Experimental Characterization of an Earth Eco-Efficient Plastering Mortar

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1 **Experimental characterization of an earth eco-efficient plastering mortar**

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5

6 **ABSTRACT**

7 Earthen plastering mortars are becoming recognized as highly eco-efficient. The

8 assessment of their technical properties needs to be standardized but only the German

9 standard DIN 18947 exists for the moment. An extended experimental campaign was

10 developed in order to assess multiple properties of a ready-mixed earth plastering

11 mortar and also to increase scientific knowledge of the influence of test procedures on

12 those properties. The experimental campaign showed that some aspects related to the

13 equipment, type of samples and sample preparation can be very important, while

14 others seemed to have less influence on the results and the classification of mortars. It

15 also showed that some complementary tests can easily be performed and considered

16 together with the standardized ones, while others may need to be improved. The

17 plaster satisfied the requirements of the existing German standard but, most

18 importantly, it seemed adequate for application as rehabilitation plaster on historic and

19 modern masonry buildings. Apart from their aesthetic aspect, the contribution of

20 earthen plasters to eco-efficiency and particularly to hygrometric indoor comfort should

21 be highlighted.

22

23 **Subject headings from the ASCE's Civil Engineering Database**

24 Mortar; Prefabrication; Test procedure; Standardization; Classification

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Introduction

Mortars are building products that are widely used in construction, principally being applied as rendering and plastering systems to protect the walls. While renders have to resist the action of rain water, plasters must contribute to the indoor air quality and comfort. Therefore plastering mortars must fulfill predetermined requirements.

After being neglected for decades, earth-based plastering mortars are nowadays becoming recognized as highly eco-efficient (Maddison et al., 2009; Darling et al., 2012). When compared to other types of mortars the sustainability of earth mortars is well known, mainly in terms of embodied energy (Swan et al., 2011). In fact, this type of mortar does not contain binders that have to be specifically produced and thus involve stone mining, transport and energy consumption. Melià et al. (2014) compared the environmental impacts of earthen plasters with those of conventional plasters based on common binders (like cement or hydraulic lime) using the LCA methodology. Their research showed that earth plasters outperformed the others with respect to all the indicators considered: cumulative energy demand, greenhouse gas protocol, ecological footprint and ReCiPe indicators (Melià et al., 2014). Aesthetic aspects, like color and texture, were also recognized. However, the technical characteristics and efficiency of these mortars has not often been scientifically proved; their technical efficiency needs to be evidenced by testing.

Compared to other types of earth-based products, as the case of earth blocks that have been deeply studied (Danso et al., 2014; Cagnon et al., 2014; Silveira et al., 2014), and other types of plastering mortars, such as air lime-based products (Veiga et al., 2010; Faria et al., 2008), earth-based mortars have been characterized in very few scientific studies (Pkla et al., 2003; Azeredo et al., 2008; Hamard et al., 2013; Delinière et al., 2014). There are few codes and standards for earth building materials (Swan et al., 2011). The recent German standard DIN 18947 (DIN, 2013) is the first standard specifically devoted to earth mortars. It defines some requirements and test methods. Many test methods are based on parts of the EN 1015 standard, developed for

masonry mortars, mainly hydraulic binder-based, while others are specific to the DIN standard (DIN, 2013). Delinière et al. (2014) have recently applied this standard to characterize five ready-mixed earth plasters.

The experimental study presented in this paper involved a ready-mixed earth plastering mortar based on natural earth, sand and plant fibers. The dry ready-mixed product was characterized in the laboratory. The same ready-mixed product was used to produce two sets of mortars. The first was prepared in the field with current mechanical equipment while the second was prepared in controlled laboratory conditions. The mortar prepared on site was used to plaster an experimental brick masonry wall that was being non-destructively tested (Faria et al., 2014), and a portion was reserved. Both mortars were characterized in the fresh state and measurements included drying shrinkage. Samples with different dimensions and methods of preparation were produced in the laboratory. The wall plaster and the samples were tested. Characterization of the hardened mortar included visual observation of the plaster applied to the brick masonry test wall and several tests performed on mortar samples to evaluate the mechanical, physical and microstructural properties of the mortar. Hygrothermal properties of the hardened mortars were also studied (sorption–desorption isotherms, vapor diffusion and thermal conductivity). The characterization and the test procedures were based on the German standard (DIN, 2013) but also included other standards and specific test procedures implemented by the authors. The influence of differences in the dimensions of samples and the methods for preparing them were assessed. The characteristics of the plaster are presented and, whenever possible, compared with the DIN (DIN, 2013) requirements and with other studies (Delinière et al., 2014; Gomes et al., 2012; Veiga et al., 2010). The aim is to contribute to the setting up of test procedures, including the validation of existing ones and the development of complementary procedures to characterize earth plasters. These indicative results should be useful for a future international standard for earthen plastering mortars.

81

Materials and methods

83   Materials

84   The experimental study presented in this paper was carried out with a ready-mixed

85   earth plastering mortar from the Embarro company (Portugal and Spain), based on

86   natural clayish earth and siliceous sand, both from the Algarve region (South Portugal),

87   and cut oat fibers 1-2 cm long. The ready-mixed mortar was mechanically produced on

88   site using a Putzmeister MP25 mixing and pumping equipment. The same equipment

89   was used for the application of mortar as a plaster on an experimental hollow brick

90   masonry wall having a surface area of 2.2 m x 1.8 m with rain protected exposure to

91   the outdoor environment (Fig. 1). A portion of this mortar was transported to the

92   laboratory (30 m distance – 2 minutes), where it was tested in fresh state conditions

93   and samples were prepared: prismatic samples 40 mm x 40 mm x 160 mm were

94   prepared in metallic molds and a 15 mm-thick mortar layer was applied to the surface

95   of ceramic hollow brick of surface area of 29.5 cm x 19.5 cm (Fig. 1). The same ready-

96   mixed mortar product was mixed in the laboratory for 5 minutes with a mixer blade

97   (commonly used on site), using the same water content as for the on-site mortar. It,

98   too, was tested in fresh state conditions and samples were prepared: disk samples 90

99   mm in diameter and either 15 mm or 20 mm thick were prepared in PVC molds over a

100   polyethylene base and rectangular samples with 200 mm x 500 mm surface and 15

101   mm thick were prepared in metallic molds (Fig. 1). All the samples were manually

102   compacted and leveled. The prismatic samples were de-molded when hardened and

103   all the samples were allowed to reach equilibrium in controlled environmental

104   conditions at 20±3°C and 65±5% relative humidity (RH).

105

106   Methods

107   *Characterization of ready-mixed product and fresh state mortar*

108 The dry ready-mixed mortar product was observed visually and characterized in terms

109 of loose bulk density, based on EN 1097-3 (CEN, 1998c), dry particle size distribution,

110 based on EN 1015-1 (CEN, 1998/2006) and by X-ray diffraction test (XRD). XRD was

111 carried out with a Phillips diffractometer with Co Kα radiation, speed of 0.05 º/s and 2θ

112 ranging from 3 to 74. Two types of fractions were analysed: a fraction designated as

113 fine fraction, which has a higher binder concentration and was obtained from the fines

114 of the ready-mixed product passing a 106 μm sieve and a fraction designated as

115 global, obtained by grinding the ready-mixed product as collected, to pass in the 106

116 μm sieve.

117 The two batches of mortar were tested by: flow table consistency, based on standard

118 EN 1015-3 (CEN, 1999/2004/2006); bulk density, following standard EN 1015-6 (CEN,

119 1999/2006a); air content, according to standard EN 1015-7 (CEN, 1998b); and water

120 content, determined by weight loss after oven drying.

121 The laboratory mortar was also tested for water retention based on draft standard prEN

122 1015-8 (CEN, 1999). To determine water retention, the weight increase of filter papers

123 in contact with the fresh mortar specimen for 5 minutes was considered, in relation to

124 the mortar solid and liquid compositions. Consistency was assessed also by

125 penetrometer, based on standard EN 1015-4 (CEN, 1998a), and by the slump

126 occurring in the flow table test sample. For the latter test, the slump of the mortar

127 specimen was determined by the difference between the height of the mold and that of

128 the highest point of the slumped test specimen.

129

130 *Drying shrinkage*

131 For the mortar mixed on site, linear drying shrinkage was determined on the basis of

132 standard DIN 18947 (DIN, 2013) by the linear geometrical length reduction due to

133 drying of six mortar samples 40 mm x 40 mm x 160 mm, assessed when they were de-

134 molded. For the laboratory mortar, shrinkage was determined by the geometrical

135   reduction of the surface of three 200 mm x 500 mm mortar samples 15 mm thick when

136   hardened on metallic molds, compared with the dimensions of the molds.

137

138   *Surface cohesion and dry abrasion resistance*

139   The superficial cohesion and dry abrasion resistance were determined to assess the

140   surface resistance and the eventual necessity for surface hardening (Röhlen and

141   Ziegert, 2011). Superficial cohesion was determined by the weight increase of an

142   adhesive tape 70 mm x 50 mm, after it had been pressed with constant intensity on the

143   surface of the samples of mortar layer on ceramic brick, using the method of Drdácký

144   et al. (2014), which expresses the loss of particles from the surface of the mortar. The

145   average and standard deviation of results obtained with six adhesive tapes applied in

146   two bricks was used.

147   Dry abrasion resistance was determined according to DIN 18947 (DIN, 2013), by the

148   weight loss of mortar samples after 20 rotations of three different circular polyethylene

149   brushes 65 mm in diameter, applied to the sample surface with a pressure of 2 kg.

150   Samples with mortar on hollow brick and samples of 90 mm diameter and 20 mm

151   thickness were tested.

152

153   *Mechanical characterization*

154   The mechanical characteristics were evaluated using the six prismatic, 40 mm x 40 mm

155   x 160 mm samples. The dynamic modulus of elasticity was determined based on

156   standard EN 14146 (CEN, 2004), defined for natural stone, using a Zeus Resonance

157   Meter. The flexural and compressive strengths were determined according to

158   standards DIN 18947 (DIN, 2013) and EN 1015-11 (CEN, 1999/2006c) using a Zwick

159   Rowell Z050 machine, with load cells of 2 kN, for bending loads and 50 kN for

160   compression.

161 The adhesive strength was determined with the pull-off adhesion test equipment

162 PosiTest AT-M and pull-head plates 50 mm in diameter, based on standards DIN

163 18947 (DIN, 2013) and EN 1015-12 (CEN, 2000).

164

165 *Sorption–desorption isotherms and vapor diffusion*

166 Water vapor permeability of the mortar was determined according to DIN 18947 (DIN,

167 2013), EN 1015-19 (CEN, 1998/2004), EN ISO 12572 (CEN, 2001) and EN 15803

168 (CEN, 2009b) using the 90-mm-diameter, 20-mm-thick laboratory mortar samples. The

169 wet method was used and the mortar specimen systems were placed in a climatic

170 chamber at 23ºC and 40% RH.

171 The sorption of the mortar was determined with the 15 mm x 200 mm x 500 mm

172 rectangular samples in metallic molds initially in equilibrium at 50% RH, according to

173 DIN 18947 (DIN, 2013). A climatic chamber was programmed for 80% RH and the

174 water vapor gain after determined periods of time in the climatic chamber (from 0.5 h

175 up to 12 h) was assessed using a scale of 0.1 g precision. It was also determined by

176 the same method but using a scale of 0.001 g precision with the 90-mm-diameter

177 circular samples with thicknesses of 15 mm and 20 mm. The samples were water-

178 vapor proofed with a polyethylene film on all surfaces except the top one. Both types of

179 samples were made with the laboratory mortar. The desorption of the mortars, initially

180 at equilibrium at 80% RH, was also determined. The climatic chamber was

181 programmed for 50% RH and the weight decrease of the same samples after the same

182 defined periods of time (from 0.5 h up to 12 h) were determined.

183

184 *Capillary absorption and drying*

185 The analysis of capillary rise is not a general requirement for non-stabilized earth

186 mortars because they are intended to be applied for plastering the internal surfaces of

187 walls or as renders but in areas protected from rain. Nevertheless, if the wall where the

188 mortar is applied presents problems of capillary rise from the ground, the mortar may

189   need to resist capillary absorption. Therefore the capillary absorption of the mortar was

190   assessed, using EN 15801 (CEN, 2009a) and EN 1015-18 (CEN, 2002), by sequential

191   weighing of the samples in contact with water to a height of 5 mm. Cubes 40 mm x 40

192   mm x 40 mm were cut from the prismatic samples, prepared and tested. Three different

193   types of sample preparation were used: waterproofing the lateral faces of the cubic

194   samples with an epoxy resin (resin), waterproofing the lateral faces with a polyethylene

195   film (polyeth.), and without any material to waterproof the lateral faces (simple). A thin

196   cotton cloth was placed on the bottom face of each sample, to avoid loss of fines, and

197   was maintained by a thin elastic band. Each sample was placed inside a net basket

198   and handled in the basket throughout the test (Fig. 2).

199   The capillary curve, with water capillary absorption by contact area with water in

200   ordinate (in kg/m^2) and the square root of time in abscissa (in $min^{0.5}$), was plotted. The

201   capillary coefficient, CC, which represents the initial capillary absorption, was

202   determined by the slope of the most representative initial segment of the capillary

203   curve.

204   The drying capacity of the mortar was assessed after samples had been wetted by the

205   capillary test, as described by EN 16322 (CEN, 2014), but without complete saturation

206   of the samples and in slightly different environmental conditions. The same samples,

207   with the three types of lateral surface treatment mentioned above, were used. The

208   drying curve was plotted with time in abscissa and water content in ordinate (weight /

209   drying surface, in kg/m^2) and was used to calculate the drying rate (DR) and the drying

210   index (DI). The DR represented the initial drying of the mortar and was determined by

211   the slope of the initial portion of the drying curve for each type of sample preparation. A

212   higher slope of the curve with respect to the horizontal axis reflected a high drying rate

213   and faster initial drying. The DI represented the difficulty of achieving complete drying,

214   in equilibrium with the environment, and was calculated following the simplified

215   procedure presented by Grilo et al. (2014). It was determined for a period of 137 h.

216   All the tests were carried out in a conditioned room at 20±3ºC and 65±5% RH.

217

218 *Thermal conductivity and microstructure*

219 Thermal conductivity was determined using six prismatic samples and the samples with

220 a 15-mm mortar layer on hollow brick, from the mortar mixed on site, and also using

221 the 15 mm and 20 mm thick circular samples with and the 15 mm x 200 mm x 500 mm

222 in metallic molds rectangular samples of the laboratory mixed mortar. Tests were

223 performed after drying of the samples and at equilibrium with the laboratory conditions

224 (20ºC, 65% RH). An Isomet 2104 Heat Transfer Analyzer was used with a 60-mm-

225 diameter contact probe, API 210412. The equipment requires a minimum surface of 60

226 mm in diameter and a height of 15 mm. The prismatic sample type did not satisfy the

227 recommendations for using the test equipment as the surface area of the contact probe

228 exceeded the surface area of the sample.

229 The bulk density was geometrically determined according to DIN 18947 (DIN, 2013)

230 and EN 1015-10/A1 (CEN, 1999/2006b) on the same prismatic samples, by means of a

231 digital caliper and a 0.001 g precision digital scale.

232 The open porosity was determined by mercury intrusion porosimetry (MIP) and the

233 same technique was used for the determination of pore size distribution. MIP was

234 applied to specimen taken from among the prismatic samples, without the influence of

235 the substrate, but also to specimen of the mortar layer on hollow brick produced in

236 controlled laboratory conditions and samples of the plastering mortar applied on the

237 experimental hollow brick masonry wall, conditioned in the exterior environment

238 protected from rain. It was determined with a Micromeritics Autopore II mercury

239 porosimeter. The masses of the test specimens were stabilized at 40°C and the mortar

240 specimens were prepared so as to occupy the greater part of the 5 cm^3 bulb of the

241 penetrometer volume. Testing began at low pressures ranging from 0.01 MPa to 0.21

242 MPa, followed by high pressure analysis from 0.28 MPa to 206.84 MPa, following a test

243 procedure that is commonly used for lime mortar testing (Grilo et al., 2014).

244

Results and discussion

Ready-mixed product and fresh state mortar characterization

The average value of loose bulk density and its standard deviation was 1.17±0.01 kg/dm^3. The ready-mixed product had a reddish color and the dry particle size distribution (average of three samples) is presented in Fig. 3.

The results obtained by XRD are shown in Fig. 4. The main minerals detected on ready-mixed product were quartz (SiO_2), K-Feldspar ($KAlSi_3O_8$), dolomite ($CaMg(CO_3)_2$), illite ($(K,H_3O)Al_2Si_3AlO_{10}(OH)_2$) and kaolinite ($Al_2(Si_2O_5)(OH)_4$). Other minerals were detected in low proportions, like calcite ($CaCO_3$) and hematite (Fe_2O_3). The fine fraction presented an increase of the proportions of clay minerals (illite and kaolinite), which is accompanied by k-feldspar, dolomite, calcite and hematite minerals.

The mortar (two batches, produced on site and in the laboratory) showed very good workability when handled. The plaster applied to the brick masonry wall (Faria et al., 2014) gave a reddish colored surface without shrinkage cracks. Some dispersed plant fibers could be seen. The average values (and, whenever at least three samples were tested, the standard deviation) of fresh mortar properties are presented in Table 1.

From Table 1, it can be observed that the fresh state characteristics of the mortars mixed on site and in the laboratory were quite similar, namely in terms of flow table consistency, bulk density and water content, despite the different equipment and conditions used for the mortar production. It is probable that the slightly higher air content and lower bulk density of the mortar mixed on site were due to the mechanical equipment that produced (and projected) the mortar.

Another fact that could have influenced the fresh state characterization was the time that elapsed between the contact of the clayish mortar product with water and the moment the tests were performed. In fact the mortar mixed on site was prepared and applied as plaster on several walls before being transported to the laboratory and tested. However, tests performed on samples from both the site and the laboratory

272 batches did not reveal differences that could be directly attributed to that situation. This

273 is very positive because it indicates good stability of the product when fresh.

274 Compared with earth mortars characterized by Gomes et al. (2012), the mortars

275 considered in the present study had higher bulk density. When the consistency, wet

276 bulk density and water content of the earth mortar tested here were compared with

277 those tested by Delinière et al. (2014), the results were observed to be in the same

278 range.

279

280 Drying shrinkage

281 The average and standard deviation of shrinkage measured on samples 40 mm x 40

282 mm x 160 mm was 0.21±0.08%. In the case of 200 mm x 500 mm laboratory

283 rectangular samples 15 mm thick the average and standard deviation length changes

284 of the shorter and longer sides of the rectangle were 0.32±0.00% and 0.58±0.23%. As

285 these samples were not de-molded, it was harder to measure shrinkage in this case

286 than for prismatic molds. It seemed that shrinkage was proportional to the measured

287 dimension and, for that reason, another mold was filled with laboratory mortar but only

288 one sample was tested, using a film-faced plywood mold 40 mm x 40 mm x 600 mm

289 generally used for testing earth for building purposes and following the Alcock test

290 (Gomes et al., 2014). Drying shrinkage was 0.61% and no crack was observed inside

291 the mold. No cracking due to drying shrinkage was observed on the plaster applied to

292 the experimental wall. The drying shrinkage was very low regardless of the samples

293 used, including the plaster applied to the experimental wall. The shrinkage measured

294 on the prismatic samples, according to DIN 18947 (DIN, 2013), was well beyond the

295 maximum of 3% defined for mortars with fibers. Comparison with the results obtained

296 with samples of other dimensions suggests that the shrinkage increases in direct

297 relation with the length of the sample.

298

299 Surface cohesion and dry abrasion resistance

300 The cohesion test was easily performed and allowed the superficial loss of material to

301 be assessed quantitatively, by weighing. It was 0.10±0.03 g.

302 It seems that, even if a precision scale is not available, the visual observation of the

303 material sticking to the adhesive tape can be qualitatively compared (Fig. 5). In real

304 conditions, this easy test can, therefore, be used for comparison between plasters and

305 between different areas of the same plaster. Comparing the results obtained by

306 Drdácký et al. (2014) for lime mortars using the same test methods, it is possible to

307 conclude that the loss of material obtained with the clayish plaster is higher, showing a

308 lower surface cohesion.

309 The abrasion relief formed on disk samples with the three brushes can be seen in Fig.

310 6. The soft brush, when pressed, exceeded the diameter of the disc. As the abrasion

311 with that brush was almost inexistent, it could not be measured with the mortar on brick

312 sample because of the scale precision.

313 The average and standard deviation of weight loss by abrasion on circular mortar

314 samples and on mortar-on-brick samples after testing with hard, medium and soft

315 brushes are presented in Table 2. The standard DIN 18947 (DIN, 2013) defines two

316 classes, SI and SII, for mortars considering their weight loss by abrasion and their

317 lower limits are also given in Table 2.

318 The differences of weight loss by abrasion of the mortar obtained with different brushes

319 are noteworthy. With the soft brush, the mortar would be classified in class SII, while

320 with the other two brushes the mortar does not meet the standard requirement.

321 Bearing in mind that DIN 18947 (DIN, 2013) only defines a plastic brush, it seems that

322 the hardness of the brush should be defined with more precision. The DIN standard

323 also defines that, instead of measuring the weight loss, the disaggregated material

324 should be weighed. That procedure would appear to be less accurate because, due to

325 the abrasion of the brush, some of the material would be scattered and, therefore, it

326 would be difficult to gather and weigh the totality.

327

328   Mechanical characterization

329   The average and standard deviation of the dynamic modulus of elasticity (Ed), flexural

330   and compressive strength (FStr and CStr), and adhesive strength (AStr) of the mortar

331   are presented, together with the lower limits of DIN 18947 (DIN, 2013) strength classes

332   SI and SII, in Table 3. The fracture pattern of the adhesion test was an adhesive

333   rupture at the interface between mortar and brick, effectively representing the adhesive

334   strength.

335   The results presented in Table 3 show that this mortar can be classified as SI because

336   its flexural strength is not less than 0.3 N/mm^2, its compressive strength is not less than

337   1.0 N/mm^2 and its adhesive strength is not less than 0.05 N/mm^2 (DIN, 2013).

338   Compared with earth mortars characterized by Gomes et al. (2014), the mortars

339   analyzed in the present study have higher dynamic modulus of elasticity, flexural

340   strength and compressive strength. Compared with five earth mortars characterized by

341   Delinière et al. (2014) the tested mortar presents flexural and compressive strengths

342   that are lower (though only slightly). Nevertheless the mortar tested has a higher

343   adhesive strength, which may show the influence that different supports can have on

344   this test. In fact, not only the support but also its preparation may have a huge

345   influence on results (Delinière et al., 2014). Different, simple tests may be considered

346   to assess adhesion, such as the one established by Hamard et al. (2013), which can

347   be easily applied on site to evaluate the compatibility of plasters with the substrate.

348   Veiga et al. (2010) suggest a range of mechanical characteristics of plastering mortars

349   to ensure compatibility with historic masonry: dynamic modulus of elasticity 2000-5000

350   N/mm^2, flexural strength 0.2-0.7 N/mm^2 and compressive strength 0.4-2.5 N/mm^2.

351   Although the range was defined for lime-based mortars, it seems acceptable that the

352   same range should be also considered for plastering mortars to be applied to other

353   masonries with similar mechanical characteristics. It can be noted that the mechanical

354   characteristics of the ready-mixed earth mortar are all within the suggested range.

355

356 Sorption–desorption isotherms and vapor diffusion

357 The water vapor resistance factor, μ, was 8.0±0.3 and the water vapor diffusion

358 equivalent air layer thickness, Sd, was 0.16±0.01 m (average and standard deviation).

359 The DIN 18947 (DIN, 2013) states that a value of 5 - 10 can generally be adopted for

360 the water vapor resistance factor of earth mortars (dry and wet method, respectively).

361 The mortar analyzed confirmed that assumption.

362 Cagnon et al. (2014) obtained values of μ between 3 and 6 with different types of

363 earthen bricks, in a chamber at 50% RH and 20ºC. Although bricks and plasters were

364 applied and tested with different thickness, a comparison of the results stressed the

365 remarkable water vapor permeability of the ready-mixed plaster.

366 The water vapor weight gain and release are presented in Fig. 7. When comparing the

367 adsorption of the mortar by the standardized rectangular sample with 1000 cm^2 surface

368 area with the lower limits of classes defined by DIN 18947 (DIN, 2013) (WSI, WSII and

369 WSIII) it can be seen that the mortar can be classified in class WSIII. Nevertheless,

370 and despite the apparently different results obtained with the other samples, for a much

371 smaller surface of 28.3 cm^2, the same class would be obtained for both types of

372 samples with 90 mm diameter and 15 mm or 20 mm thickness. Although the

373 rectangular samples show an initial increase on adsorption, their following behavior is

374 parallel to that of the circular samples. There is no difference in sorption between

375 circular samples, regardless of their thickness.

376 Concerning desorption, behavior is similar for the circular and rectangular samples,

377 particularly during the first half of the test.

378

379 Capillary absorption and drying

380 The capillary curves of the mortar tested for each type of sample preparation is

381 presented in Fig. 8, with the most representative segments of capillary absorption and

382 their equations. As explained in Methods the slope of those segments represents the

383 capillary coefficient.

384 The drying curve of the mortar for each type of sample preparation is presented in Fig.

385 9, with the segments of initial drying for the determination of the drying rate (DR).

386 The average and standard deviation of capillary coefficient, CC, drying rate, DR, and

387 drying index, DI, of the mortar samples prepared in different ways – waterproofing of

388 lateral surfaces with resin or polyethylene film and simple (without waterproofing) - are

389 presented in Table 4.

390 The capillary test showed that the preparation of the samples (without lateral

391 waterproofing or with polyethylene film or with resin) has an important influence on

392 results. For that reason, it seems to be very important to define the sample preparation

393 procedure if capillary requirements are considered. In terms of sample preparation, DR

394 results show the same tendency as CC; simple samples and resin samples show the

395 same tendency for DI and CC, while the samples with polyethylene present a different

396 tendency.

397 The mortars without mineral binder and with resin preparation used by Gomes et al.

398 (2012) presented a CC of 0.14 $kg/(m^2.s^{0.5})$ without fibers and 0.23 $kg/(m^2.s^{0.5})$ with

399 hemp fibers; their DI was 0.11 without fibers and 0.13 with hemp fibers. The period of

400 time for the determination of DI by Gomes et al. (2012) was not the same as that of the

401 present study and, also, the samples of the present study were not totally capillary

402 saturated before starting the drying test (for that reason, DI is not strictly comparable).

403 Nevertheless, when comparing the mortars characterized by Gomes et al. (2012) with

404 the ones of the present study, it can be observed that the latter have a much lower

405 capillary coefficient (0.5 $kg/(m^2.min^{0.5})$ corresponding to 0.06 $kg/(m^2.s^{0.5})$), meaning that

406 the rising water progresses more slowly, but a higher drying index of 0.18, meaning

407 that total drying is achieved later.

408

409 Thermal conductivity and microstructure

410 The thermal conductivity results (average and standard deviation for each type of

411 sample) are presented in Table 5.

412 Independently of their type, all the samples had a value close to 0.9 W/(m.K), which

413 seems to be interesting for non-thermal plasters. Considering a 2-cm-thick plaster and

414 comparing it with a plaster with chemical binder (with thermal conductivity around 1.3

415 W/(m.K), the thermal resistance increase due to the earth plaster presented here would

416 be 0.04 $(m^2.K)/W$.

417 Bulk density determined geometrically and from open porosity measured by MIP for the

418 prismatic samples, and MIP determinations for the mortar layer on brick and the plaster

419 on the outdoor protected experimental wall are given in Table 6.

420 The plastering mortar can be placed in class 1.8 in terms of dry bulk density (DIN,

421 2013) because the bulk density is between 1.61-1.80 kg/dm^3. The porosity determined

422 by MIP is quite similar for the different types of samples of the same mortar.

423 Incremental mercury porosimetry curves for specimens of prismatic mortar, mortar on

424 brick, and brick masonry plaster – for the whole range and only the lower part of the

425 range - are plotted in Fig. 10. The pore size diameter is expressed in microns and each

426 step of the mercury intrusion is in ml/g.

427 It can be observed from the curves of Fig. 10 (a) that both the mortar plaster on brick

428 masonry and the mortar on laboratory brick samples present almost the same

429 microstructure in terms of most frequent pore diameter (approximately 40 μm) and

430 differential mercury intrusion (approximately 0.20 ml/g). This shows that the mortar's

431 microstructure is not influenced by the environmental conditioning (in outdoor protected

432 conditions or in laboratory conditions) for the higher range of pores. The mortar

433 specimen from a prismatic sample presents a quite different microstructure, with most

434 frequent pore diameters at around 55 μm and 14 μm, with 0.18 ml/g and 0.12 ml/g

435 respectively. This bi-modal microstructure of the mortar applied without the influence of

436 a porous support, compared with samples of the same mortar but applied in contact

437 with ceramic brick, shows that the support has a notable influence on the mortar's

438 microstructure. In fact the brick support increases the quantity of pores with larger

439 diameter while decreasing the quantity with smaller diameters.

440 When the lower range of pores (Fig. 10b) is studied, two peaks can be observed:

441 around 6 μm mainly for the specimen from the prismatic sample and around 0.1 μm for

442 all samples. This is the range commonly recognized to have the most influence on the

443 capillary absorption of building materials (Mindess et al., 1981). However, this

444 statement is based on studies for cement-based materials and not specifically those on

445 earth mortars. For the latter type of mortars, the influence of the microstructure needs

446 to be studied in greater depth.

447

448 **Conclusions**

449 The workability achieved by both batches of the ready-mixed earth mortar was

450 excellent. Results of flow table consistency, wet bulk density and drying shrinkage

451 satisfied the requirements of DIN 18947 (DIN, 2013) for earth plasters even with

452 different mixing procedures. These tests seem appropriate for fresh state

453 characterization and demonstrate good stability of the characteristics with different

454 types of mixing equipment.

455 The mortar presents good mechanical characteristics when compared to air lime

456 mortars. It seems appropriate for application on historic walls (Veiga et al., 2010). The

457 resistance to abrasion is an issue that it is important to address for this type of mortars

458 but it is necessary to increase the detail of the test procedure mentioned in the DIN

459 18947 (DIN, 2013), namely in terms of the hardness of the brush used and the

460 assessment of the loss of weight, for comparability.

461 The mortar showed a very high adsorption capacity, and also the ability to desorb all

462 the water vapor adsorbed. The hygroscopic behavior of the mortar, and of similar

463 mortars analyzed by other authors, leads to the conclusion that this type of earth

464 mortars can indeed contribute to the hygrometric equilibrium and comfort inside

465 buildings.

466 The capillary absorption measurement is not a common requirement for this type of

467 mortars but it enables the assessment of their behavior to be broadened, which may be

468 important for some applications and uses. The definition of the lateral waterproofing of

469 the samples is crucial for comparison, as the results are more favorable when the

470 lateral waterproofing seems more efficient. Drying capacity can also be easily

471 assessed. The thermal conductivity does not seem as important for common plaster,

472 where the layers are not thick.

473 The dry bulk density determined geometrically is quite reliable. The microstructure is

474 also quite stable when the plaster is applied to different substrates (porous or metallic)

475 and under different environmental conditions (protected exterior or laboratory).

476 The ready-mixed mortar tested fulfilled all the DIN 18947 (DIN, 2013) requirements

477 assessed and showed an appropriate behavior when applied to a hollow brick test wall

478 in protected outdoor conditions.

479 It is expected that the results will contribute to a more generalized use of earth mortars

480 as plasters, or as renders in areas protected from rain, on historic but also on modern

481 masonries. The implementation of an international standard, where test procedures

482 and requirements were defined, would also help to achieve this goal.

483

488

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590 **Figure captions**

591 **Fig. 1.** Samples and tests performed.

592 **Fig. 2.** Capillary samples prepared with resin and cotton cloth (left) and with

593 polyethylene film inside the net basket (right).

594 **Fig. 3.** Dry particle size distribution of the ready-mixed mortar product.

595 **Fig. 4.** X-ray diffraction of global and fine samples of the ready-mixed product (Q -

596 quartz, F - K-Feldspar, D - dolomite, M – illite, K – kaolinite, C – calcite, H - hematite).

597 **Fig. 5.** Visual result of the cohesion test with material sticking to the adhesive tape.

598 **Fig. 6.** Abrasion relief of the circular mortar samples tested with brushes of different

599 hardness.

600 **Fig. 7.** Sorption and desorption of mortar samples.

601 **Fig. 8.** Capillary curves of mortar samples with different preparation, representative

602 segment of capillary absorption, their equation and correlation coefficient.

603 **Fig. 9.** Drying curves of mortar samples with different preparations, segments of initial

604 drying, their equation and correlation coefficient.

605 **Fig. 10.** Incremental mercury porosimetry curves – whole range (a) and only lower part

606 of the range (b).

607

608 **Table 1.** Characteristics of fresh mortars.

Fresh Mortar	On site	Laboratory
Flow table consistency [mm]	178.8±2.5	182.3±2.5
Slump by flow table [mm]	-	14.2
Penetrometer consistency [mm]	-	2.4±0.1
Wet bulk density [kg/dm^3]	2.03	2.11
Air content [%]	2.8	2.5
Water retention [%]	-	67.5±1.3
Water content [%]	20.1±0.1	19.4±0.3

609

610

611 **Table 2.** Weight loss by abrasion and standard lower limits.

ΔWt [g]	Ø9cm, 2cm			Mortar on brick		
	Hard	Medium	Soft	Hard	Medium	Soft
Average	18.1	3.9	0.3	11.2	4.5	-
StDv	3.1	0.5	0.0	2.2	0.5	-
SI (DIN, 2013)			≤1.5			
SII (DIN, 2013)			≤0.7			

612

613

614 **Table 3.** Dynamic modulus of elasticity, flexural, compressive and adhesive strength of

615 the mortar (average and standard deviation) and standard lower limits.

Dry Mortar	Ed	FStr	CStr	AStr
	[N/mm^2]	[N/mm^2]	[N/mm^2]	[N/mm^2]
Average	3610	0.3	1.1	0.15
Stdv	128	0.0	0.1	0.03
SI (DIN, 2013)	-	≥0.3	≥1.0	≥0.05
SII (DIN, 2013)	-	≥0.7	≥1.5	≥0.1

616

617

618 **Table 4.** Capillary coefficient, CC, drying rate, DR, and drying index, DI, of the mortar

619 (average and standard deviation).

Dry mortar	CC [kg/(m^2.min^{0,5})]			DR [kg/(m^2.h)]			DI [-]		
Prepar.	Resin	Polyeth.	Simple	Resin	Polyeth.	Simple	Resin	Polyeth.	Simple
Average	0.50	0.86	1.84	0.30	0.33	0.64	0.18	0.22	0.14
Stdv	0.06	0.04	0.34	0.01	0.02	0.07	0.01	0.02	0.03

620

621

622   **Table 5.** Thermal conductivity of mortars for different types of samples (average and

623   standard deviation).

Sample	λ [W/(m.K)]				
	Ø9cm 1.5cm	Ø9cm 2.0cm	Rectangular 1.5cm	1.5 m on Brick	Prismatic
Average	0.8	0.9	0.9	0.9	1.0
Stdv	0.0	0.0	0.0	0.1	0.0

624

625

626 **Table 6.** Open porosity, bulk density and standard class of mortar on a prismatic

627 sample, a plaster-on-brick sample and from the brick masonry plaster.

Sample		Bulk density [kg/dm^3]	Porosity [%]	Class (DIN, 2013)
Prismatic	Geometric	1.77 ±0.02	-	1.8
	MIP	1.78	31	
Plaster (MIP)		1.81	30	2.0
On brick (MIP)		1.99	31	

628