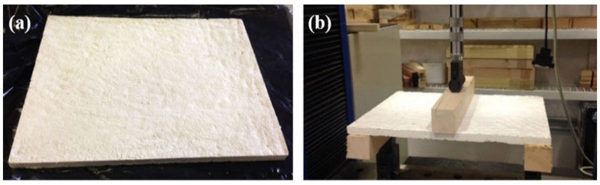

Figure 2. Composite sample (a) and the test in progress (b).

3. RESULTS AND DISCUSSION

3.1 Analysis of density and thermal conductivity

Mean values, the mean confidence intervals (at the 95% confidence level) and the Tukey test results of the density of each composite studied are shown in Figure 3.

From Figure 3, it can be observed that the reduction in density is more pronounced in the composites that have a higher presence of expanded polystyrene, where C2 and C4 presented decrease of approximately 47% in comparison with the control sample of commercial gypsum (Control 1) and 44% when compared with the sample of recycled gypsum (Control 2).

While the higher presence of cellulose fiber resulted in a lower density reduction, it can be seen that C3 and C5 showed a reduction of approximately 37% and 27%, respectively, in relation to the common gypsum sample (Control 1), and approximately 34% and 23%, respectively, in relation to the sample with recycled plaster (Control 2).

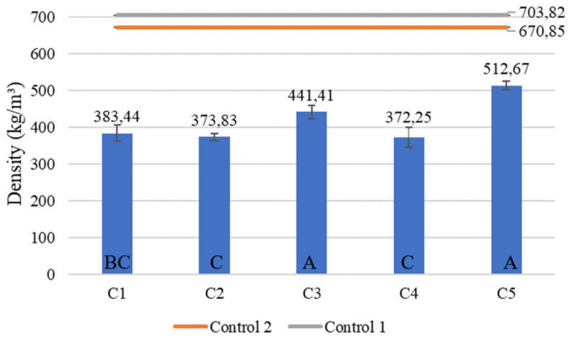

Figure 3. Composite density results.

San-Antonio-Gonzalez *et al.* (12) found density values between 460 and 660 kg/m³ for plaster composites with EPS. But, previous studies indicate that the density is mainly controlled by the amount and size of the expanded polystyrene particle aggregated to the gypsum matrix because of air contained in its interior (22), as can be seen in the graph of the relationship between the percentage of EPS used and the density of the composite, shown in Figure 4.

The graph in Figure 4 shows the linear Equation [1] that represents the relationship between the amount of EPS used in the composite production and the final density of the material, allowing to estimate density values for other percentages of EPS.

$$y = -(2.3228 * \text{EPS}) + 486{,}4 \qquad [1]$$

Figure 5 shows a graph relating the average values of density and thermal conductivity of the composites studied, where it can be observed that the samples with the highest thermal conductivity values were the ones with the highest densities, showing that the density directly affects the capacity of thermal insulation of the material. It is also observed that the higher the CF content, the greater its thermal conductivity and mass density, and the lower its insulation capacity.

The density of the material, according to the Brazilian standard NBR 15220-2, is directly related to its thermal conductivity, since the lower the mass density, the lower the thermal conductivity, and, therefore, the better its insulation characteristics (23). The results of the present study indicate that there is a correlation between density and thermal conductivity in gypsum composites (24, 25), and, according to the results in Figure 5, this correlation was again satisfied.

These values enabled obtaining the linear equation of the relationship between density and thermal conductivity of the studied composites (Equation [2]), which allowed to estimate the thermal conductivity of the composite for the other densities obtained with different EPS percentages.

$$y = (0.001 * \text{density}) - 0{,}1851 \qquad [2]$$

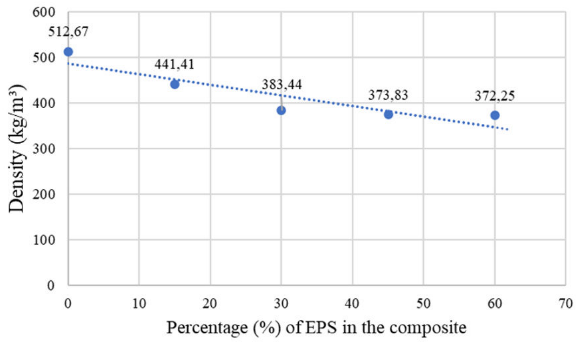

Figure 4. Scatter plot of the relationship between percentage of EPS in the composite and density.

Table 2 presents some thermal conductivity values obtained for light gypsum composites with different residues in the studies found in the literature. It was observed that the compositions studied in this work presented results compatible or better for use as thermal insulation.

Comparing the values obtained in the study with the thermal conductivity values in the Brazilian standard NBR 15220-2 (23) for gypsum board of 0.35 W/mK, it was observed that the composite produced with gypsum matrix and residues presented better thermal insulation results in all the studied configurations, with a reduction of approximately 48% for C4 and C2 and 8.57% for C5 in the thermal conductivity values.

3.2 Flexural and compression strength analysis

Figure 6 shows the mean values, the confidence intervals of the means (at the 95% confidence level) and the Tukey test results of the flexural and compression strength of each studied composite and of the control samples.

The greatest reduction in bending and compression strength was obtained in the composites containing a higher percentage of expanded polystyrene (C4 and C2), with a reduction of around 48% in relation to the sample Control 2. The best result was found in the composite with a higher percentage of fiber cellulose in the gypsum (C3 and C5), with a reduction of 31%.

The results show that the higher amount of CF improves the flexural and compression strength of the composite in comparison to the EPS. This reduction in mechanical performance when plastic waste was added was also observed in the works carried out by Macedo *et al.* (8), Serna *et al*. (9), San-António-Gonzalez *et al*. (11, 12), Alameda *et al*. (13) and Del Rio Merino *et al.* (15).

The EN 13279 (26, 27) and plaster manufacturers specify that to be considered a lightweight plaster composite, the material must meet the following minimum values: density ≤ 800 g/cm3, flexural strength ≥1 MPa, and compression strength ≥ 2 MPa.

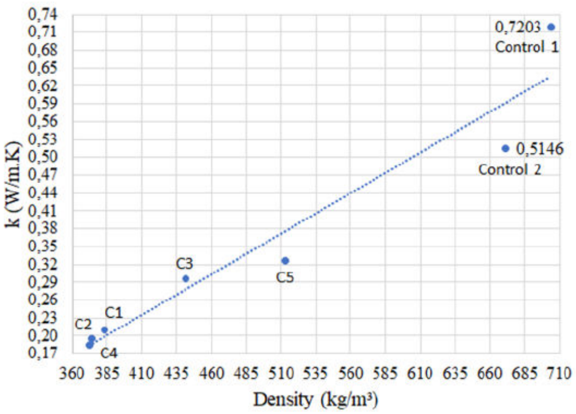

Figure 5. Scatter plot of the relationship between conductivity and density.

As shown in Figure 6, the flexural and compression strength decreases when compared to reference samples of commercial gypsum and recycled gypsum, but these values remain above the minimum required by EN 13279-1 for light gypsum composites, therefore all the composites satisfy this requirement (26).

The data obtained allowed to analyze the relationship between density and flexural strength of the material (Figure 7), where increasing the amount of EPS in the composite composition, the density decreases and consequently its mechanical strength. The graph also shows the linear equation of the relationship between the density of the material and the flexural strength (Equation [3]).

$$y = 0{,}0031 * \text{density} - 0{,}4465 \qquad [3]$$

The results of this relationship between the two properties are compatible with those found by Santa Cruz Astorqui *et al.* (28), where the authors concluded that there is an exponential relationship between the reduction of the composite density with the addition of EPS and its strength.

4. CONCLUSIONS

In general, the production of a lightweight construction material with thermal insulation properties using EPS residues and cellulose fiber together with gypsum is possible. The addition of cellulose fiber residues and EPS reduced the density by 55% when compared to the gypsum control samples without the addition of residues, and the flexural and compression strength results were above the requirements established by the standard to produce light gypsum.

The five variations produced showed improvements in thermal insulation capacity when compared to samples of commercial gypsum and recycled gypsum.

Samples C3 and C5 presented the worst thermal insulation results. In these cases, the higher the percentage of cellulose fiber in relation to expanded polystyrene, the worse the obtained results.

The C4 presented the best thermal insulation result, reducing the conductivity of the composite by 75% when compared to the reference sample of common gypsum, and approximately 48% when compared to the gypsum board.

Adding cellulose fiber to the gypsum matrix with expanded polystyrene provided an increase in the strength of the material compared to previous studies, without significant loss of the thermal insulation capacity provided by the expanded polystyrene.

The results show that it is viable to produce a gypsum matrix composite with residues of EPS and cellulose fiber for application as a material in buildings, improving some properties of common gypsum and gypsum board, also helping to reuse waste that would otherwise be discarded in the environment, and which could be used in the manufacture of panels and internal partitions due to its good

Table 2. Thermal conductivity (k) of composites with gypsum matrix.

Material	k (W/m.K)	Source
C4: G/RG + EPS (40%, 60%)	0.18	This study
C2: G/RG + CF + EPS (40%, 15%, 45%)	0.19	This study
C1: G/RG + CF + EPS (40%, 30%, 30%)	0.21	This study
C3: G/RG + CF + EPS (40%, 45%, 15%)	0.29	This study
C5: G/RG + CF (40%, 60%)	0.32	This study
Gypsum + EPS (50%, 50%)	0.25	(8)
Gypsum + EPS (40%, 60%)	0.25	(8)
Gypsum + EPS (60%, 40%)	0.36	(8)
Gypsum + Coconut fiber (10 mm)	0.35	(10)
Gypsum + Vermiculita (80%, 20%)	0.35	(14)
Gypsum + Vermiculita (75%, 15%)	0.37	(14)

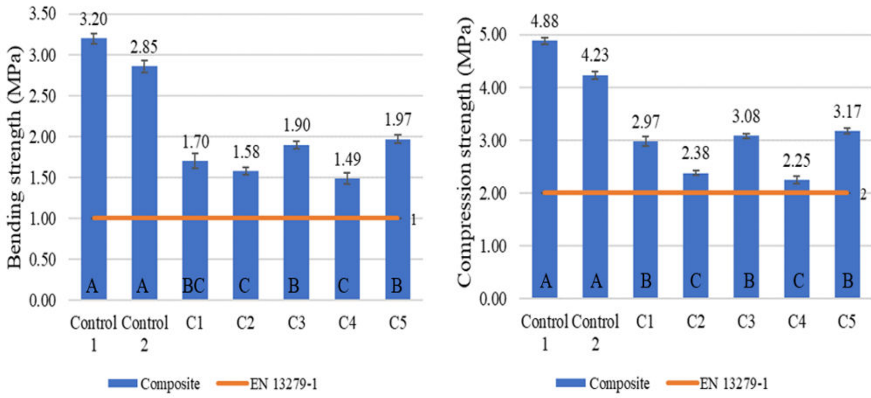

FIGURE 6. Results of flexural strength and compression strength.

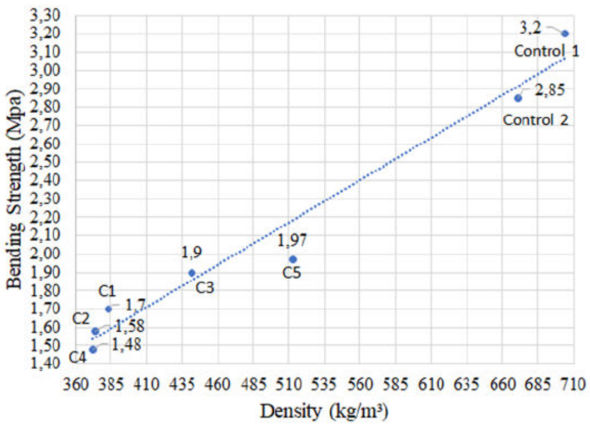

FIGURE 7. Scatter plot of the relationship between flexural strength and density.

thermal performance, thus improving the energy efficiency of buildings.

Despite presenting good results as a thermal insulator, it is necessary to consider that the material does not have high mechanical resistance, thus indicated to be used as sealing plates for walls and ceilings where mechanical resistance is not considered as the most important factor.

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