Influence of proportion and particle size gradation of rubber from end-of-life tires on mechanical, thermal and acoustic properties of plaster–rubber mortars

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A B S T R A C T

This work presents the main experimental results obtained from the study of plaster test pieces and boards with addition of various volumetric rubber fractions from mechanical grinding of end-of-life tires (ELTs), in three different particle size gradations. It includes a description of the materials employed, and their proportions. The physical and mechanical properties, as well as the thermal conductivity and acous-tic insulation properties are analyzed. Experimental results obtained for specimens with addition of recy-cled rubber are compared with similar ones, carried out on specimens of plaster of identical features without any addition, evaluating the influence of the particle size and mixture proportions. An improve-ment in thermal and acoustic performance has been obtained as well as a reduction in density, and as a result, some constructive applications for paving and slabs in rehabilitation works are proposed.

Keywords:
Rubber–plaster
Mechanical properties
Physical properties
Thermal conductivity
Acoustic insulation

1. Introduction

The aim of this study is to reuse end-of-life tires (ELTs) as rubber granular product and powder, taking advantage of its elastic properties, low density and chemical stability, to improve one of the binders most used in construction, plaster.

Many research works on the incorporation of different materials to hydraulic plaster binders have been carried out with the aim of improving some of its properties.

Among those studies analyzing the mechanical and physical properties, a distinction can be made between those that incorporate aggregates [1,2] which, in general, get a better bending strength or compressive strength; those which add lightweight aggregates [3–5] or air-entrained additives and foams [6] achieving a reduction of the density while experiencing a reduction of mechanical properties; and those which combine lightweight aggregates and strengtheners [7] with the aim of obtaining a product with improved physical and mechanical properties.

Studies have also been found to improve the thermal performance of plaster with the addition of other materials (polyamide powder and polyurethane foam), in which a reduction of strengths [8,9] also occurs.

Regarding the incorporation of ELT rubber to different binders, the main literature refers to the crumbed rubber additions in cement mortars and concretes (for structural, non-structural and self-compacted purposes). In this way, different authors have mainly studied the changes in the fresh mixtures workability and their mechanical behavior in hardened condition [10,11]. Other researches deal with rubber addition being subject to static and dynamic actions for different temperatures and frequencies [12], or the elastic behavior and dynamic modulus elasticity [13]. In addition, the thermal performance [14,15], the behavior under fire [16] as well as the chemical stability of the cement concrete with crumbed rubber and the possible existence of new phases in rubberized concrete [17] have also been of study interest.

Another line of research studied is the addition of rubber powder to bituminous materials to improve its performance as a material used for roads.

Since 2000, a large number of patents have been developed concerning the material valuation of end-of-life tires, which have, in turn, given rise to numerous commercial products.

Regarding the incorporation of recycled rubber particles to a plaster matrix, the literature found is scarce. Studies have been conducted with single particle sized crumbed additions in cement mortars [18] or plaster [19], studying their physical and mechanical properties and thermal insulation and acoustic ones; in both cases a reduction occurs on the mechanical strength – similar to those obtained in the study here presented – and an improvement in the thermal and acoustic insulation. Studies with minimal additions of rubber, between 1% and 5%, and three particle sizes of recycled ELT rubber similar to the ones in this study [20], show a decrease in the mechanical properties of plaster (16% in bending, and 18.3% in compression), and an increase in the elasticity module (between 1% and the 3%). Nevertheless, these studies conclude, as opposed to the results obtained in the present work, that there is no significant difference regarding the size of the rubber particle.

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2. Materials

To perform the mortar, just one type of plaster has been used: E-35, supplied by ALGÍSS URALITA.

The plaster technical characteristics, according to the technical specifications of the manufacturer (water to plaster ratio, by weight = w/p) are shown in Table 1.

In order to assess the influence of the particle size gradation, recycled crumbed rubber in three different particle sizes (0–0, 6 mm and 0, 5–2, 5 mm 2, 5–4, 0 mm nominal) from ELTs in room conditions have been used. All of them have been provided by the company RENECAL (Guardo-Palencia).

Physical properties and chemical analysis, as indicated in the technical specifications of the products are included in Table 2.

3. Experimental procedure

To analyze the influence of the proportions, the rubber percentage by weight was changed compared to the plaster weight according to values of 30%, 40%, 50% and 60%. Handling the previous variable, 12 different series of test pieces (Fig. 1) were performed using the rubber particle size (0–0.6 mm, 0.5–2.5 mm and 2.5–4.0 mm nominal).

Two types of specimens were prepared using the same batch procedure, and with a standard size of $4 \times 4 \times 16\ cm^3$ (three specimens by series) for the mechanical tests, and of other dimensions adapted for the tools used for performing thermal and acoustic tests: $25 \times 25 \times e\ cm^3$, dimensions boards being $e = 2$ cm and 3 cm, respectively (2 specimens by series).

The batch was prepared taking into account the workability of the mixture, trying to reach the most appropriate water/plaster ratio for each particle size and proportion by the shock or vibrating table test, in accordance with UNE standard [21]. Rubber particles initially retain a great water quantity, which makes longer the setting time and allowing for a slower hydration of the gypsum powder.

For each batch, the main physical and mechanical properties are determined by comparing them with the reference mortar without rubber powder. Also, experimental measures of thermal conductivity and acoustic insulation regarding their rubber content and particle size are included.

In Table 3, the name codes of the sample test pieces can be found (e.g. C-30-2.5), which refer to the substitution percentage of rubber, by weight of the agglomerate, and to the maximum size of the rubber particles. Table 3 contains too, the complete proportions of all the materials used in each mixture.

3.1. Tests

Physical and mechanical tests have been performed according to the relevant specific UNE standards on gypsum and plasters [21,22]. The following physical and mechanical properties have been determined: dry density, Shore C hardness, bending strength and compressive strength.

Table 1
The plaster technical characteristics, according to the technical specifications of the manufacturer.

Water for the mixing	75%
Purity index	92%
Mechanical bending tensile strength	$\geqslant 3.5\ \frac{N}{mm^2}$
Setting start (w/p = 0.8)	6–12 min
Setting end (w/p = 0.8)	20–25 min
Whitish index	>85%
Particle size gradation:	rejected < 1% in sieve of 200 μs
Water of crystallization	5.2–6.2%

Table 2
Recycled crumbed rubber: physical properties and chemical analysis.

	Minimum (%)	Maximum (%)
Chemical analysis (by weight)		
Ketone extract	10	20
Polymers NR/SR	40	55
Natural rubber NR	21	42
Carbon black	30	38
Ashes	3	7
Sulfur	–	5
Physical properties		
Density	1.10–1.27 g/cm^3	
Bulk density	0.5–0.55 g/cm^3	
Grain morphology	Angular	
Humidity	<0.75% by weight	
Textile material content	<0.50% by weight	
Ferromagnetic materials content	<0.1% of rubber weight < 0.1% of rubber weight (sizes < 0.8 mm)	
Other impurities content	<0.25% by weight	

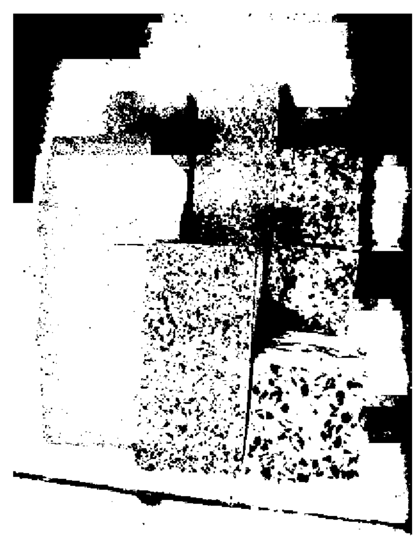

Fig. 1. Section of test pieces classified regarding their percentage in rubber weight and rubber size gradation.

Table 3
Designation and mixture proportions of the components of the samples tested.

Designation	Water (g)	Plaster (g)	Rubber (g)	Water/plaster ratio weight) (w/p)	Rubber particle size (mm)
R1	580	1000	0	0.58	
C-30-0.6	530	700	300	0.53	
C-40-0.6	600	600	400	0.60	0.0–0.6
C-50-0.6	670	500	500	0.67	
C-60-0.6	770	400	600	0.77	
C-30-2.5	450	700	300	0.45	
C-40-2.5	490	600	400	0.49	0.5–2.5
C-50-2.5	570	500	500	0.57	
C-60-2.5	690	400	600	0.69	
C-30-4.0	500	700	300	0.50	
C-40-4.0	560	600	400	0.56	2.5–4.0
C-50-4.0	570	500	500	0.57	

To determine the thermal conductivity, equipment (Fig. 2) provided by the laboratory of Physics of the School of Building Engineering of the Polytechnic University of Madrid (Spain) has been

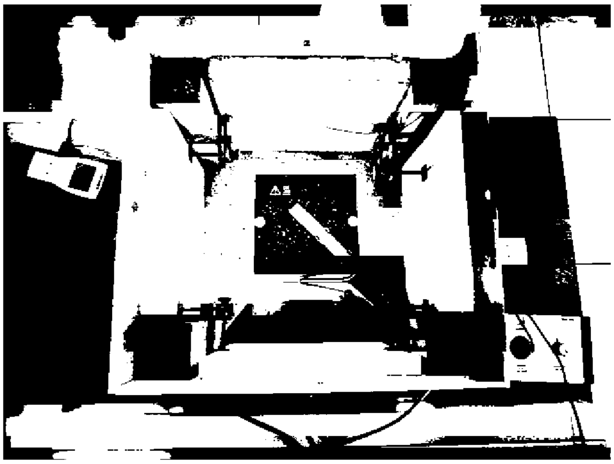

Fig. 2. "Thermal model house", with probes, thermostats and board to be tested placed.

used. The equipment consists of a thermally insulated cube with four sides, in which 21 × 21 cm^2 openings are inserted. Materials to be tested were placed in the inner face (in this research the boards were always placed with the rough side facing the interior of the box). Sheets of insulating material of 21 × 21 cm^2 (of known conductivity) are attached to the outside faces. Inside, as a heat source, a 100 W bulb and an internal thermal probe connected to a thermal regulator thermostat are inserted.

On the edges of the lateral sides, there are some holes with elastic insulation to introduce thermal probes (temperature measuring instrument with two thermocouples NiCr–Ni).

Five thermal probes have been used to measure the temperature inside the box: on the inner side of the board to be tested, at the contact surface of the board and the insulation, on the outer face of the insulation and the room temperature. All temperatures registered by the probes have been collected and noted down.

All measurements have been done at the same height and distance of the box lateral faces, to avoid differences due to the temperature gradient regarding these variables.

Once the stationary level is reached, approximately 6 h after placing the board, temperatures are registered with a frequency of 1 min, during a period of 30 min. After this, the mean temperature during that period is obtained for each of the probes, and this data is used to calculate the thermal conductivity, based on Fourier's Law.

Acoustic insulation measurement has been performed by carrying out a test used for small-scale measurements, using the tool called "acoustic box". This tool is a box with interior dimensions of 35 cm thickness × 70 cm length × 60 cm tall, and made by three layers of material. The center 5 cm layer is made of extruded Polystyrene (XPS) and works as a support for the other layers; inside, it has been lined with a 10 mm thick plaster board, and externally, it was cladding with "Copopren Acustic" porous material, 40 mm thick, and with a density of 80 kg/m^3, and a sound reduction index of Rw = 62 dB.

The board to be tested is placed in the center of the box, embedded in 3 cm wide groves performed throughout the perimeter of the box, forming hence, two different spaces – one on each side of the board – which will be the emitter and receiver. The board perimeter is surrounded by an elastic band and filled with insulating material, which is compressed when introduced into the grooves; therefore, obtaining a more precise sealed joint, and avoiding acoustic bridges.

A sound calibrator model CB-5 of CESVA that provides a frequency pure tone of 1 kHz is placed in the transmitter space for testing the airborne noise. In all tests, a 104 dB sound pressure level (3.16 Pa) at 1 kHz as been used.

Once the corresponding board has been placed in the grooves of the box, as explained above, and the transmitter working, the box is closed and time was allowed until the stabilization of the sound level meter took place.

Three measures are performed, timing 30 s for each measurement and recording minimum and maximum values for each of them. In this way, indexes of gross airborne noise insulation are obtained.

For measuring impact sound insulation, a 113 g steel ball wrapped in a net placed at 23 cm is used and dropped by gravity, with pendulum effect, from a horizontal position aligned with the rope attached to it. Using this procedure, three measures for each board are obtained.

4. Results and discussion

4.1. Physical properties

A reduction in density and hardness Shore C (Table 4) can be noticed as the proportion of rubber, for all particle sizes, increases. The largest density reductions occur with the finest particles varying between 16% and 47%. But also with this particle size the lowest values in C Shore hardness are obtained. At the same time, changes in texture and color of the batches (Fig. 3) are observed.

Results obtained from the density and Shore C hardness physical tests are in close correspondence with the w/p ratios used in the specimens tested. In both cases, linear regression equations of these properties were obtained in relation to the particle size showing a close slope.

The series corresponding to the smaller size particles show higher hardness values because these rubber particles are coated with a thicker layer of plaster.

Table 4
Name, apparent density and surface Shore C hardness.

Particle size gradation	% Rubber (weight)	% Rubber (volume)	Name	w/p ratio	Density (kg/m^3)	Shore C hardness
	0	0	R1	0.58	1222.3	90.7
	30	40.7	C-30-0.6	0.53	1032.4	69.2
0.0–0.6	40	51.6	C-40-0.6	0.60	901.6	51.0
	50	61.5	C-50-0.6	0.67	771.5	29.2
	60	70.6	C-60-0.6	0.77	653.9	13.9
	30	38.4	C-30-2.5	0.45	1140.2	78.5
0.5–2.5	40	49.2	C-40-2.5	0.49	1021.5	60.4
	50	59.3	C-50-2.5	0.57	891.0	41.4
	60	68.6	C-60-2.5	0.69	758.2	25.0
	30	39.7	C-30-4.0	0.50	1076.9	78.7
2.5–4.0	40	50.6	C-40-4.0	0.56	960.9	54.3
	50	60.6	C-50-4.0	0.57	893.4	52.3

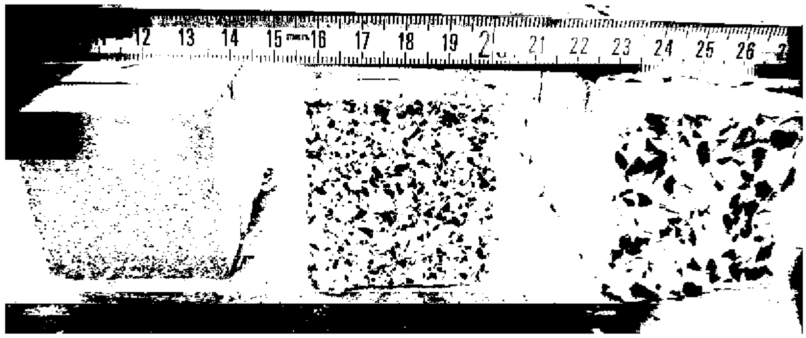

Fig. 3. Section of test pieces with different crumbed rubber gradations.

4.2. Mechanical properties

Results obtained of the specimens tested to compression (Fig. 4a) show that the plaster with rubber in all studied particle sizes have very important strength losses in relation to the reference series. Plaster without rubber reaches strengths of 23.53 N/mm^2 (Table 5), decreasing to values ranging between 5.56 N/mm^2 and 4.24 N/mm^2 for 30% rubber additions depending on the size of the rubber particle. This decline continues, although in a less pronounced way, as the percentage of rubber addition increases, reaching unacceptable values according to UNE standard for additions of 50% and 60%.

Results of the specimens tested to flexural strength (Fig. 4b) show strength decreases in relation to the reference series, but less important than those in compression. Plaster without rubber reaches strengths of 7.5 N/mm^2 (Table 5), descending depending on the size of the grain to values ranging, from 3.16 N/mm^2 to 2.57 N/mm^2 for additions of 30% rubber powder. This decline continues when increasing the addition percentage, reaching unacceptable values according to standard UNE for 60% additions in all particle sizes.

Table 5
Fracture specimen C-30-0.6 in bending and compression successive tests.

Specimen	Bending strength (N/mm^2)	Compressive strength (N/mm^2)
R1	7.5013	23.53
C-30-0.6	3.1605	5.55
C-40-0.6	2.0511	2.74
C-50-0.6	1.2442	1.24
C-60-0.6	0.7789	0.55
C-30-2.5	3.0035	5.07
C-40-2.5	2.1401	2.79
C-50-2.5	1.4670	1.38
C-60-2.5	1.0415	0.87
C-30-4.0	2.5738	4.24
C-40-4.0	1.8517	2.50
C-50-4.0	1.4963	1.56

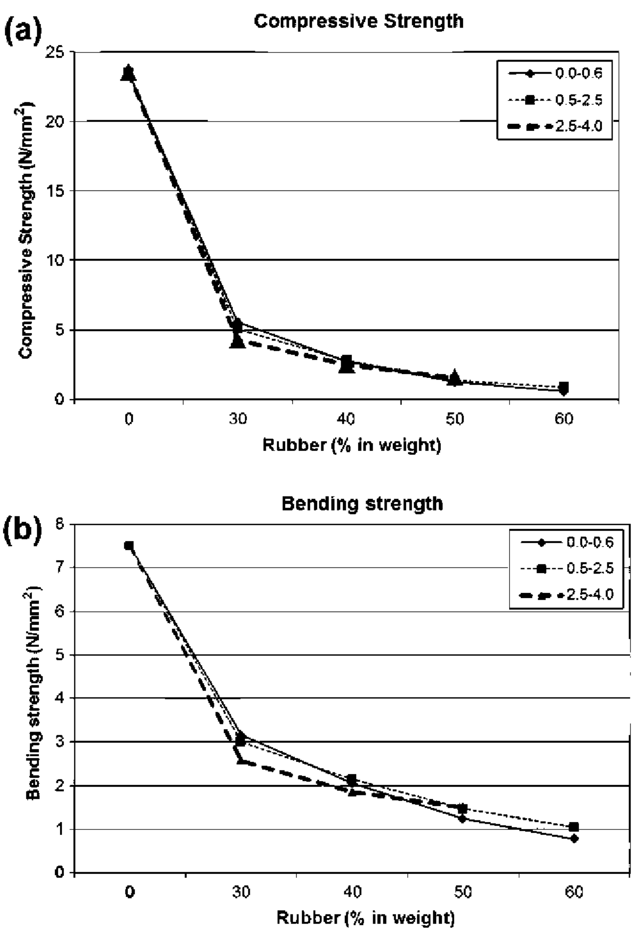

Fig. 4. Compressive and bending strength.

The experimental values here measured are in close correspondence with those obtained in previous research works on plaster with crumbed rubber [18], considering too the small additions between 1% and 5% by weight [20] considering the back extrapolation of the fitted tendency lines obtained in this investigation.

The different performance of specimens with and without fiber (Fig. 5a and b) should be noted when the ultimate stress is reached. In the case of specimens without rubber a catastrophic fracture occurs, while in those containing rubber, cracks appear without separation of the edges and being bounded by the rubber. This behavior indicates the improvement of the toughness of the compound [12].

The bending and compression study shows a minimal dispersion in the results in all the series performed, similar to the reference series. At the same time, it shows exponential tendencies with R^2 values of 0.998 which allow to predict a performance of the test pieces in relation to the addition percentage. A decrease in the curve slope can be seen as the particle size increases; that is, the strength reductions are more noticeable in the series corresponding to the smaller size particles than when greater amount of rubber is added.

4.3. Thermal test

Small fluctuations can be produced, which would require greater refinement, but these do not nullify the test based on the range of results.

In all the studied compounds, a decrease in thermal conductivity is produced in relation to the reference boards without the addition of rubber. The values obtained for λ in this research are in close correspondence too with the thermal conductivity measured in similar materials used for thermal insulation in building construction; for instance: cork–gypsum composites [5], gypsum with polyamide [8] and gypsum with polyurethane foam wastes [9].

When particle sizes gradations are compared (Fig. 6), the lowest values of thermal conductivity occur with the finest particle sizes, followed by the medium particle size. The worst values are obtained for the coarser particle sizes.

Taking into account that density in construction materials is a determining factor of their thermal capacity; the conductivity value has been calculated according to the percentage of rubber and plaster by volume, and of the thermal conductivity of the two materials, to compare it with the values obtained experimentally.

Two possible thermal behaviors of the two materials composite can be considered: in series and in parallel, being 1 and 2 the materials making up the composite.

When considering a series behavior, as shown in Fig. 7 being $T_1 > T_2$ (temperatures in °C), $e = e_1 + e_2$ (thickness in m) and $S = S_1 = S_2$ (section in m^2), the heat flow would be:

$$\phi = \frac{1}{S}\frac{\partial Q}{\partial t}\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right) \tag{1}$$

being t the time.

In compliance with Fourier's Law, and being λ_c the thermal conductivity of the composite and λ_1 and λ_2 the thermal conductivity of the material components:

$$\phi \equiv \lambda_c \frac{T_1 - T_2}{e} = \lambda_1 \frac{T_1 - T}{e_1} = \lambda_2 \frac{T - T_2}{e_2} \tag{2}$$

These expressions can be written so:

$$T_1 - T_2 = e\frac{\phi}{\lambda_c} \tag{3}$$

$$T_1 - T = e_1\frac{\phi}{\lambda_1} \tag{4}$$

$$T - T_2 = e_2\frac{\phi}{\lambda_2} \tag{5}$$

Adding the expressions (4) and (5) the following is obtained:

$$T_1 - T_2 = \phi\left(\frac{e_1}{\lambda_1} + \frac{e_2}{\lambda_2}\right), \tag{6}$$

making it equal to (3) expression,

$$\frac{e}{\lambda_c}\phi = \left(\frac{e_1}{\lambda_1} + \frac{e_2}{\lambda_2}\right)\phi, \tag{7}$$

and dividing it by e,

$$\frac{1}{\lambda_c} = \frac{e_1}{e\lambda_1} + \frac{e_2}{e\lambda_2} \tag{8}$$

is obtained

For each volumetric fraction

$$\frac{e_1}{e} = \frac{e_1 S}{eS} = \frac{V_1}{V_T} = V_{f1} \tag{9}$$

$$\frac{e_2}{e} = \frac{e_2 S}{eS} = \frac{V_2}{V_T} = V_{f2} \tag{10}$$

Substituting in expression (8) it can be deduced that:

$$\frac{1}{\lambda_c} = \frac{V_{f1}}{\lambda_1} + \frac{V_{f2}}{\lambda_2} \tag{11}$$

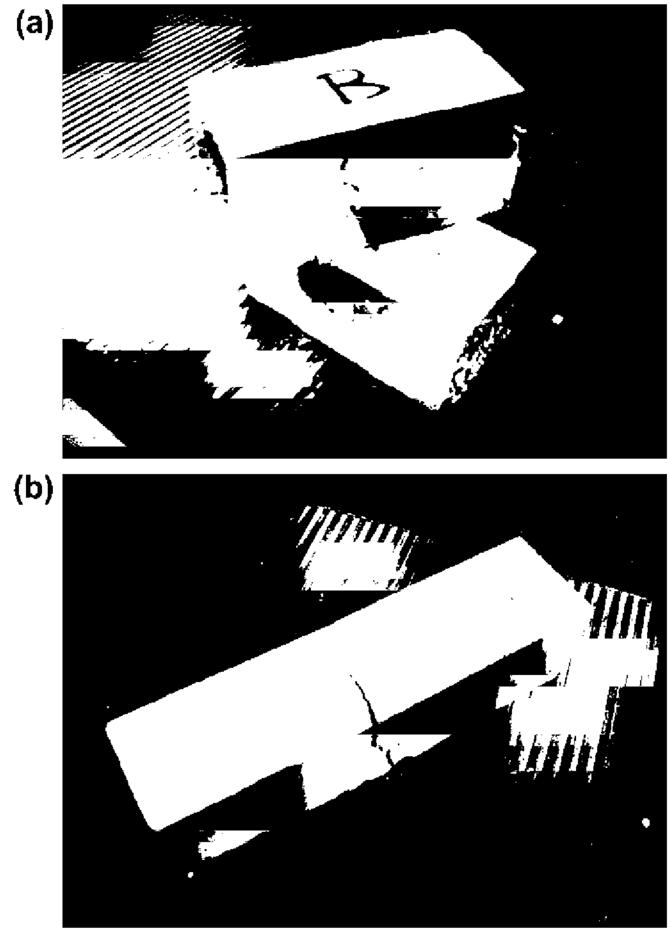

Fig. 5. Fracture specimen C-30-0.6 in bending and compression successive tests.

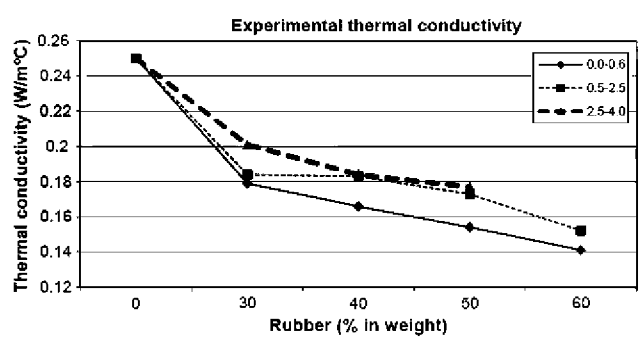

Fig. 6. Experimental thermal conductivity according to particle size gradation.

If a performance in parallel is considered, as shown in Fig. 8 and being $T_1 > T_2$ (temperatures in °C), $e = e_1 = e_2$ (thickness in m) and $S = S_1 + S_2$ (section in m^2), the thermal flow will be:

$$\phi_1 = \frac{1}{S_1}\frac{\partial Q_1}{\partial t}\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right) \tag{12}$$

$$\phi_2 = \frac{1}{S_2}\frac{\partial Q_2}{\partial t}\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right) \tag{13}$$

t being time.

In agreement with Fourier's Law, and being λ_c the thermal conductivity of the composite and λ_1 and λ_2 the thermal conductivity of the component materials:

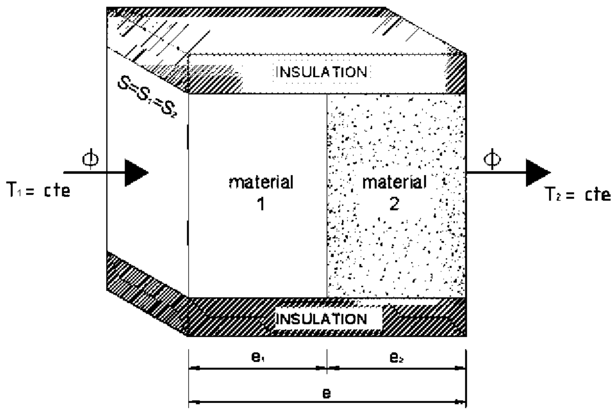

Fig. 7. Series performance of the composite.

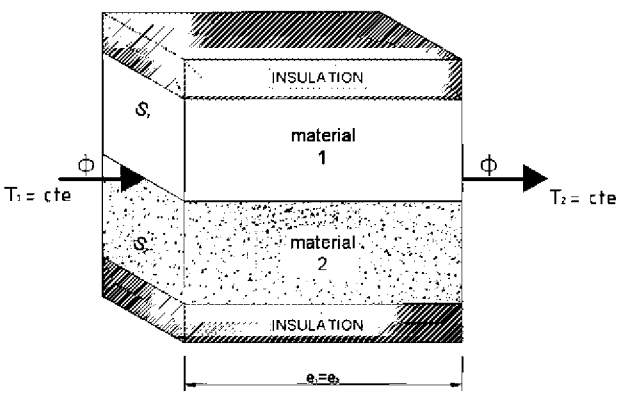

Fig. 8. Behavior in parallel of the composite.

Table 6
Thermal conductivity of the experimental and theoretical composite considering performance both in series and in parallel.

Plaster board: e = 2–3 cm Polystyrene: e = 2 cm λ = 0.037			
Name	λ (W/m °C) parallel	λ (W/m °C) series	λ (W/m °C) experimental
R1	0.250	0.25	0.226
C-30-0.6	0.209	0.197	0.179
C-40-0.6	0.198	0.186	0.166
C-50-0.6	0.188	0.177	0.154
C-60-0.6	0.179	0.161	0.141
C-30-2.5	0.212	0.199	0.184
C-40-2.5	0.201	0.188	0.183
C-50-2.5	0.191	0.179	0.173
C-60-2.5	0.181	0.172	0.152
C-30-4.0	0.210	0.198	0.201
C-40-4.0	0.199	0.187	0.184
C-50-4.0	0.189	0.178	0.177

$$\phi_1 = \lambda_1 \frac{T_1 - T_2}{e_1} \qquad (14)$$

$$\phi_2 \equiv \lambda_2 \frac{T_1 - T_2}{e_2} \qquad (15)$$

$$\phi_{total} = \lambda_c \frac{T_1 - T_2}{e} \qquad (16)$$

The total heat will be:

$$\phi S = \phi_1 S_1 + \phi_2 S_2, \qquad (17)$$

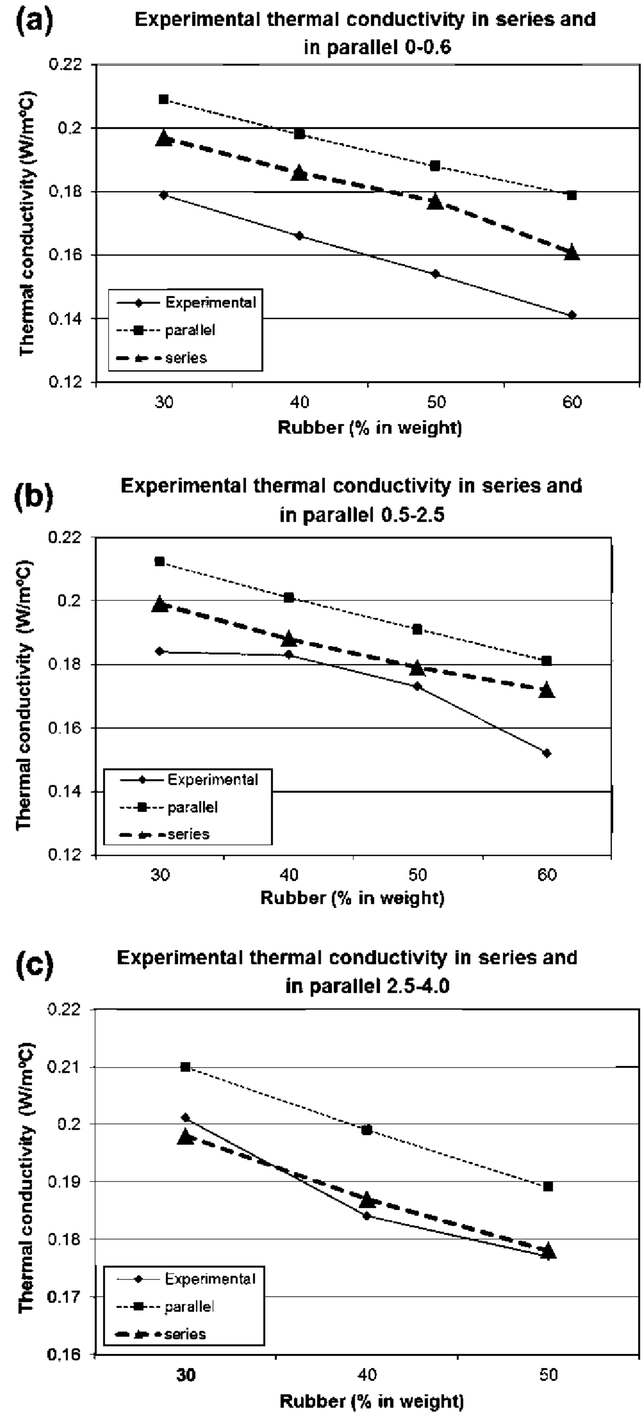

Fig. 9. Experimental thermal conductivity, in series and in parallel.

therefore:

$$\lambda_c \frac{T_1 - T_2}{e} S = \lambda_1 \frac{T_1 - T_2}{e_1} S_1 + \lambda_2 \frac{T_1 - T_2}{e_2} S_2, \qquad (18)$$

and taking into account that $e = e_1 = e_2$:

$$\lambda_c S = \lambda_1 S_1 + \lambda_2 S_2 \qquad (19)$$

dividing by S and considering both volumetric fractions

$$V_{f1} = \frac{S_1}{S} \qquad (20)$$

$$V_{f2} = \frac{S_2}{S} \qquad (21)$$

Table 7
Experimental insulation and insulation in agreement with the mass law for 2 cm and 3 cm thick boards.

Airborne noise Sound level meter SC-2C Level Meter CESVA. Output emission 104 dB a 1Khz			Plaster board: $e = 2–3$ cm Starting in vacuum of 32. 33. 34 dB	
Name	Smooth face towards emitter mean per thickness (dB)		Rough face towards emitter mean per thickness (dB)	
	Experim. insulation (dB)	Insulation L mass (dB)	Insulation experim. (dB)	Insulation L mass (dB)
2-R	44.34	40.76	43.42	40.76
3-R	43.84	44.26	42.55	44.26
2-C-30-0.6-1	44.02	39.3	42.34	39.3
3-C-30-0.6-1	46.42	42.82	47.48	42.82
2-C-40-0.6-1	43.96	38.12	43.18	38.12
3-C-40-0.6-1	44.95	41.64	43.06	41.64
2-C-50-0.6-1	43.27	36.77	42.56	36.77
3-C-50-0.6-1	44.22	40.29	45.40	40.29
2-C-60-0.6-1	38.43	35.33	44.12	35.33
3-C-60-0.6-1	41.79	38.85	43.7	38.85
2-C-30-2.5-1	42.95	40.16	43.6	40.16
3-C-30-2.5-1	44.97	43.68	46.31	43.68
2-C-40-2.5-1	43.55	39.21	42.03	39.21
3-C-40-2.5-1	45.76	42.73	44.91	42.73
2-C-50-2.5-1	44.86	38.02	43.85	38.02
3-C-50-2.5-1	43.33	41.54	43.28	41.54
2-C-60-2.5-1	43.71	36.62	41.78	36.62
3-C-60-2.5-1	41.49	40.14	44.98	40.14
2-C-30-4.0-1	44.35	39.66	43.38	39.66
3-C-30-4.0-1	40.86	43.19	44.14	43.19
2-C-40-4.0-1	42.14	38.67	43.07	38.67
3-C-40-4.0-1	40.16	42.2	41.96	42.2
2-C-50-4.0-1	43.34	38.04	42.77	38.04
3-C-50-4.0-1	41.25	41.56	42.06	41.56

the following expression is reached:

$$\lambda_c = V_{f1}\lambda_1 + V_{f2}\lambda_2 \tag{22}$$

Table 6 includes values corresponding to both behaviors according to the obtained expressions, as well as the experimental results for each series.

The experimental values of the thermal conductivity λ have been calculated by means of averaging the results obtained for the different thicknesses studied. This value is independent from the thickness of the specimens tested, but not from the particles size of the crumbed rubber mixtures, as the results obtained show.

In all the products obtained (Fig. 9a–c) experimental thermal conductivity is below the theoretical one depending on its density, both when considering a series and parallel behavior, except for the coarser particles with 30% rubber, in relation to the series behavior.

For the finer particles, 0–0.6, the decrease is greater than for the other particle sizes.

An estimation of the possible composite behavior regarding both options can be performed analyzing the λ value range regarding the volumetric fraction and the real behavior to which the compound assimilates. But graphs show experimental values lower to those behaviors. The differences obtained between $\lambda_{theoretical}$ and $\lambda_{experimental}$ can be attributed to the fact that, in the theoretical analysis, the heat transmission by convection, which would in turn produce the "heat transfer coefficient or film coefficient" has not been considered (it depends upon many factors and can be experimentally determined by using dimensional analysis methods).

Variations observed depending on the particle size, would be conditioned by the different roughness of the material, (since the rough side is placed towards the interior of the box) which varies depending on the size of the rubber particle and its % addition. This is due because the boundary layer is modified, both in thickness and in the fluid regime (laminar or turbulent) altering the aforementioned coefficient.

An estimated value for each particle size can be made regarding the results obtained, reaching the following values for behavior in parallel:

Heat transfer coefficient for particle size gradation 0.0–0.6 = 0.02 °C m^2/W

Heat transfer coefficient for particle size gradation 0.5–2.5 = 0.01 °C m^2/W

Heat transfer coefficient for particle size gradation 2.5–4.0 = 0.001 °C m^2/W

These values are acceptable given the dimensions of the test chamber, and allow assessing the validity of the experimental technique designed for measuring the thermal conductivity with small specimen sizes.

From the results obtained, it can be asserted that the convection effect inside the test apparatus was very small, due to the test conditions.

As the experimental values of λ obtained were smaller than 0.2 W/m K, it can be inferred that the composite materials designed clearly show the property of thermal insulation. Indeed, the thickness required to fulfill the required thermal insulation can be easily reached by pneumatic application of this material, on the support. Due to the quick setting of the plaster, the desired thickness of the insulation coating, in relation with the prescribed thermal performance can be obtained.

4.4. Acoustic test

4.4.1. Airborne noise

When comparing gross insulation results experimentally obtained for rubber plaster boards regarding the thickness for each particle size with the theoretical values obtained by applying the mass law (Table 7), differences can be found in the behavior, depending on the grain size and on the board thickness.

No large differences regarding the placement of the rough face position, either towards the emitter or the receiver, are appreciated.

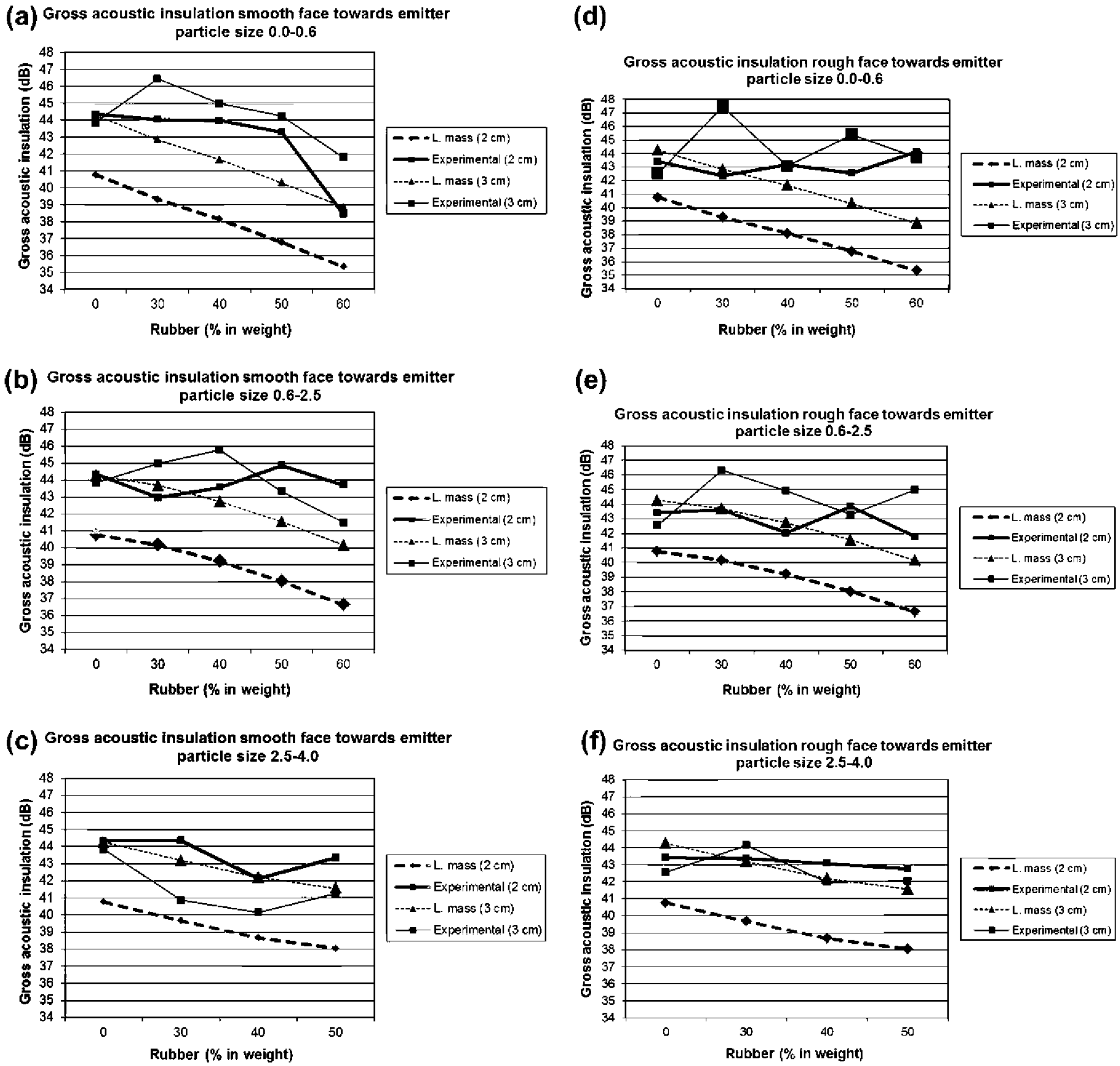

Fig. 10. Sound pressure inside the receiver space, smooth face towards the emitter (a–c) and rough face towards the emitter (d–f). Comparison by particle size gradation and by % rubber in weight for 2 cm and 3 cm in thickness.

The most effective results are obtained for the finer particles and for boards with smaller thickness (2 cm).

In this study, only the behavior for a frequency of 1000 Hz has been analyzed, but the variables of rubber percentage, particle size and board thickness have been considered.

In relation to the particle size (Fig. 10a–f) the best results obtained for the finer grain, would indicate the influence of the material inertia depending on the size: it is more difficult to make the coarser grain vibrate, with greater inertia, than the finer one. This is so because it has a lower inertia, which turns to vibrate more easily and therefore dissipates energy.

Rubber is a material that can dissipate elastic energy when vibrating. The amount of elastic energy that can be dispelled depends on the frequency and on the rubber amount the compound contains [12]. The good properties of rubber as dissipation of dynamic energy allowed obtain too better airborne insulation performance, incorporating crumbed rubber in plaster than by the addition of cork granulates in gypsum, mainly because the greater elasticity of rubber-plaster than the cork–hemihydrates gypsum one [5].

Although in absolute values acoustic insulation improves when the board thickness increases, as one would expect, when this comparison is made for each thickness in relation to the mass law, the best results are obtained for the reduced thickness (2 cm). This aspect leads to consider the possible existence of a critical thickness above which results would not improve.

As the thermal insulation increases depending on the thickness applied, there should be a thickness above which the acoustic insulation would not increase, and as a result, depending on the aim of the construction material – thermal insulation or acoustic insulation – the thickness would be different.

Table 8
Impact noise, sound pressure in receptor space.

Impact noise Plaster board: e = 2–3 cm Starting in vacuum of 32, 33, 34 dB Sound level meter SC-2C Level Meter CESVA. LAF chosen option		
Name	Smooth face towards emitter mean per thickness (dB)	Rough face towards emitter mean per thickness (dB)
2-R	107.21	100.83
3-R	99.9	102.76
2-C-30-0.6-1	81.92	81.06
3-C-30-0.6-1	86.58	79.48
2-C-40-0.6-1	89.33	80.13
3-C-40-0.6-1	80.32	81.05
2-C-50-0.6-1	83.71	82.76
3-C-50-0.6-1	84.51	87.98
2-C-60-0.6-1	84.23	78.30
3-C-60-0.6-1	85.78	82.72
2-C-30-2.5-1	81.44	90.35
3-C-30-2.5-1	90.6	92.50
2-C-40-2.5-1	80.13	80.75
3-C-40-2.5-1	86.39	90.63
2-C-50-2.5-1	92.58	89.02
3-C-50-2.5-1	84.58	80.63
2-C-60-2.5-1	84.45	85.43
3-C-60-2.5-1	90.08	88.00
2-C-30-4.0-1	90.25	87.28
3-C-30-4.0-1	92.72	90.15
2-C-40-4.0-1	85.07	81.85
3-C-40-4.0-1	89.75	90.63
2-C-50-4.0-1	78.93	82.37
3-C-50-4.0-1	81.43	84.18

4.4.2. Impact noise

The insulation capacity against impact is improved. In particular, the best results are obtained for the finest particle size and for all addition percentages (Table 8).

No clear trends based on the addition percentage are observed.

The tests and measurements here described, show that the sound bonding between the solid plaster skeleton and the rubber particles on its surface is the reason of the improvement in the acoustical and thermal insulation properties of the designed materials, particularly considering the dissipative capacity of mechanical vibrations by the rubber particles and their low thermal conductivity, respectively.

5. Conclusions

Based on the experimental results, the following conclusions can be drawn:

- Rubber addition decreases bending strength and compressive strength, reaching very low values for additions of 50–60%. Nevertheless, a slight improvement can be observed in the toughness of the compound for all particle sizes. Exponential trends in bending and compression curves follow a law that conforms with the good values of R^2 and which would allow predicting the mechanical behavior depending on the percentage of added rubber – provided the same law with a greater number of samples is maintained.
- A reduction of the density in all the series performed can be observed, and the best results are the ones obtained with the finer particles.
- The addition of recycled rubber powder improves the thermal insulation ability in all series performed. Once again, best results are those of the finer particle sizes.
- Material roughness due to the difference in particle size and addition percentage influence the heat transfer coefficient or coefficient of convection.
- As a consequence of the results obtained, the experimental technique designed for measuring thermal conductivity with small samples is considered valid.
- Rubber characteristics as a vibration-absorbing elastic material and the importance of the size of rubber particles are confirmed in the improvement of the acoustic behavior of the compound material.
- Plaster-rubber boards enhance the acoustic insulation ability against noise impact; being the particle size more relevant in all cases (the finest the best) than the addition percentage.
- Although in absolute values sound insulation improves as the thickness of the board increases, the best results are obtained for the minimum thickness (2 cm). This leads to consider the possible existence of a critical thickness above which results do not improve.
- Within the series carried out, those with the finest particle size and with percentages of rubber addition of 30% and 40% in weight are those presenting the best relationship between density, mechanical strength and thermal and acoustic behavior.
- Given the characteristics of plaster-rubber boards (density reduction, improvement of thermal and acoustic insulation to impact noise), they are appropriate in constructive applications such as floors and compression layers or slabs for buildings rehabilitation.

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