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1 Shrinkage properties of plain and recycled steel–fibre-reinforced 2 rapid hardening mortars for repairs

3 Hajir Al-musawi ^{a,*}, Fabio P. Figueiredo ^a, Maurizio Guadagnini ^a, Kypros Pilakoutas ^a

4 ^a*Department of Civil and Structural Engineering, The University of Sheffield, Sir Frederick Mappin Building,*

5 *Mappin Street, S1 3JD Sheffield, UK.*

6 * Corresponding author's email: Haal-musawi1@sheffield.ac.uk Tel: +44 (0) 114 222 5729, Fax: +44 (0) 114

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8 HIGHLIGHTS

- 9 • Non-uniform drying of rapid hardening overlays can lead to cracking and delamination.
- 10 • Mixes with CSA cement showed much lower shrinkage strains than mixes with RSC cement.
- 11 • RSC and FRSC mixes showed considerable autogenous shrinkage at the age of 60 days.
- 12 • FE analysis were used to predict shrinkage development using hygral contraction coefficient.
- 13 • Creep plays an important role in moderating stresses of overlays.

14 Abstract

15 This article investigates the time dependent transport properties and shrinkage performance of rapid
16 hardening plain and fibre reinforced mortars for repair applications. Two plain and two SFRC mixes
17 with 45 kg/m³ of recycled clean steel fibers made with rapid hardening cements (CSA - calcium
18 sulfoaluminate cement and RSC - calcium aluminate cement) are studied. It is found that mixes with
19 CSA cement have much lower shrinkage values (around 220 and 365 microstrains) compared to mixes
20 with RSC cement (around 2690 and 2530 microstrains), but most of the shrinkage in these mixes is
21 autogenous. Nonetheless, fibres reduce the drying shrinkage of RSC cement mixes by approximately
22 12%. Model code 2010 and ACI equations can be used to estimate the shrinkage development with

23 time for these mixes provided suitable parameters for each cement type are adopted. Inverse analysis
24 using finite element method is successfully employed to determine the moisture diffusivity and the
25 hygral contraction coefficient of each mix. A comparison is made between the values of shrinkage
26 strain predicted by the numerical models over time, for different depths, and code equations. A simple
27 analytical procedure is used to assess cracking and/or delamination risks due to restrained shrinkage
28 for these materials in overlay applications.

29 **Key words:** SFRC, rapid hardening cements, shrinkage and transport properties, FE analysis

30 **1. Introduction**

31 Concrete overlays are extensively used in the repair and strengthening of concrete structures either
32 to replace damaged concrete or directly cast as a new layer. In both applications, moisture from the
33 fresh layer does not only diffuse to the environment, but also to the concrete substrate, resulting in
34 faster drying shrinkage. Shrinkage is restrained by the substrate layer leading to tensile and interfacial
35 shear stresses in the repair layer. These stresses, if they exceed material capacity, can lead to cracking
36 and/or debonding, accelerating the deterioration of the repairs [1]. The cracking potential of repairs
37 increases in rapid hardening materials that are often used to minimise disruption during repair works,
38 due to faster shrinkage rate [2] and lower creep compliance [3].

39 Although fibres are reported to have a marginal effect in preventing shrinkage strains from developing
40 in concrete, they are used to control crack widths [4] as well as increase tensile strength and fatigue
41 resistance [5] in an attempt to achieve more durable repair layers. To reduce the environmental
42 impact of manufactured steel fibres (MSF), recycled clean steel fibres can also be used as alternative
43 fibre reinforcement [6, 7].

44 Recycled clean steel fibres (RCSF) were obtained by recycling steel fibre cords, left over from the
45 manufacture of tyres. As a result, they have a consistent length as opposed to recycled tyre steel fibres

46 (RTSF) which are extracted mechanically from post-consumer tyres and, thus, have more variable
47 lengths.

48 Since crack width is one of the main parameters that governs the durability of repairs [8], a thorough
49 understanding of the effect of moisture movement and restraint from the substrate is needed to
50 predict crack development in concrete, a material which has widely varied and dynamic porosity
51 systems [9]. The moisture transport mechanism of cementitious mixes is complex and is the subject
52 of extensive research [9-17]. FRC mixes, however, have been studied to a lesser extent [15, 18]. It is
53 known that w/c ratio, cement content and cement type, directly affect moisture diffusion. Fibres may
54 also affect the moisture transport properties of concrete by changing the porosity structure and thus
55 their effect needs to be better understood.

56 Silfwerbrand [19] provided an analytical procedure to calculate the tensile and shear stresses that
57 develop in overlaid concrete layers and determine the risk of cracking and/or delamination. However,
58 this procedure does not calculate cracking widths, a vital aspect in predicting concrete performance.
59 Eurocode 2 (EC) [20], Model Code 2010 (MC) [21] and ACI 209.2R-08 (ACI) [22] provide procedures to
60 predict shrinkage strain evolution for concrete structures of certain cement types with good accuracy.
61 However, they do not account for rapid hardening cements for which often little information is
62 provided by manufacturers other than setting time and strength. They also do not consider the effect
63 of fibres on concrete shrinkage strain in the predictive equations.

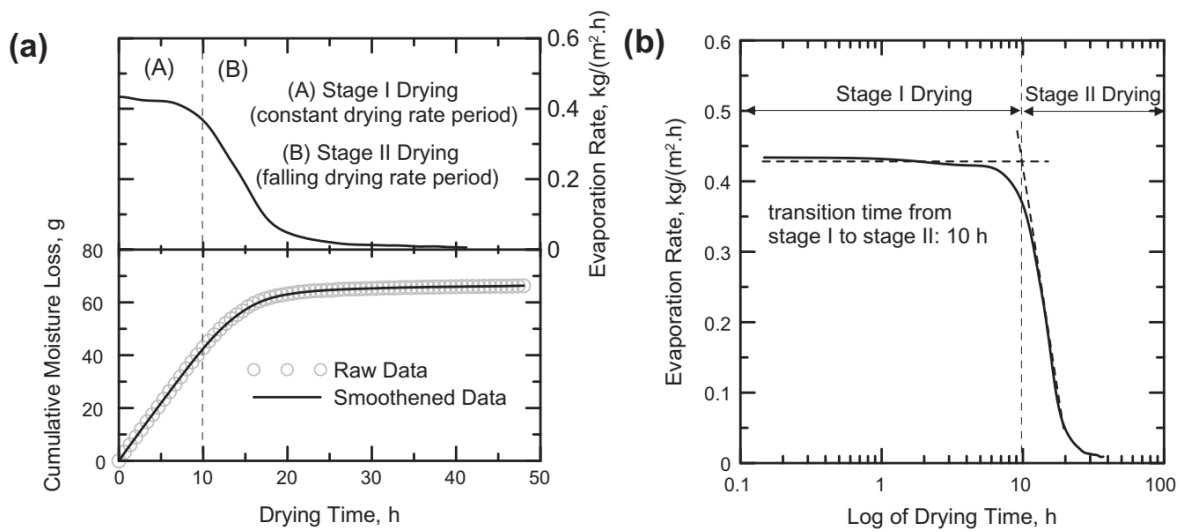
64 This paper presents a detailed investigation on the time dependent transport properties and shrinkage
65 performance of rapid hardening plain and fibre reinforced mortars for repair applications. It starts by
66 reviewing the factors involved in diffusion and shrinkage of both plain and FRC mixes. It then presents
67 experimental work on moisture movement and shrinkage. The results are used in inverse analysis to
68 determine the moisture diffusion coefficient, surface factor and shrinkage hygral coefficient which are
69 needed to predict shrinkage performance. The available code procedures to predict the shrinkage of

70 these mixes over time are also evaluated and new factors for each cement type are proposed. The
71 Silfwerbrand procedure is then used to determine cracking and delamination risks.

72 **2. Moisture diffusion and shrinkage**

73 Moisture movement during drying of concrete is characterised by two stages; a constant drying rate
74 stage which is succeeded by a falling drying rate [12, 15, 23], depending on the degree of continuity
75 between liquid and vapour phases and on driving force variations [16]. At the beginning of drying, the
76 evaporation rate is constant and is approximately equal to the rate of evaporation of water exposed
77 to the same conditions [24-25]. As the cementitious material is fully saturated, there is no hydraulic
78 potential gradient to drive the moisture movement inside the porous medium and the internal vapour
79 pressure is equivalent to the saturated vapour pressure. However, at the boundary layer, there is a
80 pressure variation from saturated vapour pressure to ambient vapour pressure, driving moisture out
81 to the surrounding air. Moisture evaporation at the surface causes a slight reduction in vapour
82 pressure [16]. This small vapour pressure gradient is sufficient to cause moisture flow towards the
83 surface, since at this stage the hydraulic diffusivity is high [26]. As drying continues, moisture
84 decreases inside the material. Drying is still considered to be in stage one as long as the capillary
85 system is saturated. When the liquid phase becomes discontinuous upon further drying, a transition
86 from stage one to stage two takes place, at which diffusion of water vapour becomes the dominant
87 mechanism for moisture transport [26]. During this stage, the evaporation rate drops, as moisture is
88 only limited to movement of water vapour rather than liquid water diffusion [27] as is the case in the
89 first stage, and the vapour pressure falls below the saturation vapour pressure value. The moisture
90 content continues to decrease until vapour pressure reaches ambient level. Figure 1 shows a typical
91 cumulative moisture loss and evaporation rate during stage one and stage two for a cement paste
92 sample [15]. It is shown that during stage one, the drying behaviour is independent of capillary
93 microstructure [26]. In a study performed by Bakhshi & Mobasher [15] to investigate the effect of

94 curing time on the diffusion characteristics of cement paste, it was found that the moisture loss was
 95 substantially reduced by curing the cement paste for 24 hours and the transition from stage one to
 96 stage two took place quicker compared to non-cured samples. This can be attributed to
 97 microstructural and pore distribution changes with additional hydration. It can be argued that for fast
 98 setting materials, stage one is expected to be much shorter than for conventional mortar, as most
 99 hydration takes place during the first few hours and phase transition happens faster. This will be
 100 investigated in this paper to understand the role of cement type on diffusion properties.



101

102 **Figure 1.** Typical cumulative moisture loss and evaporation rate of a cement paste sample versus time: (a) in
 103 linear scale; (b) in log scale [15]

104 Fick's second law (Equation 1) can be used to model moisture movement in concrete for various stages
 105 of drying, with a moisture diffusivity that represents liquid and vapour diffusion [16].

106
$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \quad \text{Equation 1}$$

107 where C is the moisture concentration (kg/m^3), D is the moisture diffusion coefficient (m^2/s) and t is
 108 time (s).

109 As the moisture transfer equations are analogous to heat transfer equations and heat transfer analysis
110 is readily available in FEA packages, this analogy is often exploited for moisture transfer studies [16,
111 18, 28].

112 Another important factor in moisture distribution problems is the surface factor or convective factor
113 (f). This factor determines the moisture exchange between the concrete surface and the atmosphere.
114 It depends on several other factors like the w/c ratio [11] and wind speed [29]. A wide range of surface
115 factors is reported in literature [(0.75-7.5 mm/day [11]), 18, 29]. However, this parameter can be
116 determined by inverse analysis for specific mortar mixes to improve the accuracy of the predicted
117 moisture distribution.

118 The hydro-shrinkage coefficient (also called hygral contraction coefficient) is a factor that links free
119 shrinkage strain to moisture content. It is a unique material property for each mix type. An exponential
120 relationship was found by Ayano and Wittmann [13] while Huang et al. [28] used a linear relationship
121 to simulate non-linear shrinkage in box girders. This factor can also be obtained through inverse
122 analysis.

123 **3. Experimental program**

124 **3.1. Mix proportions**

125 Two plain and two SFRC mixes with 45 kg/m^3 ($V_f = 0.57\%$) of recycled clean steel fibres (RCSF) were
126 investigated in this study, details of which are given in Table 1. Two commercial cement types were
127 used: calcium sulfoaluminate cement (CSA); and rapid setting calcium aluminate cement (RSC). River
128 washed sand (0-5mm, SG=2.65) was used as fine aggregates. The length of the RCSF used in this study
129 is 21 mm and the diameter is 0.2 mm. Further details on the mixes and material characteristics are
130 given elsewhere [6].

131 **Table 1**

132 Mix proportions

Mix	Cement (kg/m ³)	w/c	SP ^a	Sand (kg/m ³)	Fibre dosage (kg/m ³)
CSA	600	0.40	0.6	1420	0
FCSA	600	0.41	0.61	1420	45
RSC	600	0.35	0.2	1300	0
FRSC	600	0.36	0.21	1300	45

133 ^a % by cement mass.

134 **3.2. Flexural and Compressive strength**

135 To characterize the flexural performance, mortar prisms of 40*40*160 mm were tested according to
 136 BS EN 13892-2, (2002) [30] in displacement control to better capture the post-peak behaviour. A
 137 specially designed aluminum yoke (based on the Japanese standard JSCE-SF4 [31]) was mounted on
 138 the specimens. The prisms were tested at different ages ranging from one hour up to one year to
 139 assess the flexural behaviour over time. After flexural testing, the two parts of the fractured prisms
 140 were tested under uniaxial compressive loading according to BS EN 13892-2, (2002) [30]. The results
 141 in terms of first cracking strength ($f_{ctm,fl}$) and compressive strength (f_{cu}) (associated standard deviation
 142 is given in brackets) are shown in Table 2.

143 **Table 2**

144 Flexural strength ($f_{ctm,fl}$) and compressive strength (f_{cu}) for all mixes (MPa)

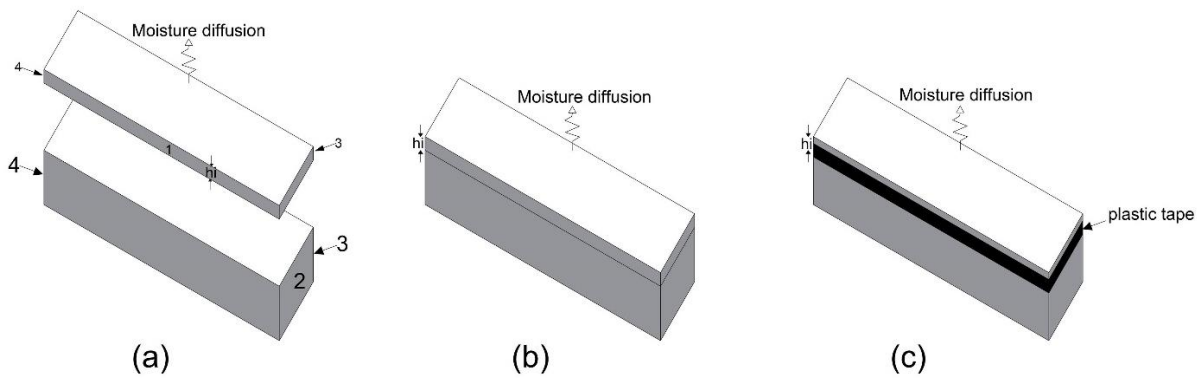
Time (Days)	FCSA		FRSC		CSA		RSC	
	$f_{ctm,fl}$	f_{cu}	$f_{ctm,fl}$	f_{cu}	$f_{ctm,fl}$	f_{cu}	$f_{ctm,fl}$	f_{cu}
(1hr) 0.0417	3.52	26.13 (4.61)	3.52	21.34 (3.04)	2.58	21.14 (2.96)	2.53	17.23 (1.92)
(3hrs) 0.125	6.76	31.55 (3.69)	3.54	28.29 (3.54)	3.98	26.92 (2.78)	2.86	24.16 (2.04)
1	6.46	36.60 (2.27)	4.98	37.92 (2.40)	4.34	31.75 (2.51)	3.54	33.01 (2.00)
7	8.18	41.05 (3.27)	5.54	46.16 (3.20)	5.30	35.97 (3.02)	4.22	40.38 (2.43)
28	8.67	43.13 (3.23)	5.65	51.52 (2.88)	5.37	38.62 (2.30)	4.39	46.51 (2.61)
365	8.67	45.47 (3.03)	5.63	54.49 (6.64)	5.40	40.90 (2.27)	4.48	48.09 (3.74)

145

146 **3.3. Moisture measurement in mortars**

147 To obtain the time history of the moisture profile, needed to obtain the moisture diffusivity of the
 148 repair layers, the modified gravimetric method was adopted following the approach of Jafarifar [18].
 149 It involves casting all specimens at the same height and then cutting them at different depths before
 150 putting them back together. Thus, the boundary condition from the underlying depth of the concrete
 151 specimens is preserved by keeping both segments in contact for the duration of the measurements.

152 The specimens were cast in 200*50*50 mm steel moulds. After around the expected setting time,
 153 water was added to the samples, while still in the moulds and they were covered with plastic sheets
 154 to prevent moisture evaporation. The setting time of cement pastes was assessed by the authors [6]
 155 using an automatic Vicat apparatus according to ASTM C191 (2013) [32]. The final setting time for CSA,
 156 FCSA, RSC and FRSC were 10.5, 11, 14.5 and 15 minutes. After around 40 minutes of curing, the
 157 samples were demoulded. Each prism was then immediately sliced into two segments at the
 158 prescribed depths of 10, 20, 30 mm, under wet conditions. Their weights were recorded, and the
 159 specimens were directly wrapped with cling film and sealed using a high performance ply laminated
 160 plastic foil tape. The surfaces 1-5 for the bottom segment and 1-4 for the upper part of the sliced
 161 specimens were sealed separately [Figure 2], creating one dimensional drying conditions.



162 (a) (b) (c)

163 **Figure 2.** Sealing specimens for the modified gravimetric method

164 After each weight measurement, the two segments were assembled back together [Figure 2] and the
 165 joint was sealed using a new plastic tape [Figure 2]. The weight measurements were taken at one hour

166 and a half, three hours, one day and every day for one week. They were then recorded every week for
167 one month and monthly for four months. After four months, the specimens were unwrapped and
168 dried in the oven for ten days at 70 C⁰. After that, the two parts of each prism were weighed. The
169 details of how to determine the moisture content at each depth over time is given in [11,18].

170

171 **3.4 Free shrinkage measurement**

172 The ASTM C157/C157M (2008) standard [33] for measuring shrinkage of mortars adopts prisms of
173 dimension of 25*25*285 mm. However, due to the use of fibres with a length of 21 mm and to
174 minimize the boundary effects, it was decided to use bigger prisms of 40*40*160 mm instead. As for
175 the specimens used for moisture transport studies, the specimens were cured for around 40 minutes
176 in the moulds. After the curing, the specimens were demolded and demec points were attached to
177 them. The total number of shrinkage samples for each mix was six prisms. Three prisms were kept in
178 an environmental chamber with a relative humidity of 40±3% and temperature of 21±2 C⁰ to measure
179 the total shrinkage while the other three prisms were wrapped in cling film and left in a mist room to
180 measure their autogenous shrinkage. After that, they were only unwrapped to take measurements.
181 Shrinkage was measured on both faces of each prism using a 100 mm Demec gauge. The shrinkage
182 measurements started at one hour and a half and continued at frequent time intervals up to 120 days.

183 **4. Experimental results and discussion**

184 **4.1. Moisture measurements**

185 The time history of moisture content for each mix is shown in Figure 3. Each curve represents the
186 mean value of two samples. The results confirm that drying is non-uniform across the depth of the
187 specimens with faster drying at the top. For all the mixes, the water content of the upper layer ranges

188 between 0.59 – 0.62 compared with 0.67 – 0.78 for the lower layers.

189 At the beginning of drying, the rate of drying is relatively faster for RSC and FRSC mixes compared to
190 specimens with CSA and FCSA mixes. However, the rate of drying slows down towards the end of the
191 drying period. The experimental moisture profiles are used in the following section to back calculate
192 moisture diffusivity and surface factor for each mix.

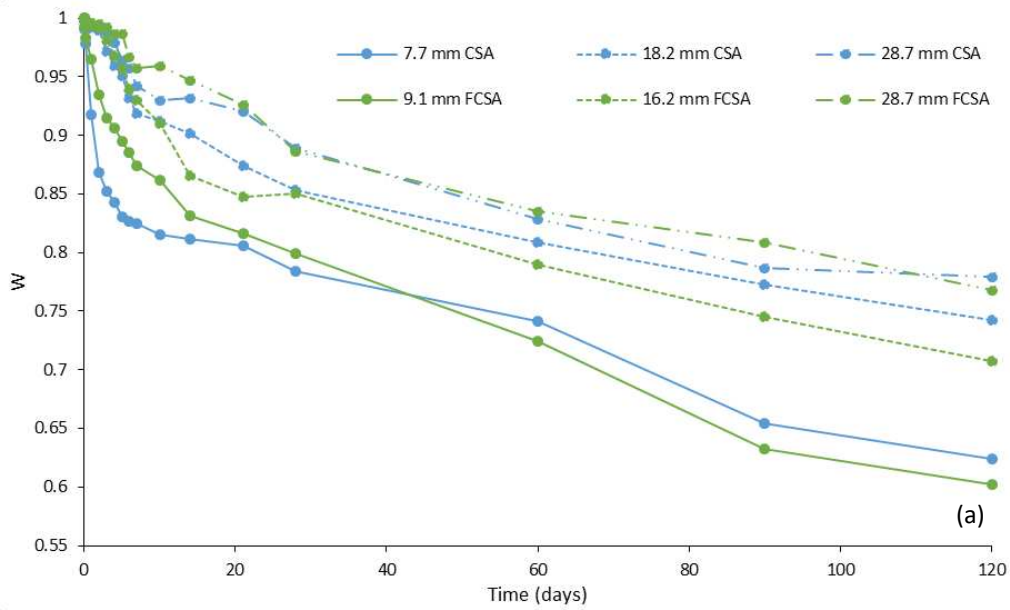
193 Although literature states that fibre may affect the moisture transport properties of concrete, in this
194 article, however, the fibre inclusion was confirmed not to have a major role on the moisture transport
195 properties of rapid hardening mortar mixes, which allows the use of the MC equation [21], that is
196 usually used to estimate the moisture diffusivity of plain concrete, to calculate their moisture
197 diffusivities.

198

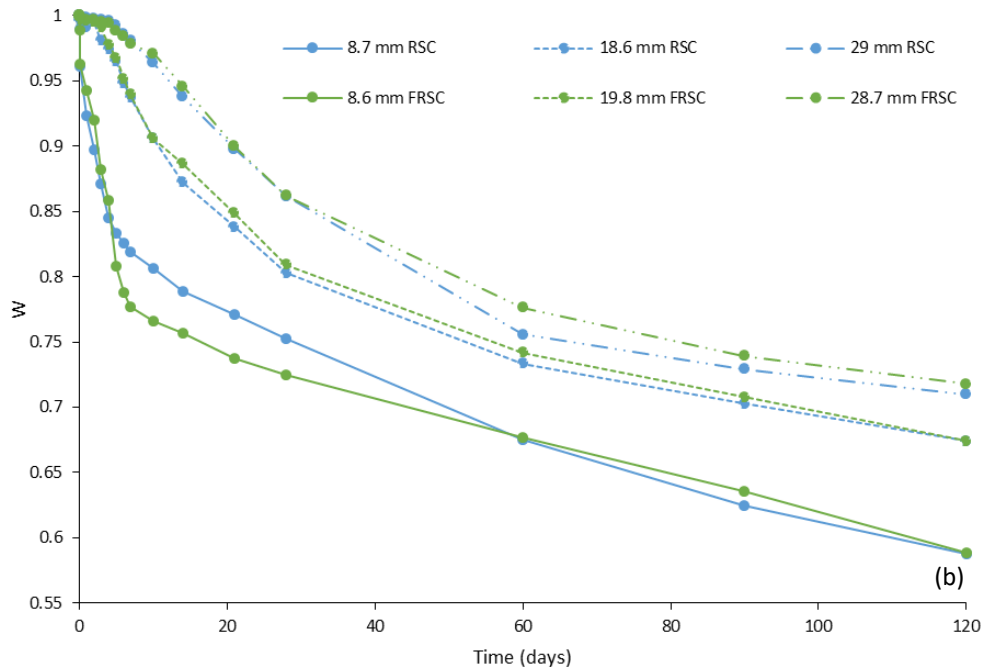
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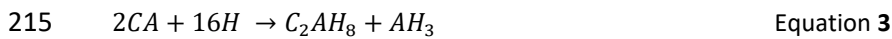
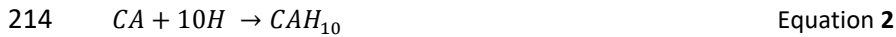
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204 **Figure 3.** Experimental moisture profiles: (a) CSA and FCSA mixes; (b) RSC and FRSC mixes

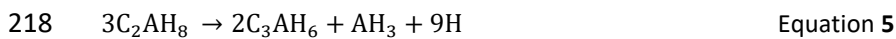
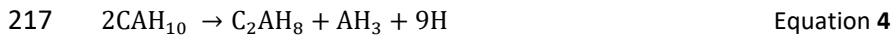
205 **4.2. Free shrinkage results**

206 The shrinkage evolution with time for all mixes is shown in Figure 4. Although a direct comparison
 207 between the shrinkage of CSA and RSC mixes is not possible due to differences in w/c ratio,
 208 superplasticizer dosage and aggregate content, the substantial difference in their shrinkage values can

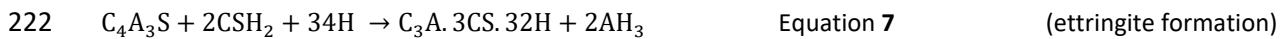
209 mainly be attributed to the different cement types. As expected, mixes with CSA cement showed much
 210 lower shrinkage strains than mixes with RSC cement. This is due to the expansive nature of their
 211 hydration products [34] and their higher water consumption during hydration [35]. For RSC cement,
 212 the reaction of its main component, monocalcium aluminate (CA), with water results in CAH_{10} and
 213 C_2AH_8 as the main hydration products as in Equation 2 and Equation 3 [36]:



216 The subsequent conversion reactions of the metastable phases to the stable phases are:



219 While for CSA cement, the main crystalline hydration products (ettringite and monosulfate) require
 220 more water to form as per Equation 6 and Equation 7 [35]:



223 If less free water is available for drying, then less drying shrinkage can occur.

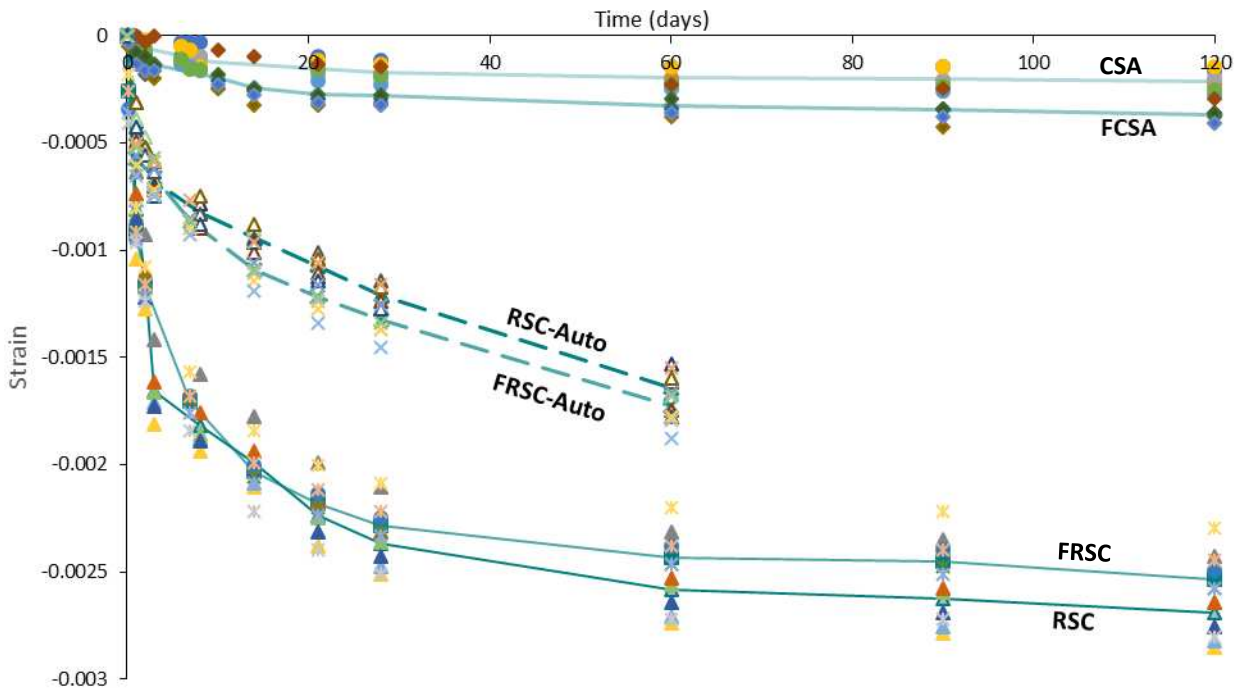
224 FCSA develops higher shrinkage strains compared to CSA at all ages. It is known that fibre inclusion
 225 introduces air in the mix [18, 37]. Also, the water content and SP dosage are higher for FCSA compared
 226 to CSA mix which can contribute to the higher recorded shrinkage values.

227 The provisions of EC, MC and ACI code were followed to obtain the shrinkage development of CSA and
 228 FCSA mixes with time. Both EC and MC require defining parameters α_{ds1} and α_{ds2} which depend on
 229 cement type. For the cements used, these parameters were obtained by nonlinear regression analysis.
 230 The ACI requires defining the ultimate shrinkage strain ϵ_{shu} . This value was obtained by multiplying the
 231 cumulative product of the correction parameters (γ_{sh} , as defined in [22]) by a factor P , obtained by

232 non-linear regression analysis. The predicted and experimental free shrinkage strain for CSA and FCSA
233 are given in Figure 5. As shown, the codes can predict the shrinkage evolution of these mixes
234 reasonably well provided suitable parameters for cement type are used.

235 The autogenous shrinkage strains obtained for both CSA and FCSA sealed specimens were very small
236 which indicates that some expansive reactions took place and, hence, not shown in Figure 4. On the
237 other hand, both RSC and FRSC mixes showed considerable autogenous shrinkage, 1644 $\mu\epsilon$ and 1722
238 $\mu\epsilon$ at the age of 60 days respectively, which accounts for about 64 % and 71% of their total shrinkage
239 at this age, respectively. Mixes with RSC cement has higher compressive strength compared to CSA
240 cement mixes. Autogenous shrinkage is known to be directly related to compressive strength. In
241 addition to, RSC has higher cement fineness that can increase the shrinkage [38]. High autogenous
242 shrinkage can also be attributed to conversion of RSC cement. Nevertheless, no compressive strength
243 reduction was noticed for RSC and FRSC specimens stored in the same conditions [6].

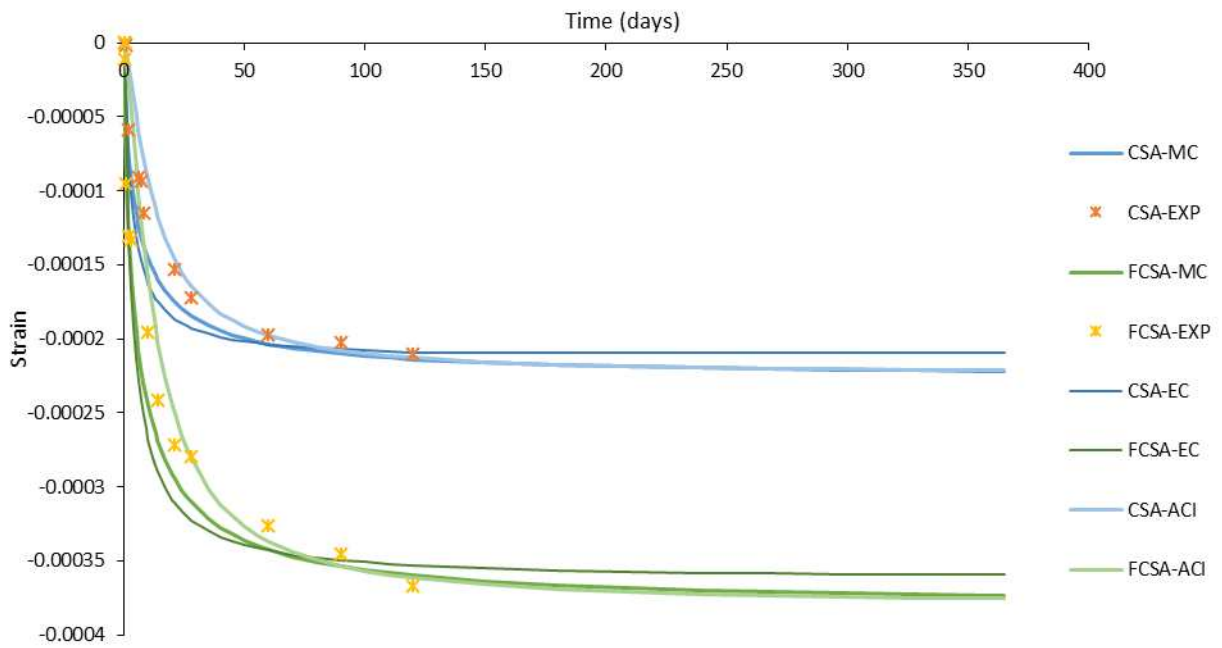
244 By examining further the RSC and FRSC results, it can be seen that drying shrinkage cannot be obtained
245 by simply deducting autogenous shrinkage from the total shrinkage as the autogenous shrinkage
246 continues at a faster rate than drying, possibly because drying affects the nature of the hydration
247 reactions [39]. Thus, an alternative method is needed to derive the drying shrinkage. MC relates the
248 autogenous shrinkage (shr_{Auto}) to the compressive strength at 28 days and to the type of cement.



249

250

Figure 4. Experimental shrinkage development for all mixes with time



251

252

Figure 5. Experimental shrinkage of CSA and FCSA prisms and their predicted values based on MC, EC and ACI

253

code

254

As the hydration reactions directly affect the strength development, these methods can be used to

255 predict Shr_{Auto} for RSC and FRSC using the compressive strength of the sealed specimens, provided
 256 that α_{bs} (a factor that is a function of cement type) is accurately calculated. The resulting shr_{Auto} for
 257 RSC and FRSC, following the MC approach and regression analysis is shown in Figure 6. The optimised
 258 α_{bs} along with the compressive strength at 28 days of drying samples were used to predict the
 259 autogenous shrinkage component from the total shrinkage strain. FRSC has slightly higher autogenous
 260 shrinkage (4.79 %) than RSC prisms, likely due to its higher compressive strength.

261 The drying shrinkage is obtained by subtracting shr_{Auto} from the total strain. The MC was also used to
 262 predict the drying shrinkage by assigning suitable α_{ds1} and α_{ds2} for RSC and FRSC, see Figure 7.
 263 Although the ACI code does not consider separate components of shrinkage, it can also be used to
 264 predict the total shrinkage (Figure 7). The shrinkage parameters used to estimate shrinkage for each
 265 mix based on the different codes are listed in Table 3.

266 **Table 3**

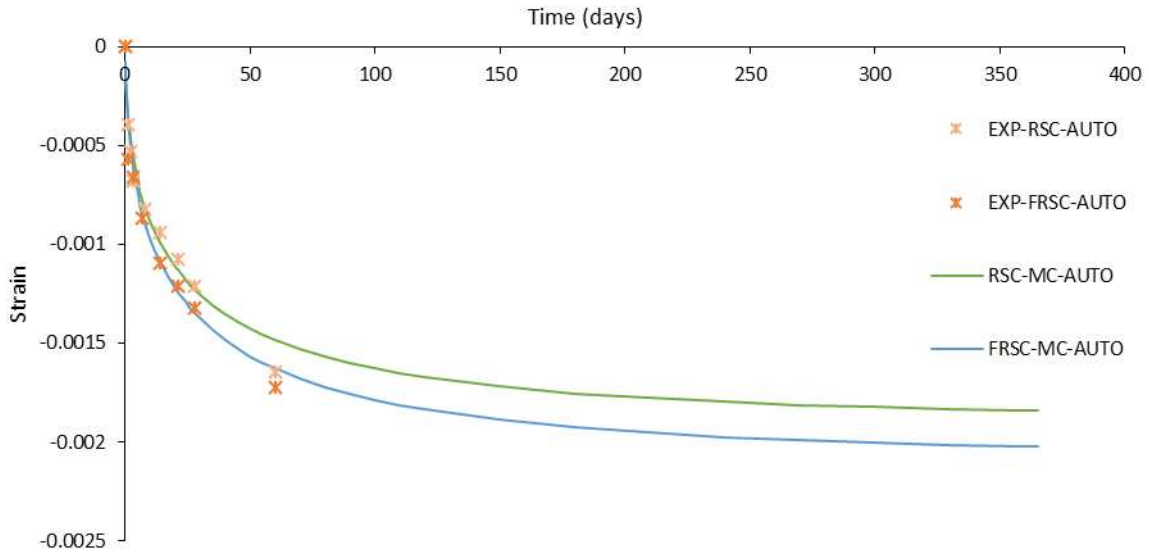
267 Shrinkage parameters for various mixes

Mixes	Codes					
	MC		EC		ACI	
	α_{ds1}	α_{ds2}	α_{ds1}	α_{ds2}	P	α
CSA	0.1	0.012	0.29	0.11	108	1.32
FCSA	1.7	0.012	0.77	0.009	180	1.32

268

Mixes	Codes					
	MC			ACI		
	Shr_{Auto}	Shr_{Dry}		Shr_{Total}		
	α_{bs}	α_{ds1}	α_{ds2}	P	α	
RSC	17900	7	0.004	1320	1.65	
FRSC	16780	5	0.004	1260	1.63	

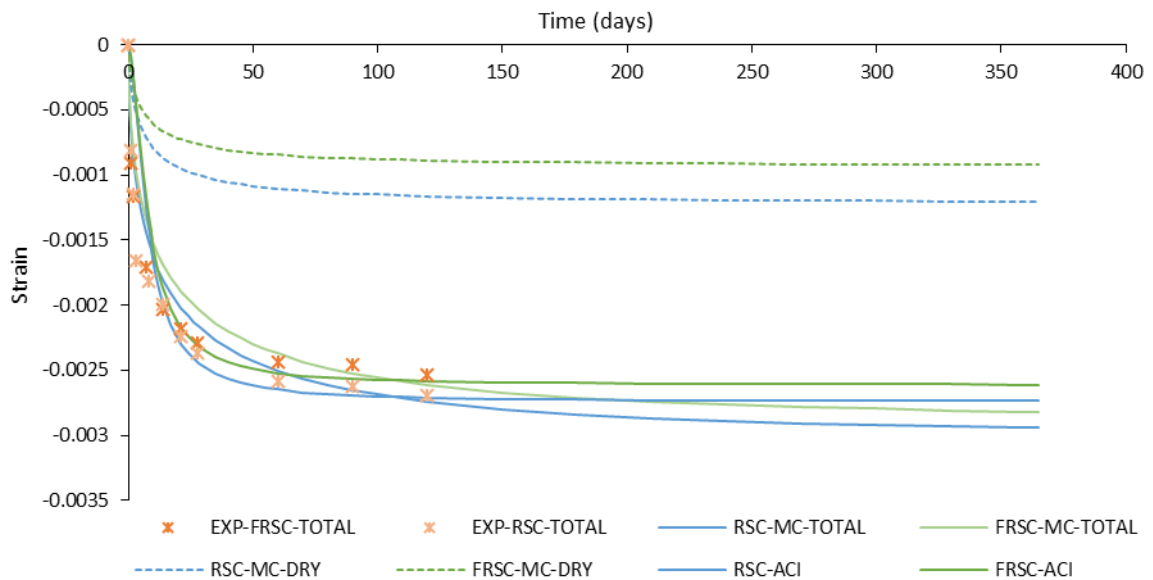
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271

Figure 6. Experimental and predicted MC autogenous shrinkage of RSC and FRSC



272

273

Figure 7. Experimental and predicted total and drying shrinkage of RSC and FRSC

274

It is interesting to note that the drying shrinkage of FRSC prisms seems to be smaller than RSC by

275

around 12.6 % at the age of 365 days. This may be due to the fibre restraining effect. However, it

276

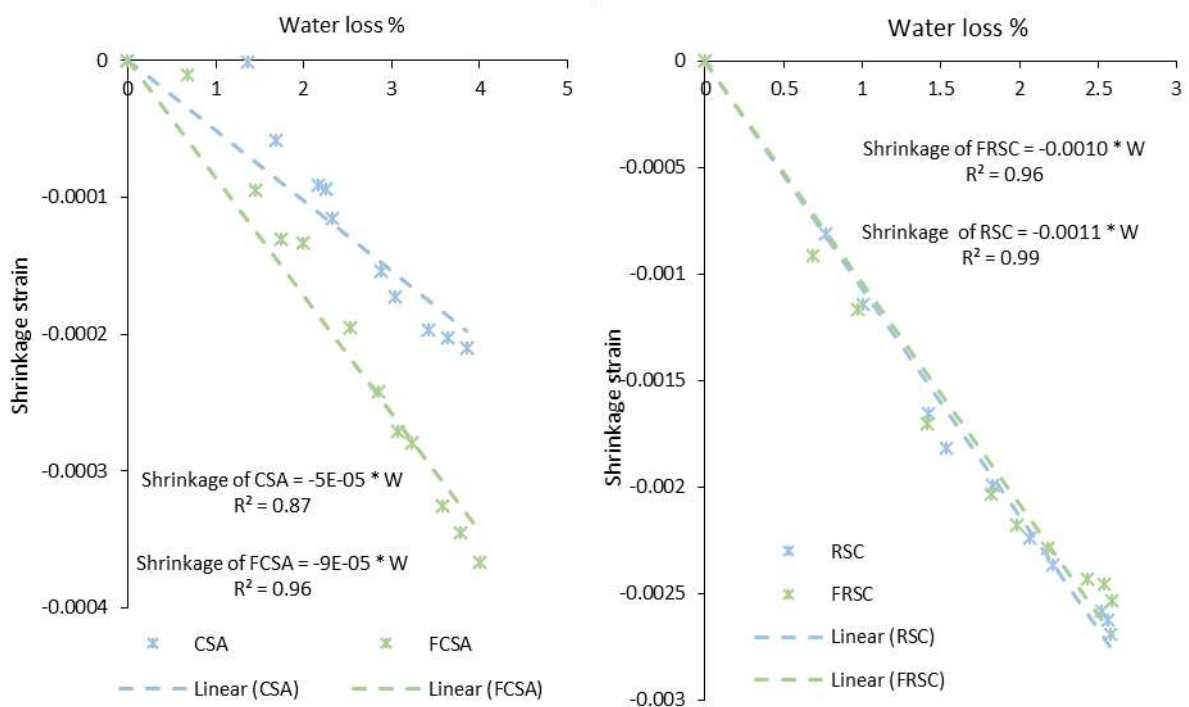
should be noted that there is no consensus in the literature about the role of fibres on the free

277

shrinkage strain.

278 **4.3. Relationship between water loss and shrinkage**

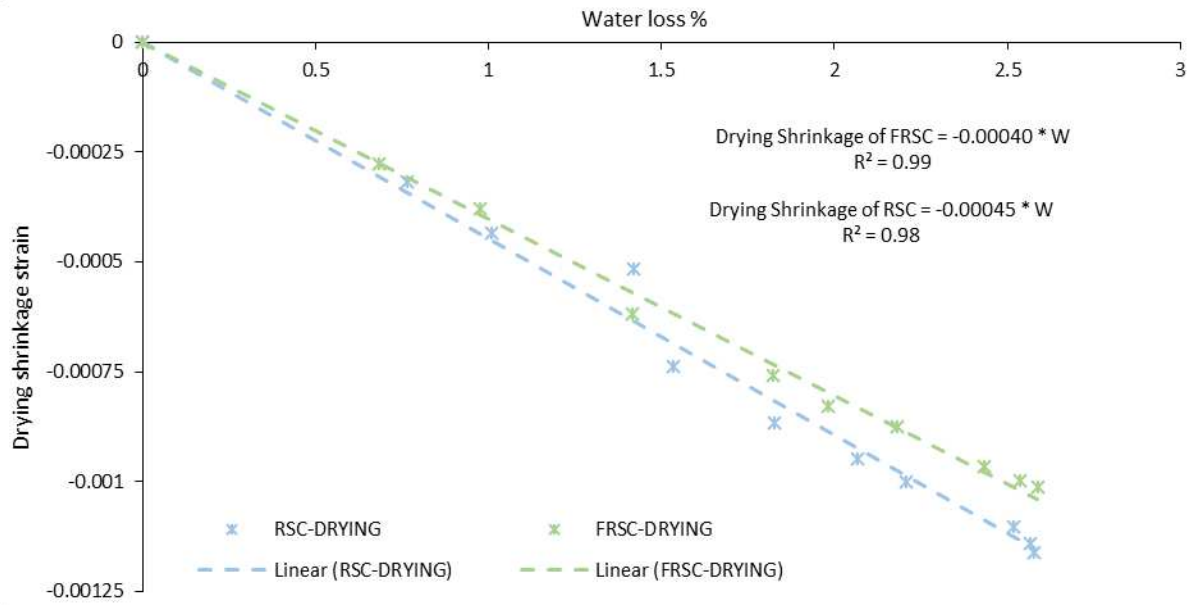
279 During the period of shrinkage monitoring, the weight of the prisms was recorded periodically. Figure
 280 8 shows the relationship between water loss percent (W) and shrinkage for CSA and FCSA and RSC and
 281 FRSC respectively. It is clear that all mixes have a linear relationship between shrinkage and water
 282 content loss with strong correlations, although, as expected, with different multipliers.



283
 284 **Figure 8.** Experimental shrinkage versus measured water loss percent for: (a) CSA and FCSA; (b) RSC and FRSC
 285 prisms

286 Such linearity was also reported in [37] for concrete reinforced with post-consumer recycled steel
 287 fibres. In general, CSA and FCSA have more water loss than RSC and FRSC as they have higher initial
 288 water content (w/c = 0.4, 0.41 for CSA and FCSA respectively). The relationship also clearly highlights
 289 the effect of cement type on the shrinkage behaviour of the mixes. For example, for a 2.5 % water
 290 loss, the equivalent shrinkage for the mixes is 0.000125, 0.000225, 0.00275 and 0.0025 for CSA, FCSA,
 291 RSC and FRSC respectively. The water loss is also plotted against the calculated drying shrinkage for

292 RSC and FRSC specimens (Figure 9). This relationship is essential when introducing shrinkage in FE
 293 modeling through the hygral contraction coefficient



294

295 **Figure 9.** Calculated drying shrinkage versus measured water loss percent for RSC and FRSC prisms

296 **5. Numerical studies**

297 **5.1. Numerical analysis approach**

298 Heat transfer analysis available in FE package Abaqus was used to model moisture diffusion during
 299 drying. For this analysis, two parameters are essential; moisture diffusion and surface factor. The MC
 300 uses an equation that relates moisture diffusivity to relative humidity. As from the measurements
 301 taken only the normalized moisture content can be determined, this parameter is adopted instead of
 302 relative humidity as shown in Equation 8.

303
$$D(C_{norm}) = D_1 \left(\alpha + \frac{1-\alpha}{1 + \left(\frac{1-C_{norm}}{1-C_c} \right)^n} \right)$$
 Equation 8

304 Where:

305 D_1 is the max diffusion coefficient when C_{norm} equals 1.0 and the samples are fully saturated ($D_1 = 1$)

306 $\times 10^{-8}/f_{ck}$, f_{ck} = characteristic concrete strength),

307 α represents the ratio D_0/D_1 ; D_0 is the minimum D , C_c is the normalised moisture concentration at

308 $D(C_{norm}) = 0.5D_1$.

309 The MC suggested values of $\alpha = 0.05$, $C_c = 0.8$ and $n = 15$ were initially used to calculate the diffusion
310 coefficient. The resultant $D(C_{norm})$ for each mix was then adopted in the heat transfer analysis.

311 Diffusive heat transfer 20-node quadratic brick elements (DC3D20) were used for the thermal analysis.

312 As in the experiments, drying was only permitted through the top surface, which was assigned a

313 surface factor, and the other surfaces were considered sealed having no moisture interaction with the

314 environment. At the beginning of the drying, the normalised moisture concentration was 100% and

315 the ambient relative humidity was considered constant at 40%. Initial values of the parameters for

316 model code model of $D(C_{norm})$ as well as surface factors were optimized (Table 4) to minimize the

317 difference between numerical and experimental moisture profile of each mix.

318 To calculate shrinkage deformations, the thermal analysis was coupled with a structural analysis in

319 which the thermal expansion is replaced by a hygral contraction coefficient. C3D20R element type was

320 used for the structural analysis. The tensile and compressive material characteristics were obtained

321 from the experimental results and inverse analysis studies; further details on the procedures used are

322 given elsewhere [6]. To accurately predict the shrinkage history, the development of the material

323 properties with time was incorporated into the structural analysis through the implementation of the

324 user subroutine, USDFLD. This allows the use of solution-dependent material properties and thus the

325 user can define the field variables at a material point as a function of time [40]. The hygral coefficient

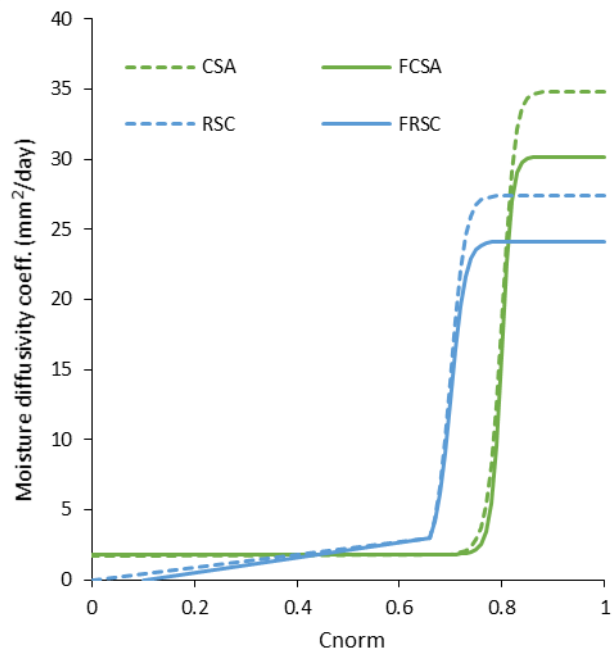
326 was optimized to minimize the difference between measured experimental and FE predicted

327 shrinkage strain.

328 **5.2. Numerical results and discussion**

329 **5.2.1. Determination of moisture diffusivities and surface factor**

330 The set of parameters implemented in MC
331 equation (Equation 8) [21] to determine the
332 moisture diffusivity coefficient for each mix
333 are listed in Table 4. The calculated moisture
334 diffusivities for different mixes, as functions of
335 normalized moisture content, C_{norm} , are
336 shown in Figure 10. The results show that CSA
337 has the highest moisture diffusion at the
338 beginning of drying (34.8 mm²/day) while FRSC
339 has the lowest moisture diffusion (24.1



340 mm²/day). The diffusivity is almost constant at
341 the beginning of drying (for 1 - 0.77 moisture content), and then decreases sharply before stabilizing
342 again. This behaviour is congruent with the mechanism of drying reported for conventional
343 cementitious materials [12, 15, 16, 18]. For RSC and FRSC, to minimize the difference between
344 measured and numerical moisture profiles, a slight change to MC approach was adopted. The slope
345 of the tail of the moisture diffusivity against moisture content was reduced to zero (from $C_{norm} = 0.66$
346 downwards) instead of being almost constant as predicted by the MC equation.

Figure 10. Moisture diffusivity versus normalized moisture content C_{norm}

347 A wide range of values is reported for moisture diffusivity (25.92 – 4665.6 mm²/day) for well cured
348 concrete specimens [29, 41, 42] and the results of this study seem to agree well with the lower bound
349 of this range.

350 The back calculated surface factors for the tested mixes range from 4 – 6 mm/day. In addition, it was
351 found that this factor only affects the moisture profiles near the drying surface and its effect
352 diminishes quickly far from the top surface [18].

353 **Table 4**

354 Optimised parameters for MC equation and inverse analysis

Mix	<i>Optimised parameters of Equation 8</i>				SF	$\beta_{(C)}$
	D ₁	α	C _c	n		
CSA	34.801	0.05	0.8	15	5	0.00038
FCSA	30.146	0.06	0.8	20	6	0.00065
RSC	27.399	0.035	0.7	20	4	0.0048
FRSC	24.139	0.05	0.7	20	4	0.0045

355

356 **5.2.2. Determination of the hygral contraction coefficient**

357 The hygral contraction coefficients for the mixes were back-calculated as functions of moisture
 358 content, C , using the free shrinkage test results. It was found that there is a strong linear relationship
 359 between shrinkage strain and moisture loss (Section 4.3), Equation 9.

360 $(\epsilon_{sh})_M = \beta_{(C)} \times (C_0 - C)$ Equation 9

361 Where $(\epsilon_{sh})_M$ is the free shrinkage strain, $\beta_{(C)}$ is the contraction coefficient and C_0 is the reference
 362 moisture content, 1.0. It should be noted that since both the total and drying shrinkage of RSC and
 363 FRSC show a linear relationship with water loss, the total shrinkage for samples of these mixes was
 364 modeled using a single hygral contraction coefficient. The calculated values of $\beta_{(C)}$ are listed in Table
 365 4. As expected, mixes with calcium aluminate cement (CSA and FCSA) have much smaller contraction
 366 coefficient compared to the other mixes. However, for FCSA, $\beta_{(C)}$ is approximately 70% higher than
 367 that of CSA. This increase of shrinkage due to fibre addition is much higher than reported in literature.
 368 Nonetheless, those studies are only limited to Portland cement with/without pozzolanic additions.
 369 The value of $\beta_{(C)}$ for FRSC is slightly lower than that of RSC, possibly due to the restraining effect of the
 370 fibres at the large shrinkage strains developed.

371 **5.2.3. Numerical moisture profiles: Results and Discussion**

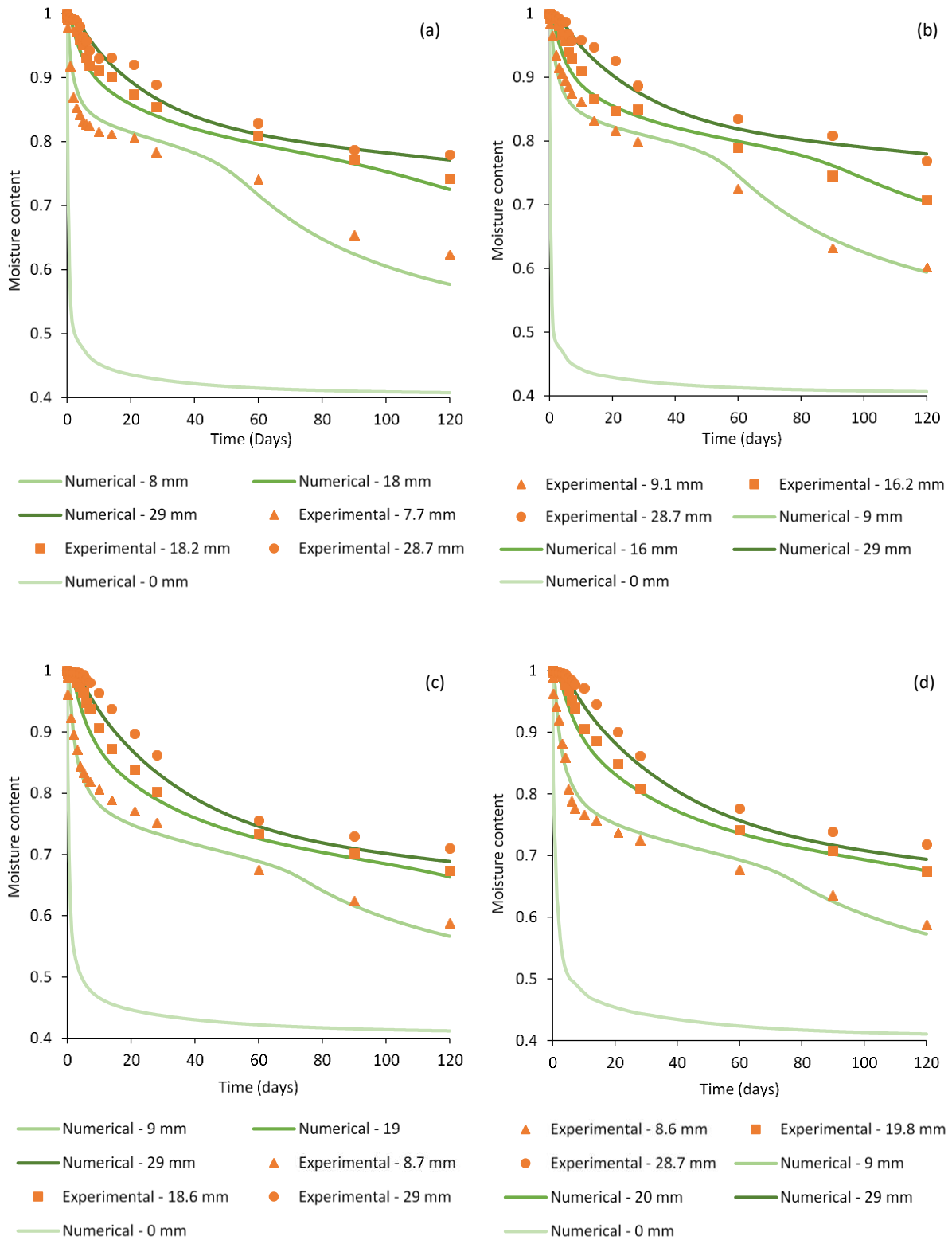
372 The numerical and experimental moisture profiles are compared in Figure 11. As it can be seen, the
373 heat transfer analysis based on moisture diffusivities, calculated based on MC equation, predicts well
374 the experimental moisture profiles with less than 5% difference.

375 **5.2.4. Numerical shrinkage strain**

376 The development of shrinkage strain with time, using parameters calculated in the previous sections,
377 is compared to the experimental curves in Figure 12. As seen in Figure 12, the FE analysis satisfactorily
378 represents the measured shrinkage, validating the factors adopted in the analysis.

379

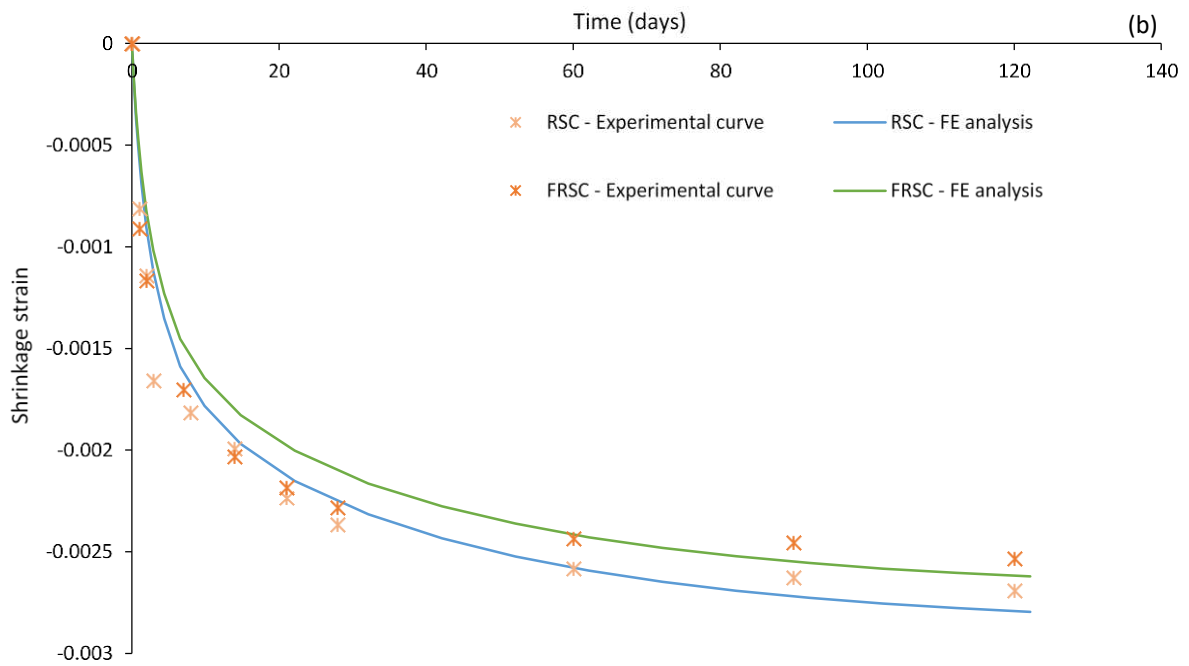
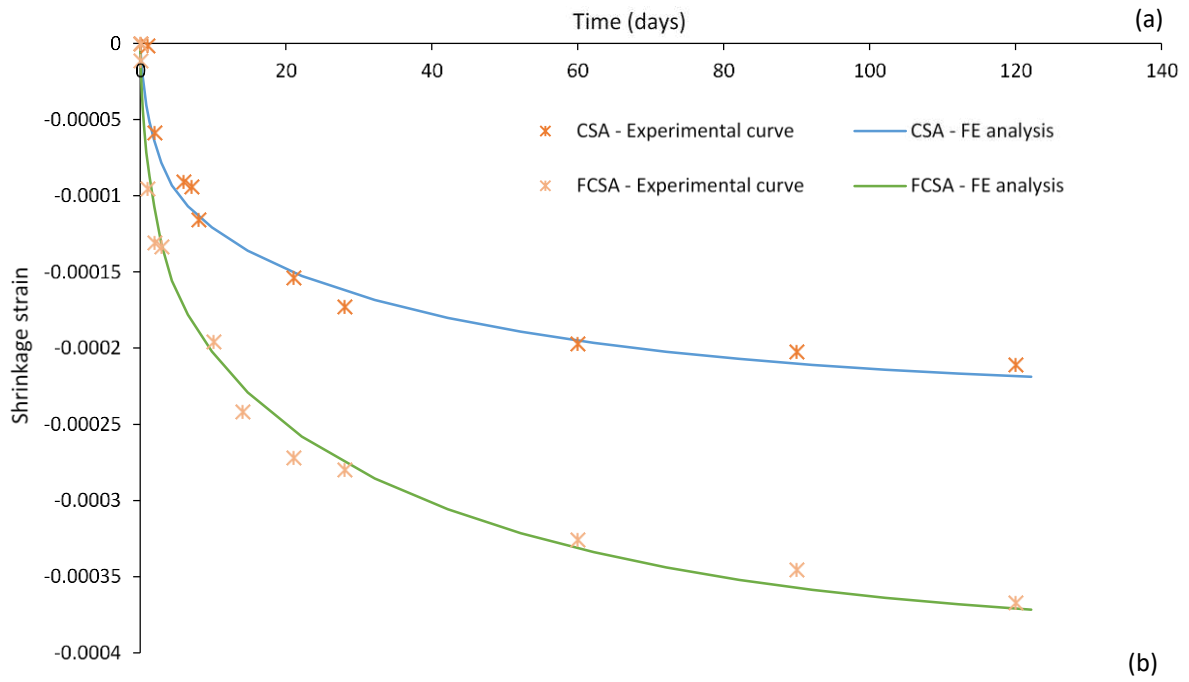
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382

Figure 11. Numerical and experimental moisture profiles: (a) CSA; (b) FCSA; (c) RSC; (d) FRSC



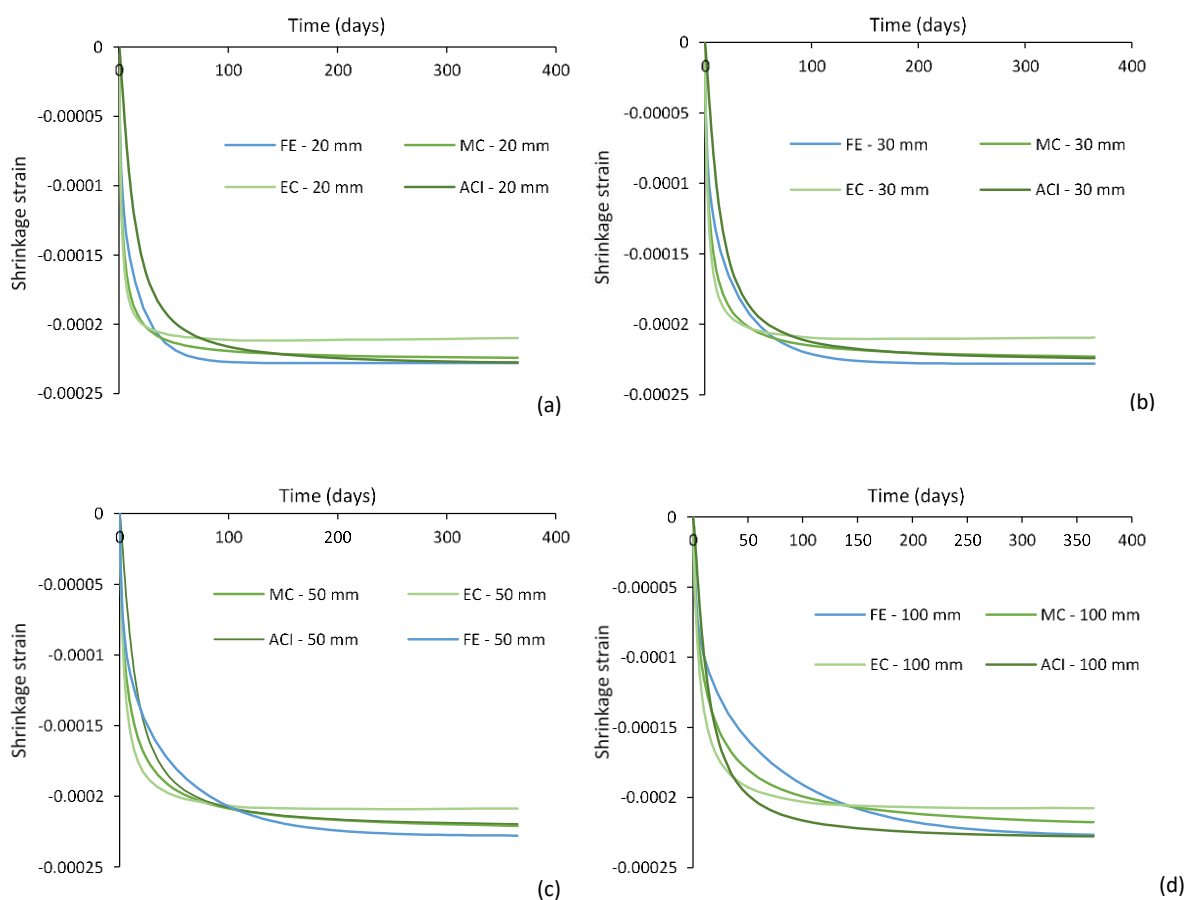
383

384 **Figure 12.** Numerical free shrinkage strain compared with experimental results: (a) CSA & FCSA; (b) RSC & FRSC

385

386 **5.3. Comparison between numerical shrinkage and shrinkage predicted using MC, EC and ACI Code**
387 **procedures**

388 The parameters proposed for each code procedure to predict free shrinkage strain are used to obtain
389 the free shrinkage of prisms of each mix with four different heights; 20, 30, 50 and 100 mm. The
390 resulting curve for each mix, for a specific height, are compared with the FE predicted shrinkage (for
391 that specific height) using the same parameters given in previous sections, Figs. 13-16.



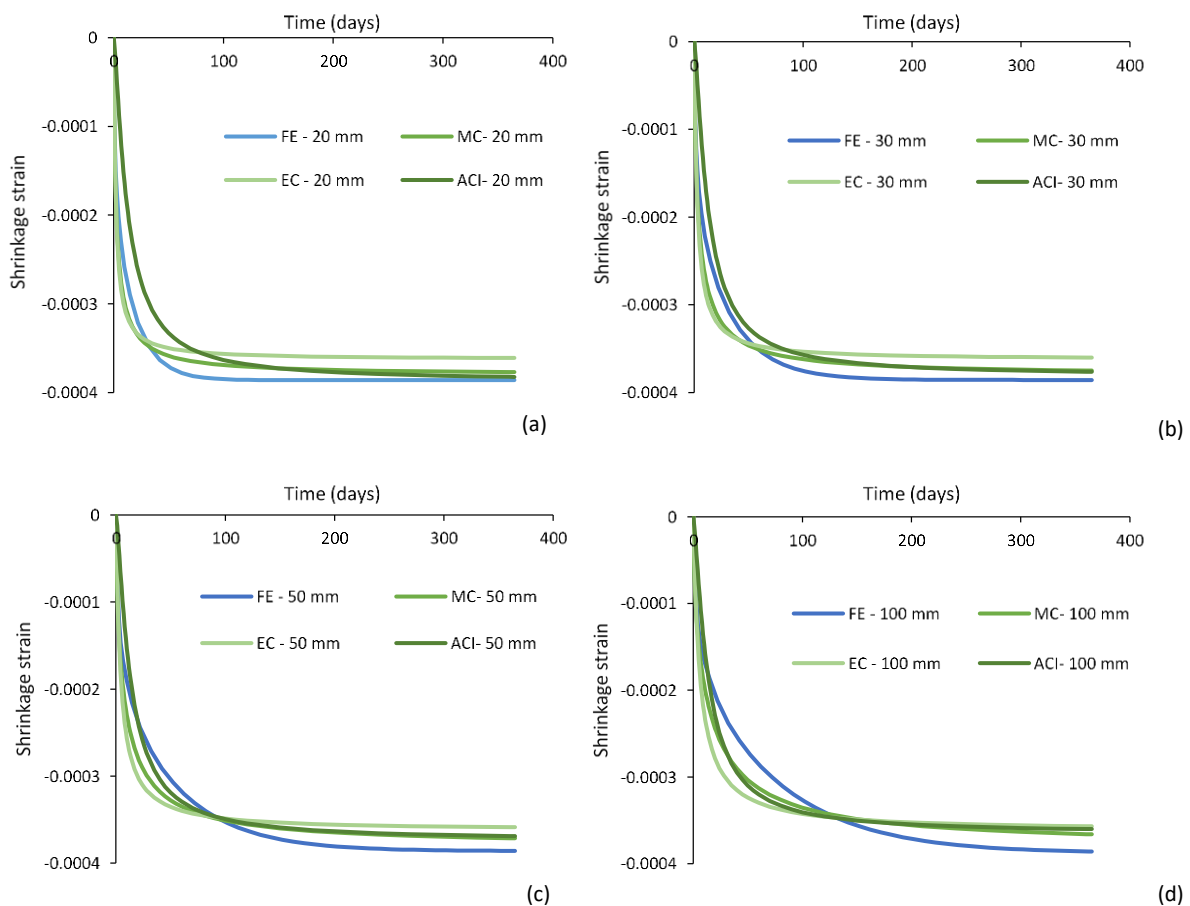
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393 **Figure 13.** Numerical free shrinkage strain compared to shrinkage predicted using different codes for CSA
394 prisms of heights: (a) 20 mm; (b) 30 mm; (c) 50 mm; (d) 100 mm

395 As seen in Figure 13 and Figure 14, the procedures are able to predict the shrinkage development of

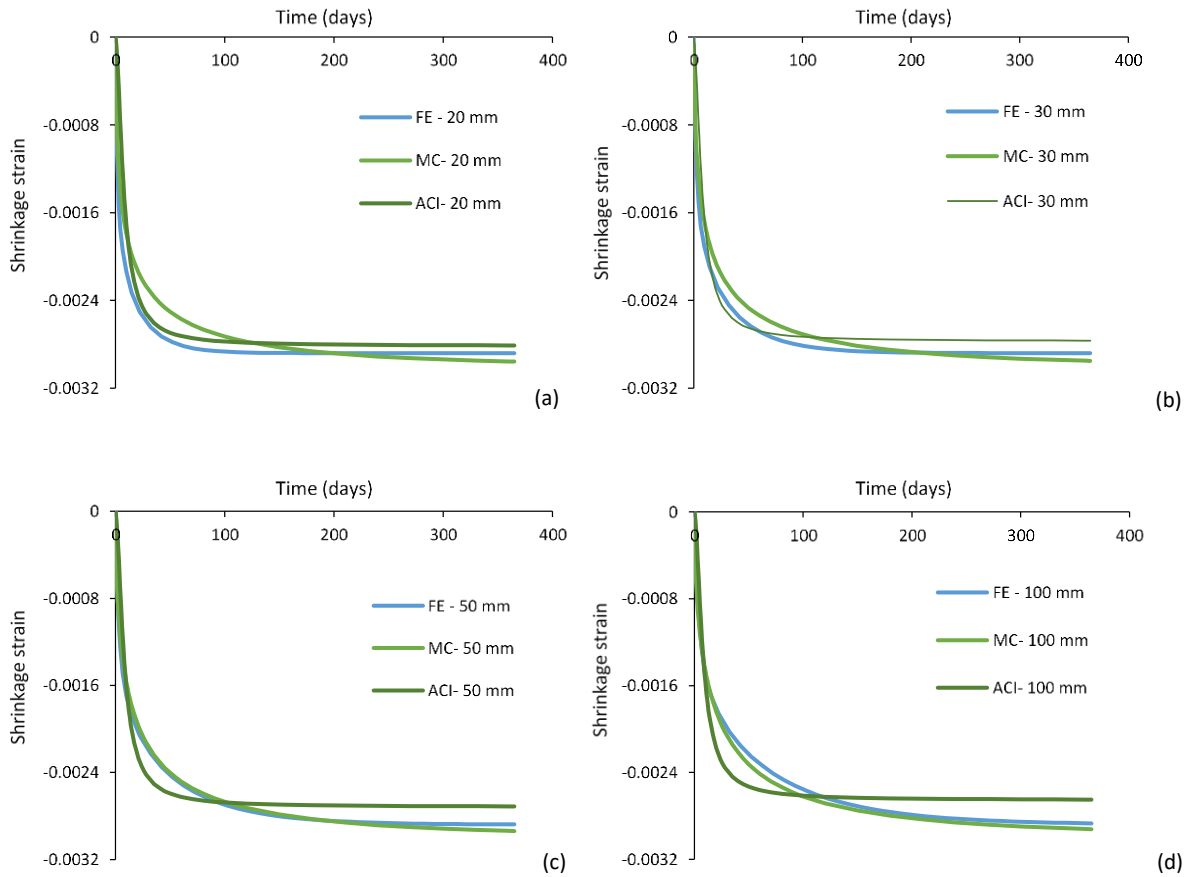
396 CSA and FCSA samples, respectively, over time with reasonable accuracy, especially for thinner
 397 sections. The MC seems to offer the best estimate at both the beginning and the end of drying.
 398 However, EC appears to slightly overestimate the shrinkage at the beginning of drying while
 399 underestimates it towards the end of the testing period.

400 The estimated curves for total shrinkage development of RSC and FRSC over time against FE predicted
 401 curves are given in Figure 15 and Figure 16, respectively. It should be noted that EC was not used to
 402 predict shrinkage of RSC and FRSC mixes as it does not consider parameters for cement type in
 403 autogenous shrinkage prediction as it is the case in MC and, thus, was not used to model the shrinkage
 404 of RSC and FRSC mixes.



405
 406 **Figure 14.** Numerical free shrinkage strain compared to shrinkage predicted using different codes for FCSA
 407 prisms of depths: (a) 20 mm; (b) 30 mm; (c) 50 mm; (d) 100 mm

408 As shown, for very thin sections, ACI offers slightly better predictions of shrinkage development with
409 time compared to MC. At thicker sections, however, the MC seems to better capture the shrinkage
410 history as ACI tends to overestimate the shrinkage development at the beginning of the testing and
411 rather underestimates the shrinkage at later stages.



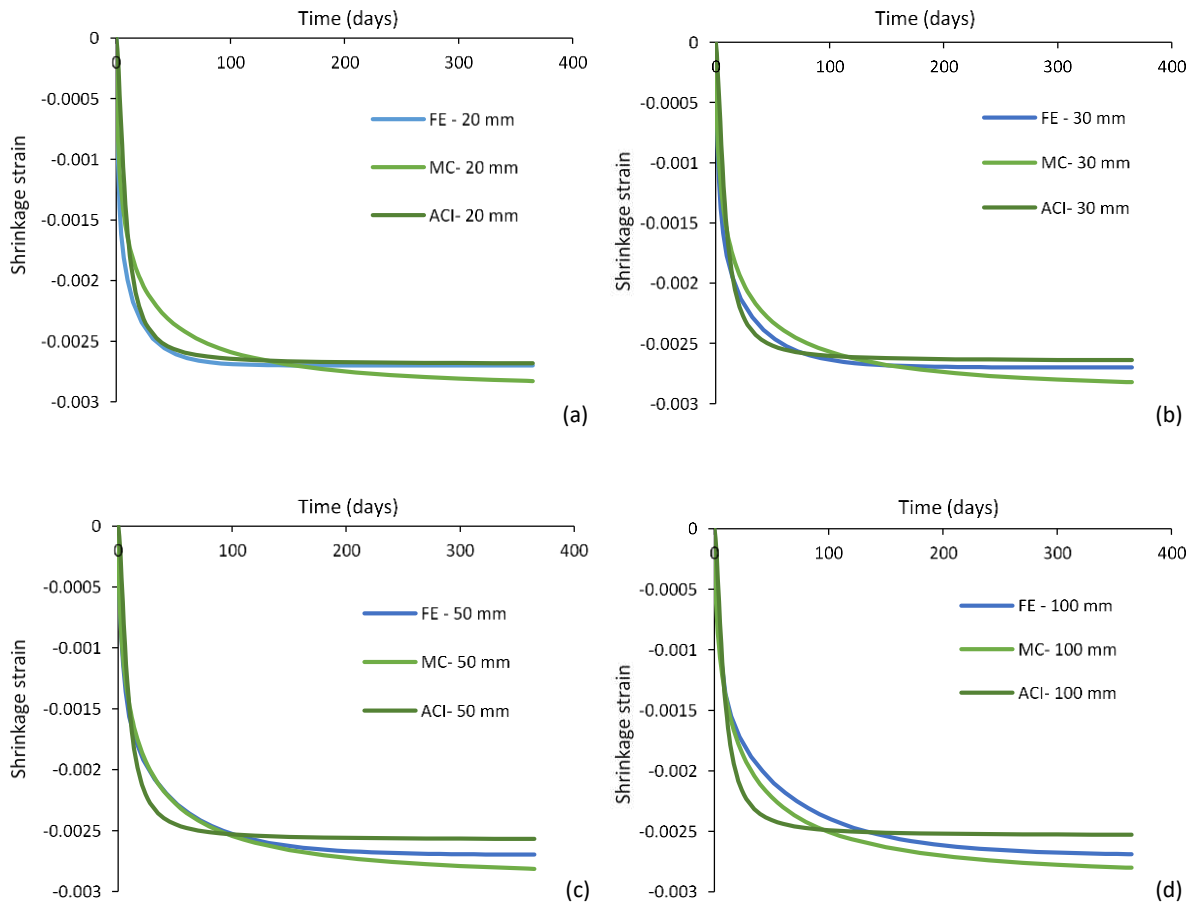
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413 **Figure 15.** Numerical free shrinkage strain compared to shrinkage predicted using different codes for RSC

414 prisms of heights: (a) 20 mm; (b) 30 mm; (c) 50 mm; (d) 100 mm

415

416



417

418 **Figure 16.** Numerical free shrinkage strain compared to shrinkage predicted using different codes for FRSC
 419 prisms of heights: (a) 20 mm; (b) 30 mm; (c) 50 mm; (d) 100 mm

420 **6. Case studies**

421 To assess the risk of cracking and/or delamination due to restrained shrinkage in repair layers
 422 prepared from the mixes developed in this study, the Silfwerbrand procedure [19] is followed. This
 423 requires knowing the free shrinkage of the overlay, the elastic modulus of the overlay layer and the
 424 substrate concrete as well as the tensile strength of the repair layer. The interface shear strength and
 425 the bond coefficient (K) should also be known.

426 To assess the risk of cracking and/or delamination, at one-year of age, the bonding conditions shown
 427 in Table 5 are considered. A layer with dimensions of 50*150*1000 mm is overlaid above an old
 428 concrete substrate with 200*150*1000 mm. The analysis is run twice for each mix; with and without
 429 creep in the overlay. When considering creep, the stresses were calculated by using the modulus of
 430 elasticity modified by creep coefficients. The creep coefficients were calculated based on the
 431 recommendations of MC 2010 [21]. As the substrate is already a few years old, it is considered
 432 conservative to neglect its creep deformations.

433 The calculated tensile stresses for CSA and FCSA overlaid prisms are shown in Fig. 17 while the shear
 434 stresses that develop at the interface are presented in Fig. 18 for different bond conditions. The effect
 435 of creep is also shown (curves labelled -c).

436 **Table 5**

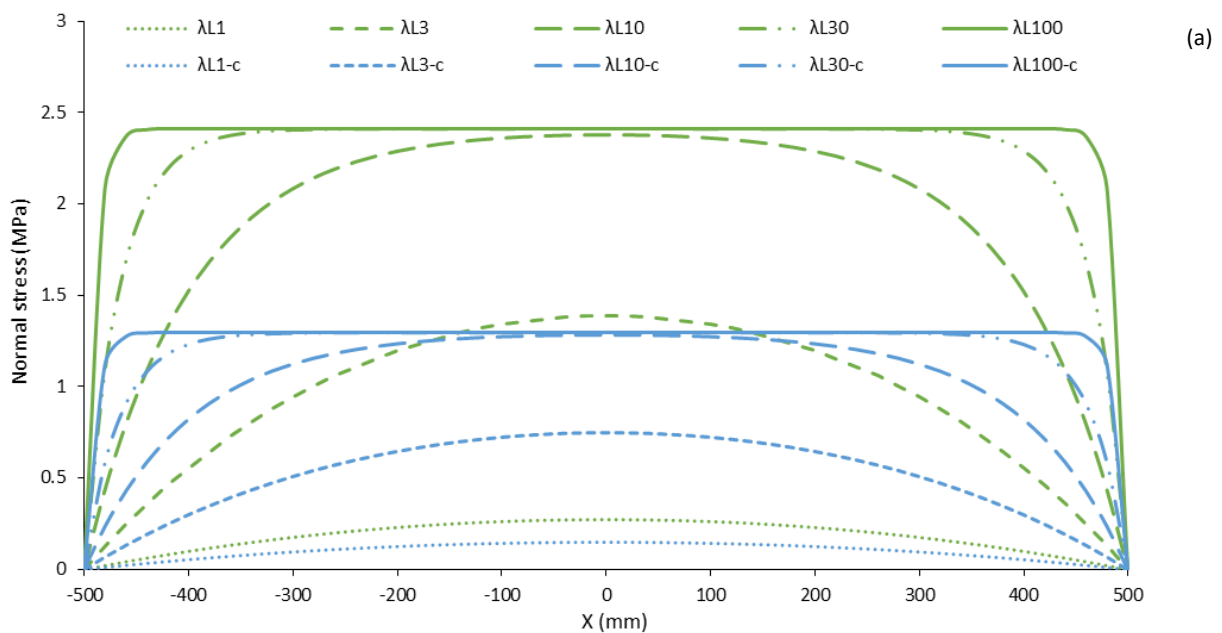
437 Material properties used for the case studies

Layer type	E_c (GPa)	Tensile strength (MPa)	λL
Substrate	35	-----	1
CSA	21.73	3.30	3
FCSA	28.00	4.00	10
RSC	20.56	3.02	30
FRSC	26.11	3.3	100

438 As shown in Figure 17 and Figure 18, neglecting creep leads to an overestimation of both tensile and
 439 shear stresses. When considering creep, for both CSA and FCSA overlays, the maximum tensile stress
 440 that develops at the interface is lower than the overlay tensile strength and thus it is predicted that
 441 cracking is unlikely to develop. However, for the strongest bond condition assumed ($\lambda L=100$), high
 442 values of shear stresses develop with 6.11 MPa and 13.15 MPa for CSA and FCSA, respectively, at the
 443 edge of the composite prism, implying delamination if the shear strength at the interface is assumed
 444 to be similar to the tensile strength of concrete for well-prepared surfaces. For smaller λL , low shear
 445 stresses developed and thus the risk of delamination is lower (see Figure 18).

446 For RSC and FRSC overlays, cracking is predicted to occur for most bond conditions as the shrinkage
447 strains are very high. The calculated shear stresses are also very high, indicating horizontal separation
448 at the interface. However, in practice, as cracks develop, energy is released and shear stresses can
449 drop.

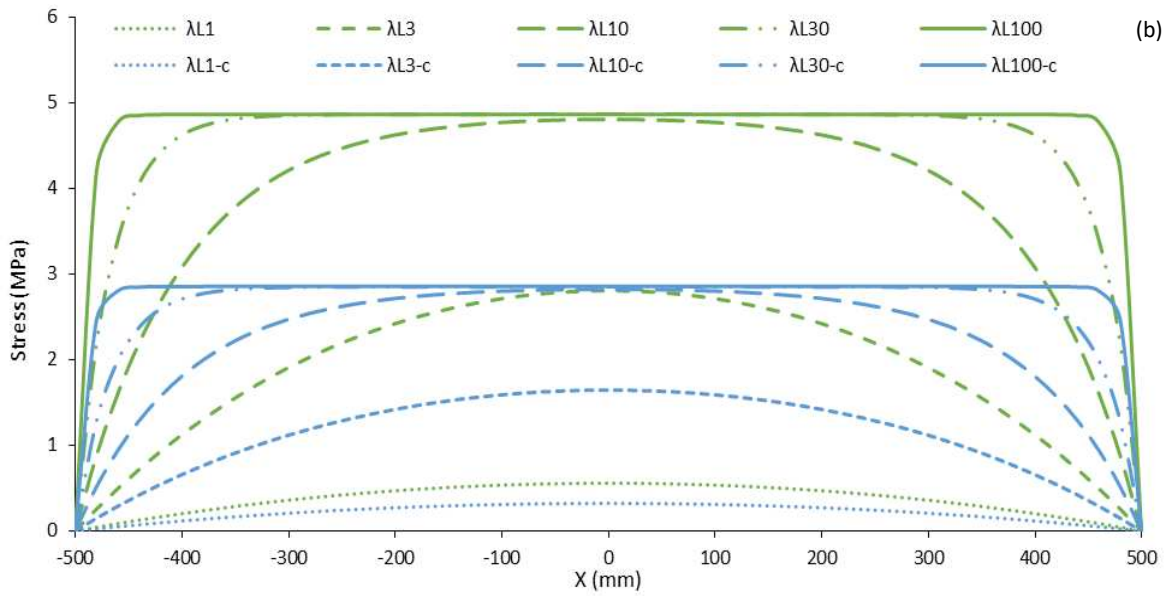
450 The Silfwerbrand procedure does not clearly specify how to determine λ_L for different surface
451 preparations and it is only useful in predicting cracking risk and, thus, the beneficial role of fibres
452 cannot be quantified. Therefore, more experimental and analytical work is needed to understand how
453 to accurately estimate λ_L and K (the bond constant) for different bond conditions. Such work can help
454 provide better predictions of cracking and delamination risks, quantify the role of fibres in materials
455 with high shrinkage values (over $2500 \mu\epsilon$) and residual strength higher than the cracking strength and
456 determine whether or not fibres have a beneficial role in resisting/delaying delamination.



457

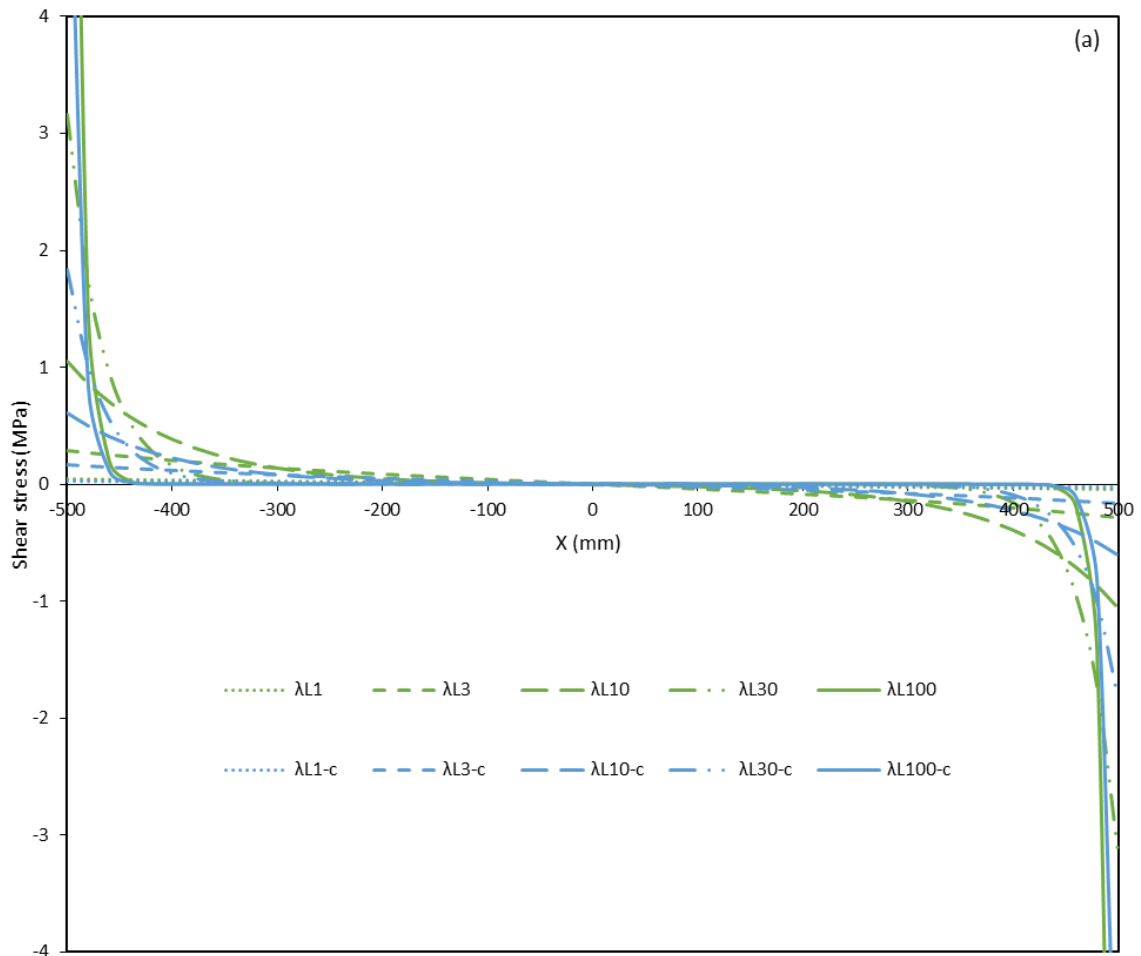
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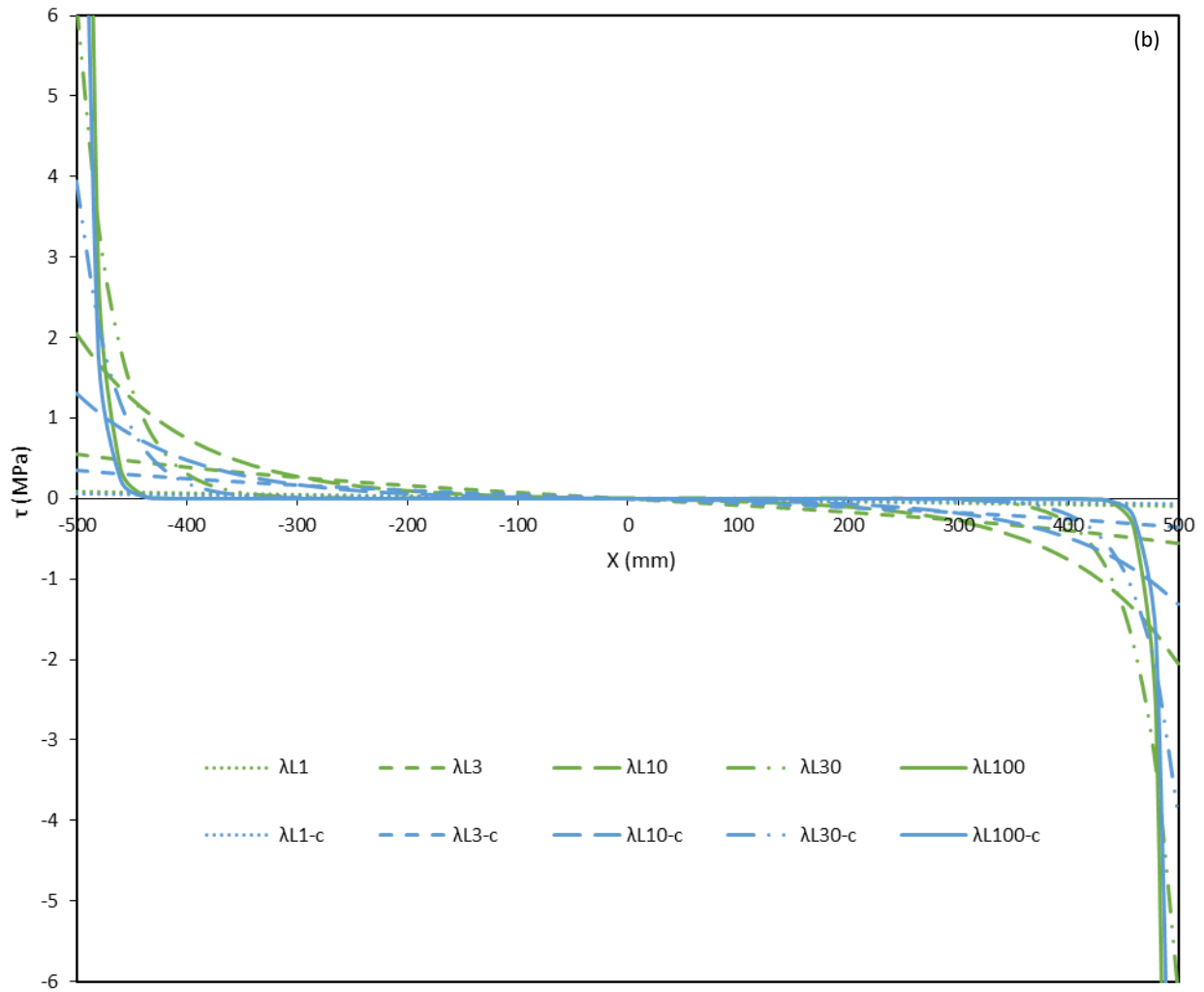


460

461 **Figure 17.** Normal stresses that develop at the interface between CSA overlay and substrate with and without
 462 creep for; (a) CSA overlay; (b) FCSA overlay



463



464

465 **Figure 18.** Shear stresses that develop at the interface between overlay and substrate with and without creep
 466 for; (a) CSA overlay; (b) FCSA overlay

467 **Conclusions**

468 This paper presents the main outcomes of a series of experimental and numerical studies on the time
 469 dependent transport properties of rapid hardening plain and fibre reinforced mortars for repair
 470 applications and on their shrinkage performance. Fibres are necessary to control crack widths in
 471 restrained conditions. The main findings of this study are:

- 472• The fibre inclusion was confirmed not to have a major role on the moisture transport properties of

473 rapid hardening mortar mixes, which allows the use of the MC equation, usually used to estimate the
474 moisture diffusivity of plain concrete, to calculate their moisture diffusivities with good accuracy.

475• Mixes with CSA cement showed much lower shrinkage strains (211 and 367 $\mu\epsilon$) compared to mixes
476 with RSC cement (2690 and 2532 $\mu\epsilon$) at 120 days. Unlike CSA and FCSA, RSC and FRSC mixes showed
477 considerable autogenous shrinkage which accounts for around 64 % and 71% of their total shrinkage
478 at the age of 60 days.

479• FE analyses were used in combination with experimental moisture distribution measurements to back
480 calculate the moisture diffusivity of the tested mixes. It was found that the moisture diffusivities for
481 mixes with rapid hardening cements are high at the beginning of drying (34.8 – 24.14 mm^2/day) and
482 remain almost constant up to moisture contents of 85% - 75%, for different mixes, then sharply
483 decreases upon further drying.

484• There is a linear relationship between shrinkage and moisture loss for all the mixes with good
485 correlation ratios.

486• The hygral contraction coefficient, for each mix, were back calculated using inverse analysis for
487 measured shrinkage strains. The coefficients range from 0.00038 to 0.0048 depending on the cement
488 type and fibre inclusion.

489• MC and ACI equations can be used to predict the shrinkage development with time provided
490 appropriate coefficients for each cement type are used.

491• Creep was found to play an important role in moderating tensile and shear stresses of the overlays.

492• The Silfwerbrand procedure is used to determine normal and shear stresses in an overlay case study.
493 Though the procedure is simple, it relies on parameters (λ_L and K) that are not easy to determine.

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