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Influence of lightweight aggregates on the physical and mechanical residual properties of concrete subjected to high temperatures

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1 ABSTRACT

2 This research studies the high temperature behavior of lightweight aggregate concretes (LWAC) by
3 providing a comprehensive study that regroups the physical, thermo-mechanical and mechanical
4 properties of three different LWACs. Then these properties are compared to the properties of a
5 normal-weight concrete (NWC) as well as to those of the mortar phase of these concretes, thus,
6 enabling us to isolate and identify specific behaviors of the lightweight aggregates (LWA). Contrary to
7 the normal weight aggregates, the LWAs showed a compatibility in thermal strain with the mortar
8 phase, which led to fewer cracks in the interfacial transition zone (ITZ) and thus, it resulted in a
9 divergence in behavior between LWACs and NWC, particularly for the residual permeability and
10 tensile strength values. While LWACs generally exhibited lower decrease of failure strengths, and
11 Young Modulus with temperature than NWCs, its Poisson's ratio was greatly decreased after 300°C.

12 Keywords: Lightweight Concrete, Expanded clay aggregate, Expanded shale aggregate, High
13 Temperature, Thermal deformation, Residual mechanical properties,

14 1 INTRODUCTION

15 The first lightweight aggregates (LWA) used in construction by the Romans were natural aggregates
16 derived from volcanic rocks, such as pumice. Today, lightweight aggregates can be manufactured
17 using natural raw materials such as clay, shale and slate [1], [2]. Due to its low density, lightweight
18 aggregate concrete (LWAC) is used in the construction of stadiums, long span bridges and even
19 offshore platforms. On the other hand, and in order to meet the environmental challenges of the 21st
20 century and the increasingly demanding thermal regulations like the French standards (RT 2012 & RT
21 2020), the structural lightweight concrete is being used to improve the energy efficiency in buildings.
22 It can reduce heating energy needs up to 15%, by replacing traditional structural concrete [3]. This
23 research work is a continuation of the work of [4] and [5] conducted at the Laboratory of Mechanics
24 and Materials of Civil Engineering of CY Cergy Paris Université. It focuses on the behavior at high
25 temperature of structural lightweight aggregate concretes, especially LWAC made of expanded clay
26 and shale aggregates, in order to ensure a safer design of buildings regarding fire. The fire resistance

27 of concrete depends on the attained temperature [6], the duration of fire [7] and the heating rate as well
28 as the material properties like the thermal conductivity and diffusivity, the porosity, the permeability,
29 the failure strength and the elastic modulus. The effective design of concrete against fire need to
30 consider both explosive spalling and loss of mechanical properties. The purpose of this research work
31 is to provide further understanding of the influence of lightweight aggregates on the evolution of
32 mechanical and physical concrete properties with respect to temperature. At material scale, the decay
33 of mechanical and physical properties mostly depends on the physico-chemical reactions that take
34 place during heating and on the thermal cracking induced between the paste and aggregate. Concrete is
35 a heterogeneous material that have different physical and chemical reactions when exposed to high
36 temperature. Around 80°C and up to 120°C the free water contained in the concrete evaporates and the
37 decomposition of ettringite (60-80°C) takes place [8]. From 110°C to 170°C the decomposition of
38 gypsum and the loss of water from part of the carboaluminate hydrates occur [8], [9]. While the
39 dehydration of C-S-H gels contained in the hardened cement can last up to 350°C-450°C [8], [10],
40 [11] other studies claim that C-S-H may suffer dehydration up to about 600°C [12]. At 750°C, the
41 transformation of C-S-H is complete into the nesosilicate form with a C₂S stoichiometry close to
42 larnite [10]. After 450°C the portlandite starts to decompose, followed by the decomposition of the
43 calcite at around 700°C [8], [11], [13]. The behavior of the concrete is also greatly influenced by the
44 aggregates as they occupy an important volume of the mixture (60 – 80%) [14], [15]. Artificial
45 lightweight aggregates already heated during their manufacturing process, have good thermal stability.
46 On the other hand, they are characterized by a higher porosity and a higher water absorption compared
47 to ordinary aggregates, which will impact the thermo-physical and water transfer properties. The
48 presence of lightweight aggregates can therefore affect the magnitude of the thermal gradient and the
49 liquid and water vapor pressures within the concrete when it is subjected to high temperatures. In fact,
50 the high porosity of lightweight aggregates leads generally to lower thermal conductivity [5], [16]–
51 [18]. Depending on the type of LWA, the thermal conductivity of LWAC is 40–53% lower than
52 that of NWC of the same composition [19]. Furthermore, the higher porosity of the lightweight
53 aggregate leads to more porous concretes whose permeability increases more or less depending on the
54 aggregate porous network and the presence or not of a thick outer shell. The porous structure within a
55 lightweight aggregate can vary significantly from one type to another. It can range from a
56 predominately closed porous structure (expanded shale) to mostly an open one (certain types of
57 expanded clays and pumice) thus influencing the permeability and migration paths of fluids inside
58 within the concrete.

59 Thermo-mechanical damage and in particular thermal cracking is influenced by the nature of the
60 aggregates. During heating, cracking is initiated at the paste-aggregate interface due to the
61 incompatibility of deformation between the paste and the aggregates on one hand, and the presence of

62 a porous Interfacial Transition Zone (ITZ) of lower resistance than the paste on the other hand [20].
63 The aggregates expand when heated, while the cement paste shrinks as a result of the dehydration of
64 the hydrates from 120°C onwards. Due to their high porosity and thermal stability, lightweight
65 aggregates have a lower expansion than ordinary aggregates. An increase of voids in the specimens
66 depending on apparent porosity results in a significant decrease in thermal expansion due to decrease
67 of internal thermal stress [21]. Another important role of the aggregate is its influence on the ITZ
68 between the cement paste and the aggregate which can lead to an important change in physical and
69 mechanical properties such as gas permeability and tensile strength. A porous ITZ can compromise the
70 internal structure of the concrete creating a network of pores across the three-dimensional
71 microstructure which may become an issue for the long-term durability of the material [22]. In this
72 regard, studies have shown that using lightweight aggregate can enhance the ITZ due to a nonexistent
73 wall effect between the mortar phase and the aggregate and the penetration of hydrated cement in the
74 porous shell of the LWA creating interlocking sites [23], [24]. Furthermore, using LWA for the
75 internal curing of concrete can reduce the volume fraction of the percolated ITZ paste [25], [26]. As
76 for high temperature behavior, research already carried out on this subject showed that LWAC
77 maintained slightly better mechanical properties compared to normal weight concrete (NWC) after an
78 ISO fire [27], losing around 50% and 91% of its initial compressive and tensile strength respectively
79 [28]. Sancak, Andic-Cakır and Karakoç [29]–[31] worked on pumice based lightweight aggregates.
80 Sancak [29], showed that pumice based LWAC had up to 28% of relative compressive left at 800°C,
81 double than that of NWC (16%). Furthermore, Andic-Cakır [30], by investigating the influence of
82 high temperature on the mechanical properties of self-consolidating concretes found that cracks follow
83 a weak and porous zone inside pumice aggregate instead of ITZ, while Karakoç [31] highlighted the
84 impact of the cooling regime on the residual mechanical strength of LWAC. Moreover, Felicetti [32]
85 attributed the difference in the tensile strength behavior between LWAC and NWC to the reduction of
86 the kinematic incompatibility between the coarse aggregate and the cement paste due the expulsion of
87 water from the LWA and the smaller stiffness of these aggregates. Yoon [33] confirmed the good
88 resistance of LWAC at high temperature with the LWAC having lower thermal strain than NWC. As
89 for the standards, the Eurocode 4 offers compressive strength, tensile strength and elastic modulus
90 curves of LWAC as a function of temperature.

91 While most of the existing studies on the high temperature behavior of the LWAC have focused on a
92 limited type of aggregate and/or a limited set of mechanical and thermal properties, few studies
93 provide an explanation of the difference of behavior between NWC and LWAC at high temperatures,
94 taking into account different density and nature of LWA. This work, tries to fill this gap by offering a
95 comprehensive study that compares the properties of three different types of LWAC with a normal
96 weight concrete (NWC) and the mortar matrix of these concretes, which enables us to isolate and

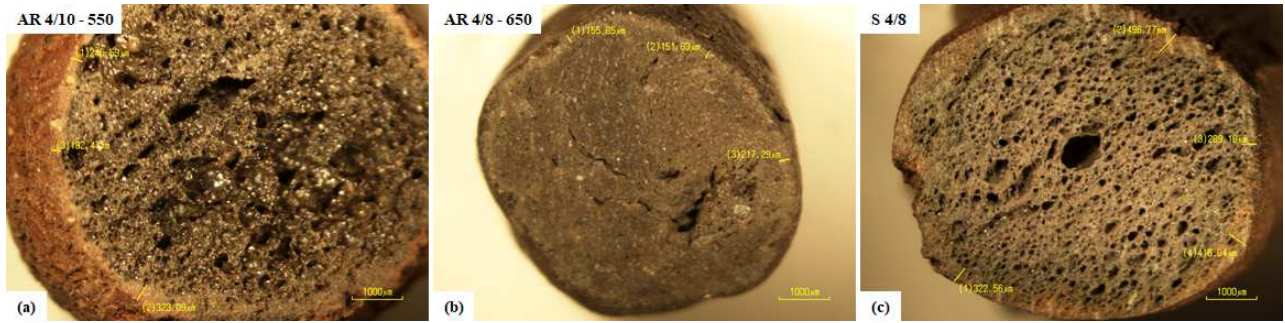
97 identify exclusive behavior of aggregates. It encompasses a large number of thermal, physical and
98 mechanical properties that are essential to the analysis of high temperature behavior and/or are
99 relevant to the assessment of concrete durability in a post fire situation. Furthermore, it provides a
100 phenomenological approach by coupling the results with a microscopic analysis of the ITZ and the
101 microstructure enabling us to study the influence of the aggregates on the cracking in the concretes.

102 **2 MIXTURE PROPORTIONING AND EXPERIMENTAL APPROACH**

103 **2.1 Aggregates**

104 Three coarse lightweight aggregates were tested: two expanded clay aggregates and one expanded
105 shale aggregate. The lightweight aggregates studied have different oven-dried particle densities, 824
106 kg / m³ for (AR-550), 1346 kg / m³ for (AM-650) and 1320 kg / m³ for (SE 4/8) determined according
107 to EN 1097-6 (Table 1). Table 1 also presents the Saturated Surface Dry particle density and the
108 apparent particle density. According to EN 1097-6, the apparent particle density is the ratio between
109 the mass of grains dried and the volume that they occupy in water, including closed pores but
110 excluding those accessible to water. Their water absorption after 48h ranges between 8.5% for S 4/8
111 and 28% for AR 550. As for the open porosity AM 650 have the highest percentage of open pores with
112 40.2% followed by AR 550 with 34.5% and finally S 4/8 with 18.5%. AR 550 has the highest closed
113 pore percentage with a total porosity of 69% followed by 50.1% and 49.2% for S 4/8 and AM 650
114 respectively. The total porosity is calculated by considering the solid density of the aggregates equals
115 to 2.65. The expanded clay aggregate (AR4/10-550) and the black limestone aggregate are of a 4/10
116 mm granular class whereas the expanded clay (AM4/8-650) and the expanded shale aggregates are of
117 4/8 mm class. The two expanded clay aggregates have different morphologies (Figure 1- a, b). While
118 AR has a spherical shape with a defined external shell (180 – 323 μm) , AM on the other hand have a
119 random geometry with a less apparent shell (150 – 220 μm). The expended shale on the other hand
120 (Figure 1- c) have a well-defined and the thickest external shell on average (280 – 500 μm). The
121 mortar phase consists of CEM I 52.5N cement and a silico-calcareous sand of 0/4 mm granular class.
122 The cement has a density of 3140 Kg / m³ and contains 97% clinker and 3% minority constituents.

123

Figure 1: Cross-section of the three lightweight aggregates

124

125

126

Table 1: Aggregate properties

Aggregates	ρ_{Lrd}^a	Density [kg/m^3]		Porosity* [%]		Absorption after 48 h [%]	Granular class	Nature
		ρ_{Lsd}^b	ρ_{La}^c	P_o	P_T			
Sand SC	2570	-	-	2.6	-	1	0/4	Silico-calcareous
AR 4/10-550	824	1169	1258	34.5*	69	28	4/10	Expanded clay
AM 4/8-650	1346	1748	2250	40.2*	49.2	24.6	4/8	Expanded clay
S 4/8	1320	1500	1620	18.5*	50.1	8.5	4/8	Expanded shale
Black limestone	2710	-	-	1.4	-	0.51	4/10	Limestone

^aOven dry particle density P_o : Open porosity^bSaturated surface dry particle density P_T : Total porosity^cApparent particle density

*Calculated after 1 month of immersion

127

128 The chemical composition of lightweight aggregates is provided by the producers. It was determined
 129 using X-ray fluorescence analysis (XRF). All aggregates consist of a large quantity of silica, from 60
 130 to 63% with an important part consisting of alumina and Iron Oxide (Table 2).

131

Table 2: Chemical composition (%) of the lightweight aggregates

Aggregates	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	S	Mn ₂ O ₃	TiO ₂	P ₂ O ₅
Expanded Shale	63.00	21.00	8.50	1.50	3.60	1.54	0.01	0.02	-	-	-	-
Expanded Clay	59.50	17.00	14.30	2.00	1.50	3.00	0.50	-	1.00	0.20	0.90	0.10

132

133 The mineralogy of expanded shale and clay aggregates are determined by the XRD analysis (Cu Ka
 134 radiation). The data from the analysis are reported from the work of Nguyen [5], [34]. The main
 135 mineral phases of expanded shale are quartz, iron oxide (magnetite) and potassium feldspar and albite.
 136 Clay aggregates mainly contain quartz, potassium feldspar, albite and iron oxide (magnetite and
 137 maghemite) and chabazite.

138 2.2 Mix design, specimens preparation and thermal cycles

139 Five mixtures were prepared, including two concretes with expanded clay coarse aggregate (LWCC1
 140 made with AR 4/10 & LWCC2 made with AM 4/8), one with expanded shale coarse aggregate
 141 (LWSC made with S4/8), a reference concrete with black limestone coarse aggregate (NWC made

142 with black limestone) and a mortar. This study considered concrete as a material that consists of two
 143 distinct phases, mortar and coarse aggregates. The mixtures were designed to maintain a constant
 144 volume of paste and aggregate for each type of aggregate and to ensure that the strength of the
 145 lightweight concretes was compatible with structural purpose, based on the results of [35]. The four
 146 concrete mixtures (Table 3) have the same water to cement ratio ($W / C = 0.45$) and the same volume
 147 fraction of coarse aggregate (37%) of the total volume concrete while the mortar has the same mix-
 148 design as the mortar matrix of the four concretes. It is thus possible to identify and isolate the
 149 exclusive behaviors of the lightweight coarse aggregates. The D_{max} of AR 550 is 10 mm and that of
 150 AM 650 and S 4/8 is 8 mm. This could affect the compactness of the granular skeleton. However, the
 151 slump values of the lightweight concretes are very close and show that the same workability
 152 (consistency) is obtained for each of the lightweight concretes. Thus we can make the hypothesis that
 153 the difference in D_{max} has little influence on the properties of the concrete.

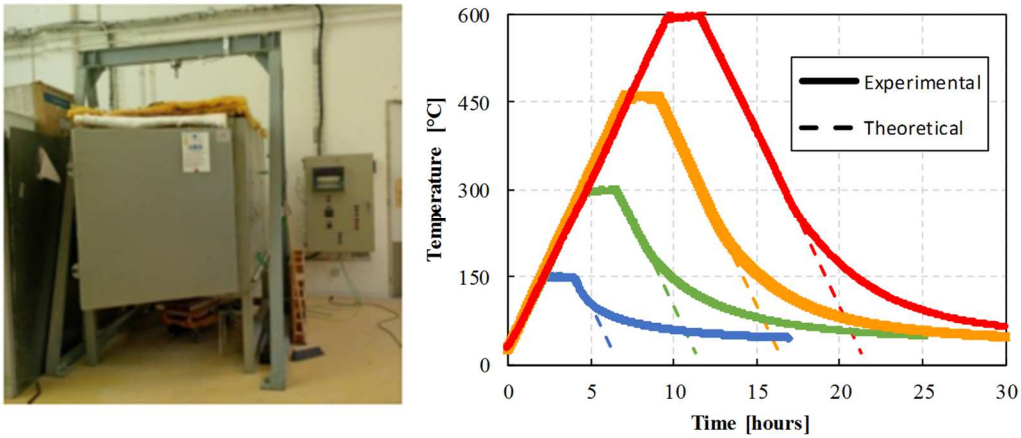
154 **Table 3: Mixture proportions of concrete per m3 (unit kg) and concrete properties**

Concrete	Cement 52.5	Effective water	Coarse Aggregate ssd	Sand	Slump [mm]	Oven dry density [kg/m ³]	fc 90 [MPa]	λ [W/m.K]
LWCC1	426	192	369	777	70	1650 ± 14.9	31.6 ± 1.1	1.05
LWCC2	426	192	585	777	65	1850 ± 11.1	49 ± 3.1	1.07
LWSC	426	192	547	777	70	1800 ± 16.9	41 ± 2.6	1.05
NWC	426	192	1002	777	110	2260 ± 3.5	57.5 ± 8.4	1.90
Mortar	676	304	-	1233	-	2090 ± 5.9	58.8 ± 0.8	1.70

155
 156 Due to the high absorption nature of the LWA, and in order to control the water-cement-ratio during
 157 mixing, aggregates were immersed in water during 48 hours before mixing and then drained for about
 158 30 minutes until their surface moisture content became constant. Mixing water was then reduced by
 159 the quantity of water brought by the LWA surface moisture. The specimens were stored in wet rags
 160 and plastic bags for 90 days. The concretes tested have compressive strengths at 90 days ranging
 161 between 32 MPa for LWCC1, 41 MPa for LWSC, 49 MPa for LWCC2 and 58 MPa for NWC, with
 162 oven dry densities of 1650, 1800, 1850 and 2260 Kg / m³ respectively. The various mechanical and
 163 physical tests were carried out after heating and cooling. The heating at 1 °C/min is followed by an
 164 isothermal stage of 2 hours at target temperatures of 150 °C, 300 °C, 450 °C, and 600 °C, in order to
 165 ensure a uniform temperature around the circumference of the test specimen and axially along the
 166 reference length [36]. The control thermocouples were placed on the surface of the specimens. As for
 167 cooling rate, the specimens are cooled at a rate of 1 °C/min until around 150 °C where this cooling rate
 168 cannot be imposed and the specimens are cooled at room temperature (Figure 2). Low heating and
 169 cooling rates are applied to limit the thermal gradient and to avoid any structural phenomenon, the
 170 objective being to provide temperature evolution laws of material properties.

171
172

Figure 2: The electrical furnace CMT (700°C) and the heating/cooling cycles at different temperature levels



173

174 The furnace has a heating capacity of 750°C with a depth of 1.20 m, a length of 1.12 m and a height of
175 1.00 m. Both side walls are equipped with heating resistors. The back of the furnace is equipped with a
176 fan to improve temperature homogenization. This furnace is equipped with a Eurotherm 2404 thermal
177 controller/programmer and a West 6700 control controller (Figure 2).

178 2.3 Tests after heating and cooling

179 The loss of mass was determined on an average of six 110Φ220 mm cylinders according to the
180 following equation:

$$181 \text{ Loss of mass (\%)} = \frac{(M_1 - M_2) \times 100}{M_1} \quad (1)$$

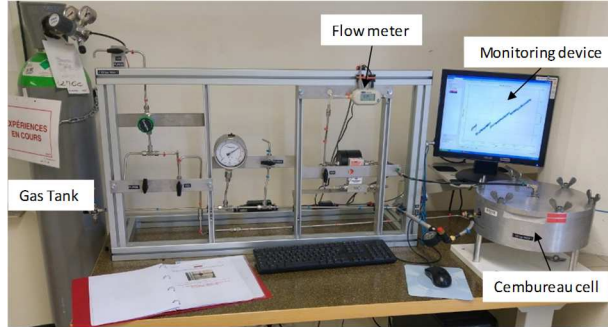
182 where M1 is the mass before heating and M2 the mass after heating.

183 The measurements of the density and the water accessible porosity under vacuum were carried out
184 according to standard NF P 18-459. The test was performed on four samples for each type of concrete.
185 For characterizations at room temperature, the samples were dried in the oven at 80 ° C to constant
186 mass. Samples exposed to high temperature are tested immediately after the heating / cooling cycles.

187 The gas (nitrogen) permeability of the concretes was measured on 150Φ50 mm specimens using a
188 Cembureau device [37]. For each target temperature level, 2 specimens were tested. The lateral
189 surfaces of the specimens were coated with self-adhesive aluminum to ensure that the gas flow only
190 passes through the bases of the specimen (sawn surfaces). Once the sample is in place, the inner tube
191 is filled with gas up to a pressure of 8 bar. The lateral pressure is higher than the injection pressure to
192 ensure the lateral support and sealing of the specimen. The specimen is ready to measure the apparent
193 permeability after a stabilization time. The operating principle of the permeameter is based on the
application of a constant pressure at the specimen inlet and the measurement of the gas (nitrogen) flow

194 rate at the inlet and outlet, after pressure stabilization, when the steady state is reached. The flow rates
 195 upstream and downstream of the sample were measured using a volumetric flowmeter. Figure 3 shows
 196 the complete gas permeability measurement system. The measurements were made at 20°C and a
 197 relative humidity of 75%.

198 **Figure 3: Gas permeability measurement system**



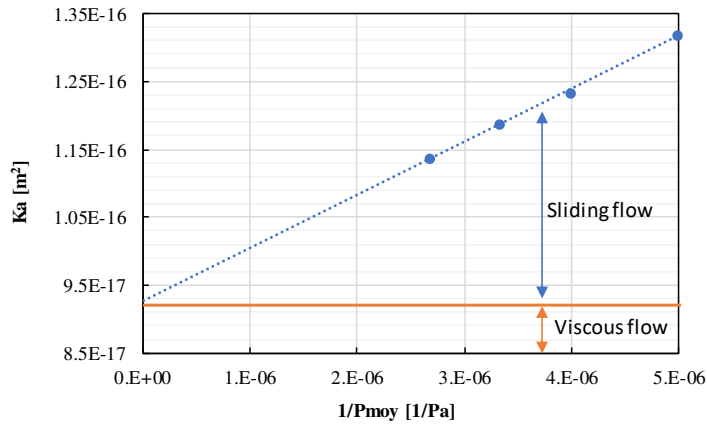
199
 200 The apparent permeability K_a is determined according to the following formula:

$$K_a = \frac{2 \times \mu \times Q \times l \times P_{atm}}{A(P_1^2 - P_{atm}^2)} \quad (2)$$

201 with μ the dynamic viscosity of the nitrous oxide N_2 [Pa.s]; Q the volume flow rate of the gas at the
 202 outlet [m^3/s]; P_{atm} the atmospheric pressure [Pa]; l the thickness of the test body in [m]; A the sample
 203 cross-section in [m^2]; P_1 the absolute gas pressure at the inlet in [Pa]. The intrinsic permeability K_{int} is
 204 deduced from the apparent permeabilities with the correction proposed by Klinkenberg [38]. The
 205 intrinsic permeability K_{int} , depending only on the viscous flow, acts on the entire volume contained in
 206 the capillary, or on the entire straight section considered, while the apparent permeability K_a also
 207 depends on the sliding flow (Figure 4). In this study, the determination of intrinsic permeability with
 208 Klinkenberg correction is obtained graphically by plotting the linear regression of the experimental
 209 points of apparent permeability K_a as a function of the inverse of the mean pressure $1/P_{moy}$.

210

Figure 4: Example of a permeability measurement



211

212 The velocity of P waves is measured on cylindrical samples 110Φ220 mm, using a Pundit. (Figure 5).

213 The dynamic Young's modulus is then calculated using the following equations:

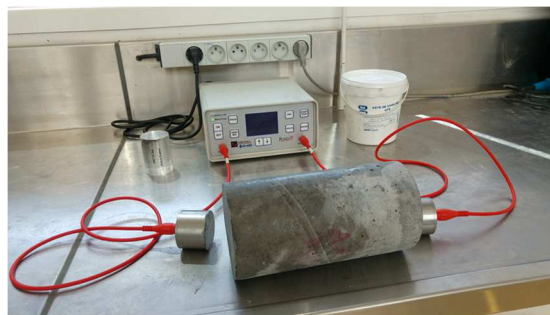
$$V_p = \frac{L}{t} \quad (3)$$

$$E_d = \frac{V_p^2 \rho(1 + \nu)(1 - 2\nu)}{(1 - \nu)} \quad (4)$$

214 where L is the length of material crossed (m); t the propagation time of the waves (s); ν the Poisson's
 215 ratio at the corresponding temperature measured by the strain gauges during a uniaxial compression
 216 test; ρ the density of the material at the corresponding temperature (Kg / m^3); V_p wave propagation
 217 velocity (m / s) and E_{dyn} dynamic Young's modulus.

218

Figure 5: Ultrasonic velocity measurement device



219

220 The uniaxial compression and splitting tensile tests are carried out on 110Φ220 mm concrete cylinders
 221 using a hydraulic press according to NF EN 12390-3 and NF EN12390-6 standards respectively. At
 222 least three specimens were used to determine the mechanical properties for each concrete and target
 223 temperature. Two to three specimens were equipped with strain gauges to determine the static elastic
 224 modulus in accordance with EN 12390-13 during compression test. Four gauges were used on the
 225 cylinder, two attached axially and two attached transversally (Figure 6).

226

Figure 6: Prepared specimens with strain gauges



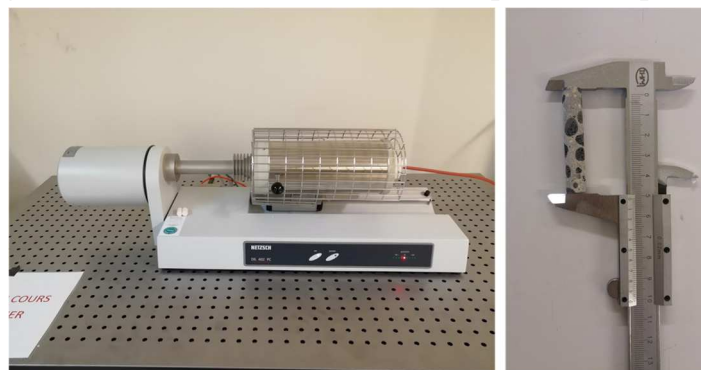
227

228 **2.4 Dilatometry and thermal expansion test**

229 The measurements of the deformation and the thermal expansion were carried out using a dilatometer
230 DIL 402-PC (Figure 7), on cylindrical samples of 10 mm in diameter and 50 mm in length core drilled
231 of 150 Φ 300 mm and 110 Φ 220 mm specimens. All samples were dried in the oven at 80°C prior to
232 testing to ensure that any moisture that might affect the test was removed. Sample was pressed against
233 sample holder by the pushrod (25 cN) with a thermocouple placed in direct proximity for temperature
234 measurement. Pushrod was linked with a displacement sensor that measures thermal expansion during
235 heating. To subtract the expansion contribution of the sample holder and pushrod, a correction
236 measurement was carried out in the same conditions using a standard sample prior to measurement.
237 The test was carried out for each type of concrete on three different samples in order to check the
238 repeatability of the test. After measuring the initial length and calibrating the device, the samples were
239 heated at a rate of 4°C / min from 20°C to 1050°C and then naturally cooled to room temperature.

240

Figure 7: Dil 402-PC device and an example of a sample used



241

242 **2.5 Microstructural investigation**

243 Observations using a scanning electron microscope are carried out on a ZEISS GeminiSEM 30 device,
244 at a variable electron beam intensity depending on the type of observation and an acceleration voltage
245 ranging between 2 kV and 15 kV. Two types of SEM observations were used in this study:

246 Observations on bulk specimen using secondary electron signal (SE), and observations on epoxy
247 impregnated specimens using backscatterd-electron signal (BSE). The latter specimens and after an
248 exposure to elevated temperatures were cut and dried at 45°C and 50% relative humidity for 48 h.
249 Following the drying period, the specimens were impregnated with epoxy resin. The samples are then
250 placed in small cylindrical plastic molds (diameter 4 cm and height 3 cm), then filled with epoxy resin.
251 They are placed under vacuum in order to evacuate the air in the resin and then air-dried for 48 hours.
252 Once the resin is dry, the samples are unmolded. All samples are polished in several steps until the
253 resin layer has been well removed and the following. Prior to the SEM observations, the samples are
254 metallized to make them conductive, using a Polaron SC502 metallizer. The SEM observations were
255 also coupled with Energy Dispersive X-Ray spectroscopy analysis (EDS).

256 Other microscopic observations were conducted using a stereo microscope on the slices of cylinders
257 used in the permeability tests.

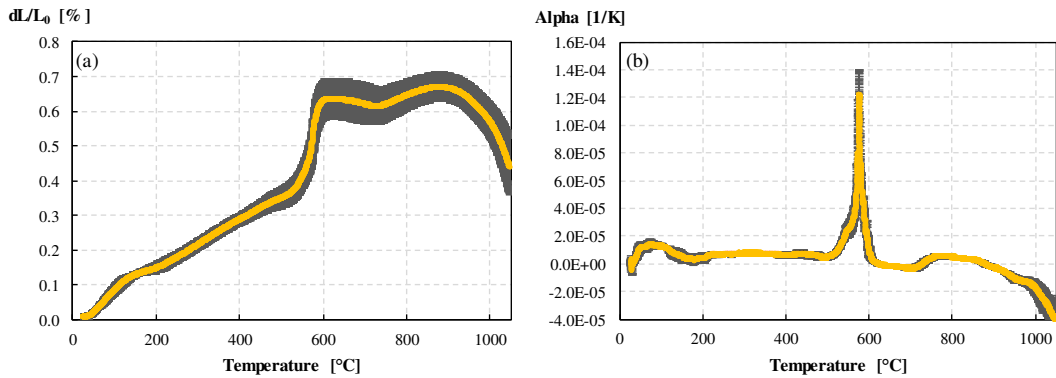
258 **3 RESULTS AND DISCUSSION**

259 **3.1 Thermal deformation and coefficient of thermal expansion (CTE)**

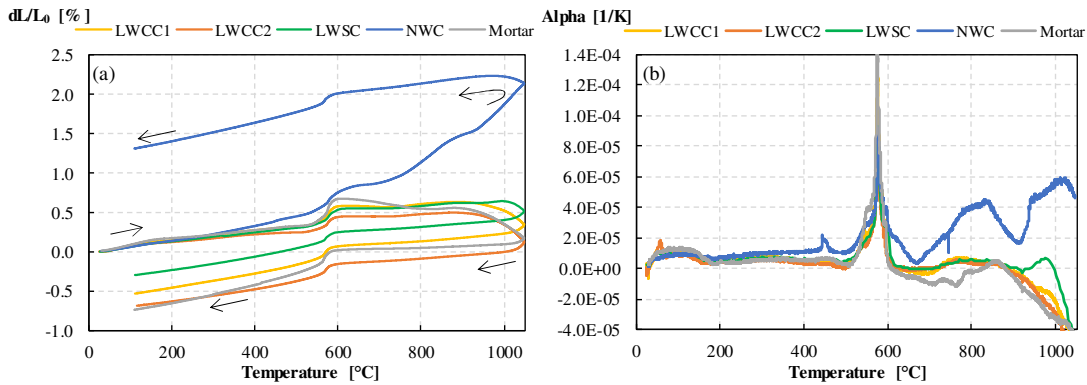
260 The values in Figure 8 represent the average over three LWCC1 samples with its corresponding error
261 bars. There was no significant variation from one test to another. Despite the small difference between
262 the diameter of the sample and the maximum size of the aggregate, it can be considered that the
263 measured result is representative of the material behavior due to the repetitiveness of the results for the
264 three specimens. From 20°C to 530°C, the deformation increases almost linearly with the temperature
265 for all concretes up to a value of 0.4% for lightweight concretes and silico-calcareous mortar, and
266 0.5% for NWC (Figure 9a). On the other hand, the coefficient of thermal expansion is more or less
267 stable up to this temperature. It varies between 5 E-06 and 1 E-05 1/K for LWCC2, LWCC1, LWSC
268 and the mortar, and between 1 E-05 and 1.5 E-05 for NWC (Figure 9b). At 570°C, there is a
269 significant increase in deformation, due to the change of α phase of the quartz to its β phase [39]
270 which results in a peak of the thermal expansion coefficient for all concretes and it reaches 1.7 E-04
271 1/K for mortar, followed by 1.2E-04, 1.0E-04, 9.1E-05 & 8.2E-05 1/K for LWCC1, LWSC, LWCC2
272 & NWC, respectively (Figure 9b). Note that the majority of the quartz comes from silico-calcareous
273 sand and the rest comes from LWA (Table 2). After 600°C, the deformation stabilizes at 0.5% and
274 then begins to decrease for lightweight concretes and mortar, while it increases rapidly for NWC after
275 700°C to reach 2% at 1000°C. At 700°C, the decarbonation of limestone aggregate takes place,
276 usually this reaction results in an overall shrinkage of the material. But this shrinkage of the limestone
277 aggregates generates high tension in the specimen creating cracks which translate to an irreversible
278 deformation in the cooling phase. On the other hand, the shrinkage effect is noticed on the LWAC and
279 the mortar by having a negative deformation at the end of the cooling phase. In general, a greater

280 expansion of limestone concrete compared to lightweight concrete is observed (even before 700°C).
 281 This can be attributed to a higher thermal expansion of the limestone aggregates compared to that of
 282 the mortar. Nirry Razafinjato [15], [40] studied the high temperature behavior of black limestone
 283 aggregates. His results of the CTE and thermal deformation are represented in Figure 10. Between
 284 20°C and 150°C the CTE of the limestone is lower than that of the mortar. After 150°C and up until
 285 530°C the trends are reversed. While the CTE of the mortar stabilizes at around 5E-06 1/K, the CTE of
 286 the limestone continue to increase reaching 2.3E-05 1/K at 500°C (Figure 10b). This increase in CTE
 287 translates into a higher thermal deformation of the limestone compared to the mortar (Figure 10a). The
 288 lower thermal expansion of the mortar compared to that of the reference concrete can be explained by
 289 the higher porosity of the mortar and by the greater volume fraction of paste which tends to shrinkage
 290 after 120°C [20]. A higher amount of voids in the specimens depending on apparent porosity can
 291 result in a significant decrease in thermal expansion due to decrease of internal thermal stress [21].
 292 The lightweight concretes undergo an expansion similar to that of the mortar suggesting a
 293 compatibility of thermal deformation between the silico-calcareous mortar and lightweight aggregates.

294 **Figure 8: Average thermal deformation (dL/L_0 [%]-a) and average CTE (Alpha [1/K]-b) as a**
 295 **function of temperature for the LWCC1 (with error bars)**

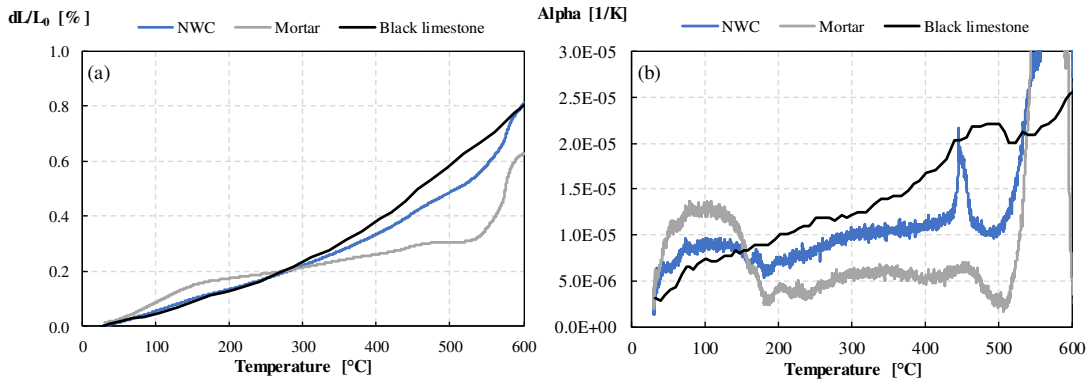


296
 297 **Figure 9: Average thermal deformation (dL/L_0 [%]-a) and average CTE (Alpha [1/K]-b) as a**
 298 **function of temperature for all concretes**



299
 300

301 **Figure 10: Average thermal deformation (dL/L_0 [%]-a) and average CTE (Alpha [1/K]-b) as a**
 302 **function of temperature for NWC, Mortar and black limestone aggregates [15], [40]**



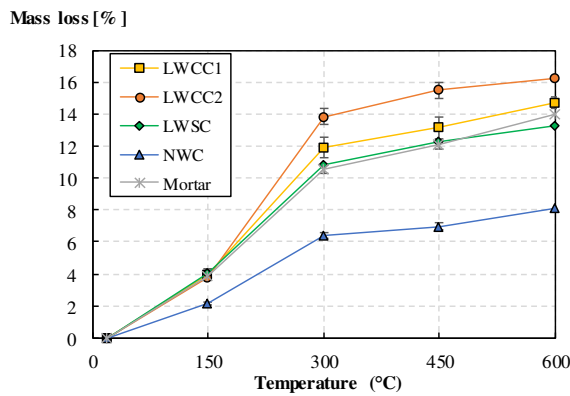
303

304 **3.2 Study of residual physical properties and thermal cracking**

305

306

Figure 11: Evolution of mass loss [%] as a function of temperature



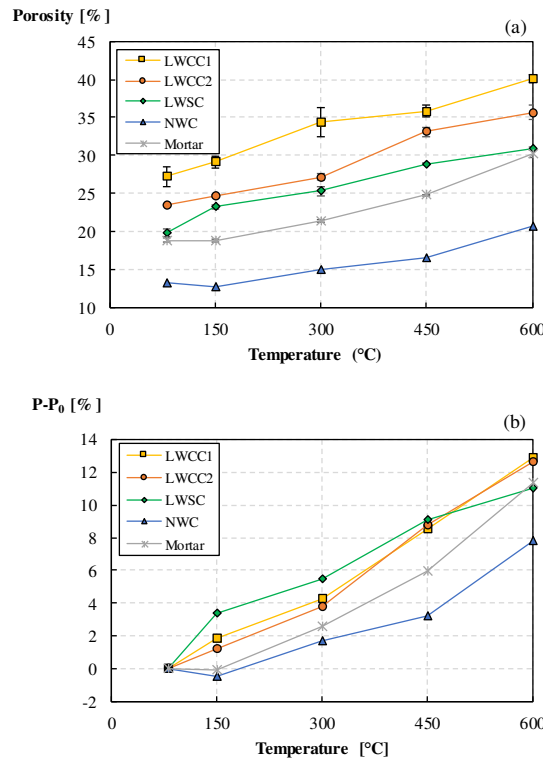
307

308 Mass loss curves show the same trend for all concretes (Figure 11). A significant loss of mass up to
 309 300°C followed by a slight increase up to 600°C. Up to 300°C, this loss of mass is linked to the
 310 departure of free water and the dehydration of CSH and ettringite [8], [13]. After 300°C, the mass loss
 311 is relatively less important and is due mainly to the decomposition of the portlandite [41]. As the
 312 lightweight aggregates were saturated for 48 hours before the concrete was made, the total amount of
 313 water is higher and therefore the mass loss in the lightweight concretes is greater, 13.5%, 14.5% and
 314 16% at 600°C for LWSC, LWCC1 and LWCC2, respectively. The mortar suffers a loss of 14%,
 315 higher than the 8% loss of the normal weight concrete. The difference between the mortar and the
 316 normal weight concrete can be explained by the greater volume fraction of cementitious paste in the
 317 mortar as the majority of the weight loss occurs in paste [11], [15], [42].

318 The evolution of porosity as a function of temperature is represented in Figure 12. There is no
 319 significant variation up to 150°C except for LWSC concrete. At 300°C, an increase of 2% to 6% is
 320 noted. Subsequently, the porosity continues to increase to reach at 600°C, 8% and 12.5% for NWC

321 and LWCC2 respectively and 11.5% for LWSC and the mortar. The increase in porosity in lightweight
 322 concrete is about 4% higher than that of the normal weight concrete. This could be related to the
 323 development of cracks within the lightweight aggregates (Figure 16), giving access to pores formerly
 324 closed. Note that the curve of LWCC1 is higher than that of LWCC2 even though the open porosity
 325 for the corresponding aggregate (AR-550) is lower than the porosity of its counterpart (AM) (Table 1).

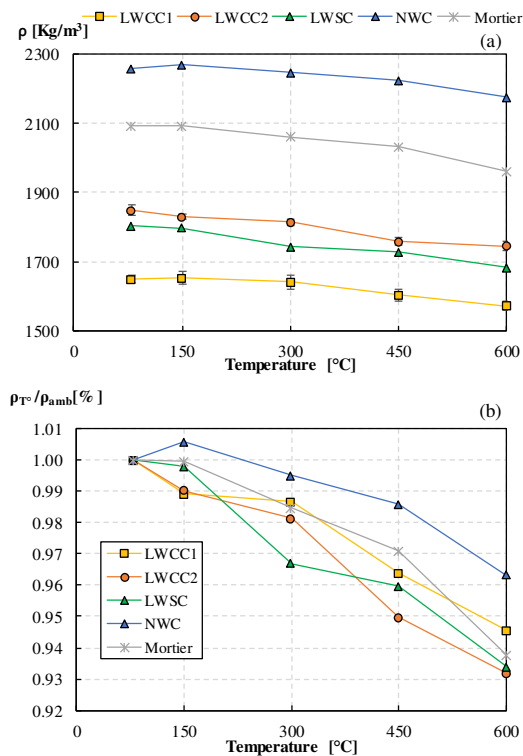
326 **Figure 12: Evolution of porosity (Porosity [%] – a), Porosity increase (P-P₀ [%] – b) as a**
 327 **function of temperature (P₀ : initial porosity, P: porosity at a given temperature level)**



328
 329 This result seemingly paradoxical can be explained by the fact that porosity of the aggregates is
 330 obtained through natural saturation whereas the porosity of the concrete is obtained through saturation
 331 under vacuum conditions. Thus, a greater part of the total porosity of AR-550 is accessible using the
 332 vacuum saturation approach. The order of the porosity values of the three lightweight concretes are
 333 thus consistent with the order of the values of the total porosity of the aggregates.

334 In regard to the density (ρ [Kg/m³] - Figure 13), the concretes lose at 600°C, between 3.6% to 7% of
 335 their initial oven-dry density, LWCC2 and LWSC being the most affected followed respectively by
 336 the mortar, LWCC1 and then NWC. As the majority of the weight loss is associated to the mortar
 337 phase which is the main contributor to the LWAC weight, and the aggregates occupy the same volume
 338 fraction in all concrete mixtures, it is expected that the oven-dry density of the LWAC would be more
 339 affected than its NWC counterpart.

340 **Figure 13: Evolution of dry density (ρ_{amb} [Kg/m³] – a), relative dry density ($\rho_{T^{\circ}}/\rho_{amb}$ [%] – b) as a**
 341 **function of temperature**

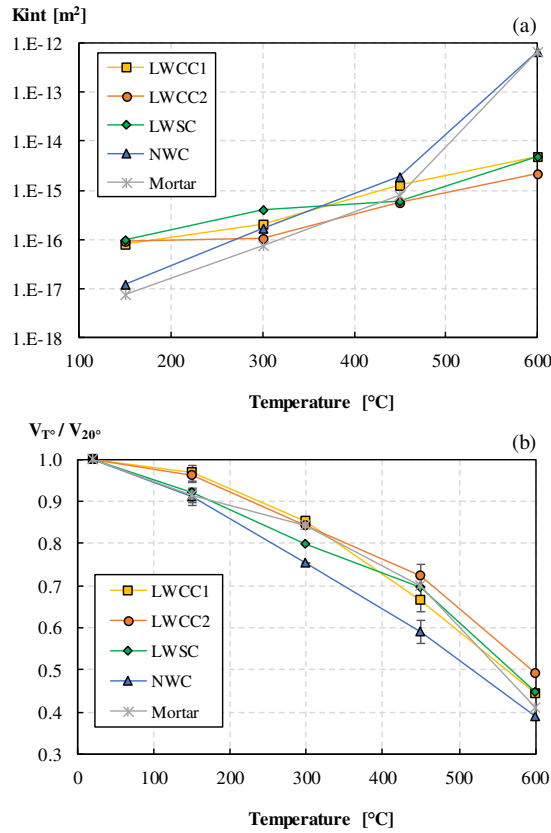


342

343 The results of the permeability measurements reported in Figure 14a, show that the LWAC are more
 344 permeable than NWC and Mortar at 150°C with values varying between $8 \cdot 10^{-17} \text{ m}^2$ and $1 \cdot 10^{-18} \text{ m}^2$.
 345 These results are coherent with the values reported by Real [43] for the LWAC and NWC with a
 346 water-cement ratio equal to 0.45. At 300°C, the permeability values of the normal weight concrete and
 347 the mortar are multiplied by 10 and join those of lightweight concretes which undergo a very slight
 348 increase. At 600°C, the permeability for the normal weight concrete and the mortar (10^{-12} m^2) is
 349 greater than for lightweight concretes ($10^{-15} \text{ m}^2 < K_{int} < 10^{-14} \text{ m}^2$). In the same way, according to [44]
 350 the permeability of normal weight concretes increases to 10^{-13} m^2 at 600°C, which is higher than 10^{-14}
 351 m^2 measured for lightweight concrete. Despite a higher increase in porosity for LWCC1, LWCC2 and
 352 LWSC, there is not a same trend for permeability and therefore the new accessible pores are rather
 353 intragranular pores within the lightweight aggregates that do not participate in the transfer processes.
 354 Conversely, for NWC and mortar, the porosity is initiated at the paste-aggregate interface and grows
 355 in the cement paste, thus creating a connected porous network (Figure 15).

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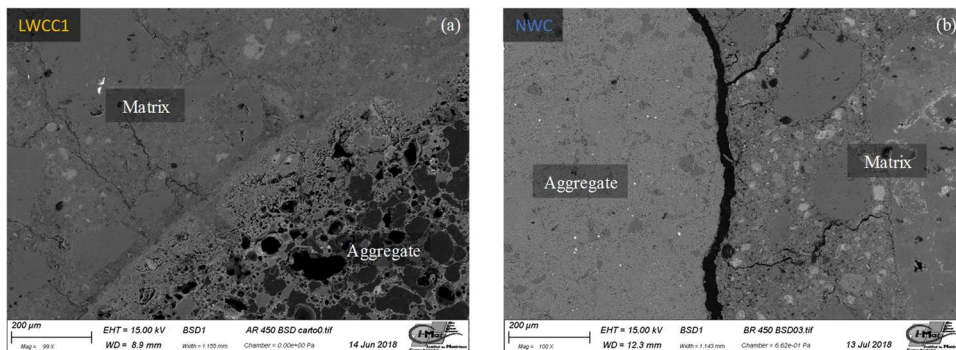
Figure 14: Evolution of permeability (K_{int} [m^2] - a), P wave velocity ($V_{T^{\circ}}/V_{20^{\circ}}$ - b) as a function of temperature



358

359 The relative evolution of ultrasonic wave velocities ($V_{T^{\circ}}/V_{20^{\circ}}$) is similar to that of the permeability,
 360 with earlier and more significant degradation of the normal weight concrete with temperature (Figure
 361 14b). The mortar behaves like lightweight aggregate concrete up to 450°C. After this temperature, the
 362 mortar undergoes a significant drop in wave velocity coupled with an increase in porosity (Figure 12).
 363 At 600°C, the wave velocity of NWC decreases by 60% and only by 50% and 45% for the three
 364 lightweight aggregate concretes. Even though, the LWAC exhibits higher increase in porosity
 365 compared to NWC, the increase in its wave velocity is more moderate. This result confirms the result
 366 of the permeability and indicates a higher depreciation of ITZ [45] in the NWC.

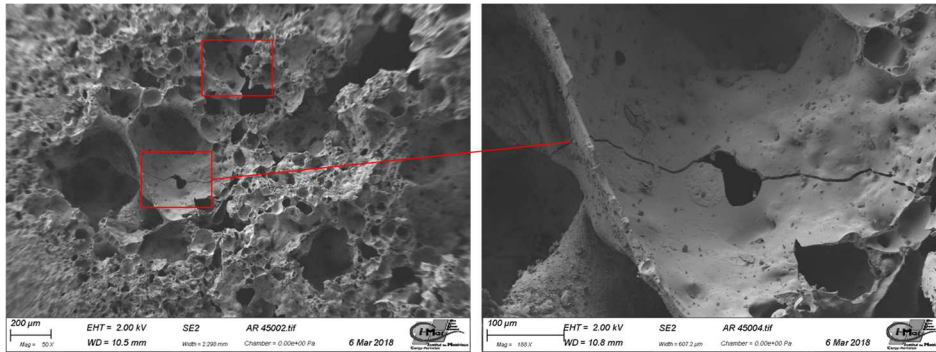
Figure 15: Paste/aggregate interface of LWCC1 (a) and NWC (b) heated at 450°C



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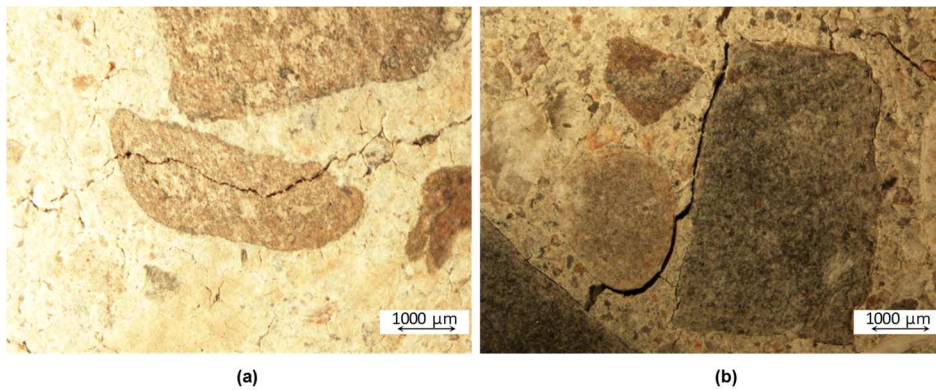
Figure 16: Cracks inside the lightweight aggregate at 450°C (LWCC1)



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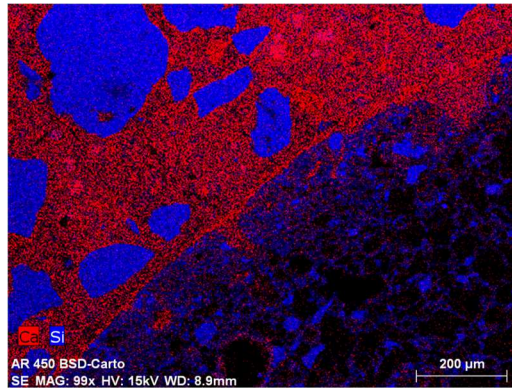
Figure 17: Cracks in concrete LWCC2 (a) and NWC (b) heated at 600°C



372

373 In order to understand the origin of the increase in permeability, the previous measurements were
374 coupled with observations under both a stereo microscope and a scanning electron microscope. It has
375 been found that the paste-aggregate interface is more damaged at 450°C for normal weight concrete
376 than for the lightweight concretes (Figure 15). Also, at this temperature, cracks inside the LWA were
377 observed (Figure 16). Similar observation was reported by Andiç-Cakir [30] who noted thermal cracks
378 inside pumice aggregates after 300°C. In addition, observations with the naked eye and stereo-
379 microscope of concretes heated up to 600°C (Figure 17), shows that the majority of cracks in
380 lightweight concretes are transgranular while cracks in the normal weight concrete go through the
381 interfacial area between the cementitious matrix and the aggregate. This can be explained by a more
382 resistant paste-aggregate bond with porous lightweight aggregates than with limestone aggregates [4]
383 and a better thermal deformation compatibility between the cementitious matrix and the aggregate
384 (Figure 9). This better bond was confirmed using EDS analysis on the paste-aggregate interface of the
385 LWA (Figure 18). The result shows a penetration of the paste inside the aggregate surface creating
386 interlocking sites between the two entities.

387 **Figure 18: Ca-Si Cartography using EDS analysis on the paste-aggregate interface of LWCC1**



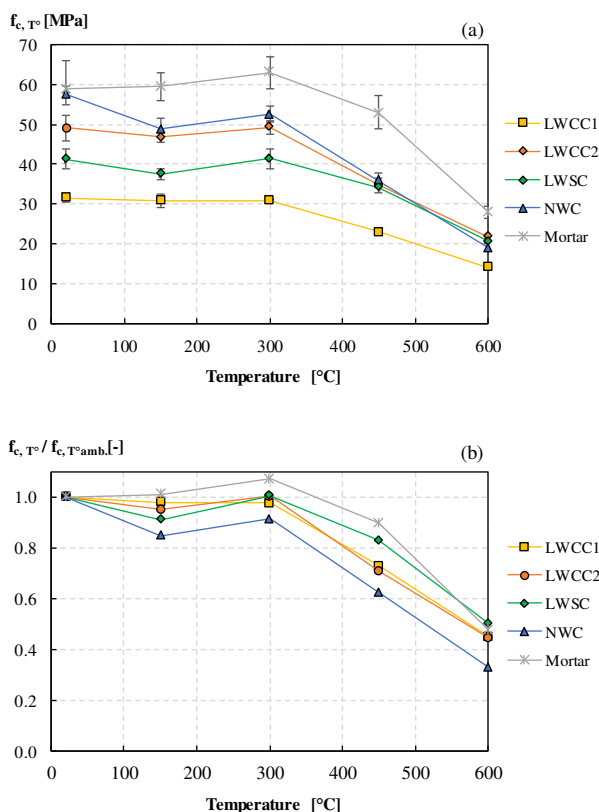
388

389 **3.3 Residual mechanical properties**

390 By substituting normal weight aggregates with lightweight aggregates, a drop in resistance is noticed
391 since strength is mainly linked to the lightweight aggregate's failure strength [4]. At room
392 temperature, the compressive strength of the concretes ranges between 58 MPa for NWC and 32 MPa
393 for LWCC1 (Figure 19). Up to 300 °C, there is a slight loss of residual compressive strength for all
394 concretes with a typical behavior of losing then gaining some strength at 150°C and 300°C
395 respectively [10], [46], [47]. Beyond this, the compressive strength decreases rapidly for all the
396 concretes but in a more moderate way for the lightweight concretes than for the reference concrete. At
397 450°C, the compressive strength of LWCC2 and LWSC become similar to NWC while the mortar
398 shows a very good behavior up to this temperature by losing only around 10 % of its initial strength
399 before quickly degrading at 600°C and losing 50% of its compressive strength. The lightweight
400 aggregate concretes follow the same trend but with 20% less loss than the reference concrete. The
401 difference in behavior between lightweight and limestone aggregates concretes is even more
402 noticeable with the evolution of residual tensile strength (Figure 20).

403
404

Figure 19: Residual compressive strength (f_{c,T° [Mpa] – a), Relative residual compressive strength ($f_{c,T^\circ}/f_{c,T^\circ\text{amb}}$ [-] – b) as a function of temperature

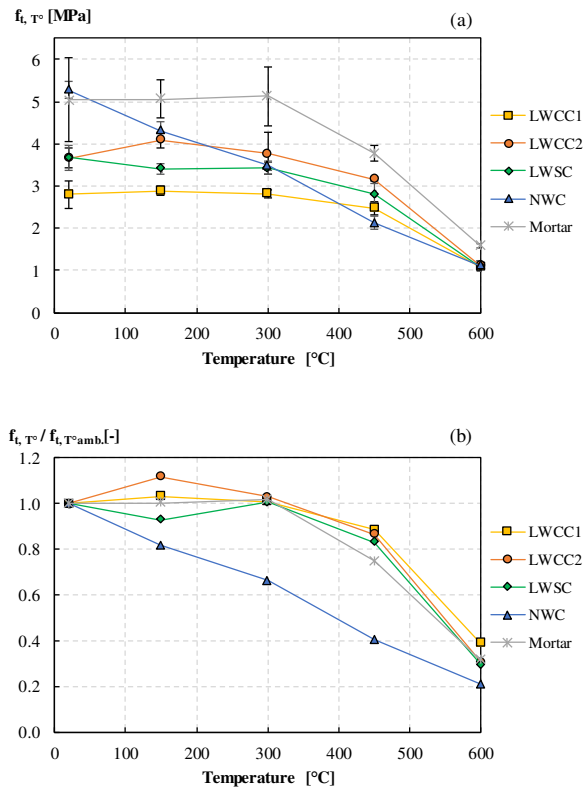


405

406 Unlike the normal weight concrete whose tensile strength decreases almost linearly with temperature,
407 lightweight aggregate concrete and mortar show only, at 450°C, a slight loss of tensile strength of
408 about 20 %, while NWC has lost more than 60 % of its initial strength. At this temperature, the
409 absolute tensile strength of all lightweight concretes becomes higher than that of normal weight
410 concrete. This can be explained by the good resistance of the paste-aggregate interface (Figure 15 &
411 Figure 17) during the thermal loading related to a thinner and less porous Interfacial Transition Zone
412 (ITZ) [23], [48]. Moreover the smaller thermal expansion of the lightweight aggregates compared to
413 the calcareous aggregate limits the differential strain between the mortar and the aggregate and
414 therefore the stress increase at the paste-aggregate interface (Figure 9). Figure 21 shows that the crack
415 path on the failure plane of the splitting test depends on the nature of aggregate and on the heating
416 temperature. In concrete with limestone aggregate, the crack path is predominantly intergranular
417 while in lightweight concretes transgranular cracks are mostly observed. With increasing temperature,
418 the crack path becomes more and more intergranular (Figure 21), which means that the tensile strength
419 is highly dependent on the interfacial zone's strength at higher temperatures. At these temperatures,
420 the ITZ is weakened due to the dehydration of the cement paste and the decomposition of the
421 portlandite coupled with an increase in thermal strain due to aggregate expansion.

422
423

Figure 20: Residual splitting tensile strength (f_{t,T° [Mpa] – a), relative residual splitting tensile strength ($f_{t,T^\circ} / f_{t,T^\circ\text{amb}}$ [-] – b) as a function of temperature

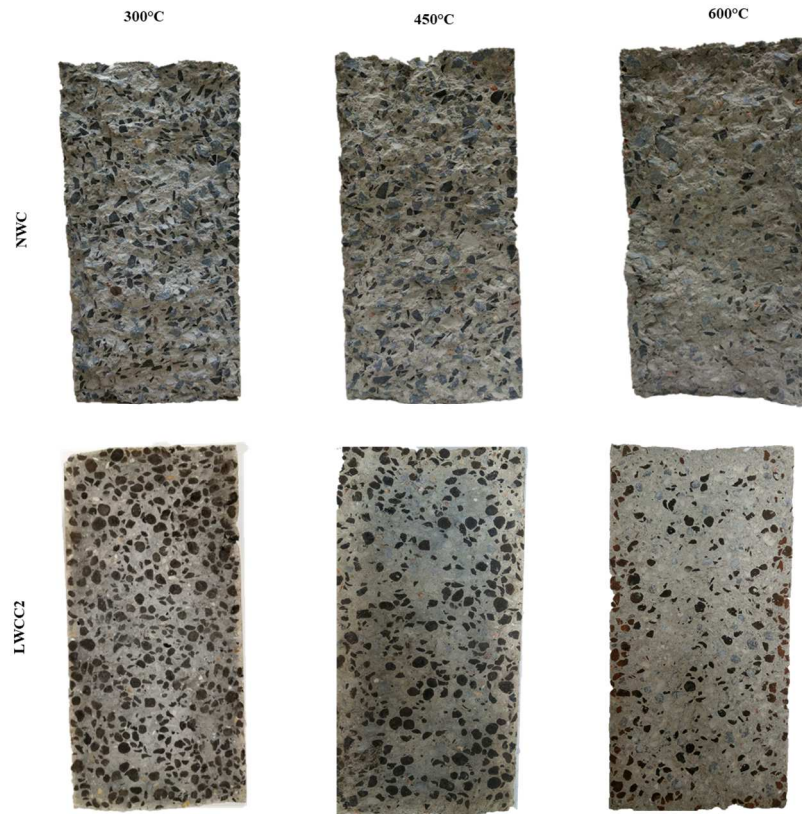


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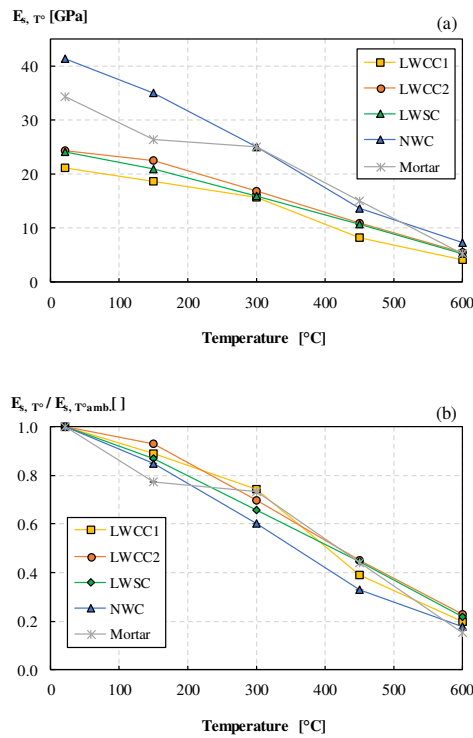
Figure 21: Evolution of the rupture plane after a splitting tensile test on 110φ220 specimens with respect to temperature



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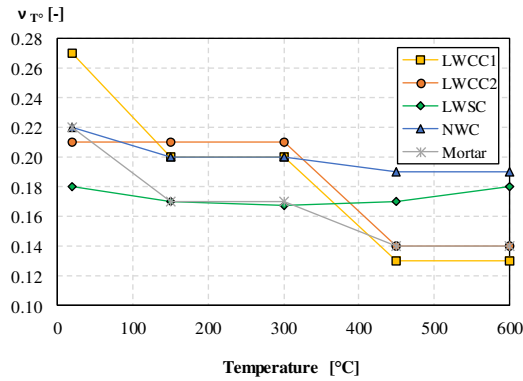
Figure 22: Residual static Young modulus (E_{s,T° [GPa] - a), relative residual static Young modulus ($E_{s,T^\circ} / E_{s,T^\circ \text{amb}}$ [-] - b) as a function of temperature



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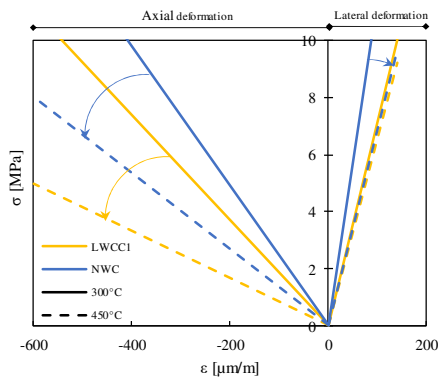
Figure 23: Residual Poisson's ratio (ν_{Ts} [-]) as a function of temperature.



433

434 The static Young's modulus decreases more linearly with temperature than the tensile and compressive
 435 strengths (Figure 22). The static modulus loss is lower for lightweight aggregate concrete and mortar
 436 than for the normal weight concrete, especially between 150 and 450°C. Similar trends and losses in
 437 mechanical strength have been observed by Toriç [49]. On the other hand, Poisson's ratio undergoes a
 438 significant drop after 300 °C for lightweight clay aggregate concrete while that of the reference
 439 concrete and LWSC is not affected very much by the temperature (Figure 23). In order to better
 440 understand the evolution of the Poisson's ratio, the linear phase of the stress-strain curve was plotted at
 441 300°C and 450°C for the NWC and the LWCC1 (Figure 24). While both concretes showed similar
 442 increase in axial deformation between 300°C and 450°C, the LWCC1 showed nearly no increase in
 443 lateral deformation. This result explains the drop in Poisson's ratio as there was no increase in the
 444 lateral deformation to compensate the increase of the axial deformation like in the case of NWC. The
 445 higher increase in the porosity of the mortar, of the LWCC1 and of the LWCC2 between 300°C and
 446 450°C explains the decrease in its Poisson's ratios over this range of temperature.

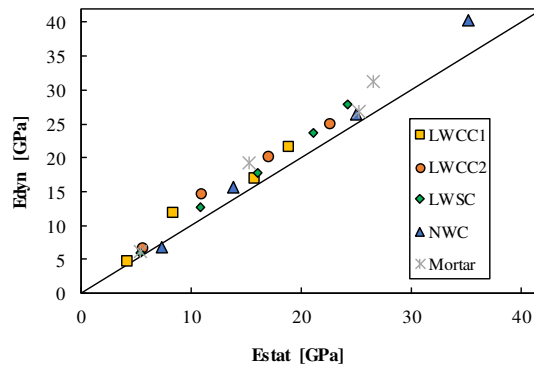
Figure 24: Stress (σ [MPa]) vs strain (ϵ [$\mu\text{m}/\text{m}$]) for LWCC1 and NWC at 300°C and 450°C



448

449

450 **Figure 25: Dynamic Young modulus (Edyn [GPa]) vs static Young modulus (Estat [GPa])**



451
 452 The comparison of the dynamic modulus (Edyn) with the static modulus (Estat) for the different target
 453 temperatures shows that the moduli are very close or identical at 600 °C (Figure 25). For the rest of the
 454 temperatures, the dynamic modulus was slightly overestimated when compared to the static modulus
 455 with a maximum difference recorded of 4 GPa for the NWC at ambient temperature. Overall, the wave
 456 velocity method accurately reflects the evolution of Young's modulus as a function of temperature.

457 **4 CONCLUSIONS**

458 The objective of this work is to study the behavior of LWAC when exposed to high temperature. This
 459 objective was achieved by measuring the evolution of properties with respect to temperature (Thermal,
 460 physical and mechanical) of three types of LWAC and comparing them to the properties of a reference
 461 concrete and a mortar. At a slow heating rate of 1°C/min, the hydric effects (the vapor and liquid
 462 pressure) and thermal gradients were reduced in the heated concrete and mortar specimens. Under
 463 these conditions, and based on the previous results, it is possible to conclude the following:

- 464 - The lightweight concretes studied showed a loss of failure strengths and Young's modulus
 465 with temperature more moderate than the reference calcareous aggregate concrete.
- 466 - Unlike the normal weight concrete whose tensile strength decreases almost linearly with
 467 temperature, lightweight aggregate concrete and mortar show only, at 450°C, a slight loss
 468 of tensile strength of about 20 %, while normal weight concrete has lost more than 60 %
 469 of its initial strength.
- 470 - Poisson's ratio undergoes a significant drop after 300°C for lightweight clay aggregate
 471 concrete while that of the normal weight concrete and expanded shale concrete is not
 472 affected very much by the temperature.
- 473 - The permeability of normal weight concrete increases faster with temperature than that of
 474 LWACs. At 600°C, the permeability of the normal weight concrete and the mortar became
 475 greater than for the three tested lightweight concretes.

- 476 - SEM and optical microscope observations have shown that the distribution and the
477 cracking path after splitting test depend on the nature of the aggregates: intergranular for
478 calcareous aggregates and transgranular for expanded shale and clay concretes. With
479 increasing temperature, the crack path becomes more and more intergranular in
480 lightweight concretes.
- 481 - From 300°C lightweight aggregates concrete showed a lower thermal expansion than the
482 calcareous aggregate concrete after 300 °C.
- 483 - The expansion of the mortar constituting the matrix of concretes was similar to that of
484 lightweight aggregate concrete, which shows a good compatibility of deformation between
485 the mortar and lightweight aggregates.
- 486 - The better residual behavior of LWAC can be explained by a more resistant paste-
487 aggregate bond with porous lightweight aggregates than with limestone aggregates and a
488 better thermal deformation compatibility between the cementitious matrix and the
489 aggregate
- 490 - Finally, despite lightweight aggregates of different densities and microstructure,
491 lightweight aggregate concretes showed similar evolution of residual properties with
492 temperature.

493

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498

499 **REFERENCES**

- 500 [1] S. Chandra and L. Berntsson, "2 - Production of Lightweight Aggregates and Its Properties," in *Lightweight*
501 *Aggregate Concrete*, S. Chandra and L. Berntsson, Eds. Norwich, NY: William Andrew Publishing, 2002,
502 pp. 21–65.
- 503 [2] R. de'Gennaro *et al.*, "Structural concretes with waste-based lightweight aggregates: from landfill to
504 engineered materials," *Environ. Sci. Technol.*, vol. 43, no. 18, pp. 7123–7129, 2009.
- 505 [3] S. Real, M. G. Gomes, A. Moret Rodrigues, and J. A. Bogas, "Contribution of structural lightweight
506 aggregate concrete to the reduction of thermal bridging effect in buildings," *Constr. Build. Mater.*, vol. 121,
507 pp. 460–470, Sep. 2016, doi: 10.1016/j.conbuildmat.2016.06.018.
- 508 [4] Y. Ke, S. Ortola, A. L. Beaucour, and H. Dumontet, "Micro-stress analysis and identification of lightweight
509 aggregate's failure strength by micromechanical modeling," *Mech. Mater.*, vol. 68, pp. 176–192, Jan. 2014,
510 doi: 10.1016/J.MECHMAT.2013.09.005.

- 511 [5] L. H. Nguyen, A.-L. Beaucour, S. Ortola, and A. Noumowé, “Influence of the volume fraction and the
512 nature of fine lightweight aggregates on the thermal and mechanical properties of structural concrete,”
513 *Constr. Build. Mater.*, vol. 51, pp. 121–132, Jan. 2014, doi: 10.1016/J.CONBUILDMAT.2013.11.019.
- 514 [6] M. a. Riley, “Possible new method for the assessment of fire-damaged concrete,” *Mag. Concr. Res.*, vol.
515 43, no. 155, pp. 87–92, Jun. 1991, doi: 10.1680/mac.1991.43.155.87.
- 516 [7] A. M. Neville, *Properties of concrete*, 5th ed. Harlow, England ; New York: Pearson, 2011.
- 517 [8] A. Noumowe, “Effet de hautes températures (20-600°C) sur le béton : cas particulier du béton a hautes
518 performances,” thesis, Lyon, INSA, 1995.
- 519 [9] L. Alarcon-Ruiz, G. Platret, E. Massieu, and A. Ehrlacher, “The use of thermal analysis in assessing the
520 effect of temperature on a cement paste,” *Cem. Concr. Res.*, vol. 35, no. 3, pp. 609–613, Mar. 2005, doi:
521 10.1016/j.cemconres.2004.06.015.
- 522 [10] G. A. Khoury, “Compressive strength of concrete at high temperatures: a reassessment,” *Mag. Concr. Res.*,
523 vol. 44, no. 161, pp. 291–309, Dec. 1992, doi: 10.1680/mac.1992.44.161.291.
- 524 [11] C. Alonso and L. Fernandez, “Dehydration and rehydration processes of cement paste exposed to high
525 temperature environments,” *J. Mater. Sci.*, vol. 39, no. 9, pp. 3015–3024, May 2004, doi:
526 10.1023/B:JMSC.0000025827.65956.18.
- 527 [12] N. Giraudo, S. Bergdolt, F. Laye, P. Krolla, J. Lahann, and P. Thissen, “Dehydration and dehydroxylation
528 of C-S-H phases synthesized on silicon wafers,” *Appl. Surf. Sci.*, vol. 433, pp. 589–595, Mar. 2018, doi:
529 10.1016/j.apsusc.2017.10.039.
- 530 [13] M. Castellote, C. Alonso, C. Andrade, X. Turrillas, and J. Campo, “Composition and microstructural
531 changes of cement pastes upon heating, as studied by neutron diffraction,” *Cem. Concr. Res.*, vol. 34, no. 9,
532 pp. 1633–1644, Sep. 2004, doi: 10.1016/S0008-8846(03)00229-1.
- 533 [14] Z. Xing, A.-L. Beaucour, R. Hebert, A. Noumowe, and B. Ledesert, “Aggregate’s influence on
534 thermophysical concrete properties at elevated temperature,” *Constr. Build. Mater.*, vol. 95, pp. 18–28, Oct.
535 2015, doi: 10.1016/J.CONBUILDMAT.2015.07.060.
- 536 [15] R. Niry Razafinjato, A.-L. Beaucour, R. L. Hebert, B. Ledesert, R. Bodet, and A. Noumowe, “High
537 temperature behaviour of a wide petrographic range of siliceous and calcareous aggregates for concretes,”
538 *Constr. Build. Mater.*, vol. 123, pp. 261–273, Oct. 2016, doi: 10.1016/j.conbuildmat.2016.06.097.
- 539 [16] K. Lo-shu, S. Man-qing, S. Xing-sheng, and L. Yun-xiu, “Research on several physico-mechanical
540 properties of lightweight aggregate concrete,” *Int. J. Cem. Compos. Lightweight Concr.*, vol. 2, no. 4, pp.
541 185–191, Dec. 1980, doi: 10.1016/0262-5075(80)90036-6.
- 542 [17] S. Mindess, J. F. Young, and D. Darwin, *Concrete*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2003.
- 543 [18] H. Uysal, R. Demirboğa, R. Şahin, and R. Gül, “The effects of different cement dosages, slumps, and
544 pumice aggregate ratios on the thermal conductivity and density of concrete,” *Cem. Concr. Res.*, vol. 34, no.
545 5, pp. 845–848, May 2004, doi: 10.1016/j.cemconres.2003.09.018.
- 546 [19] S. Real, J. A. Bogas, M. da G. Gomes, and B. Ferrer, “Thermal conductivity of structural lightweight
547 aggregate concrete,” *Mag. Concr. Res.*, vol. 68, no. 15, pp. 798–808, Aug. 2016, doi:
548 10.1680/jmacr.15.00424.
- 549 [20] F. al Nahhas, “Comportement thermo-mécanique des murs en maçonnerie de blocs creux en béton sous
550 l’action d’un feu conventionnel,” thesis, Université de Marne-la-Vallée, 2004.
- 551 [21] T. Uygunoğlu and İ. B. Topçu, “Thermal expansion of self-consolidating normal and lightweight aggregate
552 concrete at elevated temperature,” *Constr. Build. Mater.*, vol. 23, no. 9, pp. 3063–3069, Sep. 2009, doi:
553 10.1016/j.conbuildmat.2009.04.004.
- 554 [22] D. N. Winslow, M. D. Cohen, D. P. Bentz, K. A. Snyder, and E. J. Garboczi, “Percolation and pore
555 structure in mortars and concrete,” *Cem. Concr. Res.*, vol. 24, no. 1, pp. 25–37, Jan. 1994, doi:
556 10.1016/0008-8846(94)90079-5.
- 557 [23] M.-H. Zhang and O. E. Gjörv, “Microstructure of the interfacial zone between lightweight aggregate and
558 cement paste,” *Cem. Concr. Res.*, vol. 20, no. 4, pp. 610–618, Jul. 1990, doi: 10.1016/0008-8846(90)90103-
559 5.
- 560 [24] T. Y. Lo and H. Z. Cui, “Effect of porous lightweight aggregate on strength of concrete,” *Mater. Lett.*, vol.
561 58, no. 6, pp. 916–919, Feb. 2004, doi: 10.1016/j.matlet.2003.07.036.
- 562 [25] D. Cusson and T. Hoogveen, “Internal curing of high-performance concrete with pre-soaked fine
563 lightweight aggregate for prevention of autogenous shrinkage cracking,” *Cem. Concr. Res.*, vol. 38, no. 6,
564 pp. 757–765, 2008, doi: 10.1016/j.cemconres.2008.02.001.
- 565 [26] D. P. Bentz, “Influence of internal curing using lightweight aggregates on interfacial transition zone
566 percolation and chloride ingress in mortars,” *Cem. Concr. Compos.*, vol. 31, no. 5, pp. 285–289, May 2009,
567 doi: 10.1016/j.cemconcomp.2009.03.001.

- 568 [27] F. K. Kong and R. H. Evans, "Properties of structural concrete," in *Reinforced and Prestressed Concrete*,
569 Boston, MA: Springer US, 1987, pp. 18–67.
- 570 [28] L. Bodnárová, R. Hela, M. Hubertová, and I. Nováková, "Behaviour of Lightweight Expanded Clay
571 Aggregate Concrete Exposed to High Temperatures," vol. 8, no. 12, pp. 1151–1154, 2014.
- 572 [29] E. Sancak, Y. Dursun Sari, and O. Simsek, "Effects of elevated temperature on compressive strength and
573 weight loss of the light-weight concrete with silica fume and superplasticizer," *Cem. Concr. Compos.*, vol.
574 30, no. 8, pp. 715–721, Sep. 2008, doi: 10.1016/j.cemconcomp.2008.01.004.
- 575 [30] Ö. Andiç-Çakır and S. Hızal, "Influence of elevated temperatures on the mechanical properties and
576 microstructure of self consolidating lightweight aggregate concrete," *Constr. Build. Mater.*, vol. 34, pp.
577 575–583, Sep. 2012, doi: 10.1016/j.conbuildmat.2012.02.088.
- 578 [31] M. B. Karakoç, "Effect of cooling regimes on compressive strength of concrete with lightweight aggregate
579 exposed to high temperature," *Constr. Build. Mater.*, vol. 41, pp. 21–25, 2013, doi:
580 10.1016/j.conbuildmat.2012.11.104.
- 581 [32] R. Felicetti, P. G. Gambarova, and P. Bamonte, "Thermal and mechanical properties of light-weight
582 concrete exposed to high temperature," *Fire Mater.*, vol. 37, no. 3, pp. 200–216, Apr. 2013, doi:
583 10.1002/fam.2125.
- 584 [33] M. Yoon, G. Kim, G. C. Choe, Y. Lee, and T. Lee, "Effect of coarse aggregate type and loading level on the
585 high temperature properties of concrete," *Constr. Build. Mater.*, vol. 78, pp. 26–33, Mar. 2015, doi:
586 10.1016/j.conbuildmat.2014.12.096.
- 587 [34] L. H. Nguyen, A.-L. Beaucour, S. Ortola, and A. Noumowé, "Experimental study on the thermal properties
588 of lightweight aggregate concretes at different moisture contents and ambient temperatures," *Constr. Build.*
589 *Mater.*, vol. 151, pp. 720–731, Oct. 2017, doi: 10.1016/j.conbuildmat.2017.06.087.
- 590 [35] Y. Ke, A. L. Beaucour, S. Ortola, H. Dumontet, and R. Cabrillac, "Influence of volume fraction and
591 characteristics of lightweight aggregates on the mechanical properties of concrete," *Constr. Build. Mater.*,
592 vol. 23, no. 8, pp. 2821–2828, Aug. 2009, doi: 10.1016/j.conbuildmat.2009.02.038.
- 593 [36] "Recommendation of RILEM TC 200-HTC: mechanical concrete properties at high temperatures—
594 modelling and applications | SpringerLink." <https://link.springer.com/article/10.1617/s11527-007-9286-1>
595 (accessed Nov. 12, 2019).
- 596 [37] J. J. Kollek, "The determination of the permeability of concrete to oxygen by the Cembureau method—a
597 recommendation," *Mater. Struct.*, vol. 22, no. 3, pp. 225–230, May 1989, doi: 10.1007/BF02472192.
- 598 [38] L. J. Klinkenberg, "The Permeability Of Porous Media To Liquids And Gases," *Drilling and Production*
599 *Practice*. American Petroleum Institute, New York, New York, 1941.
- 600 [39] M. A. Carpenter, E. K. H. Salje, A. Graeme-Barber, M. T. Dove, and K. S. Knight, "Calibration of excess
601 thermodynamic properties and elastic constant variations associated with the $\alpha \leftrightarrow \beta$ phase transition in
602 quartz," *Am. Mineral.*, vol. 83, no. 1, pp. 2–22, Jan. 1998, doi: 10.2138/AM-1998-0101.
- 603 [40] N. R. Rijaniaina, "Comportement des bétons à haute température : Influence de la nature du granulat,"
604 Université Cergy-Pontoise, 2015.
- 605 [41] A. N. Noumowe, P. Clastres, G. Debicki, and J.-L. Costaz, "Transient heating effect on high strength
606 concrete," *Nucl. Eng. Des.*, vol. 166, no. 1, pp. 99–108, 1996, doi: 10.1016/0029-5493(96)01235-6.
- 607 [42] U. Schneider, U. Diederichs, and C. Ehm, "Effect of temperature on steel and concrete for PCRV's," *Nucl.*
608 *Eng. Des.*, vol. 67, no. 2, pp. 245–258, 1982.
- 609 [43] S. Real and J. A. Bogas, "Oxygen permeability of structural lightweight aggregate concrete," *Constr. Build.*
610 *Mater.*, vol. 137, pp. 21–34, Apr. 2017, doi: 10.1016/j.conbuildmat.2017.01.075.
- 611 [44] H. Carré, C. Perlot, A. Daoud, M. J. Miah, and B. Aidi, "Durability of Ordinary Concrete after Heating at
612 High Temperature," *Key Eng. Mater.*, vol. 711, pp. 428–435, Sep. 2016, doi:
613 10.4028/www.scientific.net/KEM.711.428.
- 614 [45] E. Hwang, G. Kim, G. Choe, M. Yoon, N. Gucunski, and J. Nam, "Evaluation of concrete degradation
615 depending on heating conditions by ultrasonic pulse velocity," *Constr. Build. Mater.*, vol. 171, pp. 511–520,
616 May 2018, doi: 10.1016/j.conbuildmat.2018.03.178.
- 617 [46] W. P. S. Dias, Gabriel. A. Khoury, and Patrick. J. E. Sullivan, "Shrinkage of Hardened Cement Paste at
618 Temperatures up to 670 C (1238 F)," *ACI Mater. J.*, vol. 87, no. 87, pp. 204–209, Mar. 1990, doi:
619 10.14359/1981.
- 620 [47] A. N. Noumowe, "Temperature distribution and mechanical properties of high-strength silica fume concrete
621 at temperatures up to 200 C," *Mater. J.*, vol. 100, no. 4, pp. 326–330, 2003.
- 622 [48] Y. Ke, S. Ortola, A. L. Beaucour, and H. Dumontet, "Identification of microstructural characteristics in
623 lightweight aggregate concretes by micromechanical modelling including the interfacial transition zone
624 (ITZ)," *Cem. Concr. Res.*, vol. 40, no. 11, pp. 1590–1600, Nov. 2010, doi:
625 10.1016/j.cemconres.2010.07.001.

626 [49] N. Torić, I. Boko, S. Juradin, and G. Baloević, “Mechanical properties of lightweight concrete after fire
627 exposure,” *Struct. Concr.*, vol. 17, no. 6, pp. 1071–1081, 2016, doi: 10.1002/suco.201500145.
628