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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

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 out in order to develop recommendations for the use of recycled aggregates in building 37 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 [10]. However, at early age, the volume change of cement-based materials is significant and is 47 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 prevent or to limit this risk. As a consequence, the development of the deformation induced 50 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 aggregates. During the hydration process, recycled aggregate can be considered as a water 60 61 tank for the cement paste and thus plays the role of an internal curing agent [16]. This phenomenon reduces and/or delays the decrease of the internal relative humidity of the 62 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 decreases the self-desiccation and the desiccation of concrete at early age. 73

74 Research related to the influence of recycled concrete on plastic shrinkage and the associated cracking sensitivity at early age is rather scarce. The ability of RC aggregates to provide 75 76 internal curing has been showed by several studies [22,25] but the same authors reported an increase in drying shrinkage and plastic shrinkage, respectively. However the consequences of 77 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 studies deal with the influence of porous aggregates at early age [33] and none with RC 87 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].

The study presented in this paper focuses on plastic shrinkage induced cracking of concrete with recycled sand and gravels at early age. The experimental part is based on active restrained shrinkage tests performed with the temperature-stress testing machine (TSTM) at ULB in Brussels, Belgium. This system has been developed in the Laboratory of Civil Engineering of ULB since 2006 [37,38] and the system was significantly updated for this 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 aggregates [42]. The properties of RC aggregates are detailed in Table 1. 133

134

	Nati	ural aggreg	ates	Recycled	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/cm ³)	2.6	2.73	2.73	2.10	2.34	2.32		

135 Table 1 - Properties of natural and recycled aggregates

136

Natural sand from Sandrancourt, France was used, and natural coarse aggregates were crushed dark limestone from Givet, France. RC aggregates were obtained by crushing unknown waste concrete from Paris region, France. They can be considered as good quality RC aggregates according to standard NF EN 206/CN [43,44]. Their coefficient of water absorption at 24 hours WA₂₄ was determined using pycnometer and hydrostatic weighing and 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.

	Compo	sition (%)	Blaine	Standard	Density
	Clinker	Limestone	fineness (cm²/g)	compressive strength (MPa)	(g/cm ³)
Limestone filler	-	99	4600	-	2.7
	87	11	3700	53	3.09
Cement	(Compound com	position of cli	inker (%)	Na2Oeq
	C ₃ S	C ₂ S	СзА	C4AF	(%)
	61	-	7.9	12	0.59

147 Table 2. Properties of cement and limestone filler

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 WA₂₄ (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.

$$W_{tot} = W_{eff} + W_{abs} \tag{1}$$

$$B_{eq} = C + k.L \tag{2}$$

162 Table 3. Studied concrete mixtures

	ORS-ORG	30RS-0RG	ORS-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, <i>L</i> (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,				
fc28 d.	31.4	29.0	28.5	27.6

165 **2.2 Testing procedures**

166 **2.2.1 Tensile strength**

167 Tensile strength has been determined on \emptyset 11x22 (in centimetres) cylindrical specimens using 168 the splitting tensile test and on prismatic specimens by using direct tensile test [28]. In addition the tensile strain capacity is tested with the direct tensile test. Direct tensile testing 169 170 [28] has been performed on mixtures at several ages from 7 to 24 hours (7 - 10 - 16 - 20 and171 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 \pm 100kN 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-

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 $(20^{\circ}C - 50\%RH)$ 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].



A twin mold was built to measure the free strain. This mold has exactly the same geometry as

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

independent, thus it corresponds to the sum of the following strains: elastic ε_{elas} , creep ε_{creep} ,

thermal ε_{ther} and shrinkage ε_{sh} . This will be defined as the cumulated strain (equation 3).

$$\varepsilon_{TSTM} = \varepsilon_{elas} + \varepsilon_{creep} + \varepsilon_{ther} + \varepsilon_{sh} \tag{3}$$

The strains in the twin mold correspond to the sum of the thermal and shrinkage strains asshown by equation 4.

$$\mathcal{E}_{free} = \mathcal{E}_{ther} + \mathcal{E}_{sh} \tag{4}$$

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

$$\mathcal{E}_{TSTM} - \mathcal{E}_{free} = \mathcal{E}_{elas} + \mathcal{E}_{creep} \tag{5}$$

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 µm/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].

The cumulated strains of the TSTM mold and the free strains of the twin mold for the conventional concrete 0RS-0RG are displayed in Figure 4 and Figure 5. The thermal strains of studied concrete were around 10μ m/m, thus the corrected and uncorrected strains are close.

248





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



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

²⁵¹

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



Figure 6. Repeatability testing: evolution of stressFigure 7. Repeatability testing: free shrinkage in
100% RG concrete.in 100% RG concrete.100% RG concrete.

263

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

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





271

Figure 8. Determination of elastic modulus from the TSTM tests

3. Results and discussion

274 Shrinkage-induced cracking depends on several properties of concrete, namely: elastic 275 modulus, free strain, creep, tensile strength, fracture energy. In this experimental study TSTM 276 was associated to other advanced techniques in order to understand the influence of RC 277 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 280 the test was performed on one cylindrical sample. The temperature of the sample is set to 281 20°C. For each repeated loading, the E-modulus is calculated from the load and displacement 282 data between 30% and 80% of loading [48,49]. Results are plotted against the age of the 283 specimen in

- 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 0RS-30RG concrete has a limited RC content (

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 ORS-100RG concrete globally
- 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

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

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.

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

Results of the direct and splitting tensile strength are shown in the Figure 10 and Figure 11below 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.

				ORS-OR	G					
Age [h]	7	10	16	20	24					
ft,d [MPa]	0.03	0.06	0.29	0.52	0.71					
ε _t [μm/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						
			3	BORS-OR	G					
Age [h]	7	10	16	20	24					
ft,d [MPa]	0.03	0.08	0.22	0.39	0.59					
ε _t [μm/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						
			(RS-30R	G					
Age [h]	7	10	16	20	24					
ft,d [MPa]	0.03	0.07	0.27	0.42	0.65					
ε _t [μm/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						
			0	RS-100F	RG					
Age [h]	7	10	16	20	24					
ft,d [MPa]	0.02	0.05	0.24	0.38	0.48					
ε _t [μm/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						

330	Table 4. R	esults of th	e direct and	l splitting	tensile strer	igth
	10010 11 10	•••••••••			constro ser or	0



Figure 10. Effect of substitution rate on the Figure 11. Zoom of the Figure 10 during tensile strength, determined from direct and the first 30 hours. splitting tensile tests

Between 16 and 24 hours, the tensile strength obtained by means of splitting and direct tensile tests are not well superimposed. Higher values of the tensile strength are obtained with the splitting tensile test. To improve the correlation between the direct and the splitting tensile strength, the 0.9 factor from Equation 7 is replaced by a value of 0.75 for all concrete mixtures at very early age (age lower than 30 hours). A good agreement is then obtained between splitting and direct tensile tests as shown in the Figure 12 for very early age results.



Figure 12. Tensile strength determined from Figure 13. Effect of substitution rate on the direct and splitting tensile tests with correction

tensile strain capacity: Determined from direct and splitting tensile tests

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

$$\varepsilon_t = \frac{f_t}{E} \tag{8}$$

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 this characterization, there are few significant differences between studied materials. This is 353 354 consistent with previous study of the authors [28] on the influence of aggregate type on tensile properties. During the first 24 hours, the development of tensile strain capacity was mainlydriven 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 compositon 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.





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 ORS-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 ORS-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 63µm and 7% at 125µm) 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. Given the boundary conditions of TSTM and twin molds, this difference is due to creep
strains. Subtracting the free strains (obtained from the twin mold) and the elastic strains from
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. ORS-ORG and ORS-30RG concrete cracked at strains of approximately 80 µm/m and 0RS-100RG reached this strain at 288 hours (12 days) without cracking. This value 432 433 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, whereas the contribution of creep during TSTM test is significant due to the duration of the 436 437 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.

The lowest strain has been measured for the 30% RS concrete. However, this mixture has the 439 highest free strain at cracking. The creep of the 30% RS concrete actually started developing 440 441 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 0RG 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-0RG concrete was 448 approximately the same as 0RS-0RG 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 ORS-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

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





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

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 ofconcrete at cracking time	0RS-0RG	30RS-0RG	ORS-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

The evolution of stresses cannot be fully understood without taking into account the elastic modulus of concrete. However there are coupled effects: the elastic modulus influences the stress development, but the stress is also likely to affect the development of elastic properties 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 (

483 Figure 9) by plotting the E_{TSTM}/E_{stat} ratio (Figure 19). This graph highlights the influence of 484 damage in concrete during the restrained shrinkage test. It is interesting to note that an 485 important reduction of E_{TSTM} occurs only for high replacement of natural gravels by recycled 486 ones whereas such reduction is also observed with recycled sand on $E_{stat.}$ In addition, it is observed for each composition that the time-evolutions and the maximal values of ETSTM were 487 488 significantly different from E_{stat} . These differences of development between E_{stat} and E_{TSTM} 489 can be related to many phenomena. E_{stat} was measured in compression whereas E_{TSTM} was 490 measured in tension. According to the literature, the elastic modulus seems to be slightly 491 higher in tension than in compression. This difference varied between 9 and 15% generally 492 [69-73], which can be related to the difference of stress level and the influence of 493 microcracking process [51]. It was also observed that the elastic modulus is influenced when 494 shrinkage is restrained [74] or when a sustained load is applied [75]. In such conditions, a 495 coupling between creep and damage exists [76,77] and results in a reduction of the elastic 496 modulus. In this study the results plotted on Figure 19 show that E_{TSTM} was lower than E_{stat} 497 from the beginning of the tests, although it was measured in tension. This suggests that the 498 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_{Stat} and TSTM tests E_{TSTM}

The TSTM characterization of ORS-ORG concrete stopped at 4 days due to cracking. The 500 501 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 ORS-ORG concrete showed the fastest increase of E_{TSTM}, which could partly explain its high stress rate (Figure 17). The evolution of ORS-30RG 506 507 properties was close. The most significant effect of damage was observed on ORS-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 ETSTM 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 elastic514 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.

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

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

Both computed stress evolutions and experimental stress evolutions are presented in Figure 20. During the first hours after setting, the calculated stresses progress in a similar way to the experimental stress. Then differences are observed and increased after each compensation cycle. A divergence takes place before an age of 24 hours for the concretes 0RS0RG and 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 phenomenon during the first days after setting when concrete is under restrained conditions. A 538 539 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.

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

551

552

553



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

The influence of recycled aggregate on the measured stresses, relaxation, damage, and 555 coupling effects is quantified in Figure 21. The values given in Figure 21 correspond to 556 557 cracking time or end of test if cracking does not occur. The analysis shows the significant influence of these phenomena on the evolution of cracking sensitivity. Tensile strength 558 559 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 shown that an elastic calculation would lead to the conclusion that the cracking sensitivity 561 562 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 compression, by using the same testing frame and procedure for both series of tests. One can 578

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

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

591 30RS-0RG 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

roughness of the RC aggregate. They used SEM and nano-indentation to investigate the properties of ITZ. A decrease of porosity was observed in the first ten micrometers for saturated sand, but the ITZ between saturated RS and cement paste is larger than with dried RS [63]. The same authors showed that the finest fractions of RS have the worst influence on mechanical properties. Finally, the elastic and creep deformations of 30RS-0RG were relatively high due to its high content of old paste but the damage or coupling effects were 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 ORS-ORG 616 concrete cracked, the ORS-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 free634 shrinkage have been experimentally defined, it is observed that:

- A reduction of the elastic modulus occurs when replacing natural aggregates by
 recycled ones. This reduction is more pronounced in presence of fine recycled
 aggregate for which the content of old cement paste is higher.
- Moderate content of recycled aggregate (<30%) does not affect significantly the
 development of the tensile strength whereas a full replacement of natural aggregate by
 recycled one decreases the tensile strength by 20%.
- The internal curing effect of recycled gravels delays and slows down the development
 of the free shrinkage at early age. This effect is more pronounced for high replacement
 ratio of natural gravels by recycled ones. The free shrinkage rate increases for concrete
 composed of recycled sand. This is induced by the high content of old cement paste
 which shrinks under drying condition.
- 646 Under restrained conditions, the development of the elastic modulus, strain and stress have647 been characterized, it is observed that:
- The development of elastic properties was found to depend on the loading history due
 to restrained shrinkage and the proportion and nature of recycled aggregates. An
 important reduction of the elastic modulus occurs for high replacement of natural
 gravels by recycled ones.

A lower development of the strain is obtained under restrained condition. This is due
 to the creep phenomenon. This effect is more pronounced with concrete composed of
 recycled aggregates and occurs earlier with recycled sand.

A slower development of the stress takes place for concretes composed of recycled
 aggregate. The age of cracking is then delayed significantly in presence of recycled
 aggregate. The full replacement of natural aggregates by recycled ones increases this
 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 to strength ratio became higher. Damage and coupling effects had a significant influence on 668 669 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.

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

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

681

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691 **References**

- 692 [1] Irex, RECYBETON, (2018) 1. https://www.pnrecybeton.fr/ (accessed September 20, 2018).
- 693 [2] J. de Brito, N. Saikia, Concrete with Recycled Aggregates in International Codes, in: Recycl. Aggreg.
- 694 Concr. Use Ind. Constr. Demolition Waste, 2013: pp. 379–429. doi:10.1007/978-1-4471-4540-0_7.
- 695 [3] Irex, ECOREB, (2019).
- 696 [4] R. Landgren, Water-Vapor Adsorption-Desorption Characteristics of Selected Lightweight Concrete
 697 Aggregates, in: Proc. Am. Soc. Test. Mater. Philadelphia, 1964: pp. 830–845.
- 698 [5] P. Bamford, Early-Age thermal crack control in concrete, 2007.
- R. Cortas, E. Rozière, S. Staquet, A. Hamami, A. Loukili, M.-P. Delplancke-Ogletree, Effect of the
 water saturation of aggregates on the shrinkage induced cracking risk of concrete at early age, Cem.
- 701 Concr. Compos. 50 (2014) 1–9. doi:10.1016/j.cemconcomp.2014.02.006.
- 702 [7] T. Mostafa, S. Parviz, Drying shrinkage behavior of recycled aggregate concrete, Concr. Int. 18 (1996)

703 58–61.

- A. Katz, Properties of concrete made with recycled aggregate from partially hydrated old concrete, Cem.
 Concr. Res. 33 (2003) 703–711. doi:10.1016/S0008-8846(02)01033-5.
- 706 [9] A. Domingo-Cabo, C. Lázaro, F. López-Gayarre, M.A. Serrano-López, P. Serna, J.O. Castaño-Tabares,
- 707 Creep and shrinkage of recycled aggregate concrete, Constr. Build. Mater. 23 (2009) 2545–2553.
- 708 doi:10.1016/j.conbuildmat.2009.02.018.
- 709 [10] S. Marinković, V. Radonjanin, M. Malešev, I. Ignjatović, Comparative environmental assessment of
 710 natural and recycled aggregate concrete, Waste Manag. 30 (2010) 2255–2264.
- 711 doi:10.1016/j.wasman.2010.04.012.
- 712 [11] F. Benboudjema, J. Carette, B. Delsaute, T. Honorio de Faria, A. Knoppik, L. Lacarrière, A. Neiry de
- 713 Mendonça Lopes, P. Rossi, S. Staquet, Mechanical properties, in: E.M.R. Fairbairn, M. Azenha (Eds.),
- 714 Therm. Crack. Massive Concr. Struct. State Art Rep. RILEM Tech. Comm. 254-CMS, 2019: pp. 69–
- 715 114. doi:10.1007/978-3-319-76617-1_4.
- J. Thomas, N.N. Thaickavil, P.M. Wilson, Strength and durability of concrete containing recycled
 concrete aggregates, J. Build. Eng. 19 (2018) 349–365. doi:10.1016/j.jobe.2018.05.007.
- 718 [13] M. Velay-Lizancos, I. Martinez-Lage, P. Vazquez-Burgo, The effect of recycled aggregates on the
- accuracy of the maturity method on vibrated and self-compacting concretes, Arch. Civ. Mech. Eng. 19
 (2019) 311–321. doi:10.1016/j.acme.2018.11.004.
- [14] S. Sadati, K.H. Khayat, Restrained shrinkage cracking of recycled aggregate concrete, Mater. Struct.
 Constr. 50 (2017). doi:10.1617/s11527-017-1074-y.
- J. Henschen, A. Teramoto, D.A. Lange, Shrinkage and creep performance of recycled aggregate
 concrete, RILEM Bookseries. 4 (2012) 1333–1340.
- 725 [16] B. Delsaute, S. Staquet, Impact of recycled sand and gravels in concrete on volume change, Constr.
 726 Build. Mater. under rev (n.d.).
- 727 [17] A. Bentur, S.I. Igarashi, K. Kovler, Prevention of autogenous shrinkage in high-strength concrete by
- 728 internal curing using wet lightweight aggregates, Cem. Concr. Res. 31 (2001) 1587–1591.
- 729 doi:10.1016/S0008-8846(01)00608-1.
- 730 [18] Z. Liu, W. Hansen, Aggregate and slag cement effects on autogenous shrinkage in cementitious
- 731 materials, Constr. Build. Mater. 121 (2016) 429–436. doi:10.1016/j.conbuildmat.2016.06.012.
- 732 [19] S. Zhutovsky, K. Kovler, A. Bentur, Efficiency of lightweight aggregates for internal curing of high

- strength concrete to eliminate autogenous shrinkage, Mater. Struct. Constr. 34 (2002) 97–101.
- R. Henkensiefken, D. Bentz, T. Nantung, J. Weiss, Volume change and cracking in internally cured
 mixtures made with saturated lightweight aggregate under sealed and unsealed conditions, Cem. Concr.

736 Compos. 31 (2009) 427–437. doi:10.1016/j.cemconcomp.2009.04.003.

- 737 [21] S. Staquet, B. Delsaute, E.M.R. Fairbairn, R. Torrent, A. Knoppik, N. Ukrainczyk, E.A.B. Koenders,
- 738 Mixture proportioning for crack avoidance, 2019. doi:10.1007/978-3-319-76617-1_5.
- I. Maruyama, R. Sato, a Trial of Reducing Autogenous Shrinkage By Recycled Aggregate, Proc. Fourth
 Int. Res. Semin. Rep. TVBM-3126, Gaithersburg, Maryland, USA. (2005) 264–270.
- 741 [23] G. Sant, M. Dehadrai, D. Bentz, P. Lura, C.F. Ferraris, J.W. Bullard, J. Weiss, Detecting the fluid-to742 solid transition in cement pastes, Concr. Int. 31 (2009) 53–58.
- 743 [24] M. Salgues, J.C. Souche, P. Devillers, E. Garcia-Diaz, Influence of initial saturation degree of recycled
- aggregates on fresh cement paste characteristics: consequences on recycled concrete properties, Eur. J.

745 Environ. Civ. Eng. 22 (2018) 1146–1160. doi:10.1080/19648189.2016.1245630.

- 746 [25] A. Gonzalez-Corominas, M. Etxeberria, Effects of using recycled concrete aggregates on the shrinkage
 747 of high performance concrete, Constr. Build. Mater. 115 (2016) 32–41.
- 748 doi:10.1016/j.conbuildmat.2016.04.031.
- 749 [26] J.C. Souche, A.Z. Bendimerad, E. Roziere, M. Salgues, P. Devillers, E. Garcia-Diaz, A. Loukili, Early
- age behaviour of recycled concrete aggregates under normal and severe drying conditions, J. Build. Eng.
- 751 13 (2017) 244–253. doi:10.1016/j.jobe.2017.08.007.
- 752 [27] T.A. Hammer, K.T. Fosså, Ø. Bjøntegaard, Cracking tendency of HSC: Tensile strength and self
 753 generated stress in the period of setting and early hardening, Mater. Struct. 40 (2007) 319–324.
- 754 doi:10.1617/s11527-006-9109-9.
- E. Roziere, R. Cortas, A. Loukili, Tensile behaviour of early age concrete: New methods of
 investigation, Cem. Concr. Compos. 55 (2015) 153–161. doi:10.1016/j.cemconcomp.2014.07.024.
- 757 [29] D. Ravina, R. Shalon, Plastic Shrinkage Cracking, ACI J. Proc. 65 (1968) 282–292. doi:10.14359/7473.
- 758 [30] K. Kovler, Testing system for determining the mechanical behaviour of early age concrete under
 759 restrained and free uniaxial shrinkage, Mater. Struct. 27 (1994) 324–330. doi:10.1007/BF02473424.
- 760 [31] O. Bjontegaard, Thermal dilation and autogenous deformation as driving forces to self-induced stresses
 761 in high-performance concrete, 1999.
- 762 [32] T. Aly, J.G. Sanjayan, Shrinkage-cracking behavior of OPC-fiber concrete at early-age, Mater. Struct.

- 763 Constr. 43 (2010) 755-764. doi:10.1617/s11527-009-9526-7. 764 [33] T. Grazia, Comportement des bétons au jeune âge, PhD thesis, Université Laval, 1999. 765 B. Delsaute, S. Staquet, Development of Strain-Induced Stresses in Early Age Concrete Composed of [34] 766 Recycled Gravel or Sand, J. Adv. Concr. Technol. 17 (2019) 319-334. doi:10.3151/jact.17.319. 767 [35] M. Königsberger, S. Staquet, Micromechanical Multiscale Modeling of ITZ-Driven Failure of Recycled 768 Concrete: Effects of Composition and Maturity on the Material Strength, Appl. Sci. 8 (2018) 976. 769 doi:10.3390/app8060976.
- M.P. Adams, T. Fu, A.G. Cabrera, M. Morales, J.H. Ideker, O.B. Isgor, Cracking susceptibility of
 concrete made with coarse recycled concrete aggregates, Constr. Build. Mater. 102 (2016) 802–810.
 doi:10.1016/j.conbuildmat.2015.11.022.
- 773 [37] A. Darquennes, S. Staquet, M.-P. Delplancke-Ogletree, B. Espion, Effect of autogenous deformation on
 774 the cracking risk of slag cement concretes, Cem. Concr. Compos. 33 (2011) 368–379.
- 775 doi:10.1016/j.cemconcomp.2010.12.003.
- [38] S. Staquet, B. Delsaute, A. Darquennes, B. Espion, Design of a Revisited Tstm System for Testing
 Concrete Since Setting Time Under Free and Restraint Conditions ., in: Concrack 3 RILEM-JCI Int.
- 778 Work. Crack Control Mass Concr. Relat. Issues Concern. Early-Age Concr. Struct., 2012: p. 12.
- 779 [39] P. Gonçalves, J. De Brito, Recycled aggregate concrete (RAC) Comparative analysis of existing

780 specifications, Mag. Concr. Res. 62 (2010) 339–346. doi:10.1680/macr.2008.62.5.339.

- [40] K.P. Verian, W. Ashraf, Y. Cao, Properties of recycled concrete aggregate and their influence in new
 concrete production, Resour. Conserv. Recycl. 133 (2018) 30–49. doi:10.1016/j.resconrec.2018.02.005.
- 783 [41] M. Arezoumandi, A. Smith, J.S. Volz, K.H. Khayat, An experimental study on flexural strength of
- reinforced concrete beams with 100% recycled concrete aggregate, Eng. Struct. 88 (2015) 154–162.
 doi:10.1016/j.engstruct.2015.01.043.
- 786 [42] T. Le, S. Rémond, G. Le Saout, E. Garcia-Diaz, Fresh behavior of mortar based on recycled sand -
- 787 Influence of moisture condition, Constr. Build. Mater. 106 (2016) 35–42.
- 788 doi:10.1016/j.conbuildmat.2015.12.071.
- 789 [43] NF EN 206/CN, Béton Spécification, performance, production et confirmité Complément national à
 790 la norme NF EN 206, 2014.
- 791 [44] A.Z. Bendimerad, E. Rozière, A. Loukili, Plastic shrinkage and cracking risk of recycled aggregates
 792 concrete, Constr. Build. Mater. 121 (2016) 733–745. doi:10.1016/j.conbuildmat.2016.06.056.

- A.Z. Bendimerad, E. Roziere, A. Loukili, Combined experimental methods to assess absorption rate of
 natural and recycled aggregates, Mater. Struct. 48 (2015) 3557–3569. doi:10.1617/s11527-014-0421-5.
- 795[46]F. De Larrard, T. Sedran, Mixture-proportioning of high-performance concrete, Cem. Concr. Res. 32
- 796 (2002) 1699–1704. doi:10.1016/S0008-8846(02)00861-X.
- 797 [47] T. Sedran, Mise au point des formules de béton de référence, PN RECYBETON., (2013) 37.
- 798 [48] C. Boulay, S. Staquet, B. Delsaute, J. Carette, M. Crespini, O. Yazoghli-Marzouk, É. Merliot, S.
- Ramanich, How to monitor the modulus of elasticity of concrete, automatically since the earliest age?,
 Mater. Struct. 47 (2014) 141–155. doi:10.1617/s11527-013-0051-3.
- 801 [49] B. Delsaute, C. Boulay, J. Granja, J. Carette, M. Azenha, C. Dumoulin, G. Karaiskos, A. Deraemaeker,
- 802 S. Staquet, Testing Concrete E-modulus at Very Early Ages Through Several Techniques: An Inter-
- 803 laboratory Comparison, Strain. 52 (2016) 91–109. doi:10.1111/str.12172.
- 804 [50] M. Irfan-ul-Hassan, B. Pichler, R. Reihsner, C. Hellmich, Elastic and creep properties of young cement
 805 paste, as determined from hourly repeated minute-long quasi-static tests, Cem. Concr. Res. 82 (2016)
 806 36–49. doi:10.1016/j.cemconres.2015.11.007.
- 807 [51] B. Delsaute, New approach for Monitoring and Modelling of the Creep and Shrinkage behaviour of
 808 Cement Pastes , Mortars and Concretes since Setting Time, Université Libre de Bruxelles (BATir) and

809 Université Paris Est (IFSTTAR), 2016.

- 810 [52] B. Delsaute, C. Boulay, S. Staquet, Creep testing of concrete since setting time by means of permanent
- 811 and repeated minute-long loadings, Cem. Concr. Compos. 73 (2016) 75–88.
- 812 doi:10.1016/j.cemconcomp.2016.07.005.
- 813 [53] B. Delsaute, J.-M. Torrenti, S. Staquet, Modeling basic creep of concrete since setting time, Cem. Concr.
 814 Compos. 83 (2017) 239–250. doi:10.1016/j.cemconcomp.2017.07.023.
- 815 [54] A. Darquennes, Comportement au jeune âge de bétons formulés à base de ciment au laitier de haut
- 816 fourneau en condition de déformations libre et restreinte, PhD thesis, Université Libre de Bruxelles,
 817 2009.
- 818 [55] A.B.E. Klausen, Early age crack assessment of concrete structures: experimental investigation of
 819 decisive parameters, NTNU, 2016.
- 820 [56] S. Omary, E. Ghorbel, G. Wardeh, Relationships between recycled concrete aggregates characteristics
- and recycled aggregates concretes properties, Constr. Build. Mater. 108 (2016) 163–174.
- 822 doi:10.1016/j.conbuildmat.2016.01.042.

- 823 [57] A.F. Stock, D.J. Hannant, R.I.T. Williams, The Effect of Aggregate Concentration Upon The Strength
- And Modulus Of Elasticity Of Concrete, Mag. Concr. Res. 31 (1979) 225–234.
- 825 doi:10.1680/macr.1979.31.109.225.
- M. Velay-Lizancos, I. Martinez-Lage, M. Azenha, J. Granja, P. Vazquez-Burgo, Concrete with fine and
 coarse recycled aggregates: E-modulus evolution, compressive strength and non-destructive testing at
- 828 early ages, Constr. Build. Mater. 193 (2018) 323–331. doi:10.1016/j.conbuildmat.2018.10.209.
- 829 [59] W.H. Kwan, M. Ramli, K.J. Kam, M.Z. Sulieman, Influence of the amount of recycled coarse aggregate
 830 in concrete design and durability properties, Constr. Build. Mater. 26 (2012) 565–573.
- 831 doi:10.1016/j.conbuildmat.2011.06.059.
- 832 [60] N. Fonseca, J. De Brito, L. Evangelista, The influence of curing conditions on the mechanical
- performance of concrete made with recycled concrete waste, Cem. Concr. Compos. 33 (2011) 637–643.
 doi:10.1016/j.cemconcomp.2011.04.002.
- W. Hansen, J.A. Almudaiheem, Ultimate Drying Shrinkage of Concrete Influence of Major
 Parameters., ACI Mater. J. 84 (1987) 217–223. doi:10.14359/1954.
- R. Le Roy, Déformations instantanées et différées des bétons à hautes performances, PhD thesis, Ecole
 Nationale des Ponts et Chaussées, Paris, France, 1995.
- 839 [63] T. Fujiwara, Effect of Aggregate on Drying Shrinkage of Concrete, J. Adv. Concr. Technol. 6 (2008)
 840 31–44.
- 841 [64] B. Bissonnette, P. Pierre, M. Pigeon, Influence of key parameters on drying shrinkage of cementitious
 842 materials, Cem. Concr. Res. 29 (1999) 1655–1662. doi:10.1016/S0008-8846(99)00156-8.
- 843 [65] E. Rozière, S. Granger, P. Turcry, A. Loukili, Influence of paste volume on shrinkage cracking and
- fracture properties of self-compacting concrete, Cem. Concr. Compos. 29 (2007) 626–636.
- 845 doi:10.1016/j.cemconcomp.2007.03.010.
- 846 [66] A. Hanif, Y. Kim, Z. Lu, C. Park, Early-age behavior of recycled aggregate concrete under steam curing
 847 regime, J. Clean. Prod. 152 (2017) 103–114. doi:10.1016/j.jclepro.2017.03.107.
- 848 [67] Z. Zhao, S. Remond, D. Damidot, W. Xu, Influence of fine recycled concrete aggregates on the
- 849 properties of mortars, Constr. Build. Mater. 81 (2015) 179–186. doi:10.1016/j.conbuildmat.2015.02.037.
- 850 [68] K. Kovler, A. Bentur, Cracking sensitivity of normal- and high-strength concrete, 2009.
- 851 [69] I. Yoshitake, F. Rajabipour, Y. Mimura, A. Scanlon, A Prediction Method of Tensile Young's Modulus
- 852 of Concrete at Early Age, Adv. Civ. Eng. 2012 (2012) 1–10. doi:10.1155/2012/391214.

- 853 [70] D.S. Atrushi, Tensile and Compressive Creep of Early Age Concrete : Testing and Modelling, PhD
- thesis, The Norwegian University of Sciences and Technology, Trondheim, Norway, 2003.
- 855 [71] B. Bissonnette, M. Pigeon, A.M. Vaysburd, Tensile creep of concrete: Study of its sensitivity to basic
 856 parameters, ACI Mater. J. 104 (2007) 360–368.
- 857 [72] S. Hagihara, S. Nakamura, Y. Masuda, M. Kono, Experimental study on mechanical properties and creep
 858 behavior of high-strength concrete in early age, Concr. Res. Technol. 11 (2000) 39–50.
- 859 [73] V.Y.G. Yanni, Multi-scale Investigation of Tensile Creep of Ultra High Performance Concrete for
 860 Bridge Applications, PhD thesis, Georgia Institute of Technology, 2009.
- 861 [74] J. Pacheco, J. De Brito, J. Ferreira, D. Soares, Flexural load tests of full-scale recycled aggregates
 862 concrete structures, Constr. Build. Mater. 101 (2015) 65–71. doi:10.1016/j.conbuildmat.2015.10.023.
- 863 [75] H.R. Sobuz, E. Ahmed, N.M. Sutan, N.M. Sadiqul Hasan, M.A. Uddin, M. Jahir Uddin, Bending and
- time-dependent responses of RC beams strengthened with bonded carbon fiber composite laminates,
- 865 Constr. Build. Mater. 29 (2012) 597–611. doi:10.1016/j.conbuildmat.2011.11.006.
- 866 [76] P. Rossi, J.L. Tailhan, F. Le Maou, Creep strain versus residual strain of a concrete loaded under various
 867 levels of compressive stress, Cem. Concr. Res. 51 (2013) 32–37. doi:10.1016/j.cemconres.2013.04.005.
- 868 [77] M. Omar, A. Loukili, G. Pijaudier-cabot, Y. Le Pape, Creep-damage coupled effects: experimental
 869 investigation on bending beams with various sizes, J. Mater. Civ. Eng. 21 (2009) 65–72.
- 870 [78] G. Mazzucco, G. Xotta, B. Pomaro, V.A. Salomoni, F. Faleschini, Elastoplastic-damaged meso-scale
- 871 modelling of concrete with recycled aggregates, Compos. Part B Eng. 140 (2018) 145–156.
- 872 doi:10.1016/j.compositesb.2017.12.018.
- 873 [79] A.E. Klausen, T. Kanstad, Ø. Bjøntegaard, E. Sellevold, Comparison of tensile and compressive creep of
 874 fly ash concretes in the hardening phase, Cem. Concr. Res. 95 (2017) 188–194.
- 875 doi:10.1016/j.cemconres.2017.02.018.
- [80] J. Zheng, X. Zhou, X. Jin, An n-layered spherical inclusion model for predicting the elastic moduli of
 concrete with inhomogeneous ITZ, Cem. Concr. Compos. 34 (2012) 716–723.
- 878 doi:10.1016/j.cemconcomp.2012.01.011.
- 879 [81] F. Grondin, M. Matallah, How to consider the Interfacial Transition Zones in the finite element
 880 modelling of concrete?, Cem. Concr. Res. 58 (2014) 67–75. doi:10.1016/j.cemconres.2014.01.009.
- 881 [82] M. Guo, S.Y. Alam, A.Z. Bendimerad, F. Grondin, E. Rozière, A. Loukili, Fracture process zone
- 882 characteristics and identification of the micro-fracture phases in recycled concrete, Eng. Fract. Mech.

- 883 181 (2017) 101-115. doi:10.1016/j.engfracmech.2017.07.004.
- 884 P. Belin, G. Habert, M. Thiery, N. Roussel, Cement paste content and water absorption of recycled [83] 885 concrete coarse aggregates, Mater. Struct. Constr. 47 (2014) 1451-1465. doi:10.1617/s11527-013-0128z.
- 886
- 887 [84] T. Le, G. Le Saout, E. Garcia-Diaz, D. Betrancourt, S. Rémond, Hardened behavior of mortar based on
- 888 recycled aggregate: Influence of saturation state at macro- and microscopic scales, Constr. Build. Mater.

889 141 (2017) 479-490. doi:10.1016/j.conbuildmat.2017.02.035.

- 890 [85] T.C. Hansen, E. Boegh, Elasticity and Drying Shrinkage of Recycled Aggregate Concrete, ACI J. 82 891 (1985) 648-652.
- 892 [86] T.C. Hansen, Recycled aggregates and recycled aggregate concrete: third state-of- the-art report 1945-

893 1989, Recycl. Demolished Concr. Mason. (1992) 336.

894