

28 **Keywords:** Concrete; Epoxy; Ground tyre powder; Ductility; Durability; Chloride
29 diffusion;

30

31 **1. Introduction**

32 Ordinary cement concrete is the most widely used construction material in the world
33 due to its low cost and its relatively good strength in compression. However, it presents
34 some drawbacks: its unfriendliness to the environment [1], its porosity (allowing the
35 ingress of deleterious substances such as chlorides and carbon dioxide [2]) which
36 compromises its durability and its low tensile strength and strain ranges [3] which, due
37 to its brittle behaviour, lead to low ductility. Current seismic design is based on the
38 structural performance which forces us to find a balance between structural ductility and
39 structural strength. Concrete with enhanced properties of ductility constitutes a feasible
40 strategy in seismic design. In addition to this, the durability of Reinforced Concrete
41 (RC) structures is becoming an important part of structural design [4]. In this context,
42 the introduction of polymers in ordinary cement concrete is gaining more traction in the
43 field of civil engineering.

44 Polymer-Modified Concrete (PMC) is made by the mixing ordinary cement concrete
45 with polymer additives such as liquid resins, polymer powders, latexes, water-soluble
46 polymers, etc. The incorporation of these polymers improves bond, strength,
47 impermeability, chemical resistance and durability properties of concrete and mortars
48 [5,6]. PMC has typically been used in repair works [7] and non-structural products
49 (waterproofing and anticorrosive finishes) [8]. However, in modern concrete
50 construction the use of PMC for structural applications is increasing day by day [9,10].

51 Polymer Cement Concrete (PCC) is a type of PMC in which a certain percentage of
52 cement is replaced by polymer. One of the polymers suitable for admixing into mortars

53 and PCC is epoxy resin [5,9]. In general, epoxy resin consists of a resin and a hardener
54 which are mixed before use. Mechanical and durability properties of epoxy-modified
55 concrete [9] and structural behaviour of RC members made with epoxy-modified
56 concrete [11,12] have been studied in the literature. Furthermore, mechanical properties
57 of epoxy-modified mortars with and without hardener have also been considered in
58 research [5]. However, little attention has been paid to the effect of partial substitution
59 of cement by epoxy resin (with and without hardener) in concrete ductility and
60 durability properties.

61 Ground Tyre Rubber (GTR) is another polymer suitable to be used in PCC [13]. The
62 growth of the automobile industry in the last years has boosted tyre production,
63 generating massive stockpiles of used tyres. These tyres are non-degradable in nature at
64 ambient conditions and, for this reason, new applications for the reuse of scrap tyre
65 rubber are needed. Numerous studies have investigated the introduction of tyre rubber
66 in concrete to replace fractions of its mineral aggregates, the so-called Crumb Rubber
67 Concrete (CRC) [14–16]. However, the works focusing on concrete mixes in which
68 cement is partially replaced by tyre-rubber powder are limited [13].

69 In this work, the compressive and flexural behaviour of epoxy-modified concrete (with
70 and without hardener) and concrete incorporating ground tyre rubber as partial cement
71 replacement is studied in comparison with traditional concrete. Here, cement
72 replacement is expressed in terms of polymer/cement mass ratio (p/c). Cement is
73 partially replaced by epoxy (p/c of 10%, 15% and 20%, with and without hardener) and
74 ground tyre powder (p/c 2.5%, 5% and 10%). The ability of each mixture to absorb
75 energy during deformation is analysed through the measurement of its toughness
76 (estimated as the area under the stress-strain curve). Chloride ingress into the concrete

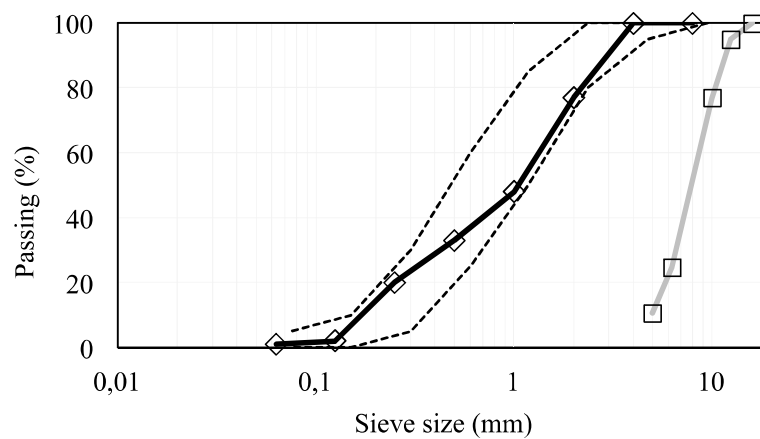
77 matrix is evaluated using an AgNO₃-based colorimetric test for each studied mixture,
 78 with the objective of improving the knowledge of its durability.

79

80 2. Materials and experimental methods

81 2.1 Materials used

82 The aggregates used in this work were siliceous crushed sand (0 – 4 mm) and gravel (4
 83 – 16 mm). Grain size distributions for sand and gravel are shown in Figure 1. The
 84 cement was Ordinary Portland cement CEM I 32.5 R with a relative density of 3
 85 kg/dm³.



86

87 **Figure 1. Sand grading (black thick line) with higher and lower boundaries (dashed black lines)**
 88 **proposed in [17] and gravel grading (grey thick line).**

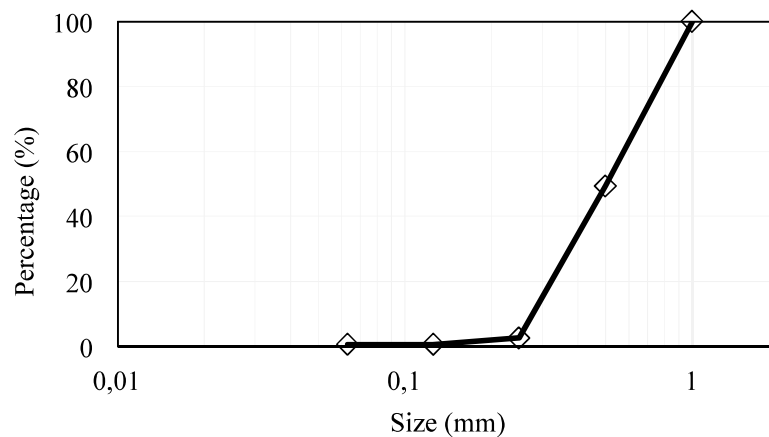
89 Bisphenol A (epichlorhydrin)-type epoxy resin was used. In this work, the term
 90 “Component A” is used to refer to the resin itself and the term “Component B” to the
 91 hardener. Both components were stored at room temperature to avoid damage. The
 92 properties of components A and B are listed in Table 1. The epoxy resin was supplied
 93 by Sika [18].

94 **Table 1. Properties of epoxy resin (components A and B) obtained from data sheet of Sikafloor®**
 95 **161.**

Component	Solid content	Density	Kinematic viscosity	Flash point
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	(% in weight)	(kg/l, 23°)	(mm ² /s, 40°)	(°C)
A	~ 100%	1.6	20.5	ca. 89
B		1.03	ca. > 20.5	> 93.33

106 The ground rubber is a commercial product whose use is widespread. In the sector of
 107 civil engineering it has been used in hot mix asphalt mixture with the aim of
 108 constructing sustainable flexible road pavement. Ground rubber used in this work was
 109 obtained from crumb tyre rubber by grinding it to powder by a mechanical trituration
 110 process. Grain size distributions for ground tyre powder used for replacement of cement
 111 are shown in Figure 2. As can be seen from Figure 2, the particles of ground rubber are
 112 generally between 63 μm and 0.6 mm. The apparent and relative densities of the ground
 113 tyre rubber are 0.4 kg/dm³ and 0.5 kg/dm³, respectively. More information about its
 114 chemical composition can be seen in [19]. In order to enhance the hydrophilicity of the
 115 rubber surface, rubber powder was surface-treated with NaOH saturated aqueous
 116 solution for 20 min as suggested in [20,21].



107
 108 **Figure 2. Tyre rubber powder grading. Adapted from [19]**

109 **2.2 Mixture proportions and mixing procedure**

110 Four types of mixtures have been studied: traditional concrete, hardener-free epoxy-
 111 modified concrete, epoxy-modified concrete with hardener and ground tyre rubber
 112 concrete. In order to have a fair comparison between the different kinds of PCC

113 considered herein and traditional concrete, the following design criteria was adopted (as
 114 shown in [22]):

- 115 – The aggregate content (by weight and volume) of PCC mixes was the same as in
 116 the traditional concrete.
- 117 – The water/cement ratio (w/c) of PCC mixtures was the same as in traditional
 118 concrete.
- 119 – The volume ratio (water + polymer + cement) to aggregate in PCC mixtures was
 120 the same as in traditional mixture.

121 Details of all the mixture proportions considered in this work are given in Table 2. The
 122 first mixture corresponds to the ordinary cement concrete, shown as T (Traditional).
 123 The design compressive strength for the traditional concrete was 30 MPa. In the
 124 hardener-free epoxy-modified concrete mixtures, cement was replaced by epoxy resin
 125 without hardener with p/c 10%, 15% and 20%. These mixtures were shown as EA- x
 126 (only component A, where x is the p/c percentage). In the epoxy-modified concrete with
 127 hardener mixtures, cement was replaced by epoxy resin with hardener with p/c 10%,
 128 15% and 20%. These mixtures were shown as EA+B- x (component A with component
 129 B at a ratio 2.5:1 by volume as specified by the manufacturer, where x is the p/c
 130 percentage). Finally, in the Ground Tyre Rubber (GTR) concrete mixtures, cement was
 131 replaced by ground tyre powder with p/c 2.5%, 5% and 10%. These mixtures were
 132 shown as GTR- x (Ground Tyre Rubber concrete, representing x the p/c percentage).

133 **Table 2. Concrete mixture proportions referring to 1m³ of concrete.**

	Gravel (4-16) (kg)	Sand (0-4) (kg)	Epoxy Component A (kg)	Epoxy Component B (kg)	Ground Tyre Rubber (kg)	Cement (kg)	Water (l)	w/c
<i>Ordinary cement concrete</i>								
T	722	1005	-	-	-	350	210	0.6

Hardener-free epoxy-modified concretes

EA-10	722	1005	32.8	-	-	328	196.8	0.6
EA-15	722	1005	47.7	-	-	318	190.8	0.6
EA-20	722	1005	61.7	-	-	308.6	185.2	0.6
<i>Epoxy-modified concretes with hardener</i>								
EA+B-10	722	1005	26.5	6.0	-	325.1	195.1	0.6
EA+B-15	722	1005	38.4	8.7	-	314	188.4	0.6
EA+B-20	722	1005	49.6	11.1	-	303.5	182.1	0.6
<i>GTR concretes</i>								
GTR-2.5	722	1005	-	-	8.31	332.2	199.3	0.6
GTR-5	722	1005	-	-	15.81	316.1	189.7	0.6
GTR-10	722	1005	-	-	28.8	288.2	172.9	0.6

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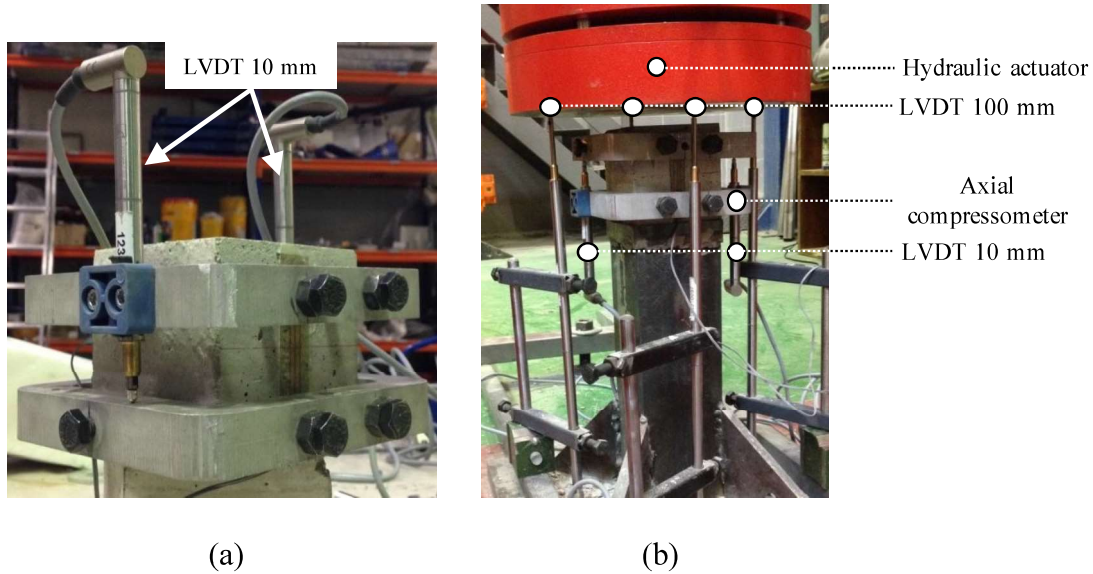
135 For all the considered mixtures, sand and gravel were initially mixed for 1 minute. Then
 136 a small amount of water was added to bring the sand to a saturated-surface-dry
 137 condition. Afterwards, cement was introduced and mixed for 5 minutes. The epoxy
 138 resin (with or without hardener) or the ground tyre rubber was slowly added to the
 139 mixture and mixed for another 5 minutes. Finally, the remaining water was introduced
 140 into the mixture and mixed for another 5 minutes [5].

141 The concrete specimens were cast and properly compacted after mixing. Moulds 100
 142 mm cube and a 100x100x400 mm prism were used for casting test specimens. After 24
 143 hours, they were demoulded and aged at standard temperature and humidity conditions
 144 ($T = 20^{\circ}$ and $RH > 95\%$) until the time of testing.

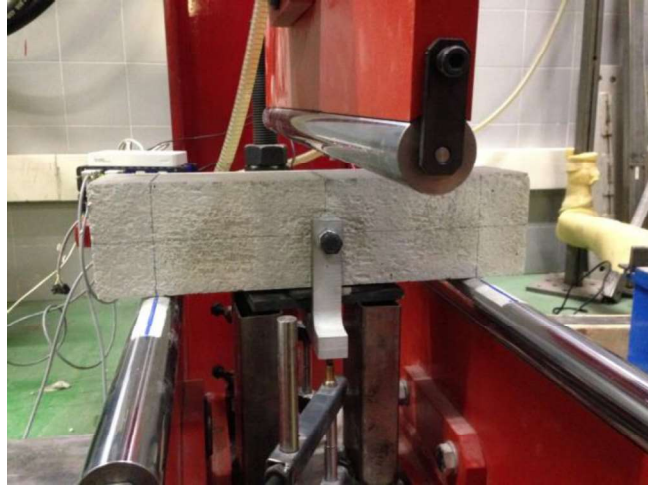
145 **2.3 Mechanical tests**

146 Six cubic specimens with a 100 mm side were used to evaluate the compressive
 147 behaviour of each concrete mixture listed in Table 2. A square compressometer was
 148 used together with two linear transducers LVDT with a range of 10 mm to measure
 149 axial deformation (see Figure 3.a). In addition to this, two strain gauges were also
 150 attached to each cubic specimen (see Figure 3.a). The piston stroke was measured with
 151 four LVDT with a range of 100 mm in order to take into account possible oscillations of

152 the loading plate and to measure the post-peak strain of the specimens (see Figure 3.b).
153 The cubic specimens (casted in steel moulds) were tested at 28 days in a compression
154 test using a hydraulic actuator with a 1000 kN capacity (see Figure 3.b). During the tests
155 the load was increased monotonically in load control with a rate of 5.89 kN/s (0.6
156 MPa/s) according to the European Standard EN 12390-3 [23].



157
158 **Figure 3. Cubic specimen with axial-square compression device (a) and test setup (b).**
159 The stress-strain (σ - ε) curve of each cubic specimen was obtained from the
160 compression test. Special efforts were made to have a high number of readings in the
161 post-peak part of the curve. The compressive strength (f_c) of each concrete mix was
162 computed according to [23]. Flexural strength was obtained using three prism
163 specimens of 100 x 100 x 400 mm dimensions (casted in steel moulds) following the
164 European Standard EN 12390-5 [24] (see Figure 4).



165

166 **Figure 4. Flexural test.**

167 Due to the high rigidity and capacity of the loading steel frame and based on the
168 measured deformation of the auxiliary steel base during the tests, the effect of the
169 stiffness of the loading machine in the measurements can be neglected.

170 ***2.4 Chlorides diffusion test***

171 Non-steady state natural diffusion tests were carried out in order to determine the
172 chloride ingress in all the concrete mixes listed in Table 2. The preparation of the test
173 specimens was the same than in [25], according to the prescriptions proposed in NT
174 Build 443 [26] and in NT Build 492 [27]. Four samples of each type of concrete were
175 immersed in a NaCl solution with a concentration of 165 ± 1 g NaCl per dm^3 at a
176 temperature between 21° and 25° C [26] (see Figure 5). The chloride source solution
177 was renewed periodically in order to maintain a constant chloride source concentration.



178

179 **Figure 5. Concrete samples immersed in NaCl solution.**

180 Two samples of each concrete mixture were removed from the NaCl solution at two
181 different exposure times: 28 and 70 days. Both samples were split perpendicularly into
182 two halves to the exposed surface. As NT Build 492 [27] indicates a sole 0.1M AgNO₃
183 solution was sprayed onto the freshly split surfaces. After the reaction, the chloride-free
184 zone adopts a darker color with respect to the chloride-affected zone and the borderline
185 between both zones is visible. The chloride penetration depth x_d corresponding to an
186 exposure time t is the average value of 5-7 valid readings at intervals of 10 mm of the
187 distance between the exposed surface and the borderline.

188 ***2.5 Chloride penetration formulation***

189 In the civil engineering field the most used method to estimate chloride ingress in
190 concrete is based on Fick's second law [25,28,29]. Even though this method adopts
191 some oversimplified assumptions (concrete is a non-reactive, homogenous and stable
192 material subjected to pure diffusion [30]) it is commonly used due to its applicability
193 and simplicity. The expression of Fick's second law is the following [25]:

194

$$c(x,t) - c_i = (c_s - c_i) \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_{app}t}} \right) \right] \quad (1)$$

195 In Eq.1 $c(x,t)$ is the chloride concentration at a depth x after a time of exposure t , c_i is
 196 the chloride concentration in concrete at time $t = 0$ (initial concentration), c_s the chloride
 197 external concentration, D_{app} the apparent chloride diffusion coefficient and erf the error
 198 function. D_{app} (obtained in non-steady state tests) implicitly takes into account chloride
 199 binding, concrete aging and chloride external concentration [29]. For this reason D_{app}
 200 can be used to predict RC structures service life [31]. In this work, it is considered that
 201 the initial concentration of chlorides in concrete is zero ($c_i = 0$). D_{app} can be computed
 202 by knowing the average chloride penetration x_d corresponding to an exposure time t
 203 using Eq.2 [25] (it is derived from Eq.1 when $c_i = 0$).

$$204 \quad x_d = 2erf^{-1}\left(1 - \frac{c_d}{c_s}\right)\sqrt{D_{app}t} \quad (2)$$

205 In Eq.2 c_d is the chloride concentration at the colorimetric depth x_d and erf^{-1} is the
 206 inverse error function. The chloride concentration c_d is not accurately known. In this
 207 work the value of $c_d = 0.07$ N proposed by NT Build 492 [27] was adopted, and c_s was
 208 assumed to be the chloride concentration of the NaCl solution. Finally, the value of D_{app}
 209 is the average value of four x_d measurements at two different exposure times for each
 210 concrete mix.

211

212 **3. Results and discussion**

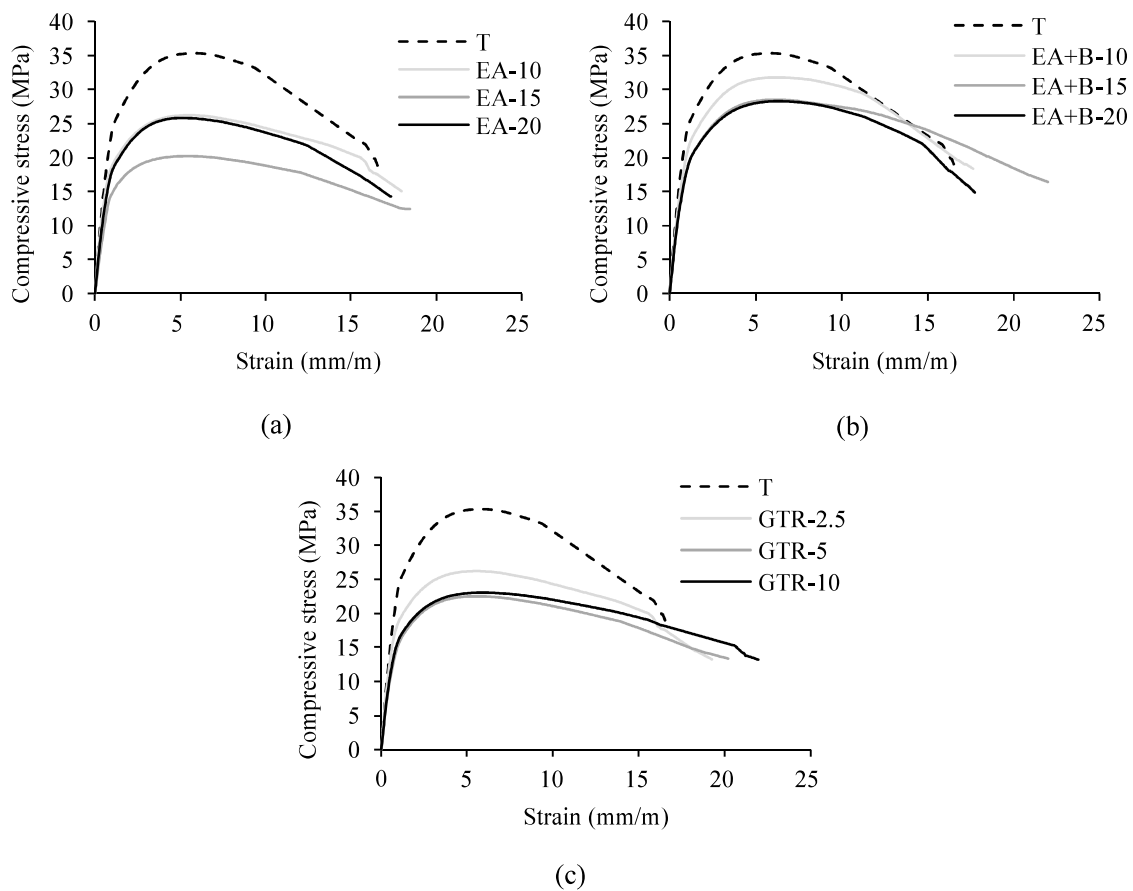
213 **3.1 Stress-strain curves**

214 Stress-strain curves of each concrete mix were calculated using Eq.3 based on the
 215 measured data of axial load and deformation.

$$216 \quad \begin{aligned} \sigma &= N / A \\ \varepsilon &= \Delta l / l \end{aligned} \quad (3)$$

217 In Eq.3 N is the axial load, A is the cross-sectional area of the specimen, Δl is the axial
 218 deformation relative to the initial length of the specimen and l is the initial length of the

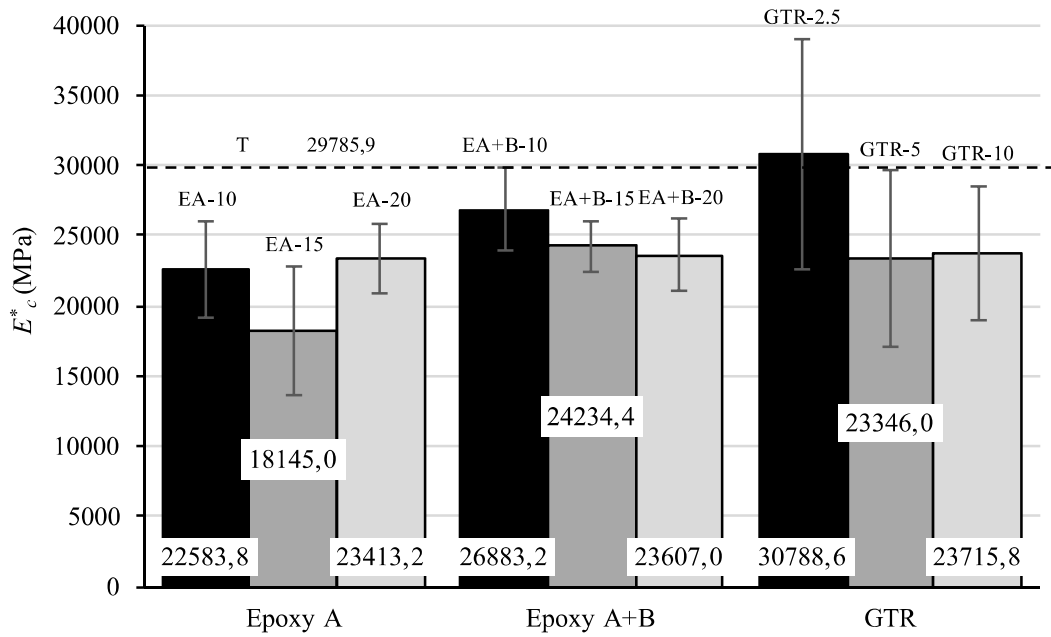
219 specimen. The strain at each stress level was obtained as follows: the strain between the
 220 start of the test and $0.7f_c$ is the average value of strain gauges and axial compressometer.
 221 Because the spalling of the concrete surface for stresses closer to failure distorts the
 222 measurement with both, the strain gages and the LVDT placed at mid-height of the
 223 specimens [32], the strain corresponding to stresses above $0.7f_c$ is taken as the average
 224 value of the strain computed through the piston stroke readings (four LVDT's, see
 225 Figure 3). Variations in readings among the four LVDT that measured the piston stroke
 226 were not significant. As the six cubic specimens had a similar σ - ε curve, an average
 227 curve was chosen. The average stress-strain curves for all mixes of concrete are shown
 228 in Figure 6. All the average experimental stress-strain curves including standard
 229 deviation are shown in Appendix 1.



230
 231 **Figure 6. Stress-strain curves of (a) hardener-free epoxy-modified mixes, (b) epoxy-modified mixes**
 232 **with hardener and (c) ground tyre rubber concrete.**

233 The addition of epoxy resin (with or without hardener) or ground tyre rubber as
234 replacement of cement increased the ultimate strain in comparison with the traditional
235 mix (see Figure 6). The values of strain at peak stress and ultimate strain in Figure 6 are
236 in line with the results obtained by Viso et al. [33] for cubic 100 mm side specimens.
237 Ascending and descending portions of the curves were also affected by the additions
238 (especially the descending part). The descent slope is related to the failure type of the
239 material: a higher slope shows greater fragility and a smaller descent slope shows a
240 better ductility. Figure 6 shows that EA, EA+B and GTR concretes presented a
241 descending part with a slope smaller than traditional concrete. The possible reduction of
242 the brittleness associated with a lower strength of concrete has been neglected in this
243 work because, according to [34], this effect has little influence on concrete when the
244 compressive strength ranging **ranges** from 20 to 40 MPa.

245 Stress-strain curves also show the elastic response of each mix. The slope of the least-
246 squared best-fit line through the points of the σ - ε curve between the start of the test and
247 $0.3f_c$ was computed. This slope (noted in this work as E_c^*) it is not strictly speaking the
248 elastic modulus of concrete (E_{cm}), but it reflects the elastic response of concrete. The
249 computation of E_{cm} was out of the scope of this research. Figure 7 shows E_c^* of all the
250 tested concretes. As in the compressive strength, the values presented in Figure 7 for
251 each concrete mix are the average values of the 6 tests. In line with the experimental
252 results presented in [13], the obtained results confirm that replacing cement for ground
253 tyre powder will reduce E_c^* of the resultant concrete. Something similar occurs with the
254 EA and EA+B mixes, with the exception of the EA-20 mix. In any case, the value of E_c^*
255 for all the studied mixes is lower than the computed for traditional concrete.



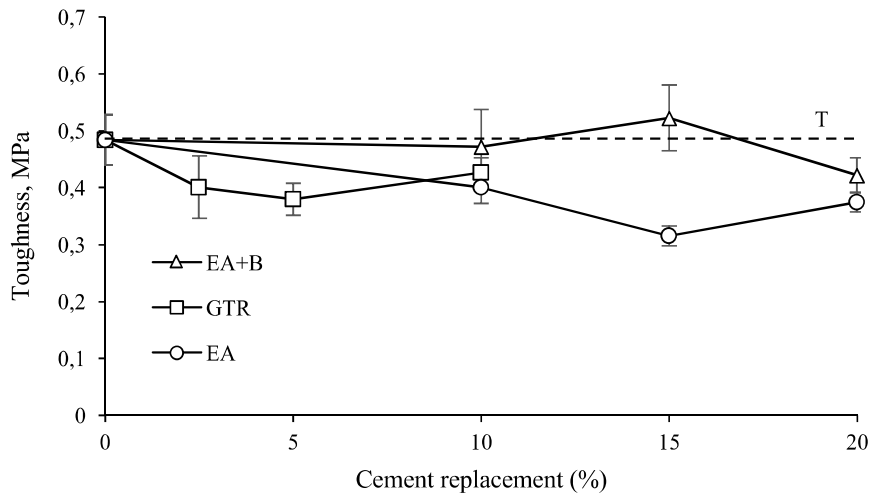
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257 **Figure 7. E_c^* of T, EA, EA+B and GTR concretes (error bars indicate the standard deviation).**

258 **3.2 Toughness**

259 The energy absorption capacity (i.e. toughness) of concrete subjected to axial
 260 compression was defined as the area under the stress-strain curve. Figure 8 shows the
 261 calculated results of the toughness for all mixes of concrete considered in this work.
 262 Figure 8 shows that only EA+B-10 and -15 mixes had a higher toughness than
 263 traditional concrete.

264 In GTR and EA mixes, toughness exhibits an initial decreasing tendency with the
 265 increase of cement replacement but toughness increased again for the higher percentage
 266 of p/c considered for both GTR and EA mixes (see Figure 8).



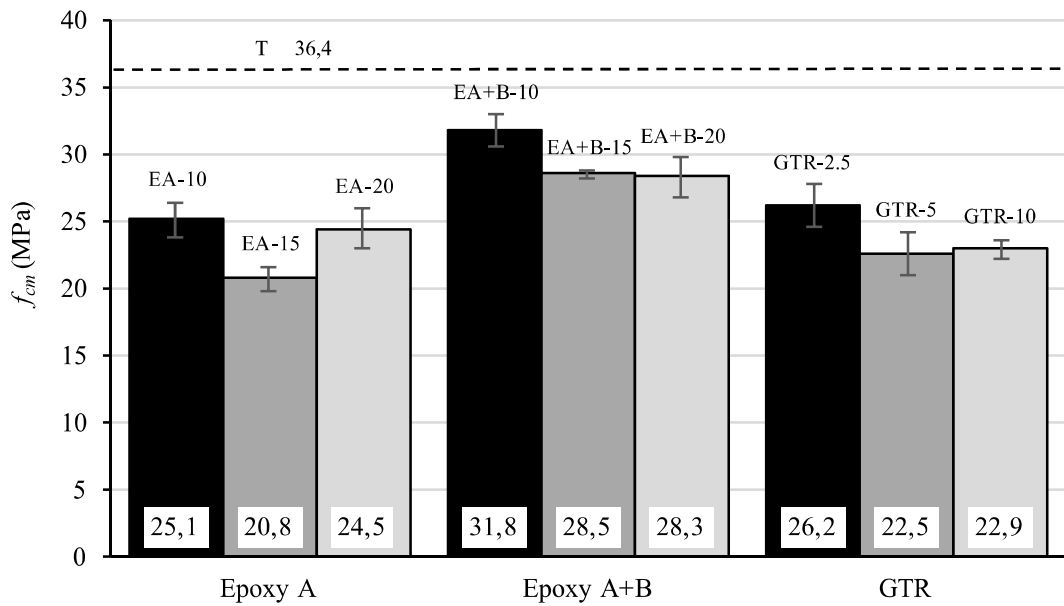
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268 **Figure 8. Changes in toughness values for the mixes listed in Table 2 (error bars indicate the**
 269 **standard deviation).**

270 **3.3 Compressive strength**

271 The results of 28-day compressive strength tests for concrete mixes are shown in Figure
 272 9. The compressive strength (f_{cm}) was computed as the average value of the maximum
 273 compressive stress registered in each of the 6 compressive tests carried out for each
 274 concrete mix. As Figure 9 shows, in all the cases the compressive strength is lower than
 275 the one of the traditional mix. In general, f_{cm} had a tendency to decrease with the
 276 increase of the percentage of cement replacement (in the range of the percentages of
 277 cement replacement considered in this work). Only EA mixes had an increase of f_{cm}
 278 with the increase of epoxy content in the case of EA-20 mix (authors have verified
 279 twice these results experimentally). In the case of EA and EA+B mixes, a reduction of
 280 11-22% and 30-43% respectively of the compressive strength with respect to traditional
 281 concrete was observed. It can be noted that EA mixes showed a lower compressive
 282 strength than EA+B mixes. This could be because an excess of unhardened epoxy resin
 283 left inside the concrete paste probably disrupted the hydration process [5]. Finally, in
 284 line with other research works, the strength of concrete mixtures containing ground tyre

285 powder as cement was reduced [13]. Replacements of 2.5, 5 and 10 % of ground tyre
 286 powder reduced the strength by 28-37% with respect to T mix.

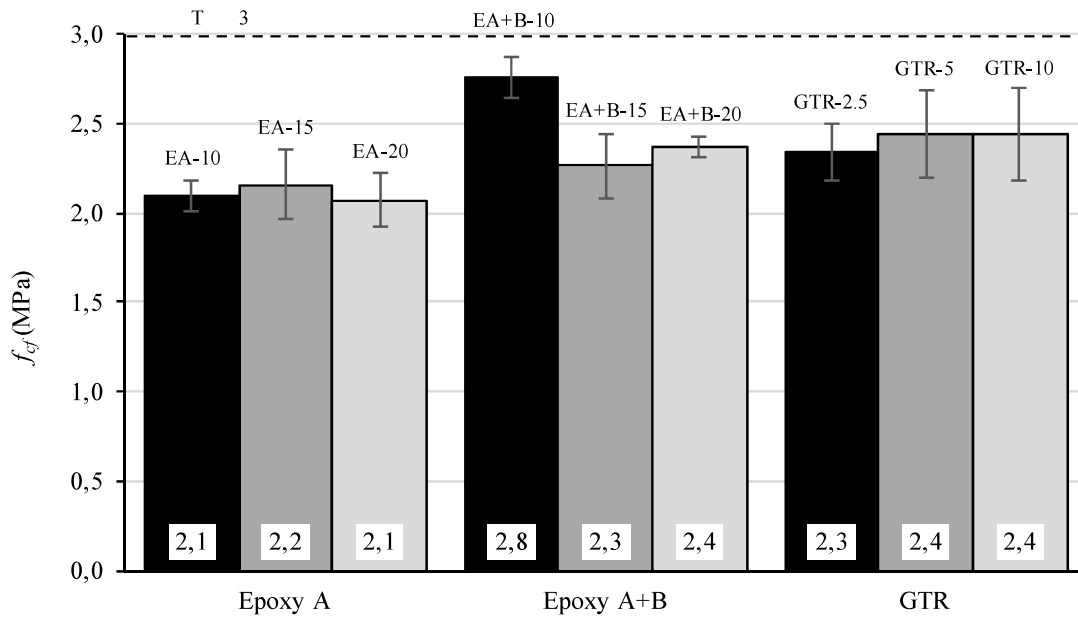


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288 **Figure 9. Compressive strength of T, EA, EA+B and GTR concretes (error bars indicate the**
 289 **standard deviation).**

290 **3.4 Flexural strength**

291 The results of flexural strength tests are shown in Figure 10. As expected, the
 292 replacement of ground tyre rubber and epoxy resin reduced flexural strength (f_{cf}) of the
 293 resultant concrete. In EA, EA+B and GTR mixes, a reduction of the flexural strength of
 294 27-30%, 7-24% and 18-21% respectively was obtained with respect to the traditional
 295 mix. GTR and EA mixes showed an almost constant value of f_{cf} regardless of the % of
 296 replacement of cement.



297

298 **Figure 10. Flexural strength of T, EA, EA+B and GTR concretes (error bars indicate the standard**
 299 **deviation).**

300 **3.5 Durability tests**

301 Chloride -free and -affected zones were visible after approximately 10 minutes from the
 302 spray test. In all the mixes the chloride-affected zone adopted a purple color, whereas
 303 the chloride-free zone turned into a dark brown color (see Figure 11).



304

305 **Figure 11. EA-10 concrete samples sprayed with 0.1 M AgNO₃ solution at 28 days.**

306 The chloride penetration depth x_d corresponding to an exposure time t was measured in
 307 two ways: with a slide calliper [27] and using an image editing software. A total of four
 308 values of x_d were obtained for each concrete mix and exposure time. Due to some
 309 problems with the epoxy-based paint coating of GTR samples, only the results
 310 corresponding to 28 days was measured for these mixes. The apparent diffusion

311 coefficient D_{app} of each concrete mix was calculated using Eq.(2) together with the
 312 measured values of x_d (see Table 3).

Concrete Mixtures	D_{app} (mm ² /year)	
	28 days	70 days
T	773,5	738,0
EA-10	353,4	369,3
EA-15	330,5	331,7
EA-20	306,8	326,7
EA+B-10	539,4	542,1
EA+B-15	524,9	528,7
EA+B-20	499,1	492,4
GTR-2.5	817,0	-
GTR-5	848,4	-
GTR-10	940,4	-

313 **Table 3. Apparent diffusion coefficients (D_{app}) for each concrete mixture tested.**

314 As can be seen from Table 3, the values of D_{app} corresponding to different exposure
 315 times were very similar. Regardless of the addition of hardener, both epoxy-modified
 316 concretes showed lower values of D_{app} than the traditional mix. Furthermore, in both
 317 epoxy-modified mixtures D_{app} decreases as the percentage of epoxy increases. This is
 318 because voids in the granular skeleton are filled with epoxy resin, decreasing the
 319 porosity of the resultant mix [5,35,36]. The apparent diffusion coefficient of epoxy-
 320 modified concretes without hardener at all the same epoxy percentages was smaller than
 321 that with the hardener. This higher resistance to chloride ion penetration is directly
 322 related to the water absorption [35] being the number of capillary pores in epoxy
 323 cement mortars without hardener lower than that with hardener [35]. The hardening
 324 reaction of the epoxy resin progresses at the surface of the epoxy resin phase, the pores
 325 being filled with hardened and unhardened resins. Water absorption decreases with
 326 increasing epoxy-cement ratio due to the presence of the unhardened resin, which is
 327 waterproof [35,37]. This water impermeability provides the lower chloride diffusion
 328 coefficient of the epoxy-modified concrete without hardener.

329 Furthermore, GTR concretes had a higher value of D_{app} in comparison with the
330 traditional mix. As a consequence of the lack of good bonding between rubber powder
331 and cement paste, the interface surface between them act as a way for water to flow into
332 the concrete [13]. For this reason, D_{app} increases as the rubber content increases.

333 The values of D_{app} obtained in this experimental campaign are in accordance with the
334 results shown in [31], where D_{app} of a considerable number of traditional concretes was
335 calculated using colorimetric methods. The values of D_{app} obtained for traditional
336 concretes range between $2.1 \cdot 10^{-12}$ and $29.8 \cdot 10^{-12}$ m²/s (66.2 – 939.8 mm²/year), all
337 referred to free chloride content. These values are in agreement with the results obtained
338 for epoxy-modified concretes with and without hardener and with ground tyre rubber
339 concretes.

340

341 **4. Conclusions**

342 In this work, the use of epoxy resin with and without hardener and ground tyre rubber as
343 a partial substitution of cement in concrete has been studied. Concrete mixtures with
344 different percentages of replacement of cement have been produced. The influence of
345 percentage of replacement on the mechanical and durability properties of the resultant
346 concrete has been experimentally determined. Based on the results obtained in this
347 research (and taking into account the percentage of cement replacement considered), the
348 following conclusions can be drawn:

349 1) The use of ground tyre rubber as cement replacement leads to a reduction of the
350 strength and durability properties of the resultant concrete.

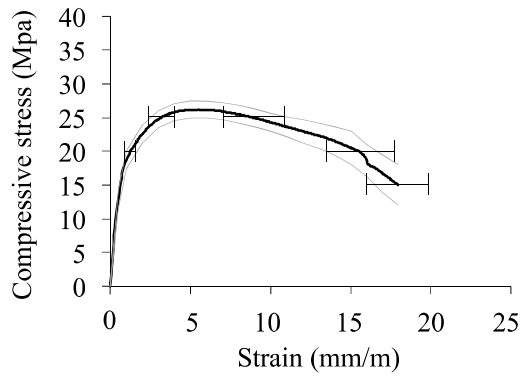
351 2) Concrete with ground tyre rubber presents a flatter post-peak branch in the
352 stress-strain and a larger ultimate strain. These properties make these mixtures
353 potentially interesting for seismic design.

- 354 3) The addition of epoxy resin with and without hardener and ground tyre rubber
355 instead of cement increases the ultimate strain with respect to conventional
356 concrete. In addition to this, a change on the descending part of the stress-strain
357 curve is observed, showing a better ductility.
- 358 4) The compressive and flexural strength of each polymer cement concrete
359 considered in this work are lower than the one obtained for traditional concrete.
- 360 5) Epoxy without hardener as cement replacement has shown worse mechanical
361 characteristics than its counterpart epoxy with hardener. Conversely, concrete
362 mixtures with epoxy without hardener as cement replacement has shown the
363 highest durability against chloride penetration.
- 364 6) Colorimetric methods based on AgNO_3 solutions can be used for the
365 determination of chloride ingress into all the polymer cement concretes
366 considered (chloride-free and affected zones were clearly visible).
- 367 7) The replacement of 15% of cement with epoxy with hardener is recommended to
368 achieve a higher resistance to chloride ingress and a slightly higher toughness
369 with respect to traditional concrete. Furthermore, the concrete compressive and
370 flexural strength are acceptably reduced.

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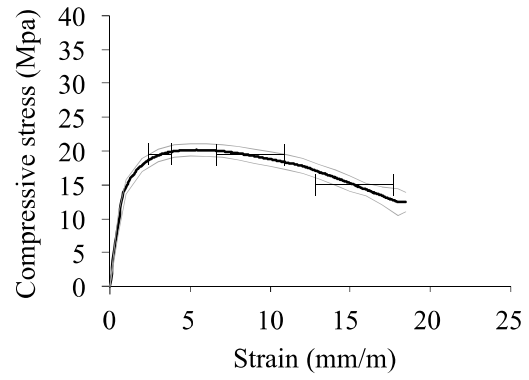
372 **Appendix 1**

373 Experimental stress-strain curves obtained for the concrete mixtures studied in this work
374 are shown in Figure 12.

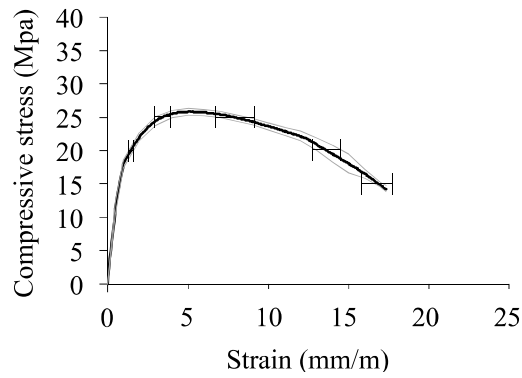


375
376

(a)

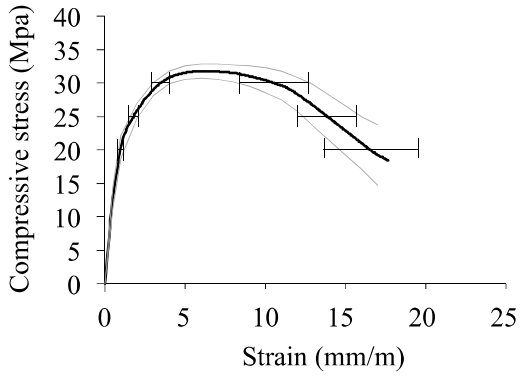


(b)

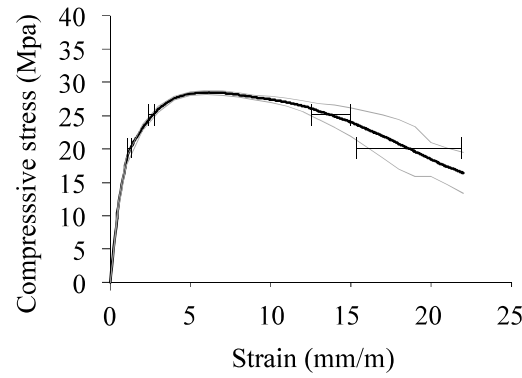


377
378

(c)

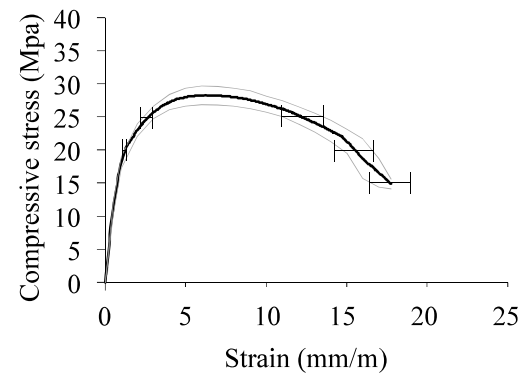


(d)

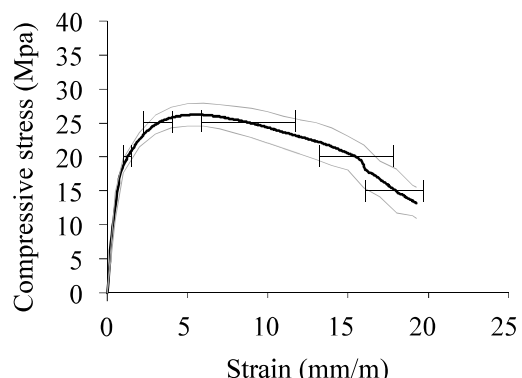


379
380

(e)

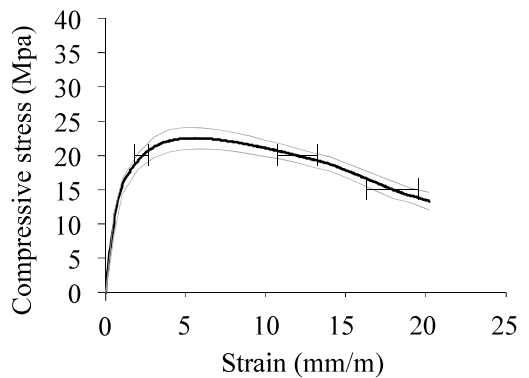


(f)

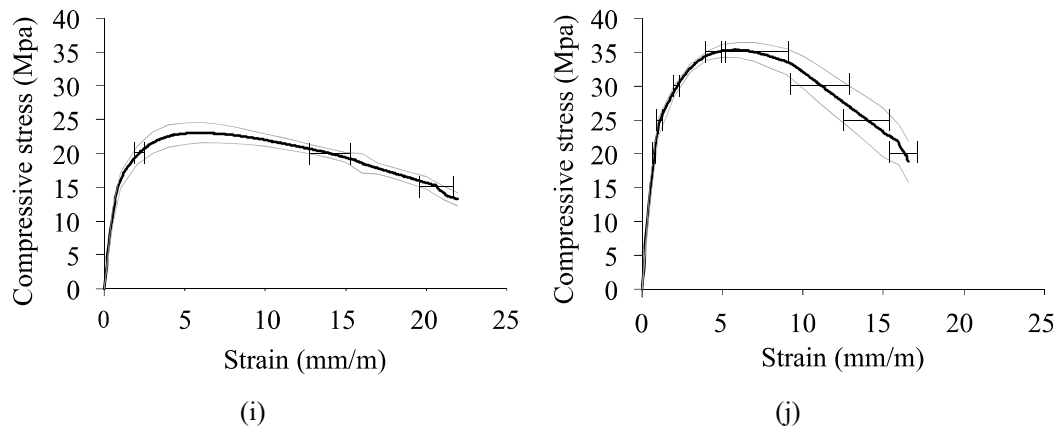


381
382

(g)



(h)



383
384

385 **Figure 12. Average stress-strain curves of all the types of concrete tested (black thick curves). Grey**
 386 **curves correspond to the standard deviation of compressive stress and black error bars correspond**
 387 **to the standard deviation of strain. EA-10 (a); EA-15 (b); EA-20 (c); EA+B-10 (d); EA+B-15 (e);**
 388 **EA+B-20 (f); GTR-2.5 (g); GTR-5 (h); GTR-10 (i); T (j).**

389

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398

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