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1 **MECHANICAL CHARACTERIZATION AND THERMAL CONDUCTIVITY MEASUREMENTS BY**
2 **MEANS OF A NEW ‘SMALL HOT-BOX’ APPARATUS: INNOVATIVE INSULATING**
3 **REINFORCED COATINGS ANALYSIS**

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14

15 **Abstract**

16 The insulation of the building envelope contributes to the reduction of annual energy
17 consumptions. The development of new materials, such as fibre reinforced insulating coatings,
18 could be useful in order to obtain an effective solution for the improvement of energy performance
19 and for reinforcement of the walls.

20 The evaluation of the thermal and mechanical characteristics of building coatings with good
21 thermal insulation properties and mechanical resistance is the aim of the present paper. A new
22 experimental apparatus, Small Hot-Box, built at the University of Perugia, was used for the
23 evaluation of the thermal conductivity of four different coatings (with and without a reinforced
24 structure). No European standards are available for this innovative facility, but it takes into account
25 some prescriptions of EN ISO 8990. The apparatus was calibrated with materials of known thermal
26 conductivity. The thermal conductivity can be calculated with both the thermal flux meter and the

27 Hot Box method. Good values of the thermal conductivity, in the range of 0.09-0.11 W/mK were
28 found for all the samples, except for one (0.21-0.24 W/mK).

29 Mechanical tests were also carried out in laboratory on all the samples and results were used to
30 evaluate the shear modulus and strength of the wall panels.

31

32 **Keywords:** Reinforced insulated coatings, Mechanical resistance, Thermal conductivity,
33 Innovative experimental apparatus, Building insulated materials.

34

35 **1. Introduction**

36 Energy consumption for buildings heating and air conditioning represents on average the 40
37 % of energy consumptions in Europe [1]. Furthermore a relevant part of the building heritage in
38 Europe is constituted by old buildings [2,3,4] with poor quality insulation materials. Therefore,
39 recent regulations, as for example the EU Directive 2010/31 [5] on energy efficiency in buildings,
40 aims at increasing target energy efficiency standards, considering both the single components and
41 the entire building. The building envelope plays a fundamental role in energy balance. The
42 evaluation of the building components thermal properties requires a high level of accuracy and
43 many experimental methods for the thermal characterization of materials have been performed
44 from research efforts all over the world. Several methods for measuring the thermal properties are
45 well known; the guarded hot plate is the most common method used for the evaluation of the
46 thermal conductivity of an homogeneous or multilayer material [6]. Many studies concerning the
47 characterization of thermal properties of materials are available; André et al. [7] presented an
48 experimental set-up based on the hot wire method for the thermal characterization of materials,
49 while a tiny hot plate method is proposed by Jannot et al. [8,9] for the thermal conductivity
50 measurement of heterogeneous materials [10].

51 Furthermore, for non-homogeneous structures, composed by different materials or
52 components (such as doors, windows or French windows), or when the heat transfer is two - or
53 three-dimensional, different techniques are used; the most common method for the thermal
54 transmittance evaluation is the calibrated Hot-Box [11,12]. Since Seventies the guidelines for Hot

55 Box design criteria are reported in EN ISO 8990 [13] and EN ISO 12567-1 [14]. In particular EN
56 ISO 12567-1 specifies a method to measure the thermal transmittance of doors or windows, but
57 also the thermal conductivity of homogeneous materials can be evaluated. The heat flux through
58 the sample can be evaluated by means of thermal flux meters installed on the surface of the
59 sample (Thermal Flux Meter Method, TFM). In this case the thermal conductivity of the panel will
60 be calculated as the (thermal flux/surface temperature difference) ratio. The flux meter
61 methodology is also considered in the UNI EN 1934:2000 [15]. At the University of Perugia
62 (Department of Engineering), a Calibrated Hot Box was built in 2008, according to UNI EN ISO
63 8990 [13,16]. It is composed of two chambers (dimensions 2.5 x 1.2 x 3.2 m height), the cold and
64 the hot one [16,17,18,19,20].

65 Considering homogeneous materials, other experimental apparatus could be used: the
66 guarded hot plate or heat flow meter method (EN ISO 12667 and ASTM C518–10 [21,22]). The
67 heat flow meter apparatus is a comparative device and requires a reference material with known
68 thermal properties for calibration. The heat flow meter apparatus establishes steady state one-
69 dimensional heat flux through a test specimen between two parallel plates at constant but different
70 temperatures [23].

71 In this context, in the present study measurements with a new experimental apparatus,
72 named Small Hot-Box, were carried out. The experimental system has been designed and built at
73 the Laboratory of Thermal Science, University of Perugia. The apparatus allows the evaluation of
74 the thermal conductivity of homogeneous materials, but the operating principle arises from the Hot-
75 Box method. The advantage of the apparatus with respect to Hot-Box is the possibility of testing
76 homogeneous materials with smaller samples (300 x 300 mm); with respect to the Hot Plate
77 apparatus, it can provide a thermal transmittance value measured in conditions similar to the in-situ
78 ones.

79 Fibre reinforced insulating coatings were characterized with the innovative apparatus. The
80 mechanical properties of the same samples were also evaluated, in order to show the influence of
81 the fibres on the mechanical resistance.

82 Retrofitting techniques for masonry constructions are extensively found in the existing
83 literature. FRP (Fibre-Reinforced Polymer) systems are increasingly used to strengthen masonry
84 structures: reinforcement is frequently bonded to the surface of existing walls, where it provides
85 tensile strength and prevents the opening of cracks [24,25,26,27].
86 The use of FRPs without epoxy adhesives is less well established [28,29]. Only recently the use of
87 non-organic matrixes has been the subject of research, and it could be a valid alternative to the
88 use of epoxy matrixes. Mechanical tests were conducted in laboratory on 1.2 x 1.2 x 0.24 m
89 brickwork panels. All wall panels were subjected to shear strength and test results were used to
90 evaluate the shear strength of the masonry before and after the application of the strengthening
91 made of a G-FRP (Glass Fibre-Reinforced Polymer) reinforced insulation coating applied on both
92 panel sides.

93 Insulation coatings can be used in many applications, such as refurbishment of old buildings,
94 on internal as well as external surfaces, and they should offer a non-invasive method for reinforce
95 historic buildings and saving energy without altering their forms. Fibre-Reinforced Polymers (FRP)
96 are composed of high-strength fibres (such as glass) embedded in a polymer resin (such as
97 polyester), durable (thanks to the resin), and lightweight. Glass fibre reinforced concrete is a
98 composite material made of components with different mechanical properties: cement mortar and
99 G-FRP in place of metal grids. Cement avoids buckling of glass fibres when compressing them,
100 glass fibres improve the tensile strength and ductility. This solution is very diffused in order to
101 improve the shearing strength of the walls [30,31]. Thermal insulation plasters, as the samples
102 investigated in the present study, consisting in innovative reinforced coatings made of mortar and
103 G-FRP, try to combine good mechanical and thermal properties for building refurbishment.
104 Innovative coating solutions are therefore in development, such as aerogel-based high
105 performance insulating plasters, but a limited number of studies exists in this field, probably due to
106 the high costs of the innovative system [32].

107

108 **2. Materials and methods**

109 **2.1 Description of the samples**

110 Four mortars with different chemical compositions were investigated, each one with and
111 without G-FRP, for eight samples in total. The G-FRP grid is characterized by a 66 mm square
112 mesh inserted into the matrix. It is produced by Fibre Net (Udine, Italy) and is fabricated with an
113 AR (Alkali Resistant) fibre glass (Fig.1 and Tab.1).

114 Samples for thermal measurements were realized by using a layer of plasterboard as
115 support base. Nine square samples were therefore realized, (including the only plasterboard
116 (PL), 13 mm thickness), with external dimensions 30 × 30 cm (total area of 0.09 m²), according
117 to the dimensions of the opening for the lodge of the samples. The thicknesses of the
118 specimens and the description of the coatings for thermal measurements are reported in Tab.2.

119 Cylindrical samples approximately 94 mm in diameter and approximately 180 mm in
120 height were realized for compression tests; 10 square walls 1.2 m x 1.2 m were assembled in
121 laboratory for shear tests.

122

123 **2.2 Thermal characterization**

124 The new experimental apparatus was built at the Laboratory of Thermal Science - the
125 University of Perugia - for thermal conductivity measurements. A general view of the apparatus
126 is represented in Fig. 2. It is composed of one box (external dimensions 0.94 x 0.94 x 0.50 m)
127 that behaves as hot chamber: the outer walls of the chamber are made of very thick insulation
128 (200 mm of foam polyurethane + 20 mm of wood), in order to minimize the thermal losses and
129 the heat flux through the walls. The thermal conductivity λ of the expanded polyurethane is
130 0.0245 W/m K and the thermal transmittance of the walls is 0.114 W/m²K. The second part of
131 the experimental system is the closure side of the box (dimensions 0.94 x 0.94 x 0.20 m thick):
132 it is a sandwich wall composed of two panels of wood (20 mm each) with a central layer of
133 expanded polyurethane (200 mm). In the central part of it there is an opening for the placement
134 of the sample, with 0.30 x 0.30 m dimensions. The contact zones between the support panel
135 and the sample are covered with insulation rubber in the perimeter joints, which are also sealed
136 with silicone during the test.

137 The cold side of the system is the laboratory room (internal dimensions 3.39 m x 4.22 m x
138 2.97 m high), completely insulated from the outside. The small Hot-Box is positioned inside this
139 room, where it is not possible to set the temperature but it was monitored during a long period
140 before the construction of the apparatus and it was observed that the daily temperatures are
141 very steady (maximum difference about 0.8 °C). During the test, the temperatures inside the hot
142 room are maintained constant by means of a heating source made of a 3 m long (50 W) S-
143 shaped heating wire. In order to avoid direct radiation effects, a screen (baffle) made of poplar
144 wood (emissivity 0.90) is placed between the heating system and the support panel. The
145 heating wire is switch on and off automatically thanks to a PID (Proportional-Integral-Derivative)
146 control system. Inside the hot chamber, 9 thermoresistances are installed in order to control the
147 surface temperatures of the sample (4 probes), of the support panel (4 probes), and the air
148 temperature (1 probe). In the laboratory cold side, 8 probes are fixed to the surface of the
149 specimen and of the support panel, and one is placed in the room for air temperature
150 measurement. Finally a thermal flux meter is placed in the central area of the sample, in order
151 to measure the heat flux from the hot side to the cold one. The apparatus diagram with the
152 sensors' position are represented in Fig.3. All the monitored data are transferred to a PC: it is
153 possible to select the time step for the data acquisition, and it is also possible to visualize and
154 save the acquired data. In order to avoid the air stratification, two fans (each one with an electric
155 current equal to 0.11 A) were installed inside. A convective equilibrium was achieved thanks to
156 this ventilation system and a maximum difference of about 0.6 °C on the hot face was achieved
157 after the fans' installation.

158 A switchboard was finally assembled: it is composed of a master switch, a PID controller,
159 an electrical energy meter, and a speed variator for the regulation of the fans' velocity.
160 Considering the evaluation of the heat flow supplied to the hot chamber in order to keep the
161 steady-state conditions, an ammeter was also installed in order to evaluate the current passing
162 through the hot wire. The heat power released by the resistance during a test could be
163 evaluated as the product of the hot wire thermal resistance (measured in Ohm) and the square
164 current through the hot wire (in ampere). On the contrary the electric energy meter measures

165 directly the energy entering the hot side, but it has a low accuracy and it was used only as a
166 control instrument.

167 The Hot Box method could be used for calculating the thermal conductivity of the
168 samples, by evaluating the heat flux through the sample as the difference between the input
169 power (P_i in W) in the hot chamber and the heat losses through the walls and the thermal
170 bridges (P_w in W). The incoming power P_i can be measured considering two contributes: the
171 heat flux released by the resistance during the test (P_r in W) and the contribute of the fans (P_f in
172 W). The contribution of the losses P_w is evaluated by means of calibration measurements and it
173 shall be plotted vs. the air temperature difference between the hot and the cold side.

$$174 \quad P_s = P_i - P_w \quad [W] \quad (1)$$

175 where:

- 176 - P_s is the power coming out through the tested specimen (W);
- 177 - P_i is the entering power in the hot chamber, measured by a power meter (W);
- 178 - P_w is the power loss through the walls and the thermal bridges, evaluated by the
179 calibration curve equation (6) (W).

180 The thermal conductivity of the specimen is then calculated by dividing the product of the
181 power through the specimen (P_s in W) and its thickness by the area of the specimen A_s (m^2) and
182 the surface temperature difference between its two sides:

$$183 \quad \lambda = \frac{P_s \cdot s}{A_s \cdot (T_{SH} - T_{SC})} \quad [W/(m \cdot K)] \quad (2)$$

184 Specific calibration panels (foam polyurethane, expanded polystyrene, plasterboard, and
185 wood) were assembled for the calibration tests and many measurements were carried out by
186 considering different set-point temperatures of the hot chamber (the air temperature difference
187 between hot and cold side was maintained higher than 20 °C for all the tests). Generally it was
188 observed that the mean error of the apparatus decreases by decreasing the set point
189 temperature of the hot side. A mean value of 50 °C for the hot chamber was considered.

190 The thermal flux meter method is based on a thermal flux meter probe placed in the
191 central part of the sample, as shown in Fig. 3. The probe (model HP01 - Hukuseflux) is a
192 thermopile operating in the -2000 ÷ +2000 W/m² power range and in the -30 ÷ +70 °C

193 temperature range. It measures the differential temperature across the ceramics-plastic
 194 composite body and generates a small output voltage proportional to the local heat flux. In order
 195 to calculate the thermal conductivity, 8 termoresistances are installed on the surface of the
 196 sample, with four sensors each side (Fig. 3). The thermal resistance R_t could be calculated as
 197 follows (Progressive Average Methodology) [33,34]:

$$198 \quad R_t = \frac{\sum_{j=1}^n (T_{SHj} - T_{SCj})}{\sum_{j=1}^n q_j} \quad [(m^2 \cdot K)/W] \quad (3)$$

199 where the index j is related to each acquisition time, T_{sH} is the mean value of the panel
 200 surface temperature of the Hot side, T_{sC} is the mean value of the panel surface temperature in
 201 the Cold side, and q is the heat flux through the sample (W/m^2). The average values of the
 202 temperatures of the four sensors installed in each side of the sample and the mean thermal
 203 heat flux were used for the calculation.

204 The value of the thermal conductivity can be calculated by the mean value of the thermal
 205 resistance R_t during the selected period (about 2 – 3 h) and the thickness of the specimen (s in
 206 m):

$$207 \quad \lambda = s/R_t \quad [W/(m \cdot K)] \quad (4)$$

208

209 **2.3 Mechanical characterization**

210 The strengthening technique is very similar of the traditional steel jacketing for masonry
 211 wall panels. Both G-FRP and thermal insulating mortars underwent a mechanical
 212 characterization. The mechanical properties of the mortars were evaluated by compression
 213 tests in compliance with EN 12390-2 2009 [35]. Compressive strength of mortar at 30 days
 214 after casting has been measured.

215 In order to study the shear behaviour of the wall panels reinforced with thermal insulating
 216 plaster, 10 wall panels were tested in diagonal tension [36,37], as reported in Fig.4.

217 Using the Turnšek and Cacovic [38] formulation, the shear strength is:

$$218 \quad \tau = \frac{f_t}{1.5} = \frac{p}{3 \cdot A_n} \quad (5)$$

219 in which p is the diagonal load and A_n is the cross-section area of the wall panel. For both
220 unreinforced and reinforced wall panels, brickwork pattern was made from all headers (*header*
221 *bond pattern*) on each course. Panels were assembled by using a lime-based mortar for
222 construction in laboratory.

223

224 3. Results

225 3.1 Thermal properties

226 By applying the Hot-Box method data was calculated with a calibration curve based on
227 materials with a known thermal conductivity higher than 0.06 W/mK (for the calibration curve
228 construction a wood panel ($\lambda = 0.12$ W/mK), a plasterboard panel ($\lambda = 0.20$ W/mK) and an
229 insulating panel with wood fibres and cement ($\lambda = 0.065$ W/mK) were used). The following
230 calibration curve was used:

$$231 \quad P_W = 0.2487 \cdot \Delta T_a + 1.4567 \quad [W] \quad (6)$$

232 where:

- 233 - P_W is the power loss through the walls and the thermal bridges (W);
- 234 - ΔT_a is the air temperature difference between the hot and the cold side ($^{\circ}\text{C}$).

235 By measuring P_i in eq. (1), P_s and λ of the sample could be calculated by applying
236 equations (1) and (2). λ of the coating should then be calculated knowing λ and s of the
237 plasterboard panel used as support base, by applying the following:

$$238 \quad \lambda_{coating} = \frac{\frac{s_{coating}}{\lambda_{total}} - \frac{s_{plasterboard}}{\lambda_{plasterboard}}}{\lambda_{total}} \quad [W/(mK)] \quad (7)$$

239

240 Results are showed in Table 3.

241 It can be observed that the R-FRP and R2-FRP have the best thermal insulation
242 behaviour, the C type has the highest thermal conductivity (0.275 W/mK without G-FRP and
243 0.189 W/mK with G-FRP grid). The same data was obtained by using the thermal flux meter
244 methodology. The thermal conductivity of the plasterboard is 0.19 W/mK (with a difference of
245 only 5% in respect to the value declared from the company, equal to 0.2 W/mK).

246 Table 4 shows the thermal conductivity values obtained for the different specimens, with
247 and without reinforced grid system: the comparison between the results is represented in the
248 table considering both the methodologies.

249 All the coatings have good thermal properties, even if they were developed as structural
250 mortars; generally the thermal conductivities are lower than the ones of traditional coatings
251 (values in 0.5-1.0 W/mK range).

252 The thermal conductivity values of the samples with G-FRP vary between 0.089 and
253 0.210 W/mK. The best mortar is R2-FRP type, the worst is C-FRP (0.210 W/mK), but it is the
254 best coating considering the mechanical resistance of the samples (see paragraph 3.2). The
255 thermal conductivity of the samples with G-FRP decreases of about 11-15 % with respect to
256 samples without G-FRP, except for R: in this case it is possible to observe an increasing of
257 about 8% probably due to a flaw of the mortar grout during the laying of the samples (Fig.5); the
258 improvement in terms of reduction of the thermal conductivity (about 11-15%) is probably due to
259 air included in the mixture.

260 Furthermore it is important to observe that the thermal conductivities of the samples with
261 and without G-FRP are not so different from the error value of the apparatus (about 10%), and
262 therefore they are not so different in terms of thermal performance: minimum changes of the
263 final thermal conductivity values are attributed especially to differences in the laying of the
264 samples.

265 Considering the comparison between the two methodologies (Hot Box and Thermal Flux
266 Meter, see Tab.4) it can be observed that the differences vary in 9 - 23% range: the thermal
267 conductivities obtained with the Hot-Box Method are in general higher than the ones obtained
268 by the Thermal Flux Meter Method for almost all the samples. Nevertheless the Thermal Flux
269 Meter Method seems more reliable, because the considered calibration curve used for the Hot-
270 Box method is preliminary and much more materials with λ in 0.05 – 0.50 W/(mK) range should
271 be used for the improvement of that curve (6).

272

273 **3.2 Mechanical resistance**

274 The technical developments of the last years have enabled to produce new mortars with
275 specific properties, such as a low salt content and size of the aggregate in function of the
276 masonry characteristics in order to achieve the highest possible compatibility with existing
277 masonry. Sixteen 94 mm diameter cylindrical samples (four for each mortar type) have been
278 tested in compression. Mortar cylinders were approx. 180 mm in height. The average
279 compression strength of the cylindrical samples at 30 days after casting was 0.66, 0.72, 0.87,
280 and 2.70 MPa respectively for mortars D-, R-, R2-, and C-type (Tab.5). These values are
281 similar both in terms of compressive strength and Young's modulus with the mortar's
282 mechanical properties of historic stone multi-leaf masonry walls [39].

283

284 *Un-reinforced panels*

285 When subjected to shear tests in diagonal tension, all un-reinforced panels exhibited a
286 failure along the compressed panel diagonal. If the diagonal compression force is strong
287 enough to exceed the lateral strength capacity of the wall panel, diagonal cracking opened
288 slowly in the mortar joints and in the bricks starting from the central part of the wall panel and
289 producing a tensile failure of the walls and an abrupt loss of lateral stiffness (shear modulus).
290 Two unreinforced brickwork panels have been tested (test n. 5 and 6) and the average lateral
291 capacity and shear strength τ were respectively 201.1 kN and 0.230 MPa, while the shear
292 modulus G was 4078 MPa. Results are summarized in Table 6.

293

294 *Reinforced panels*

295 Eight reinforced masonry panels were subjected to the diagonal tension test and a single
296 test was performed on each wall panel. In-plane resistance of unreinforced masonry wall panels
297 is mainly based on the thermal insulating mortar strength. Table 6 gives the results in terms of
298 diagonal compression capacity, shear strength and modulus for each test.

299 For panels reinforced with D-type mortar, as expected, the wall panels reinforced with this
300 technique did not resulted very stiff (shear modulus $G=4054$ MPa). Lateral capacity was 247.5
301 kN. The stress-strain curve shows a quasi-elastic behaviour with a weak yield plateau. The

302 failure mode involved a sudden loss of collaboration between the reinforcement (lime mortar)
303 and the substrate (masonry), with some cracks along the compressed diagonal observed on
304 mortar surface.

305 The results of the shear tests did not show a significant high increases both in terms of
306 shear strength and stiffness when mortar type R has been applied. The lateral capacity and
307 stiffness (shear modulus) values became, respectively, 215.6 kN and 4829 MPa, with a limited
308 increment of 7 and 18.4% when compared to the values measured for the same panels before
309 reinforcement. The failure modes observed for these panels are characterized by a very similar
310 cracking pattern as those of the un-reinforced (Fig.6).

311 For wall panels reinforced using thermal insulating mortars R2 and C-type, a significant
312 enhancement of the shear strength was detected: an increase of 114.8 and 109.1% was
313 measured for R2 and C-type mortar, respectively.

314 From these test results, a clear tendency is evident: the reinforcing technique can cause
315 an increase of the shear stiffness only if a thermal insulating mortar with good mechanical
316 properties is used (type R2 or C). For reinforced panels shear stress versus angular strain
317 responses, such as those shown in Fig. 7, a two-stage behaviour has been detected: for small
318 values of the angular strain (approx. up 0.5‰) the behaviour is almost linear elastic while it
319 becomes highly inelastic for larger values of the deformation. The elastic phase of the
320 reinforced panels curves is characterized by a similar slope as those of the un-reinforced. Thus,
321 a first consequence of the reinforcement is the increase of the strength of the wall while leaving
322 unchanged the in-plane stiffness measured in the elastic phase.

323

324 **4. Conclusions**

325 The present paper is focused on the importance of combining thermal and mechanical
326 properties in buildings refurbishment. The use of construction materials with good thermal
327 properties is in fact the first condition for greatly reducing the thermal heat losses of the final
328 products. The study is focused on glass fibre reinforced insulating mortars: they combine good
329 mechanical and thermal properties for building refurbishment.

330 The insulating behaviour of the coatings was investigated by an original experimental
331 apparatus named Small Hot-Box. It is an effective alternative system used instead of the Hot-Plate
332 apparatus for the experimental evaluation of the thermal resistance of homogeneous materials.
333 The tested samples are installed in a support panel between the hot and the cold sides; an air
334 temperature difference is maintained during the test. A heat flux pass through the sample during
335 the test: the thermal conductivity can be evaluated by measuring the heat flux and the surface
336 temperatures of the specimen. Two different methodologies are presented: the thermal flux meter
337 method and the Hot-Box one. The first method takes into account the heat flux measured by the
338 thermal flux meter installed on the sample, the second one evaluates the heat flux through the
339 specimen as the difference between the input heat flux and the heat losses through the walls.

340 Considering the thermal flux meter method, all the coatings have good thermal properties
341 (thermal conductivities variable in 0.09 – 0.23 W/(mK) range) and the best thermal behaviour can
342 be attributed to R and R2 mortars. Also considering the Hot-Box method, the lowest thermal
343 conductivities were found for R and R2 mortars. Even if both the results are aligned, considering
344 the two methodologies, the thermal flux meter method results should be considered more reliable
345 because the calibration curve used for the Hot-Box method is just preliminary and it should be
346 improved. The best thermal performance were obtained for the samples D, R, and R2 ($\lambda = 0.09 -$
347 0.105 W/mK), while for C a value of $0.19 - 0.27$ W/mK was found.

348 Generally, with the glass fibre reinforced grid the thermal conductivity of the samples
349 decreases of about 11-15 % except for mortar type R but this behaviour is probably due to the
350 small dimensions of the specimens; anyway it is expected that the thermal resistance of the
351 mortars in situ would not significantly modified by the G-FRP insertion.

352 The externally applied G-FRP mesh to masonry panels resulted in a stronger system, as
353 compared to the un-reinforced configuration. The addition of a G-FRP reinforced coating resulted
354 in an increase in in-plane load capacity between 7 and 115%. However the reinforcement can
355 produce an increase of the in-plane load-capacity only if a thermal insulating mortar with good
356 mechanical properties is used; large increases in shear capacity were only found for wall panels
357 reinforced with thermal mortars R2 and C: it demonstrates that the G-FRP grid upgrade with a

358 lime-based thermal insulating mortar is promising, but less effective compared to the reinforcement
359 with epoxy resins or concrete coatings. Mechanical shear tests have demonstrated that the
360 adhesion between the masonry panels and the coating used as a base for reinforcement (G-FRP
361 mesh) was the critical element in the reinforcing system. Failure of reinforced panels resulted from
362 the separation of the layer of thermal insulating mortar from the masonry panels and from the
363 opening of diagonal cracks along the compressed panel's diagonal.

364 Finally, by combining results of thermal and mechanical characterization, the samples with
365 the R2 mortar seem the more promising for building refurbishment, being the best compromise
366 between thermal and mechanical performance.

367

368 **Nomenclature**

369 A = panel surface (m^2)

370 e = error (%)

371 f_t = tensile strength (MPa)

372 G = shear modulus (MPa)

373 λ = thermal conductivity (W/mK)

374 P = power (W)

375 ρ = diagonal compression load (N)

376 q = heat flux (W/m^2)

377 R_t = thermal resistance (m^2K/W)

378 s = thickness (m)

379 T = temperature ($^{\circ}C$)

380

381 **Subscripts**

382 a = air

383 C = Cold side

384 f = fans

385 H = Hot side

386 HB = Hot Box method

387 i = input

388 m = mean

389 p = panel

390 r = resistance of the hot side

391 s = specimen

392 S = surface

393 t_{fm} = thermal flux meter method

394 w = walls

395

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503

504

505 **List of figure captions:**

506

507 Figure 1: G-FRP grid.

508 Figure 2: General view of the apparatus Small Hot-Box.

509 Figure 3: Apparatus diagrams and sensors' positions.

510 Figure 4: Test set-up for mechanical characterization.

511 Figure 5: Thermal flux meter method: thermal conductivity differences between mortars with and

512 without G-FRP.

513 Figure 6: Reinforced panel after failure.

514 Figure 7: Elastic and plastic behaviour of the reinforced and un-reinforced panels.