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1 Advanced techniques for the study of shrinkage-induced cracking of
2 concrete with recycled aggregates at early age

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7

8 Abstract

9 The present work analyses the impact of the substitution of natural coarse gravel and sand by
10 recycled gravel and sand on the concrete behavior under free and restrained condition since
11 setting. The methodology presented in this paper associates a Temperature Stress Testing
12 Machine (TSTM) with free shrinkage tests and other experimental advanced techniques, such
13 as direct tensile testing and the monitoring of elastic properties using repeated loading testing.
14 It is observed that the cracking sensitivity decreased with recycled concrete content in spite of
15 lower tensile strength. This is due to the major influence of relaxation, but also damage and
16 coupling effects. These phenomena contributed to a decrease of the stresses with different
17 magnitude and kinetics. For concretes with recycled gravels, the major stress reduction was
18 attributed to relaxation. The reduction of elastic modulus due to damage appeared from the
19 first 24 hours while creep seemed to develop later, as tensile stress to strength ratio became
20 higher. Concrete with recycled sand had a different behavior with earlier creep development
21 and lower damage.

22 Keywords: Shrinkage, relaxation, cracking, recycled concrete, early-age, restrained shrinkage

23

24 **1. Introduction**

25 The use of construction and demolition waste as an alternative source of aggregates for the
26 production of new concrete has become more common for the last decade. In many urban
27 areas, a critical shortage of good quality natural aggregates is detected. At the same time old
28 buildings and structures are demolished due to their obsolescence, generating waste materials
29 in these same areas. In France, 300 million tons of building wastes are produced each year
30 [1]; only a part is used for new constructions, mainly for road works. The use of recycled
31 concrete aggregates is promoted as it is expected to reduce CO₂ emission, energy
32 consumption and the use of natural raw materials. However materials used for structural
33 concrete have to comply with the requirements from standards and building codes in terms of
34 composition and mechanical properties [2]. These requirements are meant to provide users
35 with safety and serviceability of concrete structures for their whole service life. [In this
36 framework, in France, the National Projects RECYBETON \[1\] and ECOREB \[3\] were carried
37 out in order to develop recommendations for the use of recycled aggregates in building
38 materials.](#)

39 The influence of aggregates on short and long-term behavior of concrete is significant[4,5].
40 Particle size distribution, shape, nature, porosity (measured as water absorption), and initial
41 water saturation affects workability, plastic stage, setting and hardening, strength, shrinkage,
42 creep, thus durability [6]. Many studies regarding recycled concrete (RC) aggregates can be
43 found in the literature. These studies mainly focus on the influence of RC aggregates
44 proportion on the properties of hardened concrete [7–9]. [It was mainly observed that the
45 replacement of natural aggregates by recycled ones induces a decrease of the density, freezing
46 and thawing resistance and mechanical performances and an increase of the drying shrinkage
47 \[10\]. However, at early age, the volume change of cement-based materials is significant and is
48 partially or fully restrained. When shrinkage is restrained, tensile stresses are induced and](#)

49 cracking is likely to occur. To ensure the durability of the concrete structure, it is needed to
50 prevent or to limit this risk. As a consequence, the development of the deformation induced
51 by hydration (thermal and autogenous strain) and desiccation (drying shrinkage) should be
52 experimentally defined as the mechanical properties (compressive and tensile strength, elastic
53 modulus and creep/relaxation) [11]. However, only few studies have been performed on these
54 early age properties of recycled concrete (see e.g. [12,13]). It is shown that using RC
55 aggregates generally resulted in delayed cracking and lower stresses [14,15]. The evolution of
56 the properties involved in cracking sensitivity is actually coupled when shrinkage is
57 restrained. For example creep/relaxation mitigates the stress development and the stress level
58 influences creep. RC aggregates are porous thus they can absorb or release water. The
59 absorption coefficient depends on the fraction (fine or coarse) and the origin of recycled
60 aggregates. During the hydration process, recycled aggregate can be considered as a water
61 tank for the cement paste and thus plays the role of an internal curing agent [16]. This
62 phenomenon reduces and/or delays the decrease of the internal relative humidity of the
63 cement paste [17,18]. The internal curing effect was firstly observed on concrete composed of
64 porous [6] or lightweight aggregate in sealed and drying conditions [19–21] but also on
65 crushed returned concrete aggregates and recycled aggregates [22,23]. The release of water
66 from RC aggregates has been highlighted by Salgues et al. [24]. They directly monitored the
67 water saturation of aggregates from mixing time to 2 hours and showed that the actual
68 absorption of RG was higher in cement paste then aggregates started to release water from 0.5
69 hours in drying conditions but not in sealed conditions. The release of aggregates water
70 probably occurred later. As the pores of hydrating cement paste become progressively finer
71 than the pores of porous aggregates, these release water, according to Kelvin-Laplace
72 equation [20]. In consequence, the substitution of natural aggregates by recycled ones
73 decreases the self-desiccation and the desiccation of concrete at early age.

74 Research related to the influence of recycled concrete on plastic shrinkage and the associated
75 cracking sensitivity at early age is rather scarce. The ability of RC aggregates to provide
76 internal curing has been showed by several studies [22,25] but the same authors reported an
77 increase in drying shrinkage and plastic shrinkage, respectively. However the consequences of
78 these evolutions on cracking sensitivity have not been investigated yet. The authors already
79 showed the influence of RC on the cracking sensitivity at very early age [26], i.e. before
80 cracking, when fresh concrete is subjected to differential settlements. The shrinkage-to-weight
81 loss ratio and cracking risk were mainly influenced by the total water-to-binder ratio, where
82 total water includes the water added and the water used to pre-saturate the aggregates.
83 Another critical period is setting and early hardening stage, as this period corresponds to the
84 minimum of tensile strain capacity [27,28]. If the tensile strength is lower than the stress
85 caused by restrained movement, shrinkage cracking occurs [29,30]. Active restrained
86 shrinkage test rigs have been developed to investigate these phenomena [30–32] but only few
87 studies deal with the influence of porous aggregates at early age [33] and none with RC
88 aggregates. Finally, the authors have also shown that, under sealed condition, recycled sand
89 and gravels reduces the risk of cracking of concrete structure, which highlights the interest of
90 these components for mass concrete [34]. However, further experimental and numerical
91 investigations are still required to understand the impact of recycled aggregate on the early
92 age cracking sensitivity of recycled concrete [14,15,35,36].

93 The study presented in this paper focuses on plastic shrinkage induced cracking of concrete
94 with recycled sand and gravels at early age. The experimental part is based on active
95 restrained shrinkage tests performed with the temperature-stress testing machine (TSTM) at
96 ULB in Brussels, Belgium. This system has been developed in the Laboratory of Civil
97 Engineering of ULB since 2006 [37,38] and the system was significantly updated for this
98 study in drying conditions. This test was associated to free shrinkage tests and other

99 experimental advanced techniques, such as direct tensile testing and the monitoring of elastic
100 properties using repeated loading testing [in order to characterize the properties of recycled](#)
101 [concrete since very early age under free condition](#). Several phenomena are actually coupled in
102 the conditions of restrained shrinkage thus it is necessary to monitor the evolution of the same
103 properties in unrestrained conditions to estimate the coupling effects and understand the
104 influence of the different properties on the evolution of cracking sensitivity. In the following
105 sections the experimental program is first presented. Four concrete mixtures were studied,
106 namely: natural aggregates (NA) concrete, two concrete mixtures with 30% and 100% of
107 coarse RC aggregates, and one mixture with RC sand. The TSTM and the experimental
108 procedures corresponding to the other advanced testing procedures are then described. The
109 results are analysed and discussed, first free shrinkage then restrained shrinkage. The
110 evolution of stresses and the different properties are analysed and finally a methodology is
111 described to quantify the contributions of the main phenomena in the evolution of the
112 cracking sensitivity and to understand the influence of the proportion and type of RC
113 aggregates.

114

115 **2. Methodology**

116 **2.1 Experimental program, materials and mixtures**

117 The experimental program focuses on the replacement of natural aggregates by recycled
118 concrete (RC) aggregates. Four concrete mixtures are studied [in the framework of the French](#)
119 [National Project RECYBETON](#). Concretes are named “XRSYRG” where X and Y are the
120 [percentage of replacement of natural sand and gravels by recycled ones in volume](#)
121 [respectively](#). Recycled sand corresponds to 0 – 30% of the sand volume fraction and recycled
122 [gravels correspond to 0 – 30 – 100% of the gravel volume fraction](#). A moderate substitution
123 [ratio of 25 to 30% corresponds to most of recommendations \[39,40\]](#). However, a full

124 replacement allows a better understanding of the phenomena involved in shrinkage-induced
 125 cracking. Moreover, in a recent review, Verian et al. [40] concluded that higher proportions
 126 (up to 100%) can be used if the mix design, batching methodology, and the moisture
 127 condition of the aggregates are properly handled. For instance, Arezoumandi et al. [41]
 128 showed that beams with 100% recycled concrete aggregate had comparable ultimate flexural
 129 strength. Adams et al. [36] found that the use of RCA up to 100% significantly reduced the
 130 cracking risk of concrete. RC sand and coarse aggregates were initially at the saturated
 131 surface dried condition (SSD) state. The water content of cement paste and the properties of
 132 concrete actually depend on the initial water saturation of porous aggregates [6] and RC
 133 aggregates [42]. The properties of RC aggregates are detailed in Table 1.

134

135 Table 1 - Properties of natural and recycled aggregates

	Natural aggregates			Recycled concrete aggregates		
	Sand 0/4mm	Gravel 4/10mm	Gravel 6.3/20mm	Sand 0/4mm	Gravel 4/10mm	Gravel 10/20mm
Mineralogy	Silico- calcareous	Dense limestone	Dense limestone	Demolition waste	Demolition waste	Demolition waste
Water absorption WA₂₄ (%)	1.2	0.56	0.53	10.7	5.3	4.9
Density (g/cm³)	2.6	2.73	2.73	2.10	2.34	2.32

136

137 Natural sand from Sandrancourt, France was used, and natural coarse aggregates were
 138 crushed dark limestone from Givet, France. RC aggregates were obtained by crushing
 139 unknown waste concrete from Paris region, France. They can be considered as good quality
 140 RC aggregates according to standard NF EN 206/CN [43,44]. Their coefficient of water
 141 absorption at 24 hours WA₂₄ was determined using pycnometer and hydrostatic weighing and
 142 both methods gave consistent results [45]. Limestone filler from Orgon and Portland cement

143 CEM II/A-L 42.5 N from Rochefort, France were also used. Their main properties and
 144 composition are given in Table 2. All the materials were provided by French National Project
 145 RECYBETON. This project aimed at investigating the use of RC aggregates for structural
 146 concrete.

147 Table 2. Properties of cement and limestone filler

	Composition (%)		Blaine fineness (cm ² /g)	Standard compressive strength (MPa)	Density (g/cm ³)
	Clinker	Limestone			
Limestone filler	-	99	4600	-	2.7
Cement	87	11	3700	53	3.09
	Compound composition of clinker (%)				Na ₂ O _{eq}
	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	(%)
	61	-	7.9	12	0.59

148
 149 The four studied concrete mixtures (
 150 Table 3) were designed to reach the minimal strength of C25 class and the slump of S4 class
 151 [46,47]. The superplasticizer (SP) was a high-range water-reducing admixture based on
 152 polycarboxylate ether (PCE). The SP content was adjusted to reach the slump. The effective
 153 water content W_{eff} is the difference between the total water content W_{tot} and the water
 154 absorbed by aggregates W_{abs} according to their nominal absorption WA_{24} (equation 1). The
 155 equivalent binder content B_{eq} is calculated according the definition of Standard NF EN 206
 156 [43], with a coefficient of activity $k = 0.25$ for limestone filler (equation 2). The W_{eff} / B_{eq} ratio
 157 was kept constant but the paste volume, thus water and cement contents, was slightly
 158 increased for mixtures with RC aggregates to reach the target slump.

159 $W_{tot} = W_{eff} + W_{abs}$ (1)

160 $B_{eq} = C + k.L$ (2)

161

162 Table 3. Studied concrete mixtures

	0RS-0RG	30RS-0RG	0RS-30RG	0RS-100RG
NG 6,3/20 (kg/m ³)	820	829	462	-
RG 10/20 (kg/m ³)	-	-	296	701
NG 4/10 (kg/m ³)	267	190	228	-
RG 4/10 (kg/m ³)	-	-	-	163
NS 0/4 (kg/m ³)	780	549	813	806
RS 0/4 (kg/m ³)	-	235	-	-
Cement, C (kg/m ³)	270	276	276	282
Limestone, L (kg/m ³)	45	31	31	31
Superplasticizer SP (kg/m ³)	0.747	0.798	0.861	0.798
W_{eff} (L/m ³)	180	185	185	189
W_{tot} (L/m ³)	194.6	221.4	212.3	241.0
W_{eff}/B_{eq}	0.64	0.65	0.65	0.65
Volume of paste (l/m ³)	285	287	287	293
Gravel/Sand	1.39	1.30	1.21	1.07
Slump (mm)	195	204	193	195
Compressive strength, f_{c28 d.}	31.4	29.0	28.5	27.6

163

164

165 2.2 Testing procedures

166 2.2.1 Tensile strength

167 Tensile strength has been determined on $\varnothing 11 \times 22$ (in centimetres) cylindrical specimens using
168 the splitting tensile test and on prismatic specimens by using direct tensile test [28]. In
169 addition the tensile strain capacity is tested with the direct tensile test. Direct tensile testing
170 [28] has been performed on mixtures at several ages from 7 to 24 hours (7 – 10 – 16 – 20 and
171 24h). For each age of loading, 2 cylindrical samples were tested to define the splitting tensile
172 strength and one direct tensile test was performed. Data related to the repeatability of this test
173 can be found in previous work [28]. The average difference between two strength values at
174 the same age was 6%. The average difference between two values of tensile strain capacity
175 was 21%. In order to obtain the evolution of the tensile strength throughout the whole time
176 period of the TSTM tests, these values have been extrapolated using data from the splitting
177 tensile test.

178 2.2.2 Elastic modulus

179 The static modulus E_{stat} was assessed through repeated compression tests [48–50] on
180 cylindrical samples. One cylindrical sample was used for each concrete mixture. A vertical
181 testing device has been designed at ULB to monitor the elastic and basic creep properties
182 [51]. Compressive loadings can be applied a few hours after the final setting. An
183 electromechanical testing setup with a capacity of ± 100 kN is used. The machine is fully
184 controlled by computer (load and displacement). A cylindrical concrete specimen (97 mm in
185 diameter and 550 mm in height) is cast inside a Polyvinyl chloride (PVC) mold. Before
186 casting, a thermocouple is placed in the center of the mold of the dummy specimen. After
187 casting, all specimens are stored in an air-conditioning chamber at 20°C and 90% relative
188 humidity. Then samples are demolded, grinded on both circular end faces and covered by 2

189 self-adhesive aluminum sheets in order to keep the sample in sealed conditions. The sealing
190 has been checked by weighting the sample before and after the test. No significant weight loss
191 was observed. As samples are grinded few hours after setting, a thin layer of sieved concrete
192 (1cm) is placed on the top of the sample in order to avoid pulling out aggregates during
193 grinding. All the equipment is in an air-conditioned room. Displacements are measured with
194 an INVAR© extensometer composed by two rings spaced of 350 mm and three rods which
195 hold the 3 longitudinal displacement sensors placed at 120°. 3 lateral displacement sensors are
196 placed on the lower ring. Both rings are fixed to the specimens by means of three elastic
197 anchorages allowing the measurement of the longitudinal and lateral displacement.

198 The tests were performed from the end of setting and the load did not exceed 20% of the
199 compressive strength at each loading. The sample is loaded in compression in 10 seconds at a
200 constant stress rate then unloaded till a value of 0.014 MPa to always keep a contact between
201 the sample and the testing device. This threshold value is chosen to avoid any damage of the
202 sample in compression. The static E-modulus is determined during the repeated loading from
203 the data (measured load and displacement) between 30% and 80% of loading [48,49,52]. The
204 data provided by this testing procedure has been compared to other classical and non-
205 destructive methods [49].

206 **2.2.3 Temperature Stress Testing Machine (TSTM)**

207 A TSTM has been developed at the civil engineering laboratory BATir at ULB (Université
208 Libre de Bruxelles) since 2006. This system allows characterizing concrete from very early-
209 age in free and restrained conditions [37,38]. It consists of a TSTM frame and a dummy mold.

210 [An overview of the whole test setup is shown in Figure 1.](#)

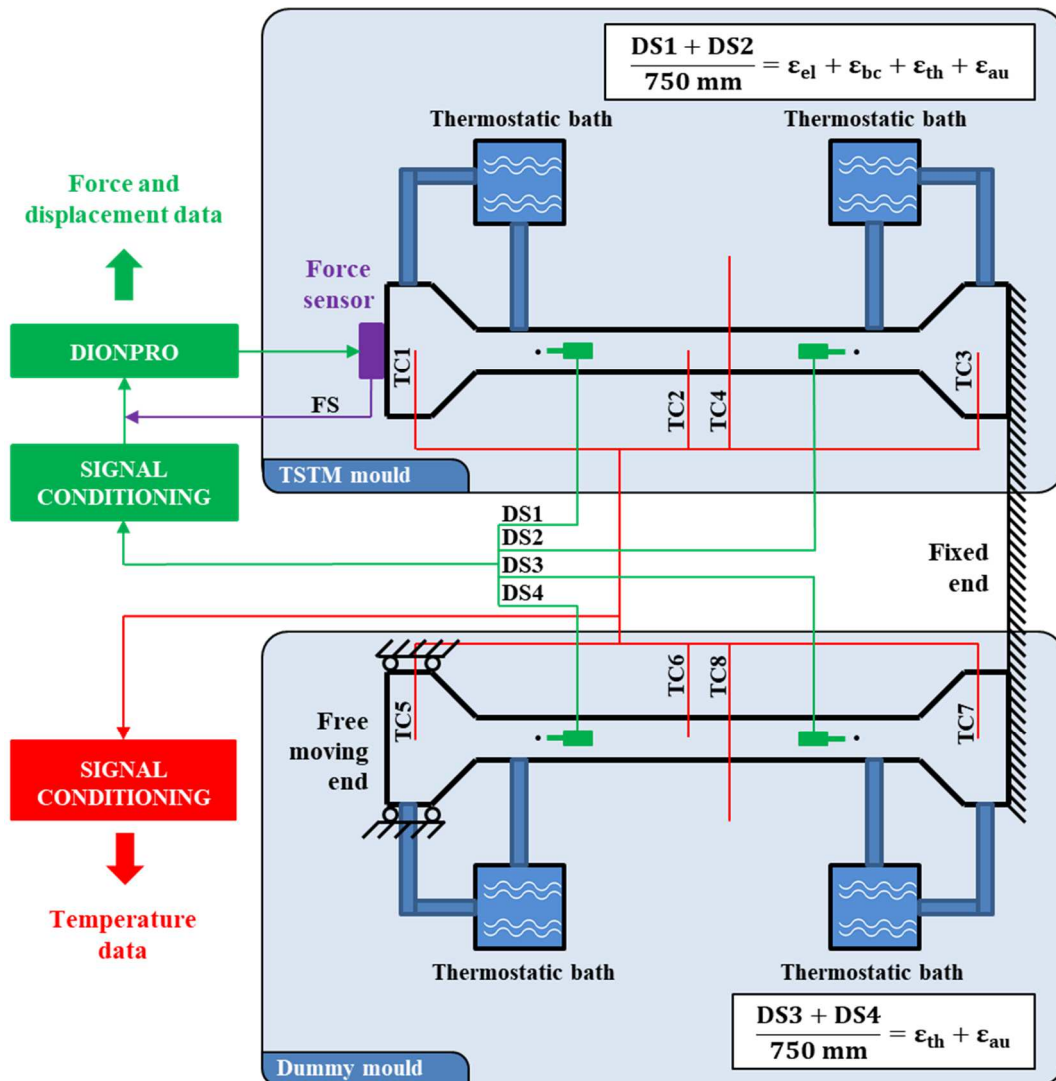


Figure 1 – Scheme of the TSTM [52]

211 The restrained shrinkage frame is based on a Walter+Bay ± 400 kN electromechanical testing
 212 setup. The concrete specimen has a dog-bone shape with a longitudinal part of 1000 mm with
 213 a 100x100 mm² cross-section in the central part and a 300x100 mm² section at both ends
 214 (Figure 2). The dimensions allow testing concrete mixtures with a 20-mm maximum
 215 aggregate size. Concrete sample is poured in the double-walled mold connected to a
 216 temperature-control system set at 20°C for the tests presented in this paper. The test takes
 217 place in a climate room (20°C – 50%RH) and only the top face is exposed to drying after
 218 casting. Thermocouples are placed at the center and at both ends of the mold in order to
 219 monitor the evolution of the actual temperature in the sample. The displacements are

220 measured by sensors without contact with a resolution of 0.014 μm which are placed on invar
 221 supports. These sensors are located at mid height of the sample at a distance of 750 mm,
 222 where the stress field is assumed to be homogenous. They are fixed on steel bars externally
 223 supported by the TSTM frame (Figure 3). The TSTM allows performing restrained shrinkage
 224 test but also to assess the evolution of the creep or the elastic modulus since setting [52,53].

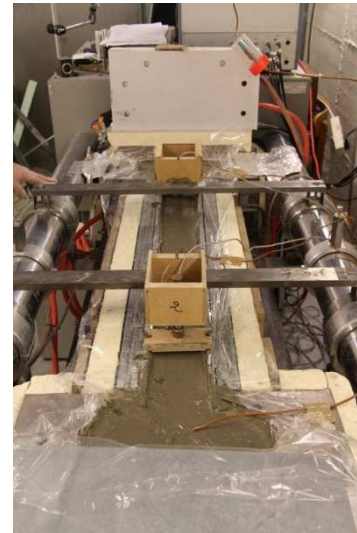
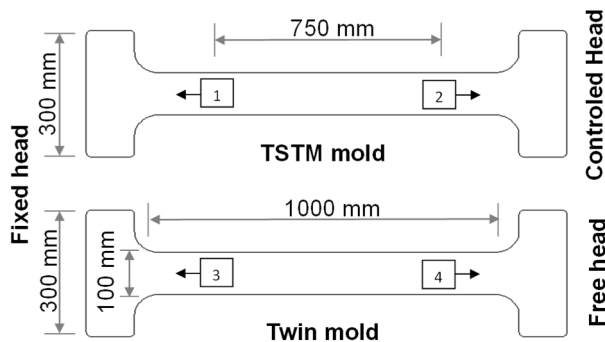


Figure 2. TSTM and twin mold with their dimensions [38].

Figure 3. TSTM mold with displacement sensors and thermocouples in place (concrete ORS-ORG).

225 A twin mold was built to measure the free strain. This mold has exactly the same geometry as
 226 the TSTM mold (Figure 2); the displacement of the free end is not externally controlled.

227 The total strain in the TSTM ϵ_{TSTM} mold is calculated assuming that the strain components are
 228 independent, thus it corresponds to the sum of the following strains: elastic ϵ_{elas} , creep ϵ_{creep} ,
 229 thermal ϵ_{ther} and shrinkage ϵ_{sh} . This will be defined as the cumulated strain (equation 3).

$$\epsilon_{TSTM} = \epsilon_{elas} + \epsilon_{creep} + \epsilon_{ther} + \epsilon_{sh} \quad (3)$$

230 The strains in the twin mold correspond to the sum of the thermal and shrinkage strains as
 231 shown by equation 4.

$$\varepsilon_{free} = \varepsilon_{ther} + \varepsilon_{sh} \quad (4)$$

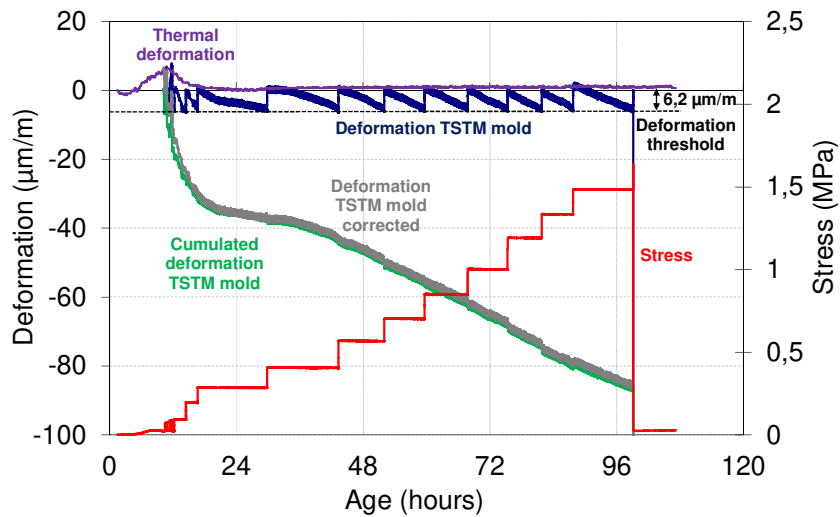
232 Subtracting the twin mold strain from the TSTM mold strain gives the elastic and creep strain
233 (equation 5). The simultaneous use of both molds allows the determination of creep effects.

$$\varepsilon_{TSTM} - \varepsilon_{free} = \varepsilon_{elas} + \varepsilon_{creep} \quad (5)$$

234 The restrained shrinkage tests started at the end of setting. At this age, concrete is stiff enough
235 to hold the rods used for strain measurement. At this time, the strain sensors are reset and the
236 TSTM test starts. The concrete in the TSTM mold starts shrinking freely until it reaches a
237 strain of 6.2 $\mu\text{m}/\text{m}$ (Figure 4). Then, the controlled head moves in the opposite direction in
238 order to reset the strain. After this, the load is maintained constant; meanwhile, the concrete
239 keeps contracting until the strain reaches the threshold value again. A new compensation
240 cycle then begins and the test continues until cracking or when the test duration exceeds 2
241 weeks. The threshold strain value has been defined by considering that it must be as low as
242 possible to be as close as possible to a full restraint situation during the whole test and at the
243 same time high enough to compute accurately the viscoelastic properties (elastic modulus and
244 creep strain) for each compensation cycle [54].

245 The cumulated strains of the TSTM mold and the free strains of the twin mold for the
246 conventional concrete ORS-ORG are displayed in Figure 4 and Figure 5. The thermal strains of
247 studied concrete were around 10 $\mu\text{m}/\text{m}$, thus the corrected and uncorrected strains are close.

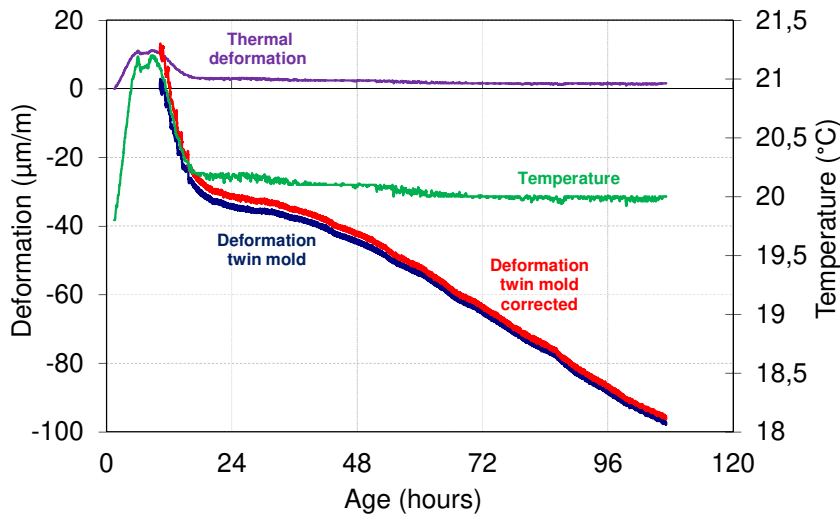
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249

250

Figure 4. Strain and stress in the TSTM mold: restrained shrinkage.



251

252

Figure 5. Strain in the twin mold: free shrinkage.

253 Each concrete mixture was tested once but 0RS-100RG was tested twice in order to estimate
 254 the repeatability of the system. This concrete mixture was chosen as RC aggregates are often
 255 considered to induce higher variability of concrete properties due to their heterogeneous
 256 nature. The results are plotted on Figure 6 and Figure 7. The literature data has not provided
 257 any repeatability tests for the TSTM except in the study of Klausen [55] who also showed a
 258 good repeatability of such tests in spite of their complexity. The first test lasted 12 days
 259 without cracking and the second was stopped after 7 days to save testing time for other tests.
 260 The stress development due to the restraint in the TSTM mold and the evolution of the free

261 strains in the twin mold are presented in Figure 6 and Figure 7 respectively. The repeatability
 262 was considered as acceptable for the presented experimental study.

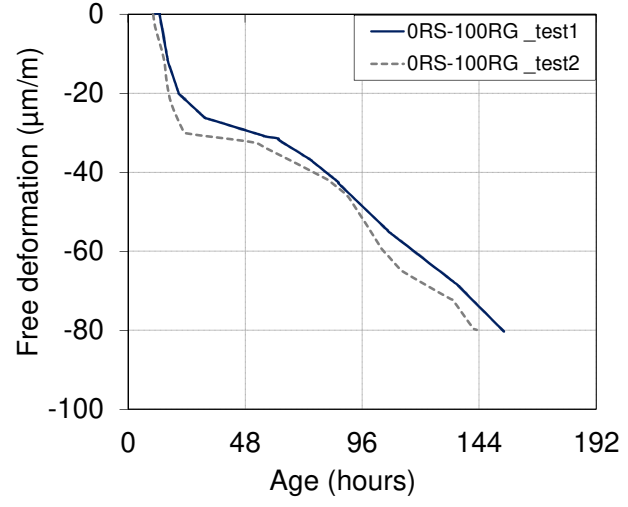
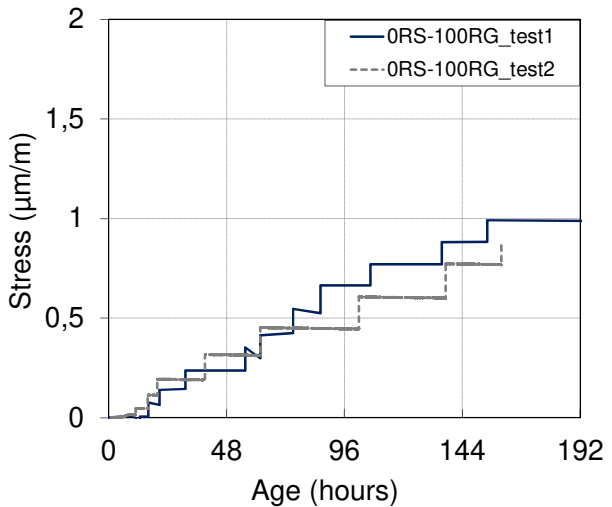
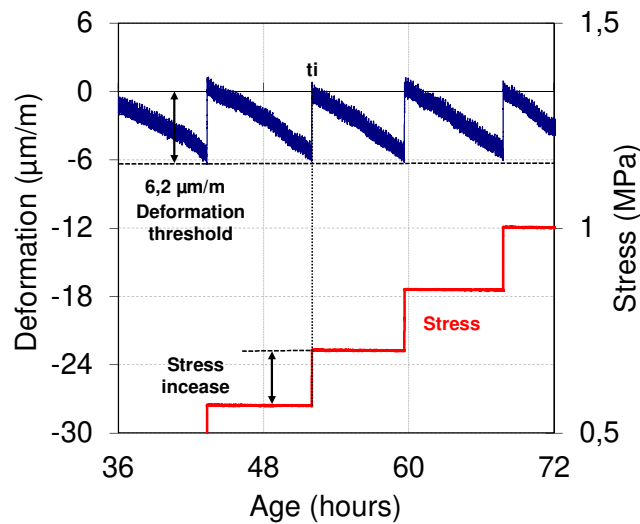


Figure 6. Repeatability testing: evolution of stress in 100% RG concrete.

Figure 7. Repeatability testing: free shrinkage in 100% RG concrete.

263
 264 During the TSTM test, the evolution of the applied load is measured to determine the
 265 cumulated stresses in concrete. The static elastic modulus of the concrete can be determined
 266 during each load cycle in the TSTM mold. Knowing the tensile stress increment and the strain
 267 increment, Hooke's law can be applied to calculate the modulus E_{TSTM} during the restrained
 268 shrinkage test. It is calculated as shown in Figure 8 and according to equation 6, using the
 269 values between 20 and 80 % of the load increment.

$$E_{TSTM}(t_i) = \frac{\Delta\sigma_i}{\Delta\varepsilon_i} \quad (6)$$



270

271

Figure 8. Determination of elastic modulus from the TSTM tests

272

273

3. Results and discussion

274

Shrinkage-induced cracking depends on several properties of concrete, namely: elastic modulus, free strain, creep, tensile strength, fracture energy. In this experimental study TSTM was associated to other advanced techniques in order to understand the influence of RC aggregates proportion of concrete properties and cracking potential at early-age.

278

3.1. Elastic modulus

279

Measurements started 4 hours after setting. The whole test duration was 1 week or more and the test was performed on one cylindrical sample. The temperature of the sample is set to 20°C. For each repeated loading, the E-modulus is calculated from the load and displacement data between 30% and 80% of loading [48,49]. Results are plotted against the age of the specimen in

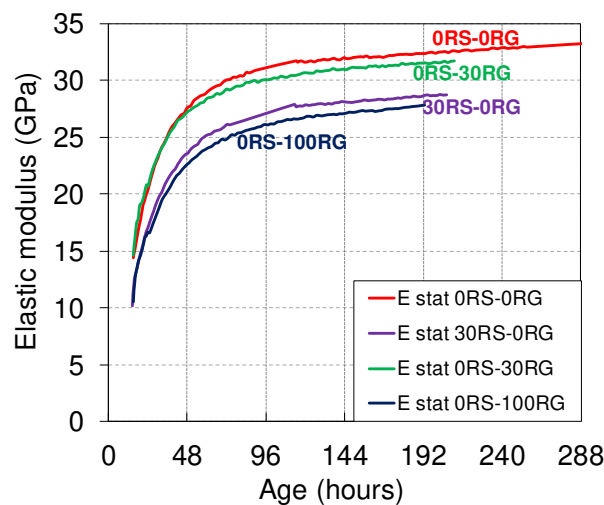
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Figure 9. The substitution of 30% of natural coarse aggregates by RG does not change significantly the evolution of the E-modulus whereas a substitution of 100% induces a decrease of the E-modulus by 5 GPa at an age of 1 week. The substitution of 30% of natural sand by recycled sand induces a decrease of the elastic modulus by 4 GPa at an age of 1 week.

288

The ORS-30RG concrete has a limited RC content (

289 Table 3). As RG have relatively low paste content, they do not affect much the elastic
 290 modulus of concrete for low replacement rate [14]. The 0RS-100RG concrete globally
 291 showed lower moduli. This is due to the lower modulus of RC 4/10 as they include more old
 292 cement paste than RG 10/20 [56] (
 293 Table 3). Elastic modulus has actually been reported to decrease with paste volume [57]. The
 294 amount of old cement paste is even higher in recycled sand. This explains why a substitution
 295 of 30% of natural sand by recycled one has a similar impact to the elastic modulus than a full
 296 replacement of natural gravels by recycled ones. Similar experimental results were obtained
 297 previously by other researchers. On hardened concrete, Thomas, *et al.* [12] have shown that
 298 very small reduction of the elastic modulus takes place when the replacement of natural
 299 gravels by recycled ones is lower than 25%. For higher replacement ratio, a significant
 300 decrease of the elastic modulus was obtained. On hardening concrete, Velay-Lizancos, *et*
 301 *al.*[58] have observed that low substitution (<30%) of natural sand by recycled one decreases
 302 significantly the elastic modulus. Omary *et al.* [56] also observed a significant reduction in
 303 elastic modulus with 30% of recycled sand. This reduction was almost as high as the
 304 reduction due to full replacement of natural gravels by recycled ones, as observed here
 305 (Figure 9).



306
 307 Figure 9. Effect of substitution rate on the elastic modulus determined from repeated loading
 308 tests.

309

310 **3.2 Tensile strength and tensile strain capacity**

311 Direct tensile testing has been performed at several ages from 7 to 24 hours. One sample was
312 tested for each age at loading (7 – 10 – 16 – 20 and 24h). In order to obtain the evolution of
313 the tensile strength throughout the whole time period of the TSTM tests, these values have
314 been extrapolated using data from the splitting tensile test (tests performed at several ages
315 from 16 to 300 hours as shown in Table 4), by applying the ratio of splitting tensile strength
316 to direct tensile strength according to equation 7 derived from the theory of elasticity, with F
317 the measured peak load [kN], D the sample diameter [cm], and L the length of the specimen
318 [cm]. Two cylindrical samples were tested for every age at loading and the results presented
319 correspond to the average of both samples.

$$f_{t,d} = 0.9f_{t,sp} = 0.9 \cdot \frac{20 \cdot F}{\pi \cdot D \cdot L} \quad (7)$$

320 Results of the direct and splitting tensile strength are shown in the Figure 10 and Figure 11
321 below and all experimental results are given in Table 4.

322 The substitution of 30% of natural gravel or sand by RC aggregates does not affect
323 significantly the evolution of the tensile strength whereas a substitution of 100% of natural
324 aggregate induced a decrease of the tensile strength by 0.23 and 0.32 MPa at ages of 24 and
325 300 hours respectively. On hardened concrete, similar results were obtained by Sadati and
326 Khayat [14] on recycled concrete composed of different type of recycled gravel and for half
327 and full replacement of natural gravel by recycled one. Omary et al. [56] observed a stronger
328 decrease of tensile strength due to the replacement of 30% of sand, but their tests were
329 performed at 28 days.

330 Table 4. Results of the direct and splitting tensile strength

ORS-ORG										
Age [h]	7	10	16	20	24					
ft,d [MPa]	0.03	0.06	0.29	0.52	0.71					
ϵ_t [$\mu\text{m}/\text{m}$]	13.1	7.3	19.5	28.7	34.2					
Age [h]	17	21	24	25	36	48	73	108	168	300
0.9 x ft,sp [MPa]	0.47	0.64	0.71	0.88	1.05	1.20	1.40	1.60	1.66	1.77
0.75 x ft,sp [MPa]	0.39	0.53	0.59	0.74						
30RS-ORG										
Age [h]	7	10	16	20	24					
ft,d [MPa]	0.03	0.08	0.22	0.39	0.59					
ϵ_t [$\mu\text{m}/\text{m}$]	13.3	11.6	18.3	25.7	34.1					
Age [h]	17	22	23	26	36	48	108	142	168	299
0.9 x ft,sp [MPa]	0.41	0.58	0.57	0.77	0.82	1.04	1.35	1.55	1.62	1.74
0.75 x ft,sp [MPa]	0.34	0.48	0.48	0.64						
ORS-30RG										
Age [h]	7	10	16	20	24					
ft,d [MPa]	0.03	0.07	0.27	0.42	0.65					
ϵ_t [$\mu\text{m}/\text{m}$]	13.2	9.5	16.9	21.9	30.4					
Age [h]	18	22	24	26	36	47	141	168	299	
0.9 x ft,sp [MPa]	0.55	0.62	0.64	0.85	0.84	1.03	1.50	1.58	1.67	
0.75 x ft,sp [MPa]	0.46	0.52	0.53	0.71						
ORS-100RG										
Age [h]	7	10	16	20	24					
ft,d [MPa]	0.02	0.05	0.24	0.38	0.48					
ϵ_t [$\mu\text{m}/\text{m}$]	14.5	9.8	19.8	26.2	29.0					
Age [h]	18	22	24	27	36	48	107	168	300	
0.9 x ft,sp [MPa]	0.44	0.63	0.48	0.79	0.68	0.85	1.10	1.34	1.45	
0.75 x ft,sp [MPa]	0.37	0.53	0.40	0.66						

331

332

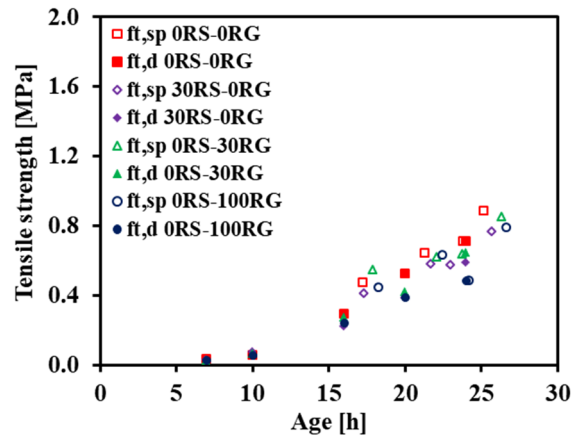
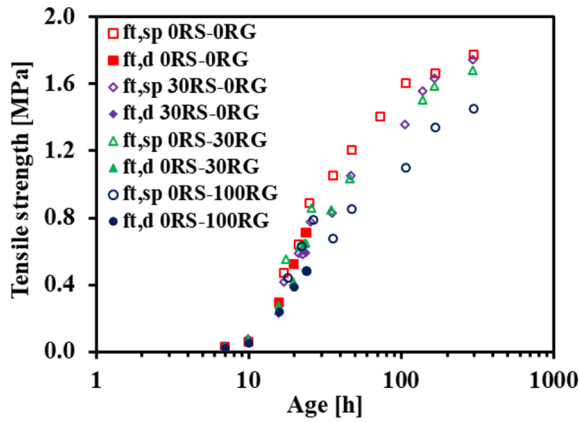


Figure 10. Effect of substitution rate on the tensile strength, determined from direct and splitting tensile tests

Figure 11. Zoom of the Figure 10 during the first 30 hours.

333

334

Between 16 and 24 hours, the tensile strength obtained by means of splitting and direct

335

tensile tests are not well superimposed. Higher values of the tensile strength are obtained

336

with the splitting tensile test. To improve the correlation between the direct and the

337

splitting tensile strength, the 0.9 factor from Equation 7 is replaced by a value of 0.75 for

338

all concrete mixtures at very early age (age lower than 30 hours). A good agreement is

339

then obtained between splitting and direct tensile tests as shown in the Figure 12 for very

340

early age results.

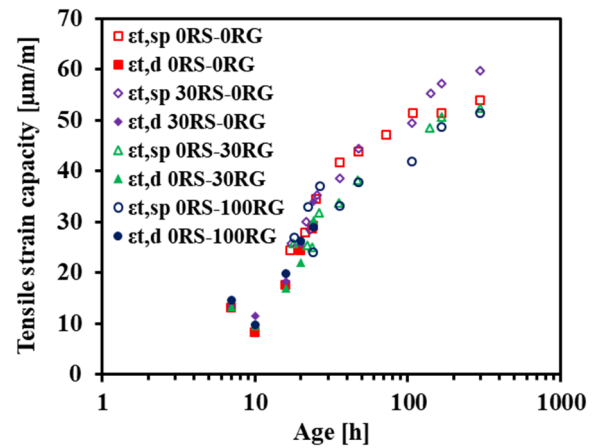
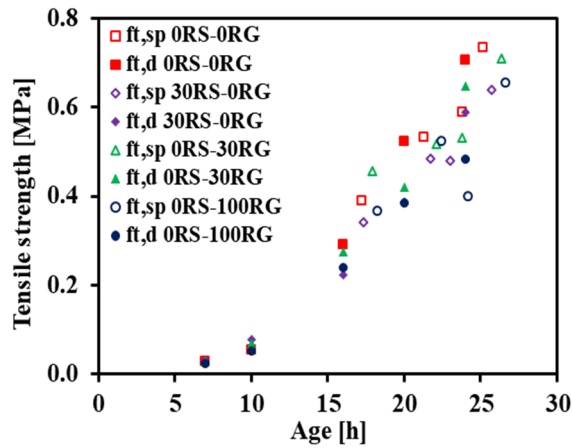


Figure 12. Tensile strength determined from direct and splitting tensile tests with correction

Figure 13. Effect of substitution rate on the tensile strain capacity: Determined from direct and splitting tensile tests

341 Based on the results of the tensile strength and the elastic modulus, the tensile strain capacity
 342 was defined according to Equation 8:

$$\varepsilon_t = \frac{f_t}{E} \quad (8)$$

343 Results of the tensile strain capacity of each material are plotted in Figure 13 according to the
 344 age of the material. Before setting, a decrease of the tensile strain capacity is observed for
 345 each concrete composition. A minimum is reached at an age of 10 hours with values close to
 346 10 µm/m. Then the tensile strain capacity increases. At an age of 24 hours, the reference
 347 composition 0-RS-0RG reaches a tensile strain capacity of 34 µm/m. The substitution of 30%
 348 of natural sand by recycled one does not change significantly the evolution of the tensile
 349 strain capacity whereas a substitution of natural gravel by recycled ones induces a slight
 350 decrease of the tensile strain capacity by 5 µm/m at an age of 24 hours. Recycled gravel has
 351 lower elastic modulus thus concrete should show higher tensile strain capacity but concretes
 352 with recycled gravel also had lower tensile strength. Taking into account the repeatability of
 353 this characterization, there are few significant differences between studied materials. This is
 354 consistent with previous study of the authors [28] on the influence of aggregate type on tensile

355 properties. During the first 24 hours, the development of tensile strain capacity was mainly
356 driven by the hydration of cement paste.

357

358 **3.3 Restrained shrinkage and related properties**

359 3.3.1. Free strain

360 As the water-to-cement ratio of studied mixtures is relatively high, the autogenous
361 deformations are relatively low and the main part of the shrinkage development is associated
362 to the plastic shrinkage, i.e. the monitoring of strains in drying conditions at 20°C and 50%
363 RH. Figure 14 gives the evolution of the free strain in the twin mold for concrete samples
364 exposed to drying since casting. The development of the free strain can be divided in three
365 stages. The first stage shows a rapid increase of the shrinkage with a magnitude of 20 to
366 30µm/m and takes place between the final setting and an age of around 20 hours. During this
367 period, the development of the free strain is mainly driven by the self-desiccation of the
368 cement paste [16]. The presence of recycled gravel and sand decreases slightly the shrinkage
369 magnitude. This difference is more pronounced with recycled gravels. At an age of around 20
370 hours, the shrinkage rate decreases significantly for each composition. For composition with
371 no or moderate amount of recycled aggregate, the second stage stops at an age of around 48
372 hours. For high replacement of natural gravels by recycled ones, the duration of the second
373 stage takes place on a longer duration. It is also observed that the shrinkage rate is slightly
374 lower during this stage for the concrete composed of recycled aggregate. After this period, the
375 shrinkage rate increases again. No significant difference is observed during this third stage
376 between the composition without recycled aggregate and the compositions with moderate
377 amount of recycled aggregate. The 100% RG concrete had the lowest shrinkage rate. The
378 monitoring of free strains stopped when the concrete specimen of restrained shrinkage frame
379 cracked, except for ORS-100RG concrete that did not crack.

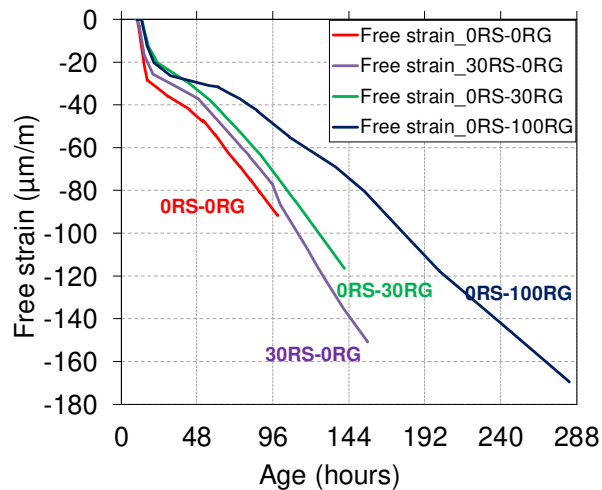


Figure 14. Free strain in twin mold.

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381
382

383 The influence of internal curing on concretes with RG and RS can be observed from final
 384 setting to 48 hours on the evolution of the free strain, and then this effect remains significant
 385 only for 0RS-100RG concrete. The RG seems to mitigate self-desiccation and desiccation by
 386 maintaining the internal relative humidity at a higher level and lowering capillary pressures.
 387 Several aggregate properties influence the autogenous and drying shrinkage as the content and
 388 the porosity of the aggregate, the elastic modulus of the aggregate, the particle size
 389 distribution and the microstructure [20,59,60]. The magnitude of the internal curing of the
 390 recycled aggregate is function of the mean distance between two adjacent aggregates. The
 391 lower this distance, the higher the water released from the aggregates reaches the whole
 392 volume of cement paste [20]. This can explain why the internal curing effect provided by the
 393 recycled aggregates is much greater in the case of the composition 0RS-100RG than for the
 394 composition 0RS-30RG. These results are in agreement with previous study [25]. The
 395 autogenous shrinkage of concretes decreased as their replacement ratio increased, which was
 396 attributed to the higher water storage capacity of recycled concrete aggregates. On the other
 397 hand, the lower stiffness of the recycled gravel is a cause of higher shrinkage due to the lower
 398 restraint of the shrinkage of the cement paste [61] as observed by Maruyama and Sato [22] on
 399 high performance concretes composed of recycled gravels. In addition, recycled gravel

400 consists of natural gravels and hardened cement paste. Under the effect of drying, the latter
401 shrinks. [62,63]. It therefore appears that the internal curing effect of recycled gravels is
402 predominant on autogenous and drying shrinkage at a very early age for high replacement
403 ratio of natural gravel by recycled ones.

404 When comparing the 30RS-00RG and 00RS-30RG concretes, it appears that, from an age of
405 96 hours, the shrinkage rate is higher for the 30RS-00RG composition. Both compositions
406 have an equivalent amount of recycled aggregate, only the size of the recycled gravel and the
407 content of old cement paste change. Recycled sand has high fine particle content (2% passing
408 at 63 μ m and 7% at 125 μ m) and a higher content of old paste. Moreover, drying shrinkage is
409 actually known to increase with paste volume [64,65]. Thus the use of recycled sand promotes
410 in the same time the internal curing effect and the shrinkage of the recycled aggregate. It is
411 therefore observed that the use of fine recycled aggregate increases the drying shrinkage in
412 comparison to recycled gravels. Thus it is concluded from these results that the internal curing
413 effect is significant for high replacement ratio of natural aggregates by recycled ones and that
414 the use of fine recycled aggregate reduces the apparent internal curing effect of recycled
415 aggregate due to their high shrinkage under drying conditions. [The studies related to early-age
416 shrinkage of concrete with recycled aggregates are relatively scarce. Hanif et al. \[66\] found
417 that using recycled aggregates resulted in a lower net shrinkage strain.](#)

418

419 **3.3.2. Strain development under restrained condition**

420 Cumulated strains under restrained conditions are plotted in Figure 15. From 24 hours their
421 evolution significantly differs from free shrinkage (Figure 14). Under restrained conditions, a
422 linear increase is observed for 0RS-0RG concrete and the concretes with RC aggregates show
423 a decreasing rate, whereas the shrinkage rate is constant or increasing during this period under
424 free conditions. The 30RS-0RG concrete even shows relative swelling from 24 to 48 hours.

425 Given the boundary conditions of TSTM and twin molds, this difference is due to creep
 426 strains. Subtracting the free strains (obtained from the twin mold) and the elastic strains from
 427 those in the TSTM mold provides the evolution of creep strain (Figure 16).

428

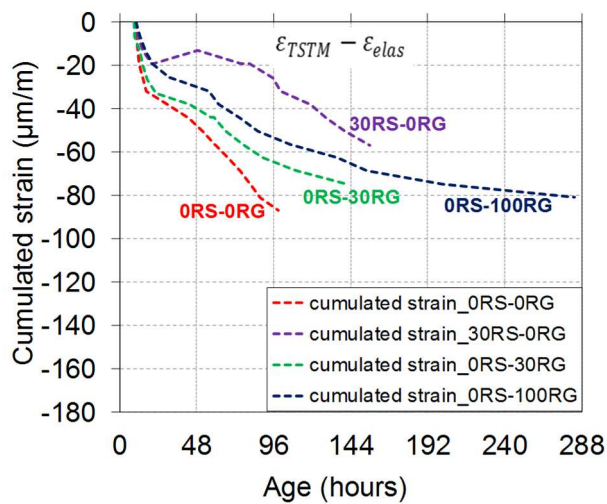


Figure 15. Effect of substitution rate on cumulated strain (TSTM mold)

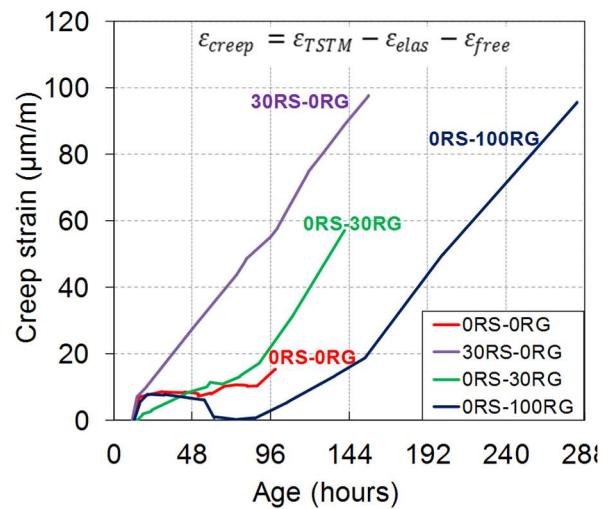


Figure 16. Evolution of creep strain calculated from free and restrained shrinkage evolutions

429

430 The reduction in shrinkage rate increases with RG content (Figure 15). This allowed delaying
 431 cracking time. 0RS-0RG and 0RS-30RG concrete cracked at strains of approximately 80
 432 µm/m and 0RS-100RG reached this strain at 288 hours (12 days) without cracking. This value
 433 is of the order of magnitude of tensile strain capacity of concrete at early-age [5,28] but lower
 434 than the values of tensile strain capacity provided by direct tensile testing (Figure 13). Direct
 435 tensile test mainly characterizes the elastic behavior, with relatively low contribution of creep,
 436 whereas the contribution of creep during TSTM test is significant due to the duration of the
 437 test. As a consequence, if the tensile strain capacity is defined as the strain at cracking time,
 438 the TSTM test provides higher values than direct tensile test.

439 The lowest strain has been measured for the 30% RS concrete. However, this mixture has the
440 highest free strain at cracking. The creep of the 30% RS concrete actually started developing
441 just after 24 hours, while no creep could be detected for the other concretes. This concrete
442 mixture has not the highest proportion of RC aggregates but RS has a much higher content of
443 old paste than RG due to the crushing process [67]. The total content of old paste in 30RS-
444 ORG concrete is probably equal or higher than 0RS-100RG concrete. As early age creep is
445 mainly due to the formation and the behavior of CSH under loading and the water mobility
446 inside the cement paste [11,52], the observed evolution seems consistent with the composition
447 of studied concrete mixtures. From 96 hours the shrinkage rate of 30RS-ORG concrete was
448 approximately the same as 0RS-ORG concrete (Figure 14) and both concrete cracked. As
449 creep is related to the time-dependent behavior of concrete, the shrinkage rate is actually an
450 important parameter of shrinkage-induced cracking. If the stress development is too fast, it
451 cannot be mitigated by relaxation effects. Kovler and Bentur [68] actually took into account
452 the stress rate for the definition of an integrated criterion of cracking sensitivity. The creep
453 strains of 0RS-ORG concrete were relatively low but this concrete had relatively higher
454 shrinkage rate and the test stopped much earlier than the others (at 99 hours).

455 3.3.3. Stress development

456 The cracking sensitivity is assessed on the basis of the stress evolution and the tensile strength
457 (Figure 17). The 0RS-ORG concrete cracks first. Then the 0RS-30RG and 30RS-ORG
458 concrete crack. This concrete showed relative expansion around 48 hours (Figure 15), which
459 is consistent with the evolution of cumulated strains, then the stress increases again at higher
460 rate than 0RS-30RG. 0RS-100RG does not cracked and the cumulated stress is still much
461 lower than the tensile strength after 12 days.

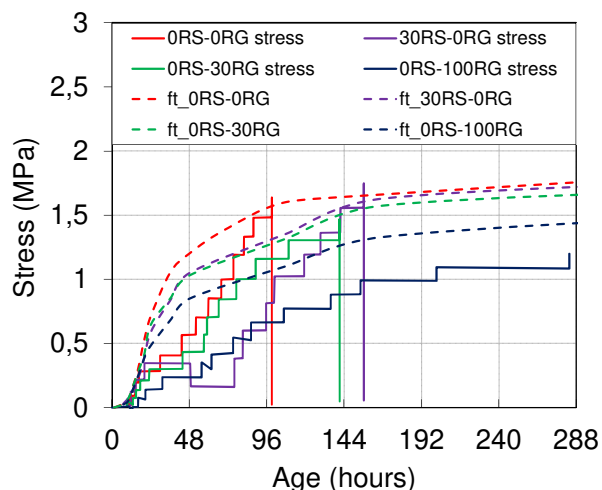


Figure 17. Tensile stresses from TSTM test and tensile strength.

462
463
464

465 Cracking is assumed to take place at the time corresponding to the intersection between the
466 strength and stress curves [27,29]. Table 5 summarizes the data from the TSTM tests and
467 direct tensile testing. From these results, the samples cracked when the stresses were higher or
468 very close to the tensile strength. The stress-to-strength ratio at cracking was lower for the
469 studied RC aggregate concrete mixtures, which suggests that their fracture energy was lower.

470

Table 5. Properties of concrete at cracking time	0RS-0RG	30RS-0RG	0RS-30RG	0RS-100RG
Start of the test (h)	10.2	10.2	9.3	10.2
Age of cracking (h)	99.1	156.2	141.1	> 290*
Cracking stress (MPa)	1.64	1.75	1.52	/
Tensile strength at the age of cracking (MPa)	1.42	1.65	1.51	/

471 *The test was stopped with no cracking.

472

473 The evolution of stresses cannot be fully understood without taking into account the elastic
474 modulus of concrete. However there are coupled effects: the elastic modulus influences the
475 stress development, but the stress is also likely to affect the development of elastic properties
476 by creating damage or influencing the growth of hydration products. As 3 out of 4 concretes

477 cracked, high stress levels were actually reached. In order to estimate the coupling effects,
478 two evolutions were assessed from experimental results, namely: static modulus in
479 compression E_{stat} , and the modulus determined during TSTM compensation cycles E_{TSTM} , as
480 detailed in sections 2.2.3 and 2.2.4 respectively. Figure 18 illustrates the results of the
481 modulus provided by the TSTM test. These can be compared to the values provided by the
482 repeated loadings in compression on cylindrical samples (Figure 9) by plotting the E_{TSTM}/E_{stat} ratio (Figure 19). This graph highlights the influence of
483 damage in concrete during the restrained shrinkage test. It is interesting to note that an
484 important reduction of E_{TSTM} occurs only for high replacement of natural gravels by recycled
485 ones whereas such reduction is also observed with recycled sand on E_{stat} . In addition, it is
486 observed for each composition that the time-evolutions and the maximal values of E_{TSTM} were
487 significantly different from E_{stat} . These differences of development between E_{stat} and E_{TSTM}
488 can be related to many phenomena. E_{stat} was measured in compression whereas E_{TSTM} was
489 measured in tension. According to the literature, the elastic modulus seems to be slightly
490 higher in tension than in compression. This difference varied between 9 and 15% generally
491 [69–73], which can be related to the difference of stress level and the influence of
492 microcracking process [51]. It was also observed that the elastic modulus is influenced when
493 shrinkage is restrained [74] or when a sustained load is applied [75]. In such conditions, a
494 coupling between creep and damage exists [76,77] and results in a reduction of the elastic
495 modulus. In this study the results plotted on Figure 19 show that E_{TSTM} was lower than E_{stat}
496 from the beginning of the tests, although it was measured in tension. This suggests that the
497 effects of loading under restrained conditions prevailed during the whole test.

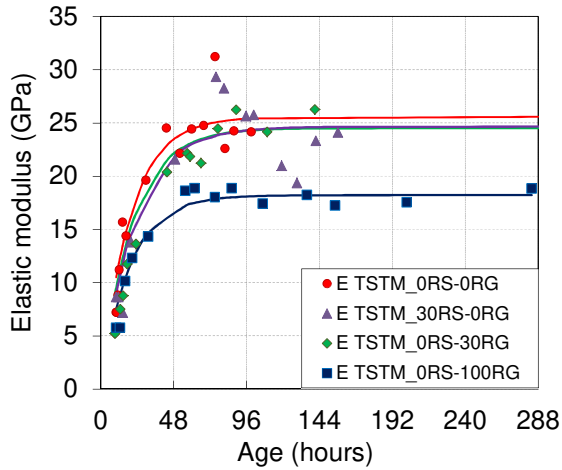


Figure 18. Effect of substitution rate on elastic modulus: Determined from TSTM tests

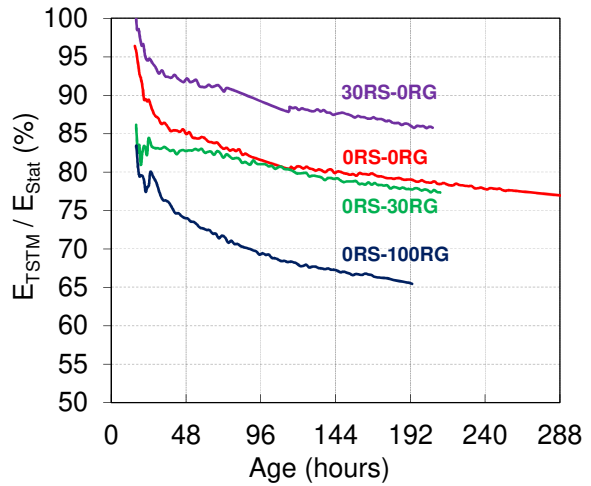


Figure 19. Ratio of elastic moduli measured under repeated loading E_{TSTM} and TSTM tests E_{Stat}

499

500 The TSTM characterization of 0RS-0RG concrete stopped at 4 days due to cracking. The
 501 values of the other concretes show a stabilization of E_{TSTM} from 4 days. The shrinkage rate
 502 (Figure 14) and stress rate (Figure 17) were actually high between 48 and 96 hours. Thus
 503 relatively high loading levels were reached at this age. This could have generated damage
 504 which could not be recovered by subsequent hydration. The E_{stat} curves actually showed a
 505 limited increase after 96 hours. The 0RS-0RG concrete showed the fastest increase of E_{TSTM} ,
 506 which could partly explain its high stress rate (Figure 17). The evolution of 0RS-30RG
 507 properties was close. The most significant effect of damage was observed on 0RS-100 RG
 508 concrete (Figure 19). The crushing process is likely to generate damage in RC aggregates and
 509 concretes with RC aggregates have more ITZ [78]. From these points of view the evolution of
 510 E_{TSTM} of 30RS-0RG concrete is not obvious. During the first 72 hours it showed
 511 approximately the same evolution as 0RS-30RG concrete (Figure 18). Both concrete mixtures
 512 had approximately the same tensile strength but the stresses were much lower for 30RS-0RG

513 concrete between 48 and 96 hours thus lower loading rate allowed the development of elastic
514 modulus with less damage and coupled effects.

515

516 **3.4 Discussion on the influence of recycled concrete aggregates**

517 The discussion presented in this section is an attempt to quantify the contribution of the main
518 phenomena involved in shrinkage-induced cracking from the data gathered in previous
519 sections. The evolutions of shrinkage and elastic modulus can be used to deduce the effect of
520 relaxation and damage on the development of internal stress. Two stress evolutions are
521 actually needed. The first one is estimated during each TSTM test cycle from the E_{TSTM}
522 modulus and the free strain (measured on the twin mold at each cycle) according to equation
523 9. The difference between the calculated elastic stress and the measured stress gives the
524 relaxation. It depends on the evolution of the E_{TSTM} modulus and the difference between free
525 and cumulated stresses.

$$\sigma(t_i) = \sum_{j=1}^i E_{TSTM}(t_j) \cdot (\varepsilon_{free\ sh.}(t_j) - \varepsilon_{free\ sh.}(t_{j-1})) \quad (9)$$

526 The second calculated stress uses the same equation (equation 9), but the E_{TSTM} modulus is
527 replaced by the static modulus determined from repeated loading tests. From this difference
528 between both calculated elastic stresses, the effect of damage and couplings on the stress
529 development can be determined.

530 Both computed stress evolutions and experimental stress evolutions are presented in [Figure](#)
531 [20](#). During the first hours after setting, the calculated stresses progress in a similar way to the
532 experimental stress. Then differences are observed and increased after each compensation
533 cycle. A divergence takes place before an age of 24 hours for the concretes 0RS0RG and
534 30RS0RG. During this period, the stress to strength ratio is close to 1 and a significant

535 influence of the creep/relaxation phenomenon is observed. For concretes composed of 30 and
536 100% of recycled gravel, this divergence occurs later at an age of 78 and 104 hours
537 respectively. The presence of recycled gravel delays the impact of the creep/relaxation
538 phenomenon during the first days after setting when concrete is under restrained conditions. A
539 divergence is also observed between both computed stresses and is associated to the
540 generation of damage when concrete shrinkage is restrained. The impact of damage is mainly
541 observed on concretes composed of recycled gravels and this effect is more pronounced for
542 the composition with higher recycled gravels content. On the other hand, the development of
543 the damage decreases for concrete composed of recycled sand.

544 As shown in Figure 20, the contribution of relaxation, damage and coupling effects
545 significantly decreases the magnitude of the stress development and, in consequence, delays
546 or cancels the cracking. The time when both computed stresses and the experimental stresses
547 exceed the tensile strength is also shown in Figure 20. It is observed that damage delays the
548 cracking of 5, 3, 20 and 51 hours whereas both damage and relaxation delay the cracking of
549 16, 67, 72 and more than 180 hours for the concrete 0RS0RG, 30RS0RG, 0RS30RG and
550 0RS100RG respectively.

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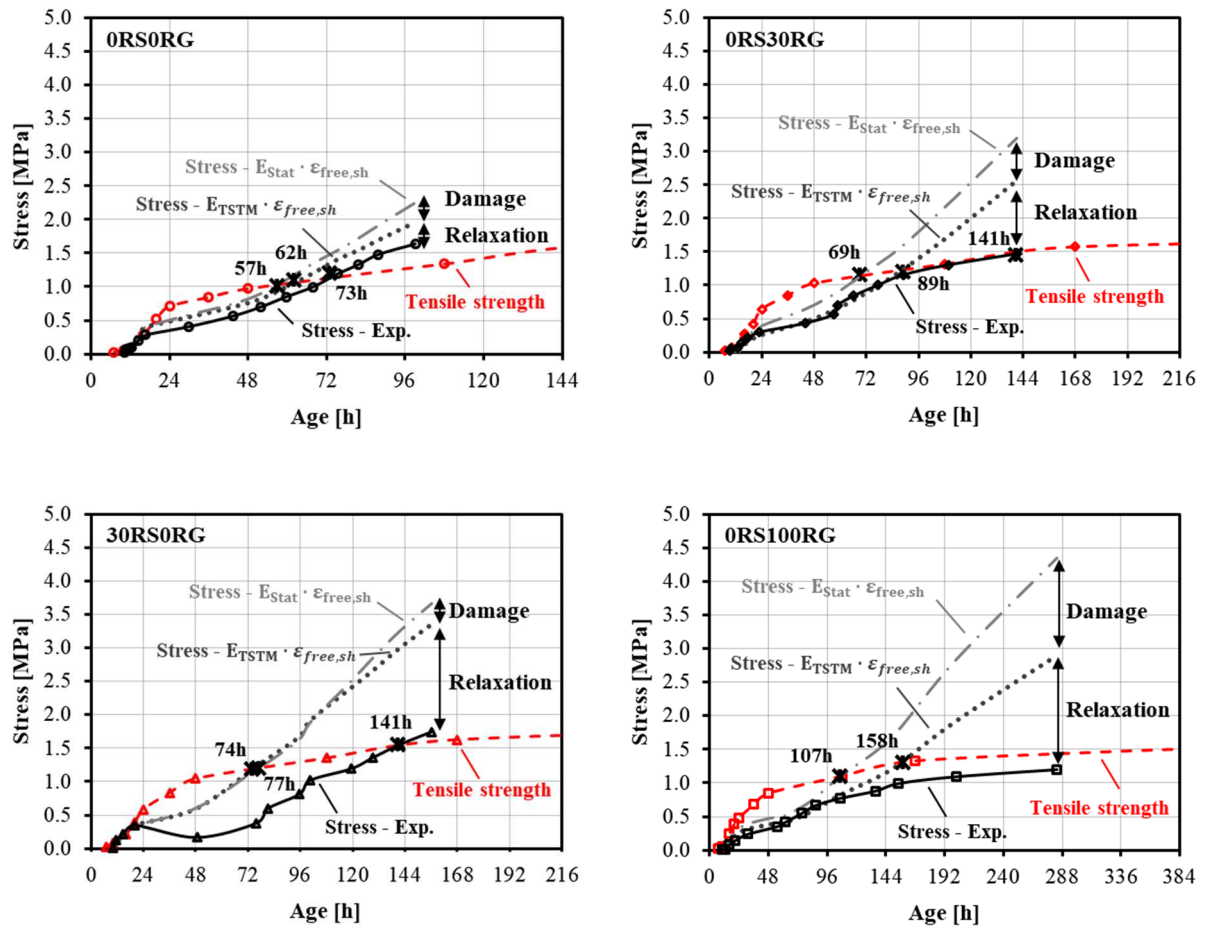


Figure 20. Evolution of experimental cumulated stress (Stress – Exp.), calculated elastic stress and tensile strength

554

555 The influence of recycled aggregate on the measured stresses, relaxation, damage, and
 556 coupling effects is quantified in Figure 21. The values given in Figure 21 correspond to
 557 cracking time or end of test if cracking does not occur. The analysis shows the significant
 558 influence of these phenomena on the evolution of cracking sensitivity. Tensile strength
 559 decreases with RC content (Figure 17), elastic stresses increase with RC content (maximum
 560 values in Figure 21) whereas the experimental stresses decrease with RC content. Thus it is
 561 shown that an elastic calculation would lead to the conclusion that the cracking sensitivity
 562 increases with RC content, which is in reality not the case when considering creep/relaxation,
 563 damage and couplings.

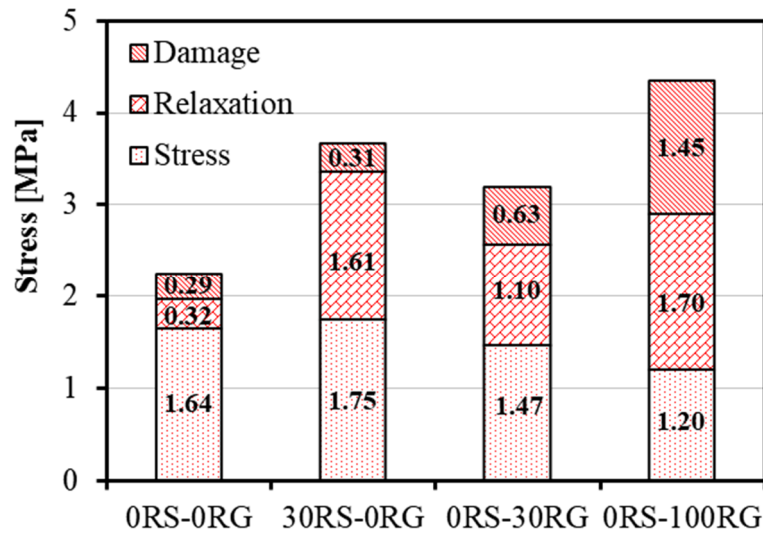


Figure 21. Experimental and calculated stresses at the end of TSTM tests.

564 These results confirm the prevailing influence of relaxation. This has already been showed in
565 Figure 15 and Figure 16 through the difference between free and restrained deformations.
566 Creep is beneficial to the behavior of concretes regarding cracking. It is also interesting to
567 note the influence of relaxation on the final value of stress (Figure 21). It is shown that
568 relaxation increases with RG content. Several experimental studies have been performed on
569 the influence of RC aggregates on creep. Most of them showed that creep increases with RC
570 content, even at relatively low contents. Domingo-Cabo et al. [8] actually reported that the
571 specific creep of hardened RC concretes increased by 25, 29, and 32% for coarse RC
572 aggregates proportions of 20, 50, and 100%. On hardening concrete, Delsaute, et al. [34]
573 showed that the specific creep increases by 60% at very early age for concrete composed of
574 recycled aggregate, whereas, at later ages, this increase is limited to 15-20% for concrete with
575 recycled gravel and to 30% for concrete with recycled sand. Most of these studies deal with
576 compressive creep whereas tensile creep occurs during restrained shrinkage tests. Klausen et
577 al. [79] reported in a recent study that concrete had the same behavior in tension and
578 compression, by using the same testing frame and procedure for both series of tests. One can

579 also note the influence of RC aggregates properties. 30RS-ORG and 0RS-100RG concrete
580 finally had the same stress decrease due to relaxation whereas the second concrete had higher
581 RC content. This can be attributed to the higher paste content of RS resulting from the
582 crushing process. This is consistent with E_{stat} data (Figure 19), as both concretes had the same
583 values. Experimental studies on the same materials have shown that the finest particles (below
584 0.5 μm) have significant paste content [42].

585 The contribution of damage and coupling effects also increases with the proportion of RC
586 aggregates. This was even clearer for coarse RC aggregates (Figure 21). Zheng et al. [80] and
587 Grondin and Matallah [81] showed a significant influence of the ITZ thickness on the relative
588 Young's modulus of concrete and the properties of ITZ on the progress of damage in
589 concrete. Königsberger and Staquet [35] also showed through a numerical study that the ITZ
590 between old cement paste and aggregates triggers macroscopic failure.

591 30RS-ORG and 0RS-100RG concretes had approximately the same contribution of creep at
592 the end of TSTM test (Figure 21) but the influence of damage and coupling effects was
593 different. This has already been highlighted by the evolutions of elastic moduli (Figure 18 and
594 Figure 19). Both concretes actually had different stress histories during the first days and this
595 could have affected the development of mechanical properties (see section 3.2). They also had
596 different microstructures. The study of Guo et al. [82] concluded on weak bond between
597 coarse RC aggregates and new mortar but this cannot be extrapolated to the bond between RC
598 sand and new paste. RC sand has actually higher content of cement paste than RG, as
599 indicated by its higher absorption [83]. RS particles have lower elastic modulus, which results
600 in lower restraining effect for the shrinkage of cement paste inducing less cracks when
601 exposed to drying. The mechanical analysis performed by Le et al. [84] showed a good
602 bonding between RS particles and the new cement matrix at 28 days of hydration, which
603 might be attributed to a good chemical affinity between old and new pastes and to the surface

604 roughness of the RC aggregate. They used SEM and nano-indentation to investigate the
605 properties of ITZ. A decrease of porosity was observed in the first ten micrometers for
606 saturated sand, but the ITZ between saturated RS and cement paste is larger than with dried
607 RS [63]. The same authors showed that the finest fractions of RS have the worst influence on
608 mechanical properties. Finally, the elastic and creep deformations of 30RS-0RG were
609 relatively high due to its high content of old paste but the damage or coupling effects were
610 lower due to good bond between RS and new cement paste.

611 Consequently, the behavior of the concrete with 100% RG is interesting. The test has been
612 performed during 12 days without appearance of cracking, although this type of concrete is
613 known to have higher drying shrinkage magnitudes [8,85,86]. Regarding recycled concretes,
614 the increase in shrinkage is associated with a decrease in modulus. Figure 21 gives the final
615 value of stresses corresponding to different ages. However, at the age when 0RS-0RG
616 concrete cracked, the 0RS-100RG concrete had much lower stresses and stress rate. This
617 concrete had actually a lowest elastic modulus and the difference between the E_{TSTM} values of
618 both concretes was even higher (Figure 18 and Figure 19). At this time the benefit from
619 internal curing was still significant thus shrinkage rate was also lower (Figure 14). Then
620 shrinkage developed but concrete had gained some strength and creep mitigated the stress
621 development. These results confirm that the cracking sensitivity is highly influenced by the
622 evolution of shrinkage, elastic parameters and relaxation and each phenomenon had a
623 significant influence of the development of stresses.

624

625 **4. Conclusion**

626 The present study focuses on the cracking sensitivity of recycled concrete under drying
627 conditions at early age. The substitution of natural sand and gravel by recycled concrete
628 aggregates is studied on four concretes for which recycled sand corresponds to 0 – 30% of the

629 sand volume fraction and recycled gravel corresponds to 0 – 30 – 100% of the gravel volume
630 fraction. A Temperature-Stress Testing Machine (TSTM) was associated to other advanced
631 techniques in order to investigate the main properties of recycled concrete under free and
632 restrained conditions.

633 Under free conditions, the development of the elastic static modulus, tensile strength and free
634 shrinkage have been experimentally defined, it is observed that:

- 635 - A reduction of the elastic modulus occurs when replacing natural aggregates by
636 recycled ones. This reduction is more pronounced in presence of fine recycled
637 aggregate for which the content of old cement paste is higher.
- 638 - Moderate content of recycled aggregate (<30%) does not affect significantly the
639 development of the tensile strength whereas a full replacement of natural aggregate by
640 recycled one decreases the tensile strength by 20%.
- 641 - The internal curing effect of recycled gravels delays and slows down the development
642 of the free shrinkage at early age. This effect is more pronounced for high replacement
643 ratio of natural gravels by recycled ones. The free shrinkage rate increases for concrete
644 composed of recycled sand. This is induced by the high content of old cement paste
645 which shrinks under drying condition.

646 Under restrained conditions, the development of the elastic modulus, strain and stress have
647 been characterized, it is observed that:

- 648 - The development of elastic properties was found to depend on the loading history due
649 to restrained shrinkage and the proportion and nature of recycled aggregates. An
650 important reduction of the elastic modulus occurs for high replacement of natural
651 gravels by recycled ones.

- 652 - A lower development of the strain is obtained under restrained condition. This is due
653 to the creep phenomenon. This effect is more pronounced with concrete composed of
654 recycled aggregates and occurs earlier with recycled sand.
- 655 - A slower development of the stress takes place for concretes composed of recycled
656 aggregate. The age of cracking is then delayed significantly in presence of recycled
657 aggregate. The full replacement of natural aggregates by recycled ones increases this
658 effect.

659 The comparison of the concrete properties under free and restrained conditions allows
660 quantifying the relative contributions of the main phenomena involved in shrinkage-induced
661 cracking at early-age. It is based on the determination of elastic stress evolutions from free
662 shrinkage data and elastic moduli provided by TSTM under sustained loading and cyclic
663 testing. From the results of this analysis, cracking sensitivity decreased with recycled concrete
664 content in spite of lower tensile strength, due to the major influence of relaxation, but also
665 damage and coupling effects. The major stress reduction was attributed to relaxation but the
666 phenomena contributed with different kinetics. The reduction of elastic modulus due to tensile
667 loading appeared from the first 24 hours while creep seemed to develop later, as tensile stress
668 to strength ratio became higher. Damage and coupling effects had a significant influence on
669 stress development, especially with 100% coarse recycled concrete aggregates. This could be
670 due to the influence of aggregates on the properties of the interfacial transition zone with new
671 cement paste and within recycled concrete aggregates. The concrete with 30% recycled
672 concrete sand had a different behavior with earlier creep development and lower damage,
673 which can be attributed to higher old paste content and better bonding between recycled
674 concrete sand and new cement paste.

675 From the experimental analyses performed in this study, it seems possible to design concrete
676 mixtures with significant proportions of recycled concrete aggregates without affecting their

677 early-age cracking sensitivity. The results are related to good quality recycled concrete,
678 initially saturated aggregates and standard drying conditions. Good curing is still
679 recommended as concrete slabs might be exposed to more severe drying conditions in terms
680 of wind speed or relative humidity.

681

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