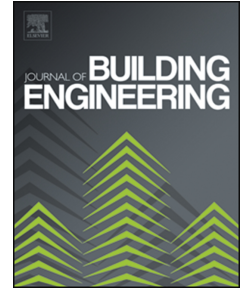


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Substitution of limestone filler by waste brick powder in self-compacting mortars: properties and durability

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1 **Substitution of limestone filler by waste brick powder in self-compacting**
2 **mortars: properties and durability**

3

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14 **Abstract:** The feasibility of using waste brick powder (WBP) in the manufacture of self-
15 compacting mortar has been investigated in this study. The limestone filler was partially or
16 totally (0%, 50% and 100%) substituted with WBP. The rheological properties, compressive
17 and flexural strengths, drying shrinkage and durability properties (including carbonation
18 resistance, chloride ion diffusion and sulphate resistance) of self-compacting mortars were
19 evaluated. The WBP-mortars presented a higher yield stress and plastic viscosity than that of
20 WBP-free mortar: the additional water has to be added in order to achieve the equivalent
21 workability. The compressive strength of WBP-mortars slightly decreased after 7 days (the
22 compressive strength of series mortars M-BP decreased 5.6% and 9.3% for 50% and 100%
23 WBP based mortars comparing with the reference mortar, respectively; while the compressive
24 strength of series with similar workability mortar M-BP100WA which was based on 100%

25 WBP decreased 16.7% and it could achieve 26.8 MPa), but the decreasing trend seemed to be
26 compensated by the pozzolanic activity of WBP and remained equivalent after 28 days (the
27 compressive strength of series mortar M-BP100WA decreased 5.3% and it could achieve 35.6
28 MPa). The substitution of limestone filler by WBP didn't seem to impair the durability
29 behavior of mortars (except for the resistance to carbonation). Therefore, it is possible to
30 manufacture self-compacting mortar by partially or totally substituting limestone filler by
31 WBP.

32 **Keywords:** waste brick powder, limestone filler, self-compacting mortar, rheology, strength,
33 durability.

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39 1. Introduction

40 Concrete is the second most consumed resource after water and is considered as one of the
41 most successful material in the world. The concrete industry's annual global production in
42 2010 is approximately 33 billion tons, which consumed nearly 3.7 billion tons of Portland-
43 cement clinker and 27 billion tons of aggregate [1]. The cement industry (global production of
44 cement is 4.2 billion tons in 2019, e.g. ~0.5 tonne per capita) is a major source of greenhouse
45 gas emissions particularly carbon dioxide (CO₂), which accounts for about 8% of total
46 world's CO₂ emissions [2]. Very large quantities of construction and demolition waste (CDW)
47 are generated yearly around the world. In the European Union (EU), the value was 868
48 million tons in 2014, accounting for 35% of the total waste generation of EU [3]. The main
49 constituents of CDW are the concrete and brick that may come from the construction of new

50 buildings, demolition of old structures, renovation-activities and from natural disasters [4–6].
51 EU Waste Framework Directive (2008/98/EC) has provided a framework for achieving that
52 by 2020 a minimum of 70% (by weight) of non-hazardous CDW shall be prepared for re-use,
53 recycled and other material recovery [7]. The demolition of brick masonry structures produces
54 huge amount of waste, including large quantities of clay brick waste [8–12]. In addition, the
55 ceramic bricks industry generates a significant amount of rejected non-conform bricks.
56 However, the fired clay brick waste (the calcination of raw clay minerals occurs the formation
57 of amorphous material during the production of fired clay brick) generally presents some
58 pozzolanic activity [13-16], which could react with calcium hydroxide and form compounds
59 with enhanced strength and durability. Therefore, the waste brick powder (WBP) might be
60 used in cement based materials to decrease the amounts of waste which have to be disposed in
61 landfill and the CO₂ emissions [17–20]. Recently, the use of WBP as a partial substitution of
62 Portland cement in the concrete has been received much attention during the past decades
63 [6,16,21–26].

64 Liu et al. [6] demonstrated that the hybrid recycled powder from clay brick and concrete
65 waste can be used as a pozzolanic material to replace part of the cement in the concrete when
66 they are well controlled.

67 Vejmelkova et al. [24] evaluated the mechanical properties, durability characteristics of high
68 performance concrete (HPC) produced with up to 60% of Portland cement replacing by fine-
69 ground ceramics. The mechanical properties and water transport properties were not
70 significantly impaired by ceramic replacement up to 20%, while the resistance against de-
71 icing salts was satisfactory only up to 10% of ceramic replacement, and the chemical
72 resistance (to Na₂SO₄ and MgCl₂) were maintained up to 40%.

73 Ge et al. [26] investigated the fresh and hardened concrete with three different replacement
74 levels up to 30% and three different particle sizes of ground clay-brick replacing cement. The

75 results demonstrated that the slump of fresh concrete significantly decreased as the
76 replacement level was over 10%. The early age strength decreased as the replacement level
77 increased, however, the strength of concrete with ground clay-brick had similar 90-day
78 compressive strength to that of the reference concrete. Concrete with ground clay-brick had
79 low chloride ion penetrability and high freeze-thaw resistance.

80 Schackow et al. [25] studied the durability of Portland cement-lime mortars of partial
81 replacement (10, 25 and 40%) of Portland cement by clay brick waste. The results showed
82 that the mortars with clay brick waste had improved strength and density due to the combined
83 physical pore filling and pozzolanic effect of clay brick waste. The mortar produced with clay
84 brick waste showed low ability to absorb chlorides and the resistance to sulphate was lower
85 than the reference mortar. It should be noted here that all results were obtained based on the
86 constant total water to cement ratio.

87 Ortega et al. [27] analysed the long-term properties of mortar (including mechanical
88 properties, microstructure and durability) incorporating up to 20% of waste brick powder
89 addition as a clinker replacement. The mortars with 10% and 20% of waste brick powder
90 presented good service properties in long-term (400 days), especially the chloride ingress
91 resistance, even better than reference mortar, which was due to their more refined pore
92 network produced by the pozzolanic activity and the filler effect.

93 Toledo Filho et al. [23] examined the potential of use crushed waste clay brick as a
94 supplementary cementitious material with the equal workability of mortars in the proportion
95 of 10%, 20%, 30% and 40% of crushed waste clay brick as cement replacement. The results
96 indicated that the optimal percentages of substitution lied between 10 to 20%. The addition of
97 crushed waste clay brick had almost no influence on the compressive strength and elastic
98 modulus up to 20% waste clay brick replacement.

99 Subasi et al. [28] reported the utilization of waste ceramic powder as filler material replacing
100 cement with the amounts of 5%, 10%, 15% and 20% in Self-Compacting Concrete (SCC).
101 The compressive strength of SCC mix decreased gradually but not a dramatically decrease.
102 The potential to use waste ceramic powder in SCC as cement replacement up to 15% is
103 suitable due to the positive effects on the fresh state properties on SCC.

104 Bouarroudj et al. [35] estimated the remaining intra granular porosity of a ground powder
105 using modelling approach and experimental approach with the help of mercury intrusion
106 porosimetry. The results showed that porosity of the ground brick is almost eliminated by the
107 grinding procedure (2% and 2.1% with the modelling approach and experimental approach).

108 It should be noted that the references mentioned above are concerned mostly with the partial
109 substitution of cement by WBP in the mortar or concrete. Limestone filler is a commonly
110 preferred filler material to increase the packing of the granular skeleton and maintain the
111 cohesion and segregation resistance of SCC [29–31]. Whereas, the source of limestone filler
112 is limited in some region and far transportation is needed for the production of concrete. The
113 WBP, which is locally available, might be used as substitution of limestone filler in SCC. The
114 rejected fired clay bricks waste, straight from the production line, whose effect on the mortar
115 or concrete has not been investigated. Because of the similarities to the bricks waste from
116 CDW, preliminary work was conducted with the rejected fired clay brick waste powder as
117 substitution of limestone filler in the self-compacting mortar.

118 The objective of this work is to evaluate the possibility of substituting the limestone filler by
119 waste brick powder (WBP) in self-compacting mortar. The properties of mortars including
120 rheological properties, mechanical properties (compressive and flexural strengths), drying
121 shrinkage, and durability properties (carbonation resistance, chloride ion diffusion and
122 sulphate resistance) were investigated.

123 **2. Materials and methods**

124 **2.1. Materials**

125 Materials used for producing mortars are presented as follows.

126 **2.1.1. Cement and natural sand**

127 The cement used in self-compacting mortar was an Ordinary Portland Cement (CEM I 52.5 N)
 128 provided by CBR company whose mineralogical composition is shown in Table 1. The
 129 density of cement was 3.10 g/cm^3 measured by helium pycnometer (Micromeritics AccuPyc
 130 1330). The sand used in this study was a siliceous Standard CEN natural sand in accordance
 131 with EN 196-1 [32].

132 **Table 1**

133 Mineralogical composition of cement determined by XRD-Rietveld

	C₃S	C₂S	C₃A	C₄AF	Anhydrite	Calcite	Gypsum
CEM I 52.5 N (%)	66.97	12.08	7.19	9.47	0.02	2.51	1.76

135 **2.1.2. Waste brick powder and limestone filler**

136 The red waste bricks (high resistance brick block: 288 mm × 138 mm × 138 mm with the
 137 compressive strength of 35 MPa, Fig. 1 (a)) were collected from a Belgian brick production
 138 company [33]. About 200 kg of the waste bricks were crushed firstly by using semi-industrial
 139 jaw crusher to obtain two fractions: 0/4 mm and 4/10 mm. The water absorption of brick
 140 (fraction 4/10 mm) was 11.3% determined by the IFSTTAR method according to Equation 1
 141 (WA represents the water absorption coefficient, M_{ssd} is the mass of brick at saturated surface
 142 dried state using colored absorbent paper, and M_{dry} is the mass of brick at 105°C oven dried
 143 state) [5].

$$WA = \frac{M_{ssd} - M_{dry}}{M_{dry}} \times 100 \quad (1)$$

144

145 The fraction 4/10 mm was grinded by using the semi-industrial ball mill (65 litres with 70 kg
 146 of specific balls) to obtain waste brick powder (WBP: fraction 0/0.1 mm used in this study,
 147 Fig. 1 (b)).



148 **Fig. 1.** WBP preparation: (a) collected red waste bricks; (b) WBP after grinding used in this study [33].

149
 150 A commercial limestone filler (more than 98.1% of calcite) from a Belgian Company was
 151 used for the production of self-compacting reference mortar. The density of WBP and
 152 limestone filler was 3.07 g/cm^3 and 2.73 g/cm^3 respectively, measured by helium pycnometer
 153 method. Table 2 shows the chemical composition of WBP determined by X-ray fluorescence
 154 (Bruker AXS, S4 Pioneer). The major chemical elements of the WBP were oxygen, silicon,
 155 aluminum and iron. Table 3 presents the mineral composition of WBP determined by X-ray
 156 diffraction (XRD, Bruker AXS D2 phaser diffractometer, $6\text{-}80^\circ$ angle, 0.2° pitch and
 157 acquisition time 0.5s). The Rietveld refinement method was used to quantify the crystalline
 158 phases and in particular the amorphous phase. The major mineral components of WBP were
 159 α -Quartz, hematite and microcline. In addition, the WBP had 16.0% of amorphous phase,
 160 which is the most important characteristic with regard to potential pozzolanic activity [6].

161 **Table 2.**

162 Chemical composition of crushed brick powder (%)

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	MgO	CaO	TiO ₂	SO ₃	V ₂ O ₃	MnO	LOI
WBP	62.8	10.4	16.3	0.6	2.1	2.2	1.7	2.4	0.6	0.1	0.2	0.5

163

164 **Table 3.**

165 Mineral composition of crushed brick powder (%)

	α -SiO ₂ Quartz	Fe ₂ O ₃ Hematite	KAlSi ₃ O ₈ Microcline	NaAlSi ₃ O ₈ Albite	SiO ₂ Cristobalite	Amorphous phase
WBP	55.0	12.8	9.2	4.0	2.7	16.0

166

167 Fig. 2 presents the particle size distributions (laser granulometry analysis) of WBP, limestone
 168 filler and cement used as constituents in the mortars. The WBP had a mono-sized and narrow
 169 particle size distribution (PSD): containing a lower proportion of fine particles (1 μm to 35
 170 μm) than limestone filler, and a higher proportion of particle between 35 μm and 75 μm ,
 171 while limestone filler presented a continuous PSD. Table 4 reports the specific surface
 172 determined by BET method, as well as D10, D50 and D90 diameters of WBP, limestone filler
 173 and cement. The WBP presented a higher specific surface area value than that of limestone
 174 filler according to the BET method.

175

176 **Table 4.**

177 Physical properties of WBP, limestone filler and cement

	WBP	Limestone filler	Cement
Specific surface area BET (m ² /g)	1.0	0.8	1.29
Density (g/cm ³)	3.07	2.73	3.10
D10 (μm)	4.03	1.74	2.53
D50 (μm)	24.80	18.27	11.14
D90 (μm)	60.84	121.67	26.00

178

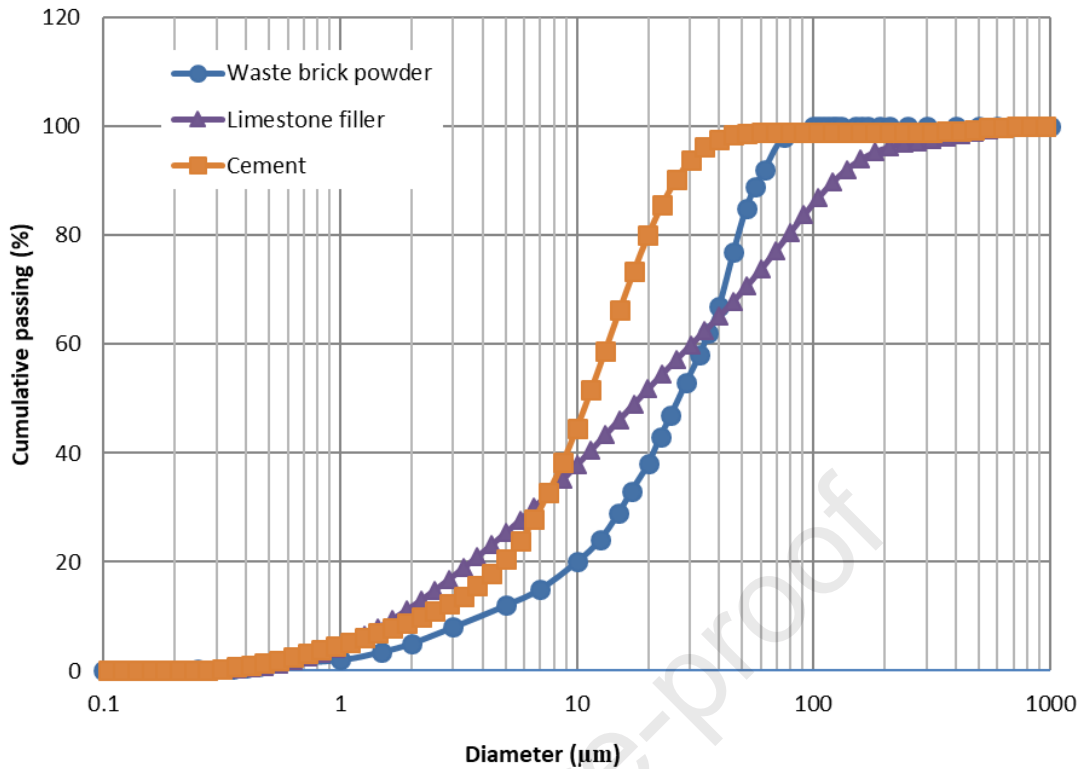


Fig. 2. Particle size distributions of WBP, limestone filler and cement.

2.1.3. Mortar design

The mix design was performed according to the method of concrete equivalent mortar (MBE) developed by Schwartzenruber [34]. Table 5 presents the compositions of self-compacting mortar. Five self-compacting mortars were manufactured with limestone filler being substituted by WBP at substitution rates (in volume) of 0%, 50% and 100% (noted M-BP0, M-BP50 and M-BP100, respectively). The same water to cement ratio (W/C) of 0.8 was used for the series of mortars M-BP0, M-BP50 and M-BP100 (Here only a high W/C ratio was used to obtain self-compacting mortar and to eliminate the effect of superplasticizers). Previous investigations realized on this material [35] showed that the porosity of WBP was very low after grinding the brick particle. Preliminary tests showed however that the substitution of limestone filler by WBP had a negative impact on the workability: preventive measures (superplasticizers or extra water addition) are required to control the workability of

193 mixture. It should be noted that the purpose of this study is to estimate the actual effect of
 194 WBP substituting limestone filler, while keeping the other variables constant. Therefore, an
 195 additional quantity of water was used for the series of mortars M-BP50WA and M-BP100WA
 196 in order to achieve similar spread flow index of mixture as reference mortar M-BP0 (WA in
 197 M-BP50WA and M-BP100WA means that water added to produce mortars with similar
 198 workability).

199 **Table 5**
 200 Compositions of self-compacting mortar (g)

Mix Type	Cement	Natural sand	Limestone filler	WBP	Effective water	Additional water	Total water
M-BP0	448.0	1350.0	298.3	0.0	358.4	0	358.4
M-BP50	448.0	1350.0	149.2	167.7	358.4	0	358.4
M-BP100	448.0	1350.0	0.0	335.4	358.4	0	358.4
M-BP50WA	448.0	1350.0	149.2	167.7	358.4	19.0	377.4
M-BP100WA	448.0	1350.0	0.0	335.4	358.4	37.9	396.3

201

202 *2.2. Experimental methods*

203 The experimental program and test methods are listed in Table 6.

204 **Table 6.**
 205 Experimental program and test methods.

Studied properties	Curing time (days)	Samples per test	Standard test method
Water demand	0	1	Beta P test [36–38]
Spreading flow index	0	2	MBE cone [34]
Shear stress and shear rate	0	1	Rheocad 400 [39]
Density of fresh mortar	0	3	EN 1015-6 [40]
Air content	0	1	EN 1015-7 [41]
Flexural strength	7, 28	3	EN 196-1 [32]
Compressive strength	7, 28	6	EN 196-1 [32]
Water absorption	28	3	NBN B15-215 [42]
Drying shrinkage	1	3	NBN B14-217 [43]
Carbonation resistance	28	3	EN 13295 [44]
Sulphate resistance	28	3	ASTM C1012-04 [45]
Chloride ion diffusion	28	2	Courard et al. [14,36]

206

207 *2.2.1. Beta P test*

208 The water demand of limestone filler and WBP was characterized by means of β_p factor [36–
 209 38]. The Beta P test was performed in order to quantify water demand β_p of the mixture
 210 corresponding to the rheological behavior of a paste with different water contents. This test

211 involved the measurement of the spreading of a paste for different water contents and a
 212 relative flow area (R) factor calculated from the spreading diameter D (mm) (Equation 2) with
 213 the mini-cone (h = 60 mm, d = 70 mm and D = 100 mm) used for European standard EN
 214 1015-3 [46].

$$R = \frac{(D^2 - 100^2)}{100^2} = (D/100)^2 - 1 \quad (2)$$

215
 216
 217 Okamura et al. [47] demonstrated that, for a paste made with any particular powder, the water
 218 powder ratio by volume (V_w/V_p) and the relative flow area (R) are linearly related (Equation
 219 3).

$$V_w/V_p = \beta_p + R \times E_p \quad (3)$$

220
 221 where β_p is the water ratio, which can be considered as comprising the water adsorbed on the
 222 powder surface together with that required to fill the voids in the powder system and to
 223 provide sufficient dispersal of the particles, needed for mix flowing; E_p is the deformation
 224 coefficient, which is a measure of the sensitivity of the fluidity characteristics of the paste to
 225 increasing water content.

226 2.2.2. *Mixing procedure for the manufacture of mortar*

227 A precise mixing procedure was followed according to European standard EN 196-1 [32].
 228 The mixtures protocol was kept the same for all the studied mortars. For the mix of M-
 229 BP50WA and M-BP100WA, the total quantity of water (efficient water plus additional water)
 230 was used to manufacture the specimens, without any pre-saturating process of WBP.

231 2.2.3. *Tests on fresh mortars*

232 After mixing, the first rheological test performed was the spread test. The spread flow of fresh
233 mortar was measured immediately after the removing the MBE cone [34] ($h = 150$ mm, $d =$
234 50 mm and $D = 100$ mm, approximately 687 ml). The spread value was measured along two
235 perpendicular diameters after 5 min mixing. The second rheological test was performed with
236 Rheocad 400 (CAD Instrumentation) [39] in order to evaluate yield and shear stresses (Fig. 3).
237 This rheometer is a mechanical computer-controlled device, which is developed specially for
238 building materials characterization, such as cement, fresh mortar and concrete. Its principle is
239 based on the measurement of the torque developed in response to the controlled rotation of a
240 measuring device in a bowl. The torque is recorded as a function of the rotation velocity.
241 Careful calibration and used program of the system [33] allowed to transfer this correlation to
242 a correlation between the dynamic viscosity of the mortar and the shear gradient (a range
243 between $0.1 - 60$ s^{-1}). The density of fresh mortars was determined in accordance with
244 European standard EN 1015-6 [40]. Before casting, the air content of mortars was measured
245 according to the European standard EN 1015-7 [41].



246 **Fig. 3.** Rheocad 400: (a) machine with bowl; (b) special impeller.

247

248 2.2.4. Mechanical behavior of mortars

249 Six specimens of 40 mm \times 40 mm \times 160 mm were prepared for measuring the mechanical
250 behaviour of mortars for each mixture. One day after casting, these specimens were

251 demoulded and stored into water at 21 ± 2 °C until the ages of 7 and 28 days. After each age,
252 both flexural and compressive strengths were evaluated in conformity with European standard
253 EN 196-1 [32]. These two mechanical strength tests were carried out with an INSTRON 5585
254 (loading capacity of 200 kN). After the failure of the three specimens in bending test, the two
255 parts of each prism were subjected to compressive strength measurement according to
256 European standard EN 196-1.

257 2.2.5. Water absorption

258 Water absorption of mortars was measured after 28 days of curing. Three specimens of 40
259 mm × 40 mm × 160 mm were used for the determination of water absorption according to the
260 standard NBN B15-215 [42]. The specimens were immersed into water until achieving a
261 constant mass. The constant mass was taken as the saturated mass of sample (M_{sat}). The dried
262 mass was obtained after drying the saturated sample in an oven at 105°C until constant mass
263 (M_{dried}). The water absorption (WA) was then obtained by ratio of the absorbed water amount
264 to the oven-dried mass (Equation 4).

$$WA = \frac{M_{\text{sat}} - M_{\text{dried}}}{M_{\text{dried}}} \times 100 \quad (4)$$

266 2.2.6. Drying shrinkage

267 Three mortar specimens (40 mm × 40 mm × 160 mm) were used for evaluating drying
268 shrinkage. The prisms were demoulded one day after casting and immediately stored in dry
269 climatic room at 21 ± 2 °C and $60 \pm 5\%$ RH, according to the standard NBN B14-217 [43].
270 The drying shrinkage measurements were continuously performed at ages of 1, 3, 7, 14 and
271 28 days. Length variances were determined in accordance with the standard NBN B14-217.

272 2.2.7. Resistance to carbonation

273 The accelerated carbonation test was performed according to the European standard EN
 274 13295 [44]. The three mortar specimens (40 mm × 40 mm × 160 mm) were cured in water for
 275 28 days and then pre-conditioned at 21 ± 2 °C and $60 \pm 5\%$ relative humidity (RH) for 28 days
 276 before the carbonation test. Specimens were then stored in the carbonation incubator with 1%
 277 CO₂ concentration and relative humidity of $60 \pm 5\%$ (21 ± 2 °C). After 28 and 56 days'
 278 carbonation, respectively, the carbonation depth of freshly broken faces was measured by
 279 means of phenolphthalein indicator following the European standard EN 13295.

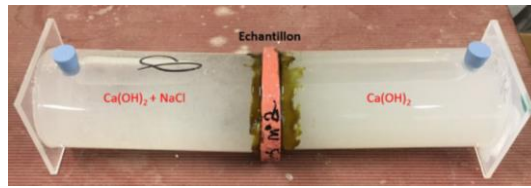
280 2.2.8. Chloride ion diffusion

281 The chloride ion diffusion coefficient of mortars was determined using two-compartment
 282 diffusion cells [14,36] (Fig. 4). After 28 days curing in water, 10 mm ± 2 mm thick mortar
 283 samples were sawed from 8 cm diameter specimens and stored in Ca(OH)₂ saturated solution.
 284 Each sample was polished with 600-grade emery paper, rinsed with deionized water and the
 285 surface dried with a tissue before being fitted into the diffusion cell. After fitting with epoxy
 286 resin and sealing with silicon paste, the cells were filled at one side with 3 M NaCl in
 287 saturated Ca(OH)₂ solution (left compartment, e.g. upstream in Fig. 4, the chloride
 288 concentration of left compartment was noted as C_{up}) and at the other side with Ca(OH)₂
 289 saturated solution (right compartment, e.g. downstream in Fig. 4, the chloride concentration of
 290 right compartment was noted as C_{down}). At periodic intervals (2, 4, 6, 8, 10, 12, 14 and 16
 291 weeks, respectively), chloride concentration (C_{down}) was determined in right compartment by
 292 means of titration from a 10 cm³ sample of the solution. The chloride ion diffusion coefficient
 293 (D_c in m²/s) was determined according to the Equation 5 [48] (where $C_{up} \gg C_{down}$).

$$D_c = \frac{C_{down}}{C_{up}} \times \frac{eV_{down}}{A(t - t_0)} \quad (5)$$

294 where e is the thickness of specimens in m, V_{down} is the volume of right compartment in m³, A
 295 is the surface area of specimens in m² and $t-t_0$ corresponds to the testing time in days,
 296 respectively.

297



298

Fig. 4. Experimental setup of chloride diffusion cells.

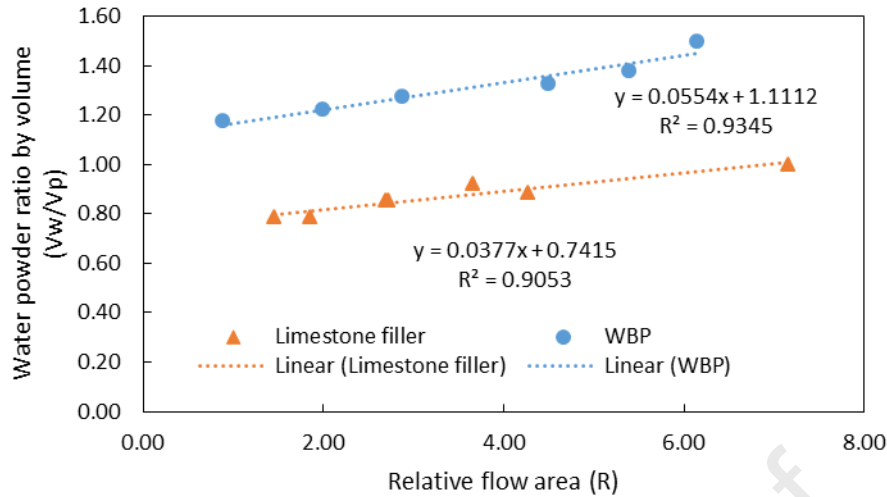
299 2.2.9. Sulphate resistance

300 The sulphate resistance of mortars was performed in accordance with the ASTM C1012-04
 301 [45]. The method involved the determination of length change of prismatic specimens
 302 immersed in a standard sulphate solution (with a sodium sulphate concentration of 50 g/litre).
 303 After the 28 days curing in the water, the three mortar specimens (40 mm × 40 mm × 160
 304 mm) were measured for length and placed in the standard sulphate solution at $21 \pm 2^\circ\text{C}$.
 305 Changes of length of the specimens were measured after storage periods of 1, 2, 3, 4, 5, 6 and
 306 11 weeks, respectively.

307 3. Results and discussion

308 3.1. Water demand of limestone filler and WBP

309 The relationship of water powder ratio by volume (V_w/V_p) and relative flow area (R) for
 310 limestone filler and WBP is presented in Fig. 5. Table 7 shows the results of Beta P test. As
 311 can be seen in Fig. 5 and Table 7, the WBP presented a higher β_p compared to the limestone
 312 filler, which can be justified by mono-disperse and narrower particle size distribution of WBP
 313 and higher BET specific surface area [26,28]. This indicates that a higher quantity of water is
 314 needed to achieve the same workability of paste for WBP. Thus WBP has a higher water
 315 demand compared with limestone filler. This finding agrees with the results of other authors
 316 [6,25]. Regarding the deformation coefficient (E_p), the WBP had a higher value
 317 demonstrating a greater sensitivity to the variation of water quantity [36,37].



318 **Fig. 5.** Relationship of V_w/V_p and R for limestone filler and WBP.

319

320 **Table 7.**

321 Results of Beta P test

Powder	β_p	E_p (deformation coefficient)	R^2
Limestone filler	0.742	0.038	0.905
WBP	1.111	0.055	0.935

322

323 **3.2. Properties of fresh mortars**

324 Fig. 6 presents the spread values of mortars as a function of WBP content. In the series of
 325 mortars M-BP (M-BP0, M-BP50 and M-BP100), the spread of mortars decreased when
 326 substituting limestone filler by WBP. Other researchers reported that the workability of
 327 mortar or concrete decreased as the substitution of the cement by brick powders increased
 328 [21,25,26,28]. In the series of mortars M-BPWA (M-BP50WA and M-BP100WA), the
 329 substitution of limestone filler by WBP didn't seem to affect the spread flow properties of
 330 mortars. The mixture M-BP50WA presented slightly higher or similar spread value as the
 331 reference mixture. This outcome is probably due to the higher water demand of WBP
 332 compared with limestone filler [25,26] and the higher quantity of water that is added to the
 333 mix.

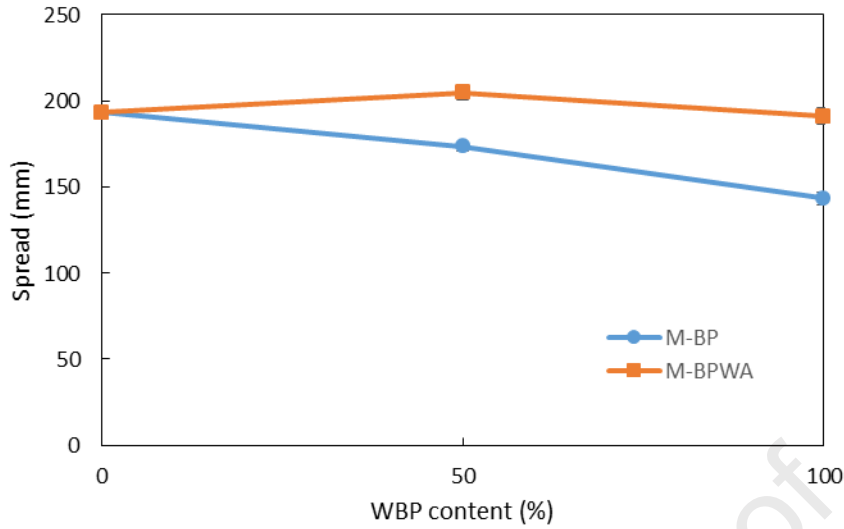


Fig. 6. Spread of fresh mortars as a function of WBP content (M-BP refers to the series of mortars M-BP0, M-BP50 and M-BP100; while M-BPWA refers to the series of mortars M-BP50WA and M-BP100WA).

The flow curves were analysed with the standard Bingham model to study the rheological properties of non-Newtonian fluids such as cement pastes, mortars and concretes (Equation 6).

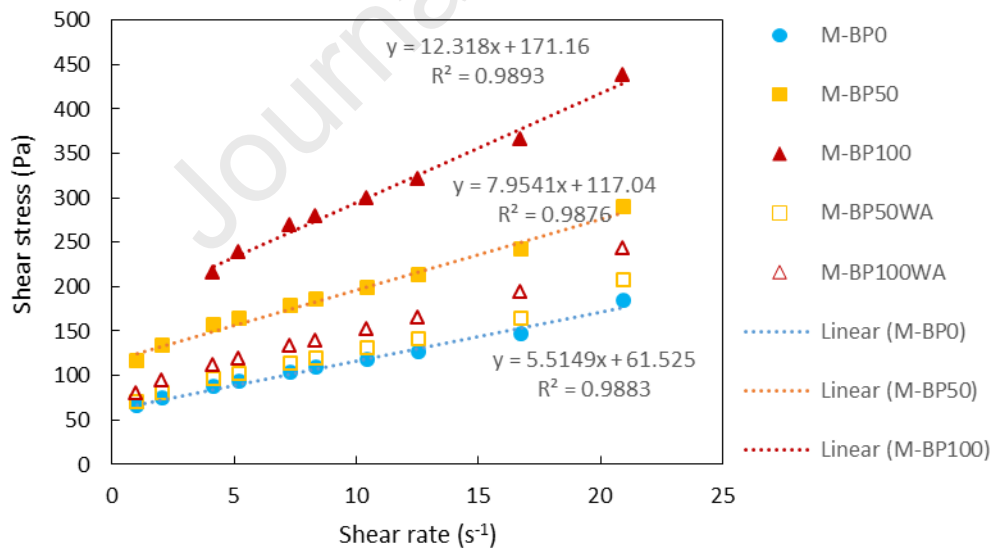
$$\tau = \tau_0 + \mu\dot{\gamma} \quad (6)$$

where τ is shear stress, τ_0 is yield stress, μ is plastic viscosity and $\dot{\gamma}$ is shear rate.

Fig. 7 shows that the flow curve of mortars provided a perfect fit to a straight line for shear rates in the 1-22 s⁻¹ range. The yield stress, plastic viscosity and the correlation coefficient (R^2) are presented in Table 8. The results showed that the mortars with substitution of limestone filler by WBP presented a higher yield stress and plastic viscosity than that of reference mortar. The trend line equation of the reference mortar presented the lowest yield stress and plastic viscosity. For the series of mortars M-BP, the yield stress and plastic viscosity of mortar increased with the substitution rate of WBP, which is in accordance with spreading flow test. Indeed, these behaviors probably depended on the internal friction between the particles and the fluidity of mortars: the WBP presented a mono-size and narrower PSD, a higher surface specific area and probably higher internal friction between the

351 particles than limestone filler. In addition, a few of water was adsorbed by the WBP during
 352 the mix, which led to decrease of the availability of free water in the mix: thus the torque and
 353 the viscosity of mortar increased with the substitution rate [39,49]. For the series of mortars
 354 M-BPWA, the yield stress and plastic viscosity of mortar slightly increased when substituting
 355 limestone filler by WBP, which is probably due to higher internal friction of WBP (the
 356 additional water was added to produce the mortar with the similar workability level).

357 On the basis of the values obtained by Rheocad tests, it can be considered that the series of
 358 mortars M-BP presented initial yield stress and plastic viscosity higher than the series of
 359 mortars M-BPWA. For the series of mortars M-BPWA, the fluidity of the mix increased
 360 because of the additional water used, which led to the decrease of the viscosity and the torque
 361 or shear stress. These results are consistent with the workability of mortar evaluated by means
 362 of spreading flow test.



363 **Fig. 7.** Flow curve of mortars and evaluation of the yield stress.

364

365

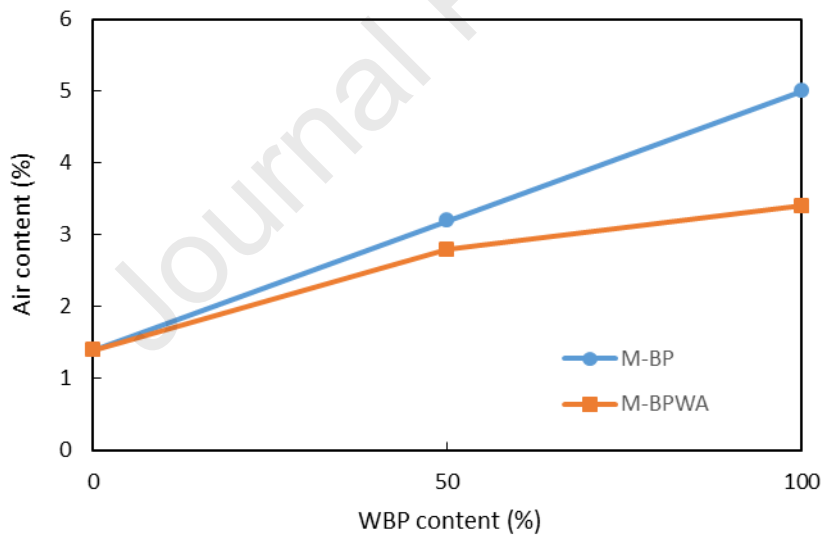
366

367 **Table 8.**
368 Rheological properties of mortar

Mortar	τ_0 (yield stress, Pa)	μ (plastic viscosity, Pa s)	R^2
M-BP0	61.52	5.51	0.99
M-BP50	117.04	7.95	0.99
M-BP100	171.16	12.32	0.99
M-BP50WA	65.60	6.36	0.99
M-BP100WA	76.03	7.55	0.99

369

370 Fig. 8 indicates the air content of mortars as a function of WBP substitution rate: the higher
371 the substitution rate, the higher the air content. This is probably due to the higher specific
372 surface area and mono-sized and narrower PSD of WBP compared with the limestone filler
373 and induces the inclusion of air bubbles during the mixing procedure. Moreover, the density
374 of the fresh mortars decreased when substitution rate increased. Similar observations were
375 found with waste ceramic powders by Subaşı et al. [28].



376

Fig. 8. Air content of mortars as a function of WBP content.

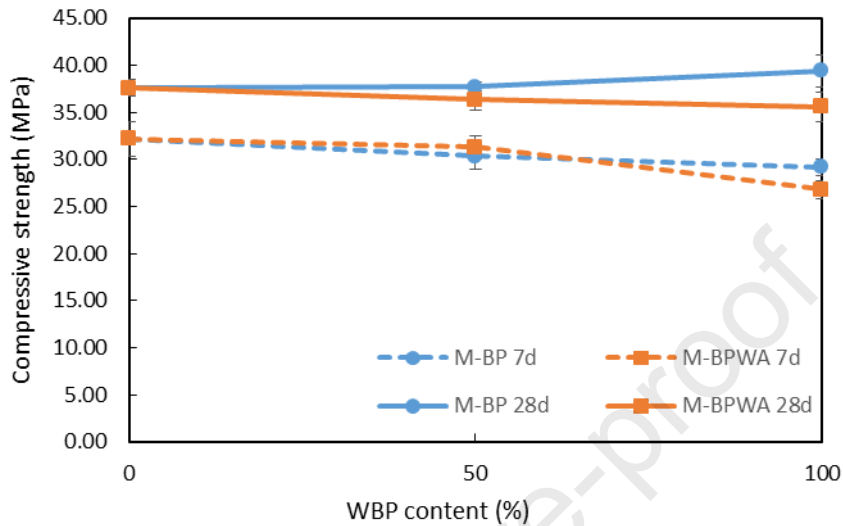
377

378 3.3. Properties of hardened mortars

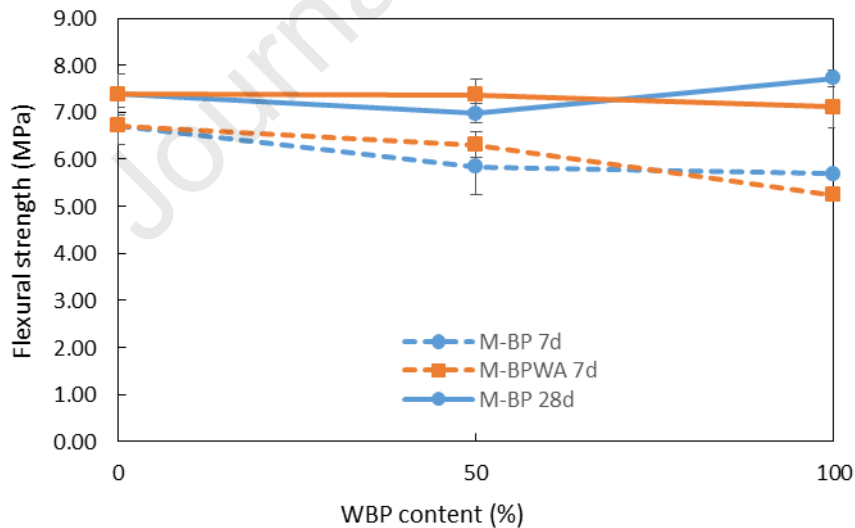
379 3.3.1. Mechanical properties

380 Fig. 9 and Fig. 10 show the results of compressive and flexural strengths of mortars as a
381 function of WBP content. When the substitution of limestone filler by WBP increased, the
382 compressive strength of mortars slightly decreased after 7 days (the compressive strength of
383 mortars M-BP decreased 5.6% and 9.3% for 50% and 100% WBP based mortars comparing
384 with the reference mortar, respectively; while the compressive strength of mortars M-BPWA
385 decreased 2.7% and 16.7% for 50% and 100% WBP based mortars, respectively; the
386 compressive strength of series mortar M-BP100WA could achieve 26.8 MPa), which is
387 probably due to the higher air content for mortars with WBP. After 28 days, the compressive
388 strength of mortars with WBP was equivalent to reference mortar with limestone filler (the
389 compressive strength of series mortar M-BP100WA decreased 5.3% comparing with the
390 reference mortar and it could achieve 35.6 MPa); the decreasing trend seems to be
391 compensated, probably by the pozzolanic activity of WBP [6,27] (Ortega et al. [27] showed
392 the quantity of portlandite for mortar made with 10% and 20% of brick powder did not
393 increase much or even decreased from 15 to 90 days, due to the consumption of portlandite in
394 the pozzolanic reactions based on thermogravimetric analysis) and this effect could be
395 enhanced after 90 days [50]. The compressive strength of the mixture M-BP100 was slightly
396 greater (1.7 MPa) than the mixture M-BP50. The 16% of amorphous phase content present in
397 WBP could react with calcium hydroxide and form hydrated products as calcium hydrated
398 silicates (C-S-H) and calcium aluminate hydrates (C-A-H), which progressively enhance
399 strength and durability properties of cement based materials [16,23,24,27]. For the series of
400 mortars M-BP, the compressive strength was slightly higher than the series of mortars M-
401 BPWA. The difference between the two series was the highest for the 100% substitution rate,
402 since additional water quantity was added for the series of mortars M-BPWA, and thus the
403 higher water to cement ratio induced the decrease of the compressive strength of mortars for
404 the series of mortars M-BPWA. It is important to notice that all the specimens fulfil the

405 requirements of the European standard EN 998-2 [51] about the specification for mortars for
 406 masonry (the compressive strength of masonry mortars Grade “Md” should be greater than 25
 407 MPa). Similar trends were observed for the flexural strength of mortars.



408 **Fig. 9.** Compressive of mortars as a function of WBP content.

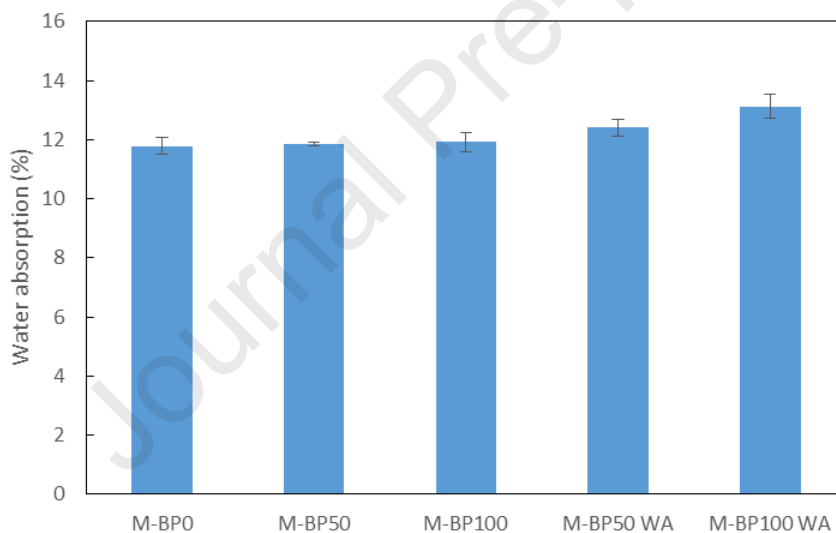


410 **Fig. 10.** Flexural strength of mortars as a function of WBP content.

411 3.3.2. Water absorption

412 The water absorption of mortars cured for 28 days are presented in Fig. 11. For the series of
 413 mortars M-BP, the water absorption values were similar for the different WBP contents. The

414 water absorption values of mortars M-BPWA were slightly higher than the series of mortars
 415 M-BP, which is due to the additional water: this is inducing a higher initial water to cement
 416 ratio when compared to the series of mortars M-BP and leading to higher porosity. In
 417 addition, the reaction between $\text{Ca}(\text{OH})_2$ and the amorphous compounds (pozzolanic effect),
 418 such as silica and alumina present in WBP, will generate supplementary silicate/aluminate
 419 hydrates similar to those produced in the cement hydration; it will induce to a refinement of
 420 the pore structure and a decrease of the porosity of the cement matrix [16,23,27]. Tests
 421 performed at 90 days should confirm even better this trend [50]. Finally, the porosity or water
 422 absorption values were similar for the different WBP contents for the series of mortars M-BP,
 423 while the slightly higher values were obtained for the series of mortars M-BPWA.

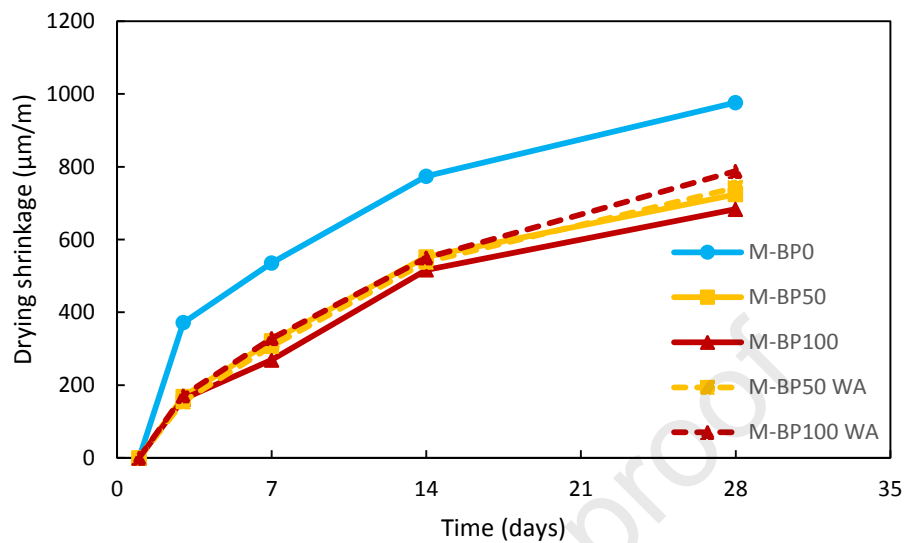


424 **Fig. 11.** Water absorption of mortars at 28 days.

425 3.3.3. Drying shrinkage

426 The drying shrinkage of mortars is presented in Fig. 12. The incorporation of WBP induced a
 427 reduction of the drying shrinkage of mortar in comparison with that of limestone filler, which
 428 is probably due to their more refined pore network produced by the pozzolanic activity [50].
 429 The results on series of mortars M-BPWA showed a reduction of the drying shrinkage of
 430 mortar, but to a lesser extent. It should be noted here that the use of additional water for

431 mortars MP-BPWA increased the initial water to cement ratio and this should contribute to an
 432 increase in drying shrinkage compared with the mortars MP-BP [36,52–54].



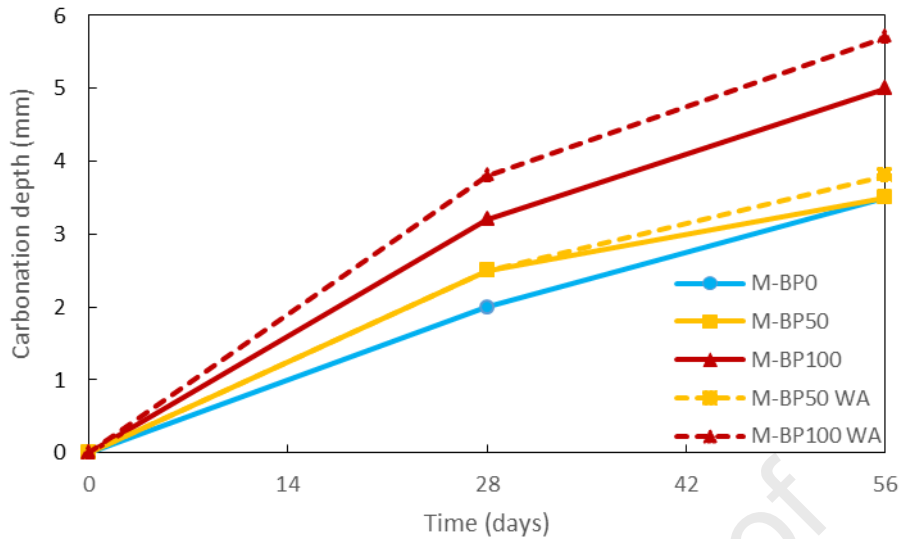
433 **Fig. 12.** Drying shrinkage of mortars.

434 3.4. Durability of mortars

435 3.4.1. Carbonation

436 Fig. 13 shows the carbonation depth of mortars under accelerated conditions. The substitution
 437 of limestone filler by WBP increased the carbonation depth of mortars. In addition, the
 438 carbonation depths increased with time. Accelerated carbonation in the mortars is the result of
 439 the reaction between carbon dioxide and calcium hydroxide, calcium silicate hydrates
 440 produced upon hydration [5,54,55]. As discussed earlier in Section 3.3.2, the WBP content
 441 slightly increased the permeability of the open pore network, which should promote the
 442 penetration of CO₂ and, consequently, an increase in the carbonation rate [25]. The results
 443 obtained with the series of mortars M-BPWA showed a higher carbonation depth than that of
 444 series of mortars M-BP, which is due again to a higher porosity of the mortar.

445



446 **Fig. 13.** Carbonation depth of mortars as a function of time.

447

448 3.4.2. Chloride ion diffusion

449 Fig. 14 presents the evolution of chloride ion diffusion through mortars versus time. The
 450 standard deviations of M-BP0 and M-BP100WA are also presented in Fig. 14. The apparent
 451 chloride ion diffusion coefficient of mortars is shown in Table 9. Transport through reference
 452 mortar was observed after 16 weeks, with an apparent chloride diffusion coefficient of
 453 $4.01 \times 10^{-13} \text{ m}^2/\text{s}$. The apparent chloride diffusion coefficients of mortars with WBP were
 454 similar to that of the reference mortar (except for the mortar M-BP100WA presenting slightly
 455 greater value, which may due to the highest porosity of mortar M-BP100WA [23,26,27]; the
 456 mortar M-BP100 presenting lowest value, which may due to the pozzolanic effect and a
 457 refinement of the pore structure [50]). But globally, the substitution of limestone filler by
 458 WBP didn't seem to significantly impair the chloride ion diffusion resistance of mortars.

459

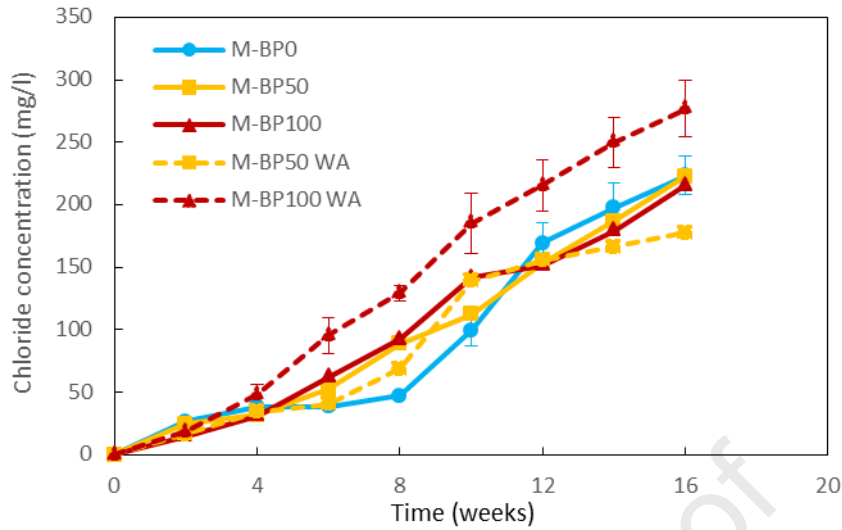


Fig. 14. Chloride diffusion rates for mortars with limestone filler and WBP.

Table 9.

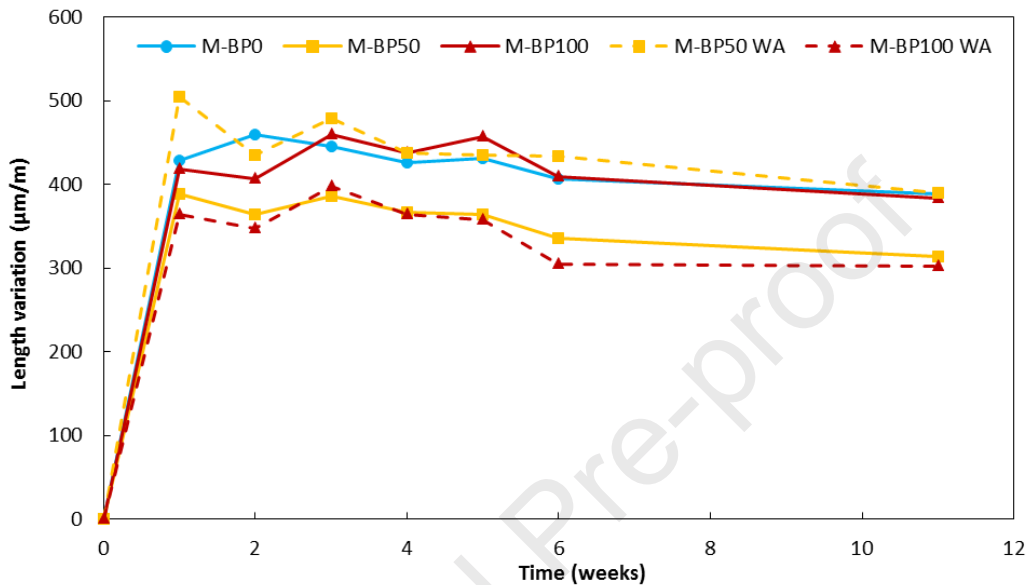
Chloride diffusion rates for mortars with limestone filler and WBP

Mortar	Apparent chloride diffusion coefficient (m^2/s)	Standard deviation (m^2/s)
M-BP0	4.01×10^{-13}	1.83×10^{-14}
M-BP50	4.00×10^{-13}	2.81×10^{-14}
M-BP100	3.69×10^{-13}	1.49×10^{-14}
M-BP50 WA	4.03×10^{-13}	6.89×10^{-15}
M-BP100 WA	4.94×10^{-13}	3.33×10^{-14}

3.4.3. Resistance to sulphate

Fig. 15 presents the variation in length of mortars immersed into Na_2SiO_4 solution. All the mortars exhibited similar expansion after only a few days. The expansion of the mortars M-BP50 and M-BP100 after 11 weeks was measured as $314 \mu\text{m}/\text{m}$ and $383 \mu\text{m}/\text{m}$, respectively. The expansion of the series of mortars M-BPWA show similar values as the reference mortar (the expansion was measured as $388 \mu\text{m}/\text{m}$ for the reference mortar). The mortar M-BP100 presented slightly higher length variation after the sulphate attack compared with the mortar M-BP100WA, which may due to the lower porosity than that of the mortar M-BP100WA, and thus the lower porosity means the lower ability to resist the expansion of the formed ettringite [56]. According to the literature, the resistance to sulphate is related to the pore sizes, as well

476 as the total porosity and permeability of cement based materials. The substitution of limestone
 477 filler by WBP slightly increased the permeability of the open pore network, which was
 478 compensated by the pozzolanic effect of WBP [23,25]. The substitution of limestone filler by
 479 WBP didn't seem to affect the behavior of mortars with regard to sulphate attack.



480
 481 **Fig. 15.** Length variation of mortars with limestone filler and WBP in sulphate solution.

482 483 **4. Conclusions**

484 The possibility of substituting limestone filler by Waste Brick Powder (WBP) in self-
 485 compacting mortar has been evaluated. The main conclusions can be drawn as follows:

- 486 1) The WBP are characterized by a higher β_p (a higher water demand) compared to the
 487 limestone filler. This indicated a higher quantity of water is needed to achieve the
 488 same workability of paste for WBP.
- 489 2) The mortars produced by substitution of limestone filler by WBP presented a higher
 490 yield stress and plastic viscosity than that of reference mortar. In the series of mortars
 491 M-BP, the yield stress and plastic viscosity of mortar increased with the substitution
 492 rate of WBP, which is consistent with the workability measured by means of spread

493 test (the spread of mortars decreased with the substitution rate of limestone filler by
494 WBP). In the series of mortars M-BPWA, the substitution of limestone filler by WBP
495 didn't seem to affect the spread properties of mortars.

496 3) When the substitution rate of limestone filler by WBP increased, the compressive
497 strength of mortars slightly decreased after 7 days (the compressive strength of series
498 mortar M-BP100WA decreased 16.7% and it could achieve 26.8 MPa), but the
499 decreasing trend seemed to be compensated by the pozzolanic activity of WBP and
500 remained equivalent after 28 days (the compressive strength of series mortar M-
501 BP100WA decreased 5.3% and it could achieve 35.6 MPa). After 28 days, the
502 compressive strength of mortars with WBP was equivalent to reference mortar with
503 limestone filler; the decreasing trend seems to be compensated by the pozzolanic
504 activity of WBP and this effect should be enhanced after 90 days. In the series of
505 mortars M-BP, the compressive strength of mortars was slightly higher than the series
506 of mortars M-BPWA. It is important to notice that all the specimens fulfil the
507 compressive strength requirement of the European standard EN 998-2 for masonry
508 mortars Grade "Md".

509 4) The conclusion can be drawn the choice whether on constant flow index (series of
510 mortars M-BPWA) or constant water to cement ratio (series of mortars M-BP). The
511 mortars prepared with additional water (mortars M-BPWA) showed poorer
512 mechanical properties. On the contrary, for the series of mortars M-BP, the WBP's
513 filler or pozzolanic effect will be enhanced by the presence of less water (decrease of
514 flowability). There is a beneficial effect from WBP if no additional water is added.
515 However, in the case of higher WBP substitution rate (100%), it is needed to add extra
516 water or superplasticizers in order to achieve the workability requirement of fresh
517 mortars, especially for the self-compacting mortars.

518 5) The incorporation of WBP induced a reduction of the drying shrinkage. The
519 substitution of limestone filler by WBP however increased the carbonation depth of
520 mortars: the results obtained with series of mortars M-BPWA presented higher
521 carbonation depth than that of series of mortars M-BP, which is due to the higher
522 porosity of the mortar. Finally, the substitution of limestone filler by WBP didn't seem
523 to impair the behavior of mortars in case of sulphate and chloride ions.

524 The use of Waste Bricks Powder (WBP) as an alternative to limestone fillers seems to be a
525 good opportunity for recycling waste brick and reducing natural resource depletion. Fresh and
526 hardened properties of mortars globally fulfil the requirements for self-compacting mortars.
527 Particular attention should be paid to the use of these materials in the case of the presence of
528 reinforcements and the risks associated with carbonation. However, a more in-depth study, in
529 particular on samples at 90 days for which the manifestation of the pozzolanic effect would be
530 more evident, should still be carried out for future research.

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539

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Highlights

- Waste brick powder (WBP) presented a higher water demand than limestone filler (LF)
- The mortars produced by WBP presented a higher yield stress and plastic viscosity
- The mortar M-BP presented a higher compressive strength than that of mortar M-BPWA
- The substitution of LF by WBP didn't seem to impair the durability of mortars
- It is possible to manufacture SCC by partially or totally substituting LF by WBP

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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