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Industrial-scale valorization of fine recycled aggregates in cement raw meal: Towards sustainable mixtures

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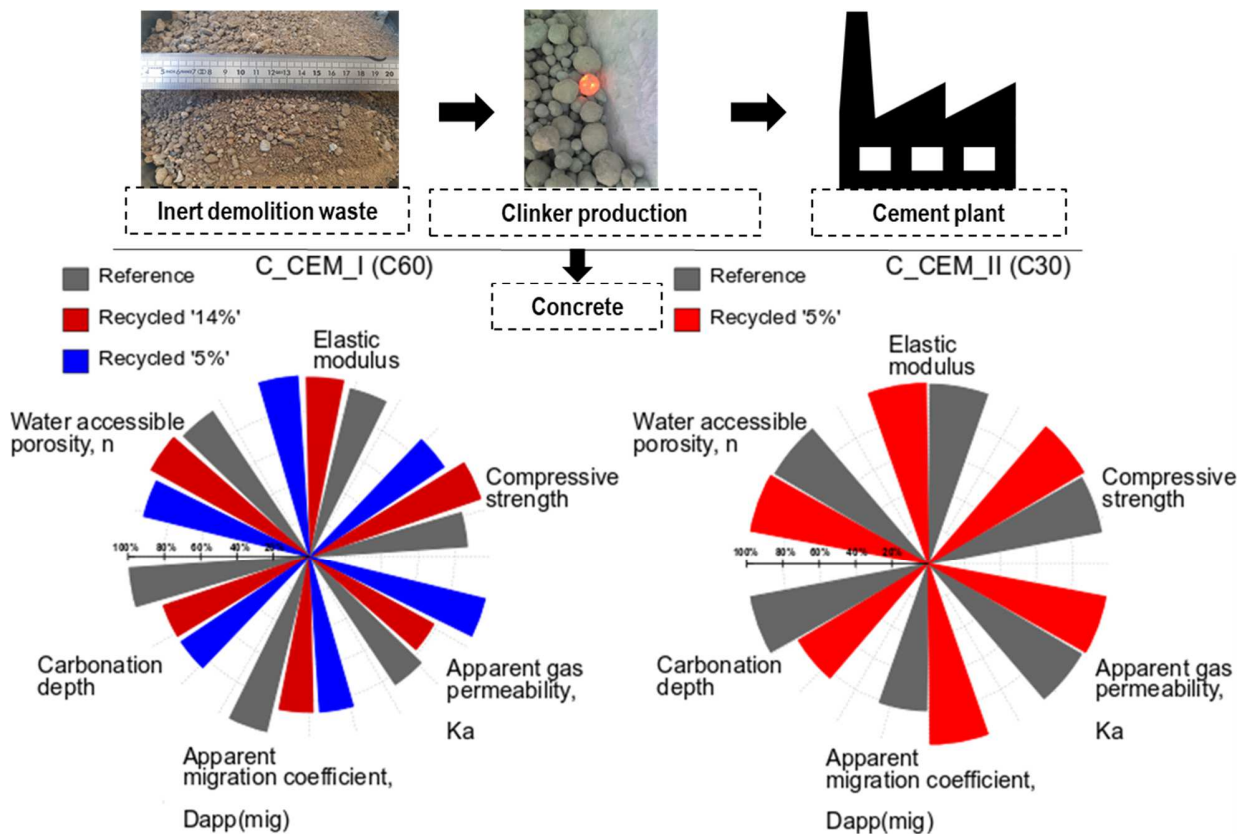
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10 Graphical Abstract



11

12 Abstract

13 The aim of this study is to improve the sustainability of cement and concrete mixes. To
14 do so, the fine recycled aggregates (FRA) from construction and demolition wastes
15 (CDW) were used in cement raw meals (CRM) to produce recycled clinker and cement
16 to be used in the mix design of new concretes. About 7,000 tons of clinker containing
17 1,000 tons of FRA were generated at industrial scale, in a cement plant. Clinker was
18 then incorporated into CEM I and CEM II recycled cements. The findings of this study
19 confirm the feasibility of producing clinkers and cements with FRA, meeting the

1

20 industry's required performance, and at the same time reducing resource depletion in
21 the cement industry. These cements were also incorporated in new ordinary and high
22 performance concretes. The results show slight differences in mechanical and durability
23 properties, when recycled cements are used. From a performance approach viewpoint,
24 the high performance concretes (conventional and recycled) are ranked as highly
25 durable, while the ordinary concretes are ranked as low-medium durable ones,
26 regardless the presence of FRA in cements.

27

28 Keywords: Construction & demolition waste; Fine recycled aggregates; Industrial cement production;
29 Cement raw meal; Durability; Mechanical properties.

30 **1 Introduction**

31

32 Cement is one of the main materials used in the building and civil works industry. Some
33 4 billion tons of this material were produced in the world during 2018 [1]. This figure
34 should increase over the coming decades, which in turn will induce a major depletion of
35 natural resources, along with a greater consumption of land and energy. Moreover, the
36 greenhouse gas emissions of cement are significant, represent the lion's share of
37 concrete impacts, and actively contribute to the rise in the Earth's temperature, as
38 raised in the last IPCC report [2]. Thus, cement producers are prone to act locally to
39 consume wastes in a circular economy to both decrease waste volumes and preserve
40 natural resources.

41 In parallel, the building and civil works industry generate important quantities of
42 construction and demolition wastes (CDW), from which concrete is one of the most
43 prevalent [3,4]. In Europe, for example, this industry is responsible for approx. 800
44 million tons of CDW per year [5]. Such materials are reused and recovered at a high
45 rate within a low circular economy approach, especially as backfilling, which is now
46 considered as a recovery by the new WFD [6]. Recovery rates vary from one EU-27
47 country to another (67% to 100%) [7]. Moreover, over the last two decades, numerous
48 studies have shown that these materials could also be used as recycled aggregates in
49 concrete mix designs [3,8–12], as mineral additions with hydraulic binders [13–17] or as
50 alternative materials in cement raw meal (CRM) [18–24]. However, the specific
51 performances of recycled aggregates from CDW (e.g. porosity and high water
52 absorption) can severely undermine the fresh and hardened properties of the produced
53 composite materials (e.g. concretes, mortars and/or hydraulic binders) [25]. This
54 phenomenon is much more restrictive in the case of fine recycled aggregates (FRA); the
55 water absorption of this fraction is generally higher than that of the material as a whole.
56 This finding is due to the high content of hardened cement paste in the FRA fraction
57 [26–28], along with its tendency to contain more impurities as soluble sulfates or clays
58 [29]. That is to say, its re-use and recovery should be more investigated.

59 In order to take advantage of the presence of hydrated cement paste, studies [30,31]
60 have investigated the thermal activation of the recycled aggregate particles. For the
61 binders containing this kind of recycled addition, the environmental impact [32] and the
62 developed specific properties [33-35] show the advantages and draw backs of the
63 process, which is still improving [36].

64 Although this way of activation is promising for producing composite cement, the reuse
65 of RA directly in CRM offers complementary opportunities for Portland cement
66 manufacture while reducing landfills and preserving the natural resources consumed by
67 the cement industry. The valorization potential of this fraction is still undermined in the
68 cement and concrete industries. At the laboratory scale, the feasibility of using FRA in
69 CRM has already been confirmed [18–23]. These recycled materials are incorporated
70 into CRM by substituting a portion of natural materials with a chemical composition
71 meeting the conventional clinker criteria. Depending on the CDW chemical composition,
72 as well as the clinker characteristics and clays and limestone used, the incorporation
73 rate of FRA can typically reach around 10% to 30% [19]. Despite small differences,
74 clinker produced with FRA has revealed standard properties matching those of
75 conventional products. However, the introduction of high FRA proportions might exert a
76 negative impact on burnability if used at industrial scale. In fact, the high quartz content
77 in FRA can increase free lime content and affect the mineralogical composition of
78 clinker. More specifically, a high quartz content can decrease burnability by forming
79 belite clusters, which strongly react with free lime in order to form alite [37–39].

80 Fridrichova et al. [24] used FRA to produce clinker in a pilot plant kiln (length: 3.9 m,
81 diameter: 15 cm, capacity: 2 kg/clinker/hour). Three types of CRM were prepared in
82 order to produce: (i) a reference “alite” clinker containing only conventional raw
83 materials, (ii) an “alite” clinker made with 25% FRA, and (iii) a “belite” clinker with 30%
84 FRA. The final products all showed a similar mineralogical composition and comparable
85 mechanical properties obtained on the cement pastes. Another industrial scale [40],
86 within the French project “Recybéton”, aimed to incorporate near 15% of pure recycled
87 aggregates in CRM. Compared to classic production, the CRM contained more of
88 quartz, which negatively affected the burnability, the mineralogical composition and the
89 mortar performances.

90 Although the scientific and technical literature already deal with the properties
91 assessment of concrete mixes with recycled concrete aggregates or other recycled
92 wastes [3,12,25,40–43], no studies were found on durability and performance approach
93 of concretes made with recycled cements. Thus, this paper seeks to overcome this
94 research gap by the valorization of wastes from CDW and their incorporation at
95 industrial scale to produce different clinkers and cements without significant variations in
96 the cement plant processes.

97 The novelty of this work lies in the following:

- 98 - Understanding the impact of both the type (recycled concrete aggregates and
99 mixed aggregates) and quantity (5% and 14%) of FRA on clinker properties at
100 the facility scale without significant changes to the processes. This approach has

101 been complemented by industrial trials as a support to clarifying the introduction
102 and use of FRA in cement raw meal, which has received barely any attention in
103 the literature. Properties of cements and mortars produced from this clinker were
104 investigated.
105 - Assessing mechanical and durability properties of concretes made with reference
106 and “recycled” cements. Then, a performance approach to rank the produced
107 concretes was performed.

108 In this paper, the two industrial batches of cements incorporating FRA in cement raw
109 meal were produced within the European project SeRaMCo [44–46]. The
110 physicochemical properties of clinker and cements output were evaluated by means of:
111 X-ray diffraction, selective dissolution, scanning electron microscopy, calorimetry,
112 mortar flow, and compressive strength. Next, slump, the compressive strength, elastic
113 modulus, water accessible porosity, carbonation, rapid chloride diffusion and gas
114 permeability of the concretes made with these cements were assessed as per the
115 protocol. Lastly, concrete classes were assigned according to the performance
116 approach method [47]. The objective was to assess how similar the produced recycled
117 clinkers, cements and concretes are to the conventional ones.

118 **2 Materials and methods**

119

120 **2.1 Materials**

121 Two industrial scale trials (T1 and T2) aimed at using FRA in CRM were conducted
122 afterwards; these tests resulted in two clinker specimens incorporating FRA in their
123 CRM, denoted "T1c" and "T2c". Two conventional clinkers (T1f and T2f), produced in
124 the same cement plant during the same periods, have also been used for purposes of
125 comparison (Table 1). These reference products are representative of the usual
126 production for this cement plant. In all, 7,000 tons of clinker were produced for the two
127 trials in incorporating 1,000 tons of FRA.

128 During the first test, about 14% of recycled concrete aggregates containing mainly
129 concrete were incorporated into the CRM, which accounted for the maximum
130 incorporation rate, considering the chemistry of the FRA used and the expected cement
131 composition. The recycled aggregates received were coming from two different
132 recycling sites. These crush concretes were screened at 30 mm (gravel) or 10 mm
133 (sand). In the second test, the incorporation rate of mixed aggregates (containing
134 recycled concrete aggregates, ceramics, soils, etc.) was limited to 5% since this value
135 would not affect the conventional process parameters and ensure a continuous waste
136 flow for the inputs. This mixed aggregate was furnished (for the second trial) by one
137 recycling plant, which has provided an aggregate screened at 40 mm. Beyond marl
138 and/or limestone, the raw meal contained a number of corrective additions (foundry
139 sand, excavated soils (ES), iron ore and bauxite).

140 For these different trials, the recycled aggregates and the conventional raw materials
 141 were pre-blended in a stockpile, milled (refusal at 200 μ m below 1.5%) and
 142 homogenized in silos. This process allows blending different recycled materials with
 143 various chemical composition and particle size distributions. These CRM are then
 144 appropriately properly fired at around 1450°C in a rotary kiln where the minerals (quartz,
 145 feldspar, etc.) are completely reacting and combined with lime forming thereby a new
 146 clinker.

147 It should be noted that in order to keep the free lime content low, kiln energy
 148 consumption had to be increased during the first trial; this step is highly likely linked to
 149 the high FRA proportion (high silica content) in the cement raw meal. This over-burning
 150 of the clinker could yield cement with large silicate grains, which happen to be less
 151 reactive [48].

152 These clinkers were blended with gypsum and/or limestone in order to produce Portland
 153 cements; CEM I and CEM II; according to European standard EN 197-1 [49]. Their
 154 constitution and chemical-mineralogical composition are given in Table 1. Further
 155 details concerning these properties and the industrial trials were previously published in
 156 [50].

157 Table 1. Constitution and chemical-mineralogical composition of the elaborated cements

Clinkers references	First test			Second test	
	T1f	T1c		T2f	T2c
Recycled aggregates in the raw meal (%)	-	14 %,wt of recycled concrete aggregates screened at 30 mm		5%,wt of mixed aggregates screened at 10 mm	-
Corrective additions in the raw meal	- foundry sand - excavated soils - Iron ore - Bauxite	- Iron ore - Bauxite		- foundry sand - excavated soils - Iron ore - Bauxite	- foundry sand - excavated soils - Iron ore - Bauxite
Grinding means for the clinker	Pilot scale grinder			Industrial grinder	Pilot scale grinder
Cements references	CEM II-T1f	CEM II-T1c	CEM I-T1c	CEM I-T2f	CEM I-T2c
Cement particle size distribution (d ₅ -d ₁₀ -d ₉₅)	0.71-1.22-32.85	0.74-1.34-36.00	0.78-1.38-32.65	0.61-0.98-36.00	0.70-1.27-31.78
Calcium Sulfate (Wt. %)	7		5		
Limestone (Wt. %)	13		-		
Kiln energy	Standard	Higher		Standard	Standard

consumption						
Chemical composition (Wt. %)	LOI*	8.45	7.21	1.91	1.52	1.67
	SiO ₂	17.39	17.79	20.63	20.66	20.77
	Al ₂ O ₃	4.19	4.33	5.22	4.85	4.95
	Fe ₂ O ₃	2.52	2.75	3.20	3.16	3.06
	CaO	60.54	60.76	62.20	62.65	62.80
	MgO	1.30	1.14	1.29	1.47	1.53
	MnO	0.10	0.09	0.10	0.12	0.13
	SO ₃	2.96	2.71	3.40	3.12	3.15
	K ₂ O	0.83	0.66	0.61	0.97	0.89
	Na ₂ O	0.21	0.23	0.24	0.22	0.22
	TiO ₂	0.15	0.14	0.17	0.16	0.18
	P ₂ O ₅	0.22	0.25	0.29	0.25	0.21
	SrO	0.08	0.07	0.09	0.09	0.10
Mineralogical composition (Wt. %)	Alite	52	53	66	66	71
	Belite	10	10	9	10	5
	Aluminate	4	5	6	5	6
	Ferrite	8	9	10	12	10
	Arcanite	1.0	1.1	0.4	1.4	1.4
	Sulfate calcium	8	7	8	5	7
	Calcite	16	14	-	-	-

*: Loss of ignition, calculated after a calcination at 1000 °C

158
159

160 The generic properties of these cements were also measured. Densities determined
161 with a helium pycnometer were: 3.10 ± 0.03 g/cm³ and 3.16 ± 0.01 g/cm³ for CEM II and
162 CEM I, respectively. The cements have a Blaine fineness varying from 3,900 to 4,500
163 cm²/g with a mean diameter (d_{50}) of 9.8 ± 0.7 μm. Despite such comparable properties,
164 the water demands of these products slightly vary (1.2% between samples). More
165 specifically, the water-to-cement ratio (w/c) in weight, required to obtain normal
166 consistency of the cement pastes, was slightly higher (w/c = 0.35 ± 0.01) for CEM II-T1f,
167 CEM II-T1c and CEM I-T2c compared to CEM I-T1c (w/c = 0.32) and CEM I-T2f (w/c =
168 0.30). It must be pointed out that all clinker specimens were produced in a cement plant.
169 However all the clinker was crushed in a pilot plant, except for cement CEM I-T2f that
170 was produced in a conventional plant. Even though the particle size distribution and
171 Blaine fineness are similar, the change in grinding condition (grinding agents, grinder
172 configuration, etc.) could modify the product's characteristics and their compactness, in
173 addition to explaining the higher w/c ratio for cement produced at the pilot scale.

174

175 2.2 Methods

176

177 **2.2.1 Clinker characterization**

178 The four clinker specimens were ground until reaching zero residue on a 100- μm sieve.
179 Their chemical composition was determined by means of X-ray fluorescence analysis
180 using the fusion bead method.

181 The mineralogical composition was determined by a Rietveld refinement of the X-ray
182 diffraction diagrams and moreover confirmed by selective dissolution with KOH-Sucrose
183 (silicate phase dissolution) and salicylic acid-methanol methods (aluminate phase
184 dissolution). Other methods exist in order to further concentrate and differentiate
185 between the various silicate phases (alite and belite), as reported in the literature [51].
186 These methods were not applied herein. For the mineralogical analyses, the clinkers
187 were ground until a zero refusal at 40 μm . The XRD diagrams were obtained on a
188 Bruker[®] D8 Advance with $K\alpha_{(\text{Cu})} = 1.54506 \text{ \AA}$. This analysis was conducted over a range
189 of angles 2θ ranging from 10° to 80° with a step of 0.020° and a step count of 10 s, as
190 recommended by Courtial *et al.* [52]. The mineralogical composition of all products was
191 estimated by a Rietveld refinement of XRD diagrams. The crystalline structures used for
192 this analysis are listed in Table 2.

193 Table 2. PDF and ICSD IDs of the mineralogical phases structures used for Rietveld refinement

Mineralogical phases	PDF-ID	ICSD-ID	Ref.
Alite-M3	85-1378	94742	[53]
Belite – β	33-302	81096	[54]
Tricalcium aluminate (orthorhombic)	83-1359	100220	[55]
Ferrite	30-226	9197	[56]
Free lime	37-1497	52783	[57]
Periclase	41-1022	9863	[58]
Arcanite	5-613	79777	[59]

194

195 The clinker microstructure was also investigated by means of electron microscopy
196 analyses. The 1-2 mm fraction of clinker nodules were encapsulated in epoxy resin, cut
197 and polished with a silica-carbide paper grade 320 to 4000 using absolute ethanol for
198 lubrication. For the electron microscopy analyses, the polished sections were turned
199 conductive by applying a fine carbon coating deposit. The samples were then observed
200 under the electron beam of an FEI[®] Quanta 650 FEG scanning electron microscope.
201 For this analysis, an acceleration voltage of 15 kV was maintained during all
202 observations.

203 **2.2.2 Cement and mortar characterization**

204 Cement properties were determined on standard mortars (EN 196-1) [60]. The
205 workability of these composites was evaluated by measuring their consistency in the
206 fresh state with a flow table test, according to the NF EN 1015-3 standard [61].
207 Hydraulic reactivity was determined by measuring the heat of hydration until 7 days with
208 a semi-adiabatic calorimeter, according to the EN 196-9 standard [62]. Mechanical

209 strength was assessed by measuring the compressive and flexural strengths on
 210 prismatic samples (4 x 4 x 16 cm³), according to the 196-1 standard [60]. The mortar
 211 samples were cured in water at around 20°C and tested at between 1 day and 1 year.

212 2.2.3 Concrete characterization

213 The aggregates used in this study were calcareous sand (0/4 mm) and calcareous
 214 gravel (4/20 mm). Only natural aggregates were introduced for the concrete specimens.
 215 Their properties match the EN 12620-A1 standard requirements [63] and are described
 216 in [64].

217 Ordinary (C30) and high performance (C60) concretes were manufactured. The first one
 218 is based on a CEM II 42.5 cement, while the latter on a CEM I 52.5 cement. Both
 219 cements have been described in the previous section (2.1). All concrete specimens
 220 were produced, molded, and conserved under identical conditions. The preparation of
 221 these cylindrical (11 x 22 cm) specimens was described by Adessina *et al.* [64] and the
 222 mixing proportions are given in Table 3.

223

224 Table 3. Mix proportion of the concrete (kg/m³).

Concrete strength class	C60			C30	
Mixture	C_CEM I-T2f	C_CEM I-T1c	C_CEM I-T2c	C_CEM II-T1f	C_CEM II-T1c
Cement	380	380	380	280	280
Sand	867.8	867.8	867.8	904	904
Gravel	993.2	993.2	993.2	997	997
Effective water/cement ratio	0.42	0.42	0.42	0.6	0.6
Superplasticizer. Master Glenium SKY 671	2.34	2.34	2.34	0.47	0.7

225

226 Superplasticizer content was adjusted in order to reach an S4 class concrete with a
 227 slump ranging from 160 to 210 mm (\pm 10 mm) according to European standard EN 206
 228 [65]. Afterwards, the quantity of water added to each mix proportion took into account
 229 both the absorption capacity of aggregates and the water brought by the
 230 superplasticizer.

231 When demolded after a 24-h period, specimens were water-cured at 20°C in order to
 232 set up the mechanical and durability tests. Then, mechanical and durability tests were
 233 carried out over different time frames.

234 - Fresh properties: Workability and fresh density

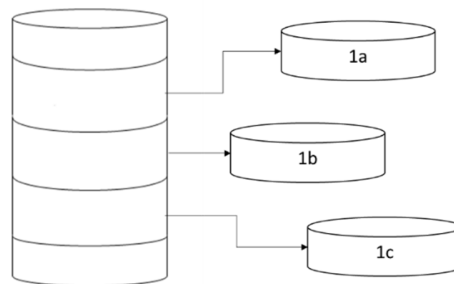
235 These properties were measured according to the NF EN 12350-2 standard [66].

236 - Mechanical properties

237 Based on standards EN 12390-3 [67] and EN 12390-13 [68], the compressive strength
238 and elastic modulus were respectively measured. The same batch load at the same age
239 (7, 28 and 90 days) was considered for each concrete mixture. The elastic modulus was
240 measured on the same specimen used for compressive strength testing by means of
241 three distributed LVDT sensors.

242 - Durability properties

243 These tests encompass: water accessible porosity, carbonation, rapid chloride diffusion,
244 and gas permeability. They were conducted on specimens after a 90-day curing period
245 in water at 20°C. The specimens were prepared as presented in Figure 1. As indicated
246 in this figure, each specimen was sawed into three 50-mm samples (1a, 1b and 1c) and
247 two other endpoints. The first sample (1a) was used for carbonation, the second (1b) for
248 rapid chloride diffusion, and the third for both water porosity and gas permeability.



249

250 Figure 1. Concrete specimens preparation for durability tests

251

252 The water accessible porosity test was performed according to standard NF P18-459
253 [69] in incorporating a few changes. For this test, a 72-h specimen saturation under the
254 same pressure was considered, instead of the 44-h duration required by the standard.
255 The objective of this change is to estimate the real porosity of the studied concretes.

256 Chloride diffusion by migration testing was performed according to standard NF P18-
257 462 [70] and applying a 30-V voltage (corresponding to a 26-V voltage at the sample
258 edge). The sample saturation process was performed with a basic solution (NaOH).

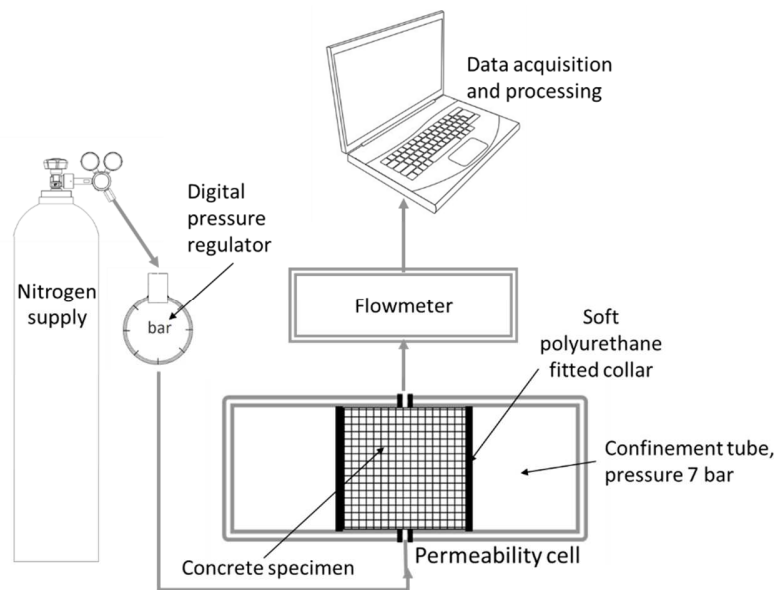
259 The carbonation test was performed according to standard XP P 18-458 [71]. The
260 carbonation intensities were 3% and 50% for C30 and C60 concretes, respectively.
261 Tests were run following an exposure duration of 28 and 90 days, after which the
262 carbonation depth was measured.

263 Lastly, a gas permeability test was performed on specimens (after a drying period at
264 105°C) using a CEMBUREAU permeameter supplied with nitrogen [72,83]. An overview
265 of the test is shown in Figure 2. In order to assess the apparent permeability of

266 concrete, an entry pressure of 2 bar was applied on samples. Permeability was
 267 measured while injecting gas flow until reaching steady state. Each test lasted
 268 approximately 30 minutes and 1 hour for C30 and C60 class concretes, respectively.
 269 The apparent permeability coefficient k_a (m^2) was then calculated for the entry pressure
 270 as follows:

271
$$k_a = 2 \cdot \frac{\mu \cdot h \cdot Q \cdot P_{atm}}{S \cdot (P_1^2 - P_{atm}^2)}$$

272 ' μ (Pa.s)': nitrogen viscosity coefficient (1.71 E-05); ' h (m)': sample thickness; ' Q (m^3/s):
 273 measured nitrogen flow; ' P_{atm} (Pa)': atmospheric pressure; ' S (m^2): specimen cross-
 274 sectional area; and ' P_1 (Pa)': applied absolute pressure.



275
 276 Figure 2 Schematic layout of the gas permeability test

277 All results (fresh, mechanical and durability properties) provided in this paper were
 278 obtained by averaging at least three tests for each property.

279 In addition to the obligation of means required to assess concretes through the
 280 prescriptive approach, in strict accordance with standard NF EN 206 [65], another
 281 approach aimed at reaching sustainable concretes with lower environmental impacts, as
 282 well as economic benefits, was considered in this paper. Such an approach promotes
 283 the reuse of alternative materials and seeks to avoid natural resource depletion.

284 The obligation of results was described in the performance approach methodology that
 285 lays out concrete qualification from a durability point of view [47]. Thus, three criteria out
 286 of five have been selected in this study to assess the general durability of concretes,
 287 namely: water accessible porosity ($n\%$), apparent migration coefficient ($D_{app(mig)}$ (10^{-12}
 288 $m^2 \cdot s^{-1}$)), and gas permeability (k_a ($10^{-18} m^2$)). This performance approach is intended to
 289 be agile and modular when assessing concrete from a durability perspective.

290 According to this approach, five durability classes are considered, i.e.: Very low (VLD),
 291 Low (LD), Medium (MD), High (HD), and Very high durability (VHD). The durability
 292 assessment criteria for each indicator are presented in Table 4 below.

293 Table 4 Durability assessment criteria for the performance approach [47]

Durability potential	VLD	LD	MD	HD	VHD
Water porosity - n (%)	>16	14 to 16	12 to 14	9 to 12	6 to 9
Apparent migration coefficient – $D_{app(mig)}$ ($10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$)	>50	10 to 50	5 to 10	1 to 5	<1
Apparent gas permeability – k_a (10^{-18} m^2), for P=2 bar	>1000	300 to 1000	100 to 300	10 to 100	<10

294

295 3 Results and discussion

296

297 3.1 Chemical-mineralogical properties of clinkers

298

299 The chemical and mineralogical composition of the clinkers studied is presented in
 300 Table 5. Since it has been decided to maintain very similar chemical parameters for all
 301 raw meals, no significant differences are observed between the “recycled” (T1c and
 302 T2c) and reference clinkers (T2f and T2f). Magnesium oxide and sulfur oxide are
 303 present as minor elements in all clinker specimens, and their contents vary from 0.8 to
 304 1.5%. These two oxides have a direct impact on the formation of alite polymorphism,
 305 and their quantities would correspond to the alite polymorph M3 as the predominant
 306 variety in all clinkers [74,65].

307 The minor deviations (0.8 to 1.5%) might be due to: the repeatability error in the
 308 chemical analysis, minor changes in the raw meal chemical composition, or the
 309 combustibles employed.

310 This chemical composition has been corroborated by the mineralogical composition,
 311 also shown in Table 2. The quantity of alite, belite, ferrite and tricalcium aluminate are
 312 standard for Portland clinkers, and no significant differences can be observed when
 313 comparing “recycled” clinkers (T1c and T2c) with the reference ones (T1f and T2f).
 314 However, when drawing a comparison between the results of these two tests, clear
 315 differences are noticed. Indeed, a significant variation is found in terms of belite content:
 316 it is 50% less for clinkers resulting from the second test, whereas the alite percentages
 317 are slightly higher. These variations are due to improvements of the industrial process in
 318 this plant that were applied between the two tests. Considering these remarks and the
 319 similarity between “recycled” and reference products, it can be concluded that the
 320 incorporation of recycled aggregates in cement raw meals did not highly affect the
 321 mineralogical composition.

322 Further mineralogical analyses, carried out by selective dissolution on the ground
 323 clinkers, have confirmed these similarities. The clinkers contain roughly 83% silicate
 324 phases (mainly alite and belite) on average and around 17% of aluminate phases
 325 (mainly tricalcium aluminate and ferrite). Let's note that the sum of these compositions
 326 may in some cases exceed 100%, which can be attributed to an incomplete dissolution
 327 of silicate and/or aluminate phases when using these techniques.

328 XRD analyses, conducted on the treated KOH-Sucrose (KOHS) and salicylic acid-
 329 methanol (SAM) clinker residues, exposed the polymorphism of the alite and tricalcium
 330 aluminate formed (Figure 3). Compared to observations by Courtial *et al.* [72] on some
 331 2θ ranges (W1 to W5) and taking into account previous observations (i.e. clinker
 332 chemical composition), it seems that M3 polymorph of the alite is the major phase
 333 formed in all clinkers. No significant differences among the four clinkers were found on
 334 XRD diagrams.

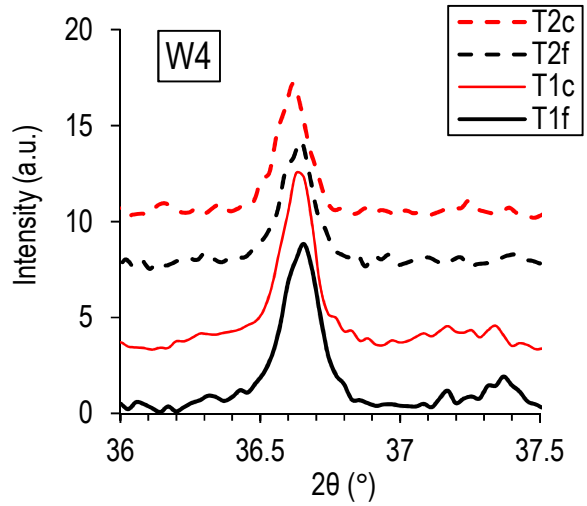
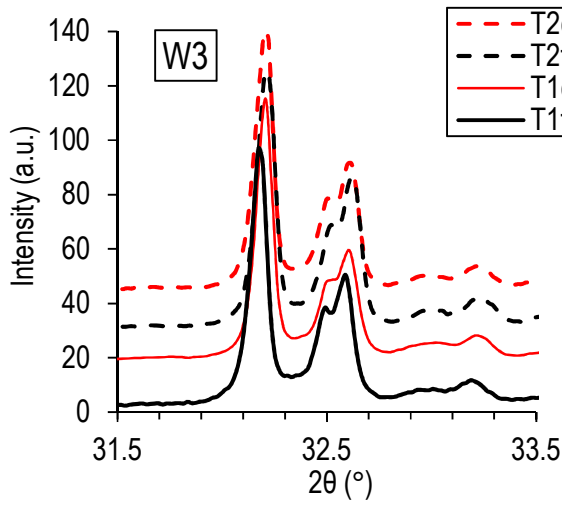
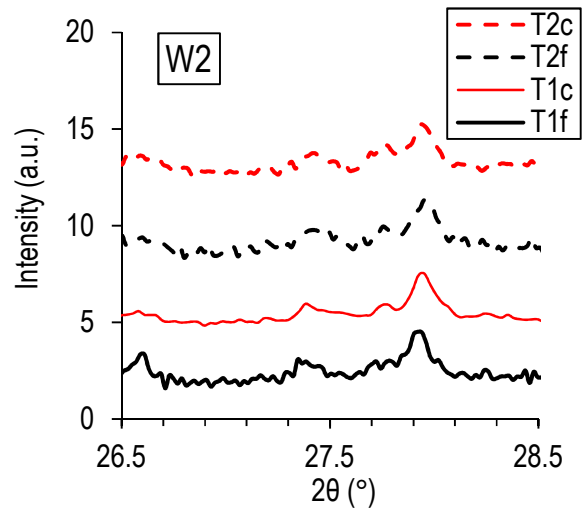
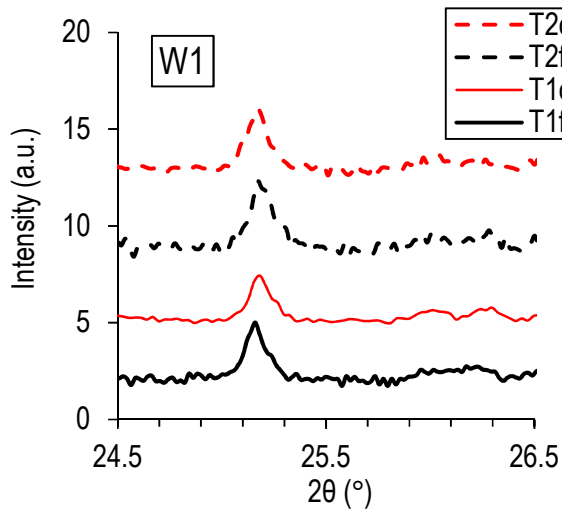
335 Concerning tricalcium aluminate, the orthorhombic polymorph is the most present
 336 variety in these industrial clinkers, according to the W6 range in the same figure, as
 337 described in [69,70].

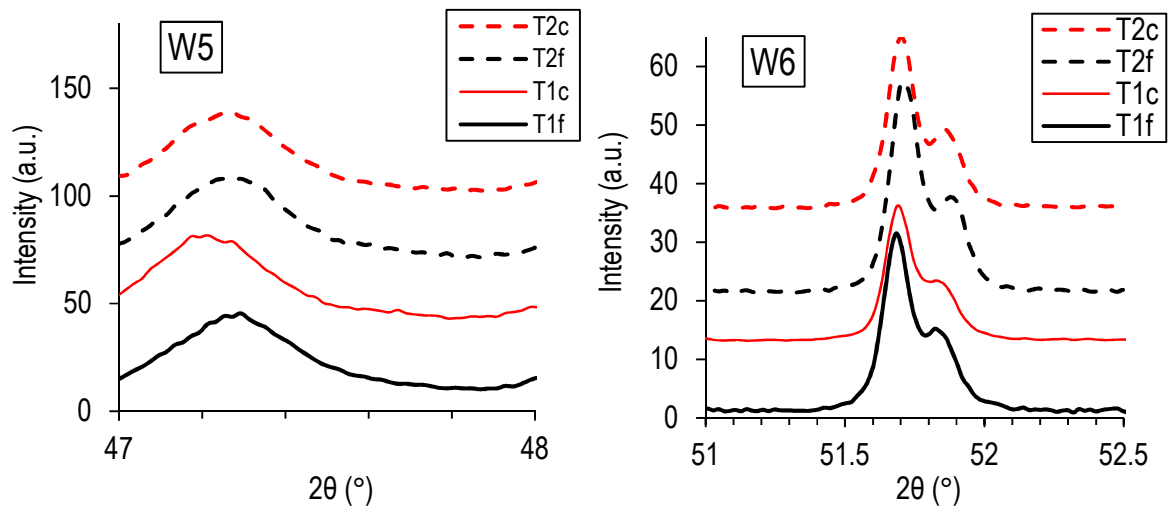
338 The belite phase polymorphism was not determined by the qualitative analysis on XRD
 339 diagrams as a result of the nontrivial observations in this phase. The major peaks of
 340 these polymorphs in fact coincide with those of alite. Some methods do allow
 341 concentrating the belite phase, to the detriment of the alite phase, as reported in [71].
 342 Such methods however were not used in this study. For the Rietveld refinements, it was
 343 decided to select β -belite (please refer to Table 5) as the representative polymorph by
 344 virtue of being the most widespread variety in industrial clinkers [71,78,79].

345 Table 5. Chemical-mineralogical properties of reference (T1f, T2f) and "recycled" clinkers (T1c, T2c)

		T1f	T1c	T2f	T2c
Chemical composition (Wt. %)	LOI	-	1.01	0.31	0.20
	SiO ₂	22.43	22.09	22.28	22.20
	Al ₂ O ₃	4.81	4.92	5.17	5.32
	Fe ₂ O ₃	2.92	3.14	2.99	3.17
	CaO	64.99	63.46	65.18	65.18
	MgO	1.47	1.13	1.55	1.54
	MnO	0.12	0.10	0.13	0.13
	SO ₃	1.17	1.32	0.82	0.86
	K ₂ O	1.09	1.34	0.85	0.99
	Na ₂ O	0.24	0.30	0.25	0.25
	P ₂ O ₅	0.22	0.32	0.21	0.21
	TiO ₂	0.17	0.16	0.17	0.19
	SrO	0.08	0.07	0.08	0.08
	Mineralogical composition (Rietveld refinement, Wt. %)	Alite (M3)	69	66	74
Belite (β)		13	17	7	10
Tricalcium aluminate		6	6	5	4

	Ferrite	11	9	11	11
	Free lime	0.77	1.30	0.61	0.59
	Arcanite	1.09	0.91	1.75	1.16
	Periclase	0.17	0.12	0.31	0.29
	R _{wp}	9.30	10.98	9.61	10.45
Mineralogical composition (Selective dissolutions, Wt. %)	Silicates (%)	84	80	85	85
	Aluminates (%)	16	17	17	17





347 Figure 3. XRD diagrams ranges of the insoluble residu of selective dissolutions (SAM methods “W1 to
 348 W5” to KOHS “W6”) treated industrials clinkers

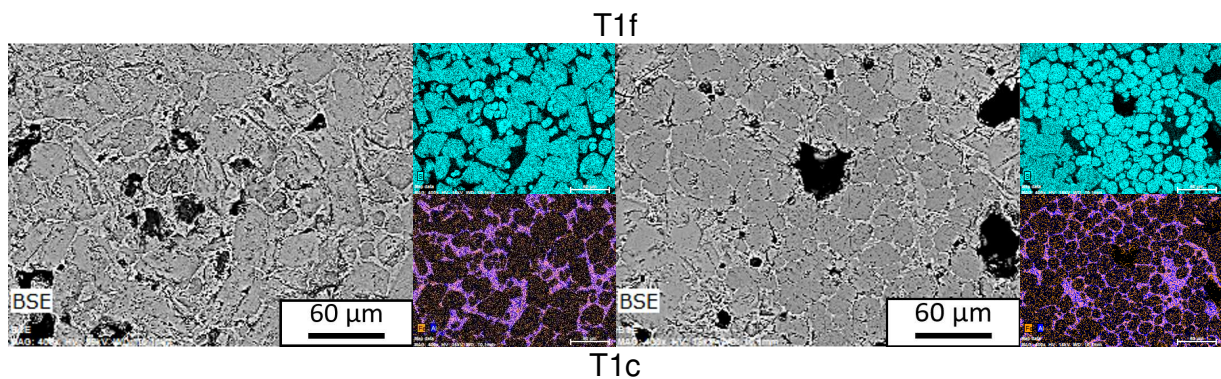
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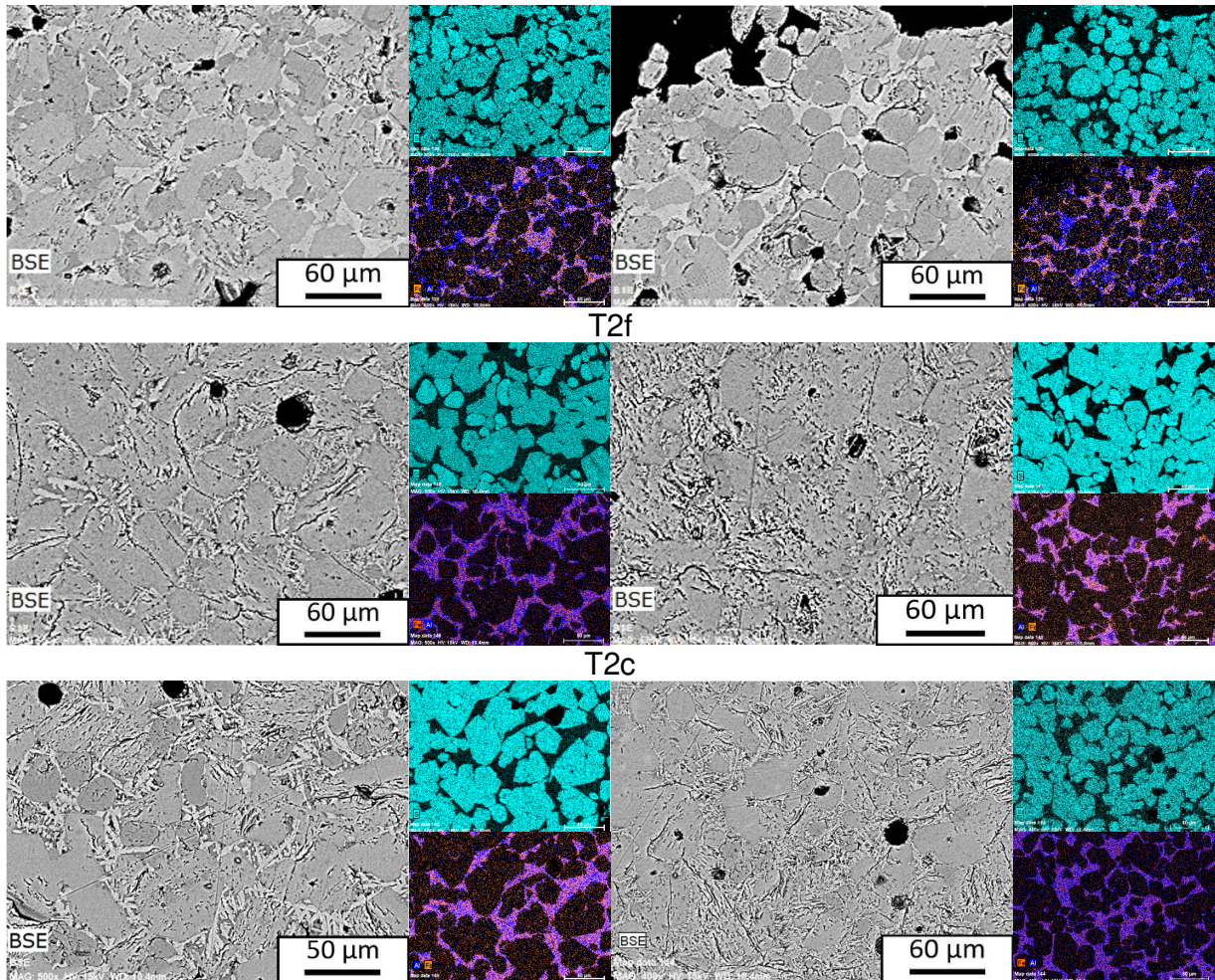
350 3.2 Clinkers microstructure

351

352 Under the electron beam, alite crystals are observed in an angular shape while belite
 353 grains exhibit a rounded shape. Average crystal sizes (CL) are on average approx. 40
 354 μm for alite and 25 μm for belite. Belite clusters are also present for all samples but very
 355 scarce in quantity compared to the total amount observed for this mineral. These values
 356 are typical and no significant differences are noted between “recycled” clinker and the
 357 reference. These results serve to confirm that the over-burning during the first trials (T1-
 358 c) did not significantly change the clinker microstructure.

359 The micrographs obtained in backscattered electron (BSE) mode show (Figure 4) that
 360 tricalcium aluminate and ferrite phases (purple color on the iron and aluminum mapping)
 361 are distributed around the alite and belite crystals (cyan color on the silicon mapping) in
 362 the interstitial phase.



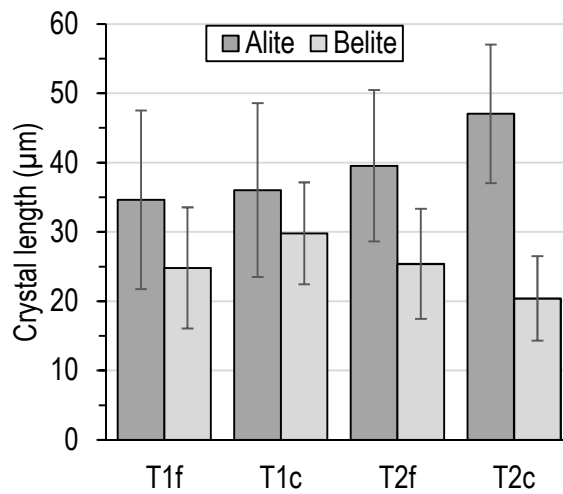


363 Figure 4. Micrographs of "recycled" and reference clinkers obtained with SEM-BSE mode and their EDX
 364 mapping analyzes for silicon (cyan), aluminum (dark blue) and iron (orange)

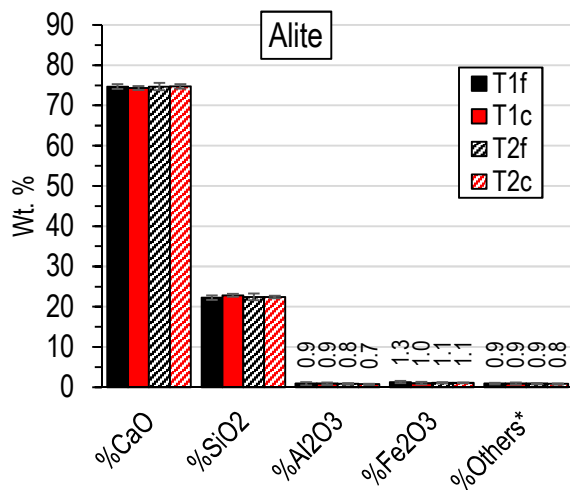
365

366 Complementary analyses (e.g. EDX point analysis) underscore that alite and belite
 367 particles have a qualitative comparable chemical composition in the various clinkers. In
 368 all samples, CaO content equaled on average $74.6 \pm 0.6\%$ and SiO_2 content was $22.5 \pm$
 369 0.5% for alite crystals. For belite crystals, the CaO proportion was logically lower ($66.7 \pm$
 370 0.6%), whereas the SiO_2 content was higher ($28.7 \pm 0.5\%$).

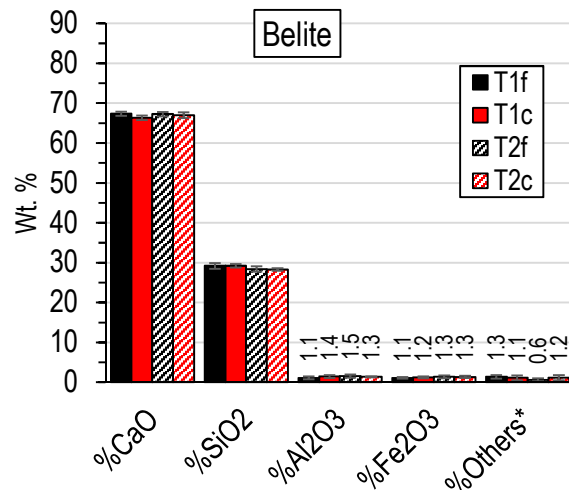
371 Minor elements (% Others in Figure 5) were also present. For alite, magnesium oxide
 372 (MgO) was found to be the main one; its content on average was $0.7 \pm 0.5\%$ with no
 373 sulfur oxide present in this mineral.



a) Alite-Belite crystals size in the clinkers



b) Chemical composition of Alite crystals



c) Chemical composition of Belite crystals

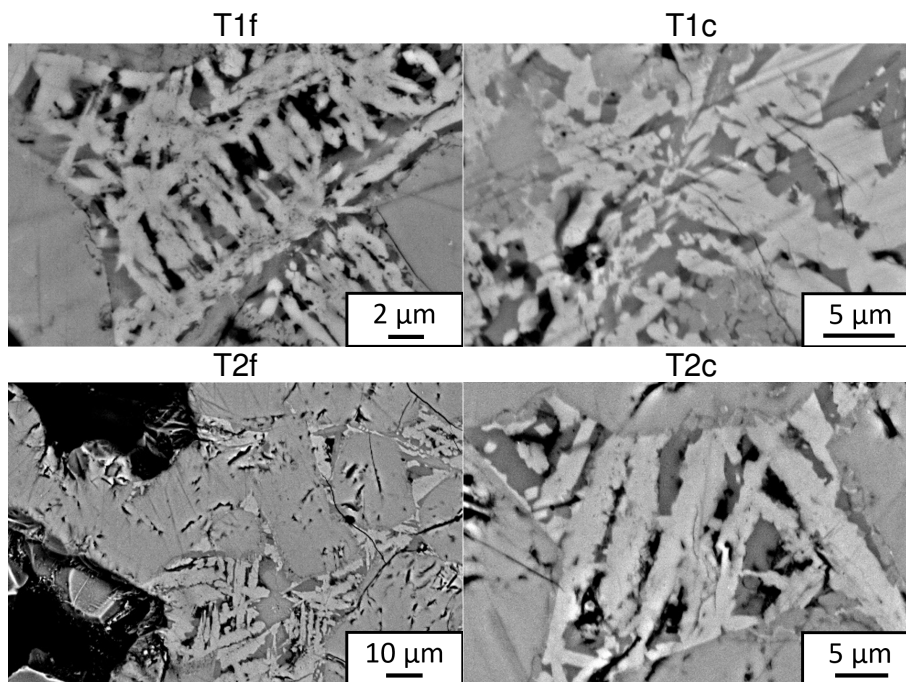
374 Figure 5. Microstructure properties of the main clinkers constituents (*: MgO+Na₂O+K₂O+SO₃+P₂O₅).

375

376 More focused analyses were performed on the interstitial phase (see Figure 6 for these
 377 micrographs). Images show the interstitial phase as “crossing” needle-shaped crystals
 378 with differing chemical contrasts. In very rare cases, a “dendritic” interstitial phase can
 379 also be observed (i.e. case of sample T1c in the micrographs). An example of EDX
 380 analyses is presented in Table 6, according to the contrast observed in the micrographs
 381 (“dark” and “clear” regions). These analyses did not concern the “dendritic” form of
 382 interstitial phases. As expected, the interstitial phase contains mainly calcium oxide with
 383 alumina and iron. The chemical analyses, however, showed that the variation in
 384 contrast depends for the most part on iron content. “Clear” regions seem to be
 385 composed mainly of solid ferrite solutions while “dark” regions by a tricalcium aluminate

386 phase. For all clinkers, the interstitial phase also contains large quantities of secondary
 387 elements (principally silicon, magnesium and alkalis).

388 According to the observations by Crumbie *et al.* [80] on industrial clinkers with various
 389 iron content amounts, the contrast variation was reported to the polymorphism of
 390 tricalcium aluminate (orthorhombic polymorph would have a clearer contrast than the
 391 cubic variety). These differences can be confirmed by chemical analyses as well (the
 392 orthorhombic variety would incorporate more potassium atoms in its lattice compared to
 393 the cubic polymorph) [51,80]. However, a comparison of the chemical composition on
 394 tricalcium aluminate with results observed in the literature (i.e. K₂O content [51,77,80])
 395 did not yield any significant change and moreover did not allow determining with
 396 accuracy the main variety of this phase present in the various industrial clinkers.



397 Figure 6. Focused SEM analyzes on the interstitial phase of the industrial clinkers
 398

397
 398

399 Table 6. Chemical analyzes on the interstitial phase obtained by EDX analysis on minimum 5 points per
 400 phase (wt.%)

		Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	TiO ₂
T1f	Dark	0.9	1.6	23.4	4.2	0.1	1.2	56.5	12.0	-
	Clear	0.1	2.8	20.9	3.7	0.4	0.4	51.0	20.7	-
T1c	Dark	1.1	1.0	23.3	4.9	0.1	0.9	58.5	10.0	0.3
	Clear	0.1	2.5	17.9	4.0	0.1	0.2	51.1	23.4	0.8
T2f	Dark	1.0	3.0	24.2	3.9	0.1	1.3	57.4	9.2	-
	Clear	0.1	2.7	20.4	3.2	0.1	0.2	50.9	22.3	-
T2c	Dark	1.4	1.7	25.9	4.9	-	1.2	60.2	4.6	-
	Clear	0.1	2.9	18.9	3.3	-	0.1	51.2	22.3	1.2

401 **3.3 Physical and mechanical properties of standard mortars**

402

403 **3.3.1 Fresh state**

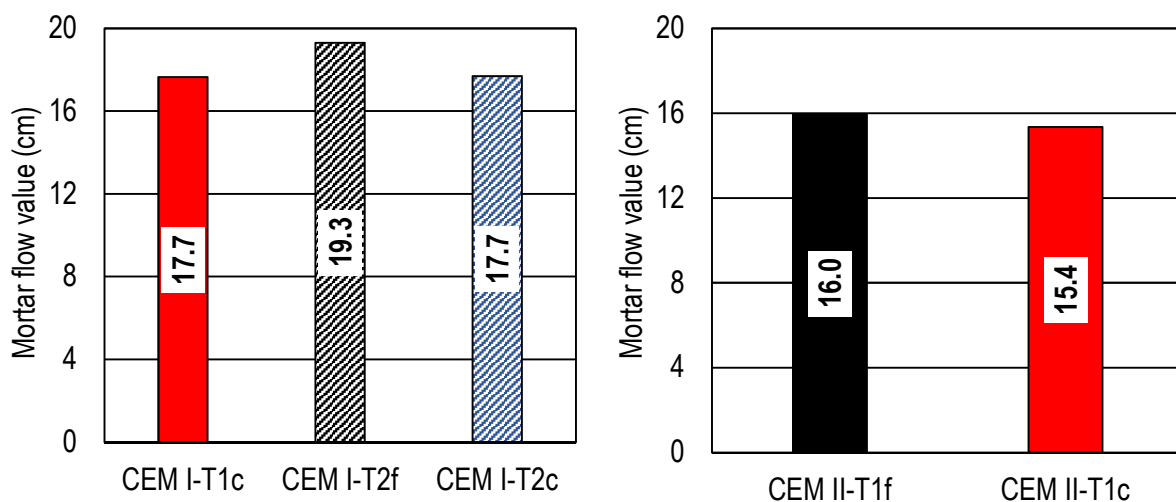
404

405 The table flow test was performed on standard mortars containing both reference and
406 “recycled” cements (Figure 7). The workability of mortars containing CEM II cements is
407 lower (flow: 15-16 cm) than for CEM I (flow = 18-19 cm). However, only a minor
408 difference is observed (less than 1 cm) between the reference (CEM II-T1f) and
409 “recycled” (CEM II-Tc) CEM II cements. This decrease in workability can be due to
410 limestone addition in the constitution of CEM II cements. Consequently, it can be
411 concluded that the incorporation of recycled aggregates into cement raw meal does not
412 significantly alter the main fresh characteristics of final products.

413 Concerning CEM I cements, a slight difference (variance of 1.6 cm) is noticed between
414 the reference cement (CEM I-T2f) and “recycled” cements (CEM I-T1c and CEM I-T2c).

415 As explained above (Section 2.1), reference cement CEM I-T2f was produced in a
416 cement plant, while the other CEM I specimens were milled using a semi-industrial pilot
417 grinder. This change of grinder slightly modifies the particle size distribution and
418 increases the w/c ratio of paste with standard consistency. The lower workability of
419 “recycled” cement is due to the various grinding conditions (grinding agents and nature
420 (i.e. fineness and composition) of the additives) and not to the presence of recycled
421 aggregates in cement raw meal. The cement-manufacturer tend to use such additives
422 during the grinding phase to ensure a stable quality of the product.

423



424

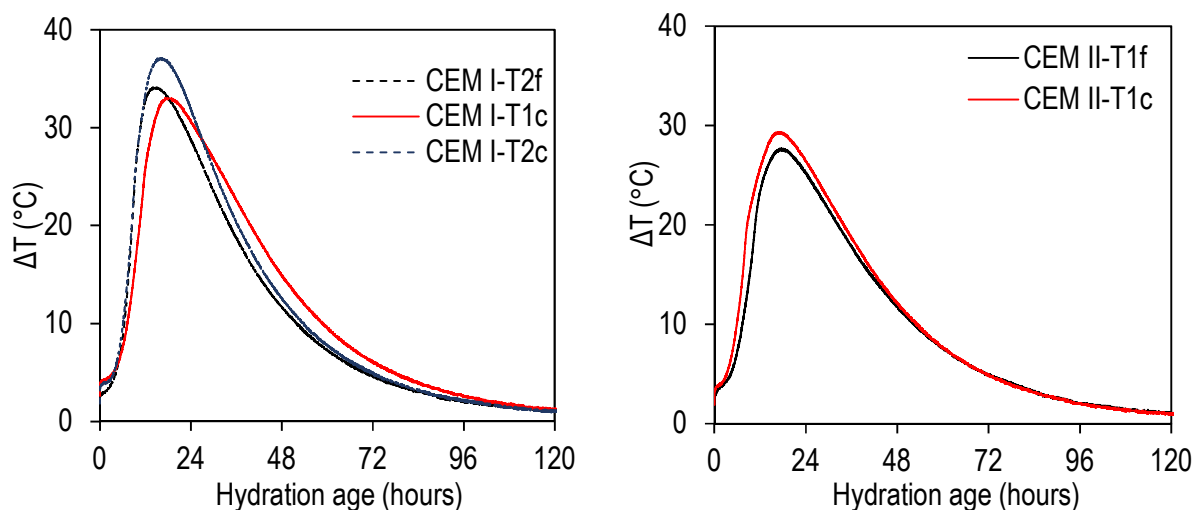
Figure 7. Flow value of reference and “recycled” cements on standard mortars

425

426 **3.3.2 Heat of hydration**

427 The hydraulic reactivity of all cements was evaluated by means of Langavant
428 calorimetry. Results are expressed by temperature differences (ΔT) between the
429 recipient containing the mortar and the reference vs. hydration age (Figure 8). Three
430 main hydration phases of Portland cements were observed, namely induction period,
431 acceleration period and post-acceleration period. The pre-induction period, which
432 occurs directly after the water-cement contact, was not observed due to the extensive
433 time interval between mortar mixing and data acquisition (≈ 7 min).

434 Very comparable curves were found across all cements. The peak indicating the end of
435 acceleration phase occurred after approx. 20.2 ± 0.5 hours of hydration, and no
436 differences were observed between reference and "recycled" cements. CEM I cements
437 showed a higher temperature during the acceleration phase ($\Delta T_{\max} = 36 \pm 2^\circ\text{C}$)
438 compared to CEM II ($\Delta T_{\max} = 27 \pm 2^\circ\text{C}$). This outcome is mainly due to the high clinker
439 content in CEM I cements. Once again, these results confirm that incorporating recycled
440 aggregates in cement raw meal does not affect the hydraulic reactivity mechanisms of
441 final products.
442



443 Figure 8. Hydration heat curves of reference and "recycled" cements obtained on normal mortars

444

445 **3.3.3 Mechanical properties**

446 Mechanical properties were evaluated by measuring the flexural and compressive
447 strengths of mortars between 1 day and 1 year of hydration age. Results are expressed
448 in strength differences observed between reference and "recycled" cements (Δ flexural
449 and compressive strengths) in Figure 9.

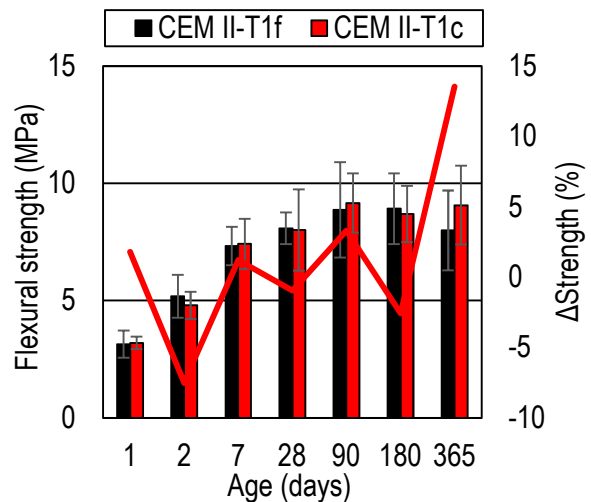
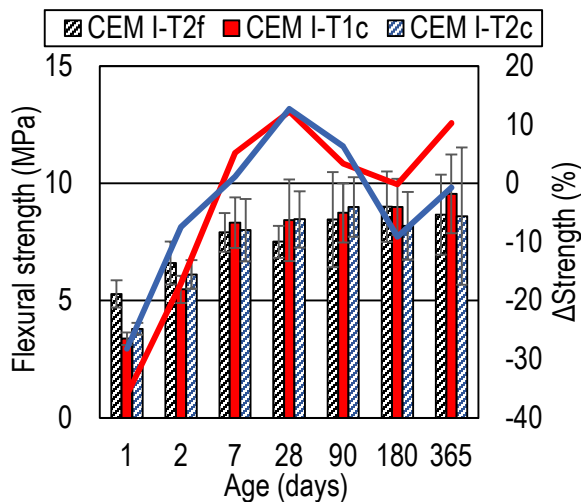
450 At a very early age (i.e. after 1 to 2 days of hydration), major differences are detected
451 when comparing "recycled" CEM I-T1c and CEM I-T2c with reference CEM I-1f
452 cements. These values can be as much as 30% to 35% less than those of the reference

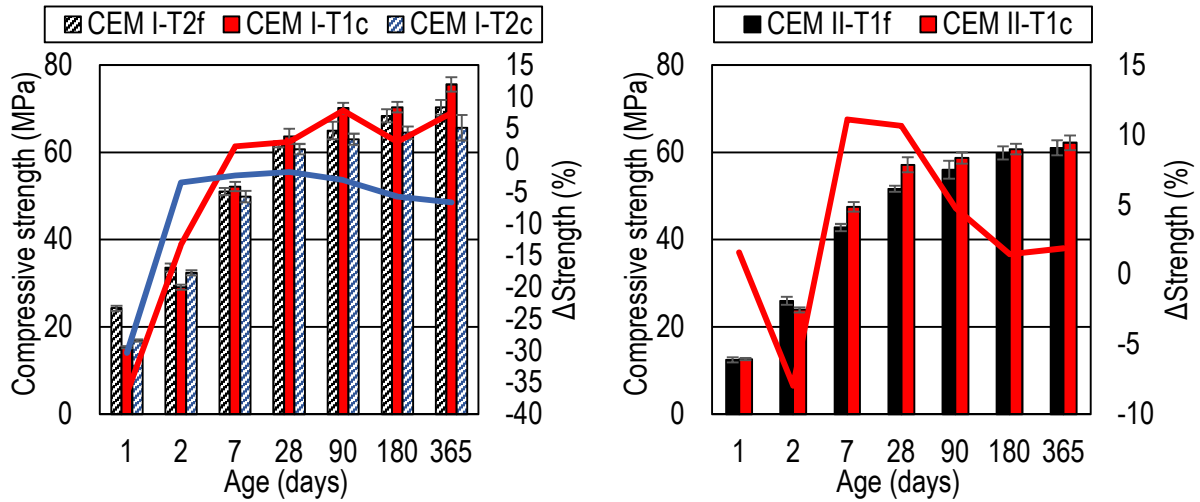
453 cement at 1 day and 13% at 2 days, but for the most part remain above 30 MPa.
 454 However, CEM II-T2c displays mechanical properties similar to the reference at this
 455 stage of hydration. It is difficult to explain these differences and correlate them to the
 456 use or non-use of recycled aggregates in raw meal since many factors may be
 457 contributing to this early age strength (presence of minor phases, tricalcium aluminate
 458 content, etc.).

459 Over the medium term (7 to 90 days of hydration), the compressive strengths of
 460 “recycled” cements became very similar to those of the reference cements. At 28 days,
 461 the average measured compressive strengths of CEM I-T2f, CEM I-T1c and CEM I-T2c
 462 were respectively around 62, 61 and 64 MPa. From the standpoint of the European
 463 standard (EN 197-1), in terms of mechanical properties, all CEM I meet the
 464 conventional Portland cement requirement with a class resistance of 52.5 R.

465 Beyond 90 days and until 1 year of hydration, the mechanical properties become more
 466 stable, and the compressive strengths all lie above 60 MPa for CEM II cements and 66
 467 MPa for CEM I. No decrease in this performance was observed since.

468





469 Figure 9. Mechanical strengths of reference and "recycled" cements evaluated on mortars and expressed
 470 by flexural and compressive strengths (bars diagram, MPa) and by Δ Strength (curves, %) in function of
 471 hydration age

472 The overall performance of cements and mortars made with CDW (recycled aggregates
 473 and more particularly FRA) are aligned with the benchmarked trials reported in
 474 references [24] and [40].

475 3.4 Concrete properties

476

477 3.4.1 Fresh properties of concrete

478 The slump test was performed on each batch. Results for C60 class concrete are
 479 presented in Table 7, while Table 8 lists the results for C30. According to these results,
 480 the slump interval for both concrete classes is 170-230 mm, which corresponds to the
 481 S4 class of targeted concretes [66]. Concretes C_CEM I-T1f and C_CEM I-T1c exhibit a
 482 similar slump. A 25% decrease in slump is noticed for the C_CEM I-T2c (170 mm vs. an
 483 average of 225 mm for other concretes). In contrast, if the same quantity of
 484 superplasticizer used for C_CEM II-T1f were introduced for C_CEM II-T1c, the rheology
 485 of the recycled concrete would be hard, with a slump of 5 ± 1 cm. Hence, to obtain an
 486 S4 class concrete for C_CEM_II_R, superplasticizer quantity was increased by 150%,
 487 but this remains within the technical tolerance according to the product's technical specs
 488 (up to 3% total mass of the binder). The slight changes can be due to limestone
 489 additions as well as to the fact that the CEM I reference cement was milled in a cement
 490 plant, while the other CEM I cements were produced at a pilot plant, as explained in
 491 Section 3.3.1.

492

Table 7 Physical properties of the studied C60 concretes

Mixture	C_CEM I-T1f	C_CEM I-T1c	C_CEM I-T2c
Slump (mm)	220	230	170
Fresh density (g/cm ³)	$2.42 \pm 6E-3$	$2.44 \pm 1E-2$	$2.43 \pm 3E-3$

493

494

Table 8 Physical properties of the studied C30 concretes

Mixture	C_CEM II-T1f	C_CEM II-T1c
Slump (mm)	170	210
Fresh density (g/cm ³)	2.39 ± 7E-3	2.41 ± 5.5E-3

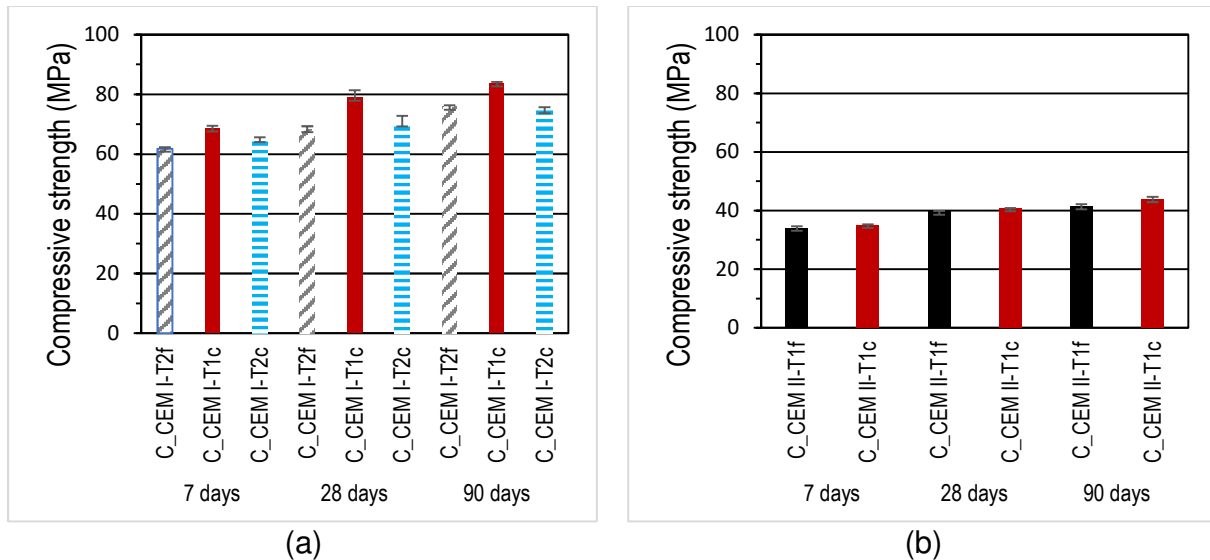
495

496 Furthermore, the densities of the concretes evaluated in the fresh state were calculated.
 497 Table 7 and Table 8 reflect, in general, similar concrete densities when substituting
 498 reference cements with recycled ones. Thus, the fresh properties of concretes show
 499 similar results when using “recycled” cements in both C30 and C60 concretes.

500

501 **3.4.2 Mechanical properties**

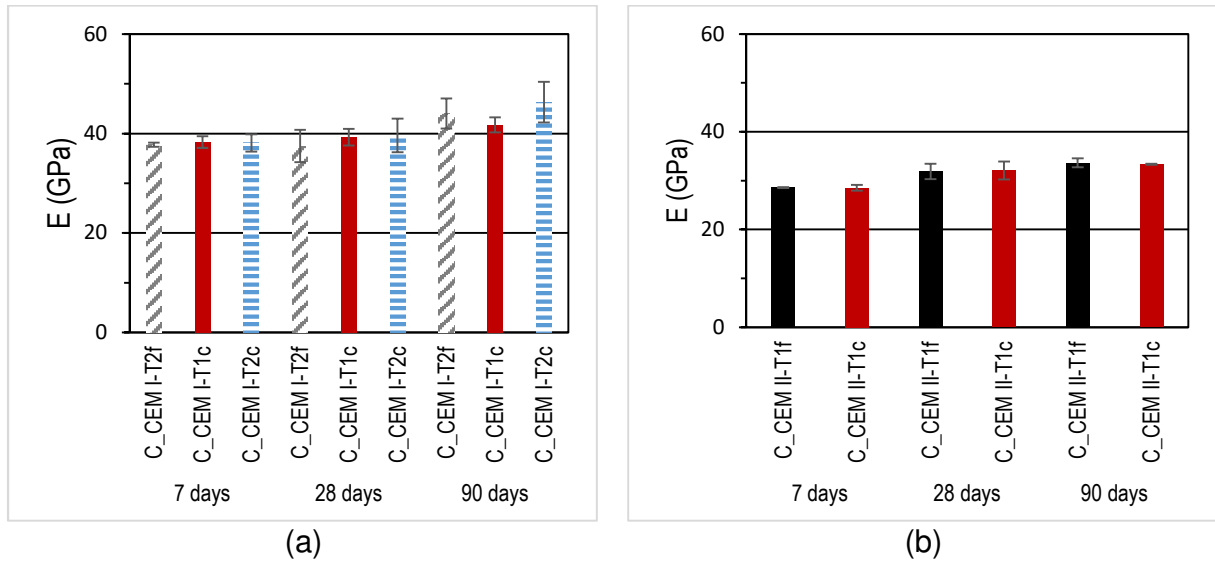
502 Three time intervals were considered for compressive strength and elastic modulus
 503 testing (7, 28 and 90 days). Figure 10 reveals similar compressive strengths for the C60
 504 class concretes, with a slight increase noted for C_CEM I-T1C. The same result applies
 505 to C30 concretes, with compressive strengths for both concretes found to be similar.
 506 This outcome is in line with what was previously observed on mortars (see Fig. 9,
 507 Section 3.3.3). In addition, they reflect an equivalent class of both C30 and C60
 508 concretes, including recycled and reference cements. From these findings, the
 509 feasibility of producing C30 and C60 class concretes with “recycled” cements has been
 510 proven.



511 Figure 10. Compressive strength for all specimens: a) C60 class concretes, b) C30 class concretes

512

513 A similar trend was also noticed for the elastic modulus, as presented in Figure 11.
 514 Concretes made with “recycled” cements have similar elastic modulus as those
 515 produced from reference cements (the maximum variance is less than 2.6 MPa for
 516 C_CEM I at 90 days, and less than 1 MPa for C_CEM II at the same time interval).

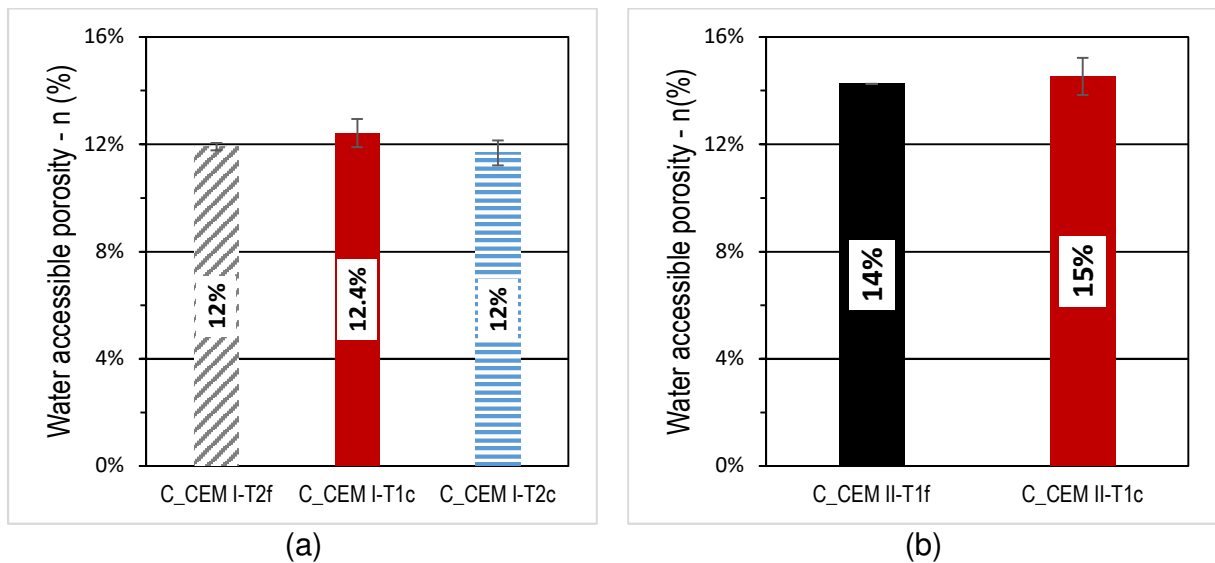


517 Figure 11. Elastic modulus for all specimens: a) C60 class concretes. b) C30 class concretes)

518 **3.4.3 Durability properties**

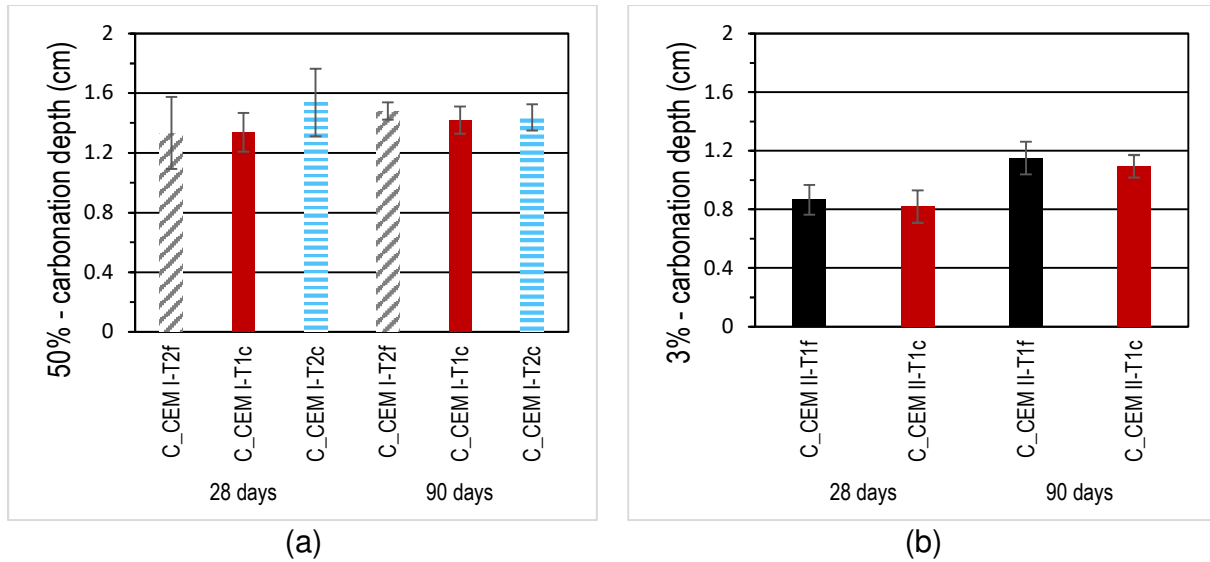
519 All durability properties were tested after 90 days. Water porosity was assessed first,
 520 followed by carbonation, chloride ion migration and gas permeability. Next, an
 521 evaluation of the studied concrete was carried out according to a performance-based
 522 approach.

523 The water accessible properties are presented first in Figure 12. C60 class concretes all
 524 showed similar water accessible porosity, i.e. around 12%. As for C30 class concretes,
 525 they also displayed similar water porosities, in acknowledging that this concrete class is
 526 more porous than C60. These results were aligned with those obtained by Ben Fraj et
 527 al. [81], wherein the porosity of C30 concretes was 1.2~1.3 times higher than that of
 528 C60.



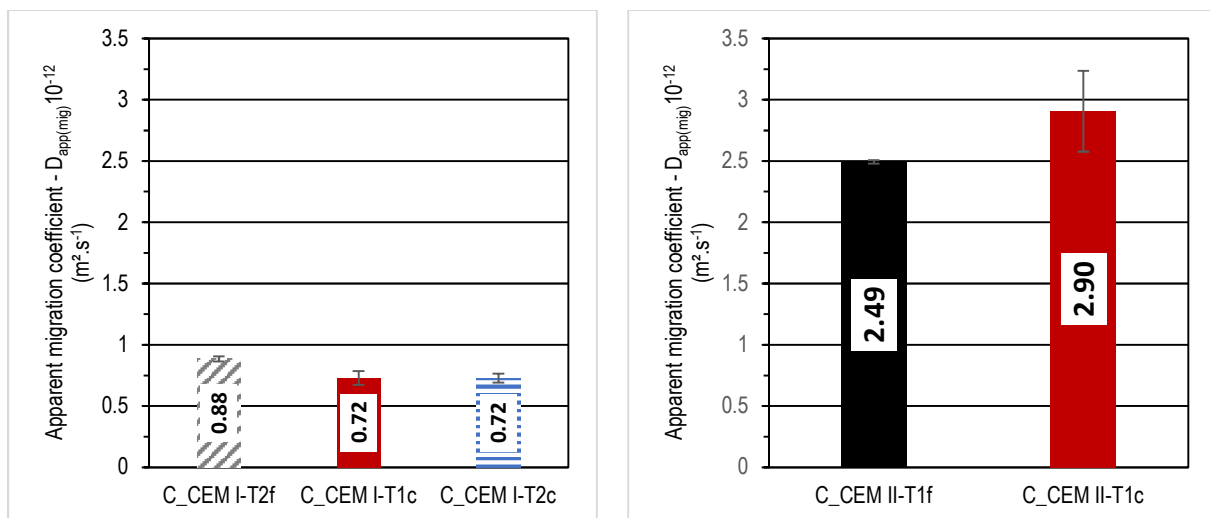
529 Figure 12. Water accessible porosity for all specimens: a) C60 class concretes. b) C30 class concretes

530 The same results were again found for carbonation depth of the studied concretes. By
 531 considering uncertainties, as depicted in Figure 13, C60 and C30 concretes made with
 532 “recycled” cements have similar carbonation depths, compared to the C60 and C30
 533 references.



534 Figure 13. Carbonation depth: a) 50% CO2 for C60 class concretes, b) 3% CO2 for C30 class concretes

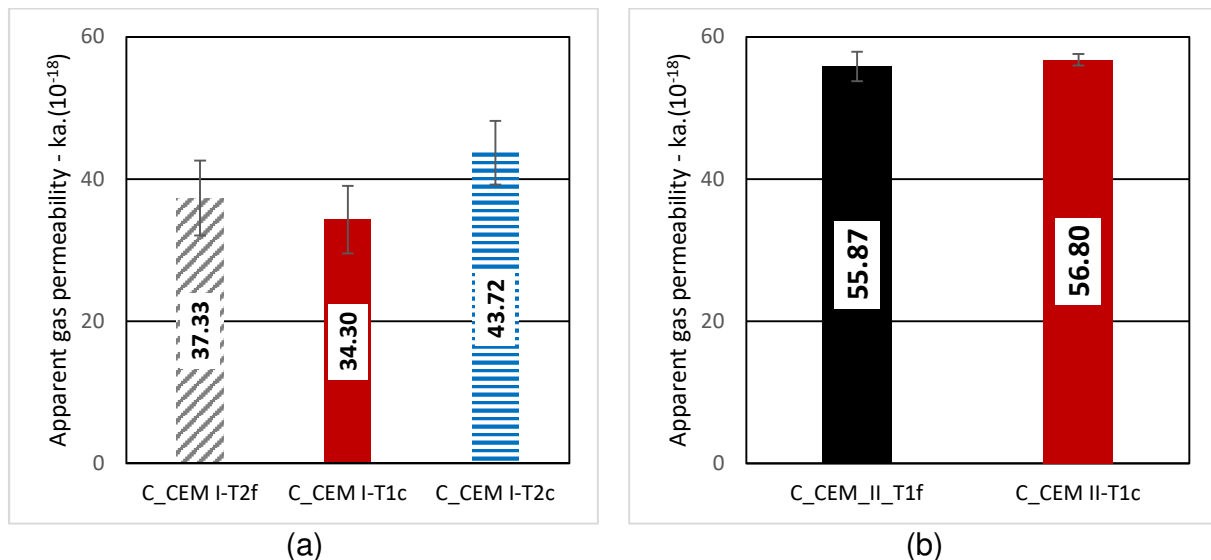
535 Figure 14 depicts the apparent migration coefficient of C60 and C30 class concretes.
 536 Results here show a similar apparent migration coefficient when comparing the
 537 reference concrete with concretes containing “recycled” cements for C60, whereas a
 538 small increase ($0.41 \text{ m}^2 \cdot \text{s}^{-1}$) is visible in diffusion migration for the C30 with “recycled”
 539 cement. The apparent migration coefficient depends on both concrete porosity and
 540 structure. These results are also in line with water accessible porosity trends (Fig. 12).
 541 Generally speaking, it seems that the apparent migration coefficient for C30 is three
 542 times greater than that of C60 concretes, also in line with results obtained by Ben Fraj
 543 et al. [81].



(a) (b)
 Figure 14 apparent migration coefficient: a) C60 class concretes. b) C30 class concretes

544

545 The apparent nitrogen permeability coefficients presented in Figure 15 correspond to a
 546 global pressure of 2 bar. Like other durability properties, these figures indicate a similar
 547 apparent gas permeability coefficient for the C30 class concrete. As for C60, C_CEM I-
 548 T2f and C_CEM I-T2c show similar results, whereas a slight decrease ($\sim 3 \times 10^{-18} \text{ m}^2$) is
 549 detected in the gas permeability for C_CEM I-T1c. Yet it was explained above that
 550 recycled CEM I cements were milled using a semi-industrial grinder, while the reference
 551 cement was produced at a regular cement plant. The change of grinder between these
 552 cements may slightly modify the particle size distribution and thus exert an impact on
 553 the concrete durability properties. Notwithstanding these slight changes, no significant
 554 differences could be observed when comparing concretes with “recycled” cements (T1c
 555 and T2c) and those with reference cements (T1f and T2f), which corroborates the
 556 conclusions drawn in the clinker and mortar sections. As for an overall comparison,
 557 these figures are in line with a similar study conducted by Ben Fraj et al. [81], wherein
 558 the gas permeability of C30 concretes is on average 1.5 times higher than that of C60.



559 Figure 15: Apparent gas permeability coefficient: a) C60 class concretes. b) C30 class concretes

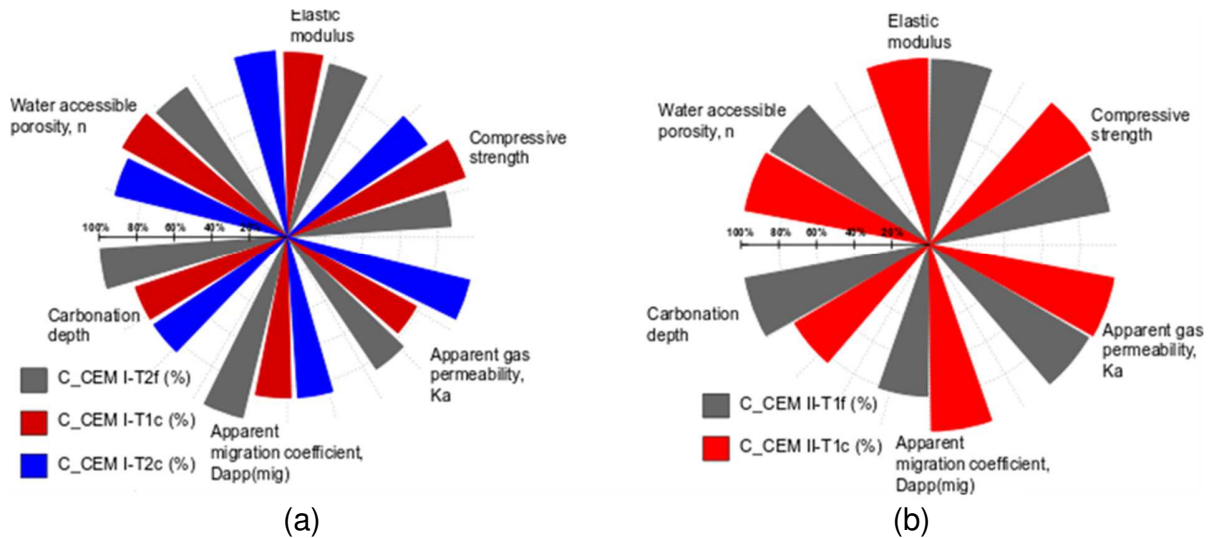
560 A comparison of durability properties of the studied concrete using a performance
 561 approach [47] provides insight on the overall durability of concrete along with a general
 562 prediction of its behavior over time (see Table 4 for performance criteria). The results of
 563 this performance approach are given in Table 9. Based on water accessible porosity,
 564 the C60 class concretes score a durability rank of HD. However, the C30 class has a
 565 water porosity range lying between 14.2% and 14.5%, which assigns these concretes a
 566 durability rank between LD and MD (LD<>MD). As for the apparent migration
 567 coefficient, C30 class concretes are considered as highly durable (HD), with an average

568 apparent migration coefficient below $2.8 \cdot 10^{-12}$ ($\text{m}^2 \cdot \text{s}^{-1}$). Meanwhile, for C60, the average
 569 apparent migration coefficient equals $0.78 \cdot 10^{-12}$ ($\text{m}^2 \cdot \text{s}^{-1}$), placing these concretes in a
 570 durability class between HD and VHD (HD<>VHD). The average apparent gas
 571 permeabilities for C60 and C30 class concretes are respectively 38 and $56 \cdot 10^{-18}$ (m^2),
 572 which ranks both of them as highly durable (HD). Thus, taking the performance
 573 approach methodology into account, C30 concretes are classified between LD and MD
 574 (LD<>MD), whereas C60 receive a high durability (HD) concrete classification.

575 Table 9 Performance approach performances, the sign '<>' stands for an average value standing
 576 between the two durability ranks.

Concrete class	Label	Performance approach			Durability rank
		Water accessible porosity – n	Apparent migration coefficient – $D_{app(mig)}$	Apparent gas permeability – K_a	
C60 concrete	C_CEM I-T2f	HD	HD<>VHD	HD	HD
	C_CEM I-T1c	HD	HD<>VHD	HD	HD
	C_CEM I-T2c	HD	HD<>VHD	HD	HD
C30 concrete	C_CEM II-T1f	LD<>MD	HD	HD	LD<>MD
	C_CEM II-T1c	LD<>MD	HD	HD	LD<>MD

577



578 Figure 16: Performance approach assessment: a) C60 class concretes. b) C30 class concretes. Values
 579 are in “%”, where the maximal value refers to the highest one between the compared concretes.

580 In sum, Figure 16 compares concretes within the same classes. C60 concretes possess
 581 similar properties (more than 90% similarity), except for carbonation and apparent gas
 582 permeability indicators, whose similarities still lie above 80%. C30 concretes also
 583 possess similar properties (more than 90%), except for carbonation and apparent
 584 migration coefficient indicators, whose similarities remain higher than 80%. This figure
 585 proves the ability to produce concretes made of “recycled” cements that feature
 586 properties similar to those made with reference cements. Moreover, both concretes

587 were assessed using the performance approach, with the conventional concrete C30
588 being characterized as a moderately low durability concrete (LD<>MD), whereas C60
589 was characterized as highly durable (H). This result confirms that the first-class
590 concrete can be used for the building sector, with the latter being reserved for high-
591 performance use (e.g. structures).

592 A next step towards a more sustainable concrete, in achieving adequate mechanical
593 and durability performance, will be to assess its ability to reach equivalent performances
594 while integrating recycled concrete aggregates. The objective therein will be to assess
595 the properties of recycled aggregates concrete [64] made with “recycled” cement. The
596 same combination of analyses should also be performed in using a life cycle analysis
597 [64].

598 **4 Conclusion**

599

600 This study investigated the quality of mortars and concrete containing cement produced
601 at an industrial scale with valorization of various recycled aggregates in the cement raw
602 meal. Two batches of 3,500 tons of each clinker were produced with 14% recycled
603 aggregates and 5% mixed ones. Recycled clinkers were used to produce recycled CEM
604 I and CEM II cements that were incorporated in C60 and C30 concretes, respectively.
605 The following conclusions can be drawn:

- 606 - The Clinker Production with an incorporation rate of around 5% seems to be
607 more effective since it prevents against side problems related to the industrial
608 process (e.g. higher quartz content leading to higher energy consumption,
609 competition with other wastes, absence of clays). Altogether, recycled clinker is
610 proven to be of a standard level.
- 611 - Same ascertainment is noticed for mortars and concretes containing recycled
612 cements. Only minor differences in workability were observed; these were most
613 likely related to grinding in a semi-industrial plant and not correlated with the
614 incorporation of recycled aggregates into the raw meal.
- 615 - Based on the performance approach, the conventional C30 concrete was ranked
616 as a low to medium durable concrete, whereas the C60 class concrete produced
617 was characterized as highly durable, with a slight increase in mechanical
618 properties when introducing “recycled” cement content into the concrete mixture.

619 The use of a few percent of recycled aggregates in the cement raw meal will be
620 sufficient for the reuse of hundreds of tons of the fine fraction of recycled aggregates
621 with a high content of impurities and hardened cement paste. In order to quantify the
622 potential environmental interest of this process, a life cycle assessment is underway to
623 consider the content of non-carbonated calcium oxide in the recycled aggregates, as
624 well as its transportation, etc.

625 This paper has thus proven the feasibility of producing, at an industrial scale, “recycled”
626 clinker and cements with the same properties as their conventional counterparts. This

627 feasibility has been confirmed by the mechanical and durability properties of concretes
628 made with these “recycled” cements.

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633

634 **5 References**

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