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ORIGINAL ARTICLE

Reuse of recycled crushed concrete fines as mineral addition in cementitious materials

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Abstract Environmental issues have led European stakeholders to join around an ambitious project, the reuse 70 % of inert wastes from construction and demolition by 2020. Among available solutions, the reuse of fine recycled aggregates as substitute of natural sand is somewhat problematic due to their high water absorption. The aim of the present research is to study a new way of recovery for fine recycled aggregates. We propose to use them as mineral addition, after a process of crushing and sieving resulting in powder (particles diameter lower than 80 μm). For this purpose, Recycled Crushed Concrete Fines (RCCF) were prepared from a 5 years old concrete and characterized by a physico-chemical approach. Attention was paid to assess the content of anhydrous cement. Mortars with different substitution levels of Portland cement by RCCF (Recycled Crushed Concrete Fines) or limestone filler were also studied at both fresh and harden states. The studied RCCF were found to have low content of anhydrous cement and thus low hydraulic properties. However, RCCF (Recycled Crushed Concrete Fines) was found to play a similar role than limestone filler on cement hydration. Portland cement could be substituted by RCCF (Recycled Crushed Concrete Fines) up to 25 % without altering properties of mortars. These results are encouraging and lead us to continue our research with inert wastes from real demolition sites.

Keywords Recycled crushed concrete fines · Limestone filler · Hydration · SEM · Recycling · Mineral additions

1 Introduction

In 2008, the European Parliament adopted a directive to improve the recovery and recycling of wastes [1]. In particular, the European directive lays down an ambitious target of minimum 70 % by weight for re-use, recycling and recovery of construction and demolition wastes by 2020. Among measures to achieve this target, the recovery of cementitious materials is probably the easiest, because it represents the highest quantity of construction wastes. For instance, in France, cementitious materials represent more than a third of the 20 millions of tons of wastes generated per year by the construction industry [2].

Numerous studies show that the reincorporation of Recycled Concrete Aggregates (RCA) in concrete is a possible solution, alternative to their use as gravels in road applications [3]. However, RCA can have negative effects on concrete properties. RCA tend to

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alter the workability because they absorb more water than natural aggregates, e.g. [4–6]. Compressive strength of concrete with RCA can be up to 40 % lower, depending on the substitution level and the quality and origin of aggregates [7]. Most of indicators of durability are affected by the presence of RCA, e.g. [8, 9]. These side-effects can be controlled by adjusting the mix design (e.g. chemical admixtures content) or by using more efficient crushing processes resulting in 'clean' recycled aggregates [10]. Other methods, such as carbonation of RCA [11] prior to their use, offer also solutions to overcome these issues.

Although many researches point out that the reuse RCA in concrete is feasible, it is in practice often limited to the coarsest RCA. In fact, using recycled sands seems not to be viable yet. The side-effects of RCA listed above are more pronounced in the case of fine grade RCA due to their very high water absorption [3]. Therefore, other ways of recovery have to be found for fine RCA.

The present research deals with the feasibility of using finely crushed concrete sourced from demolition sites as a constituent for concrete. Instead of using fine RCA as aggregates (i.e. sand substitute), we propose to use them as mineral addition (also called supplementary cementing material SCM), after an additional process of crushing and sieving. The latter aims at producing a powder with maximal diameter lower than 100 µm (typical value for mineral additions). In the following, this powder is denoted RCCF (Recycled Crushed Concrete Fines). Although this approach requires additional process for the transformation of the raw material, it presents a priori several environmental benefits. Firstly, it increases the recovery potential of concrete. Secondly, RCCF can be used as a substitute of usual addition such as limestone filler what would reduce quarrying of natural resources. Thirdly, mineral additions are more and more used for partial replacement of Portland cement [12]. A partial substitution of cement by RCCF would undoubtedly reduce environmental impacts of concrete, since Portland cement is known as the most impacting constituent of concrete [13].

While literature on substitution of cement by powders produced from wastes or by-products (from fly ash and granulated blast furnace slag to glass wastes) is rich, literature on substitution of cement by RCCF (Recycled Crushed Concrete Fines) is relatively limited. Studies on the incorporation of fine RCA in mortars or concrete were often focused on the substitution of the natural sand, e.g. [14]. Some researchers considered the use of recycled concrete fines after a thermal treatment [15, 16]. The latter aims at dehydrating the fines which can rehydrate when put in contact with water in concrete or mortar mixes. Thermally treated fines can also activate binders such as blast furnace slag [16] or fly ash [17]. Florea et al. concluded that recycled concrete fines, even without thermal treatment, can replace the cement without loss of strength providing that the substitution level is lower than 20 % [16]. Braga et al. showed also that the reduction of the cement content in a mortar can be compensated by the presence of crushed concrete fines in the sand [18].

We present the results of investigations about Particle size distributions, SEM, DTG, packing densities, the heat release, compressive strength, evolution of activity coefficient, done on a 5 years old concrete. This raw material was prepared by crushing and sieving. The obtained RCCF was characterized with a physico-chemical approach in order to evaluate its potential to be used as mineral addition for concrete. Attention was paid to assess the content of anhydrous cement contained in the RCCF and its eventual effect on RCCF properties. In addition to powder characterizations, mortars with different substitution levels of Portland cement by RCCF were also studied. Properties at both fresh and harden states were measured. The mortars with RCCF were compared to mortars made with limestone filler, i.e. a mineral addition currently used in concrete.

2 Materials and experimental procedures

2.1 Preparation of RCCF

The studied fines were prepared with a concrete taken from a construction site near Paris during the French APPLET project [19]. After 3-month water curing, cylindrical specimens of this concrete (Ø11 × 22 cm) were stored during 5 years in a room at 20 °C and relative humidity higher than 90 %. The APPLET concrete mixture contains Portland cement (CEM I 52.5 N from Holcim, Dannes, France), fly ash (FA) and limestone aggregates (Boulonnais quarries, France). Chemical and physical characteristics of these materials are given in Table 2. Its average 28-day

Table 1 APPLET concrete composition (in kg per cubic meter of concrete)

CEMI 52.5 Dannes	Fly ash	Limestone aggregates			Water	Superplasticizer	Density (kg/m^3)
		0/4	5/12	12/20			
350	80	900	320	630	157	2.45	2437

compressive strength is 55 MPa. The composition of concrete is given in Table 1. In 2013, in France, the production of aggregates was estimated by UNPG around 365.9 Mt which 28 % had calcareous origin [20]. It's quite important but still minor if compared with the situation in UK (47 %) even Norway (78 %) [21]. However, even if no national data specific on the proportion of limestone aggregates used for ready-mixed concrete exists, we can suppose that around 20 Mt of limestones aggregates out of 74 Mt of aggregates are used for ready-mixed concrete.

To prepare RCCF, an iterative process was used. First, several APPLET concrete cylinders were broken in small pieces by compression. Then, the concrete pieces were crushed to obtain a powder with maximal diameter lower than 300 µm (laboratory jaw crusher RETSCH BB200). Finally, the powder was sieved at 80 µm. At the end of the process, the obtained fines (RCCF) represent about 60 % of the initial mass of the concrete cylinders. This process is not complete since a part of the original concrete is not used. In fact, we choose to sieve the obtained particles at 80 µm because this size is commonly used for mineral additions [22]. By using more efficient equipment (such as industrial ball mill), the percent of recovery could be much higher than 60 %.

Table 2 Chemical and physical analysis of materials studied

Chemical composition	CEM I 52.5 N Dannes	CEM I 52.5 N Lafarge	Fly ash	Limestone aggregates
CaO	64.1	64.8	2–8.5	53.4
Al_2O_3	5.0	4.5	23–32	0.2
SiO_2	20.1	20.5	42–58	–
Fe_2O_3	3.0	2.0	3–15	0.1
SO_3	3.2	3.4	0.2–2.0	–
MgO	1.0	1.5	2.0–3.5	2.7
K_2O	0.7	0.8	0.5–4.6	–
Na_2O	0.2	0.1	0.1–4.0	–
LOI	1.2	1.1	1.5–5	–
$CaCO_3$	–	–	–	88.43
C_3S	65	64.6	–	–
C_2S	11.2	12.9	–	–
C_3A	8.5	7.8	–	–
C_4AF	9	8.4	–	–
Density (g/cm^3)	3.19	3.12	2.42	2.68

2.2 Characterization of RCCF

The density of RCCF was measured using a pycnometer according to European standard EN 1097-7 [23]. The specific surface area was assessed by the Blaine test according to standard EN 196-6 [23]. The particle size distribution and the median diameter (D_{50}) were measured by laser diffraction in water solution (CILAS 1190 LD).

Thermogravimetric analysis (TGA, SETARAM SETSYS EVOLUTION) was used to quantify the proportions of calcium carbonate ($CaCO_3$) and Portlandite ($Ca(OH)_2$). 100 mg of powder was introduced into an alumina crucible and heated at the rate of 10 °C/min up to 1000 °C under inert atmosphere of Argon (flow rate = 20 ml/min). Four samples were tested by TGA.

The residual reactivity of RCCF due to anhydrous cement was assessed by a Langavant semi-adiabatic calorimeter test in accordance with the European standard [23]. The test was carried out on mixes made with RCCF and water rather than on mortars as recommended in the standard, so as to increase the measurement accuracy. The water/RCCF mass ratio was chosen equal to 0.45 so as to obtain an easy casting of the mix in the Langavant cylinder.

The water demand of the RCCF was also determined. This property influences the consistency of mix of powder and water. In our study, it was assessed by the method proposed by Sedran [24, 25]. It consists in determining the amount of water which results in a consistency change of the tested mix (powder + water) from a "wet pellets state" to a "smooth state". This test is carried out by adding water directly in a mortar mixer.

Although the assessment of the water demand is visual, the test repeatability (for a given operator) is rather good.

The RCCF composition was also investigated through SEM images. For this purpose, images were obtained for samples of APPLET concrete firstly sawn and polished (1 × 1 cm pieces) in Backscattered Electron (BSE) mode. A high resolution scanning electron microscope was used (ESM QUANTA Model 200 and FEI/Philips brand with a given voltage of 20 kV). The MEB is coupled to an energy dispersive spectrometer (EDS) of the type of mark EDAX Genesis. Images were then analyzed using classical treatments based on grey levels, e.g. [2, 26, 27], in order to assess the content of anhydrous cement.

2.3 Compositions of mortars with RCCF and limestone filler

In order to study the use of RCCF as mineral addition, mortars were prepared with a volume fraction of sand fixed at 54 %. The mortars contained 0/4 mm siliceous sand and Portland cement (CEMI 52.5 N, Lafarge, La Couronne, France). Note that this cement is close to the one used in APPLET concrete (CEMI 52.5 N from Dannes) [19]. Four mortars were prepared: one mortar with 100 % cement and three mortars with 25, 50 and 75 % of the cement volume replaced by RCCF. The water content remained constant. In the same way, three other mortars were prepared with 25, 50 and 75 % of cement substitution by limestone filler (from MEAC, Erbray, France). The latter contains 97 % of $CaCO_3$. The water to binder ratio of mortars (W/(A + C)) depends on different compositions as showed in Table 3. The mortar containing neither RCCF nor limestone filler is used as reference and is denoted Ref. Note also that the high substitution level of 75 % is used only to better understand the influence of the cement substitution on mortars properties (such a high substitution has a priori no industrial interest).

2.4 Properties of mortars

At the fresh state, the consistency was determined by means of slump measurements with a small Abrams cone (height = 150 mm, diameter = 100 mm). Prismatic specimens (4 × 4 × 16 cm) were also manufactured in order to measure the compressive strength at the ages of 2, 7, 28 and 90 day [23]. Before testing, specimens were cured in water at 20 °C. Hydration kinetics of the mortars made with RCCF was studied during one week by means of Langavant semi-adiabatic calorimeter tests carried out according to [23].

3 Results and discussion

3.1 Properties of RCCF

3.1.1 *Physical properties*

Absolute dry densities, specific areas and median diameters of the studied materials are given in Table 4.

The density of RCCF is almost equal to the overall density of the APPLET concrete that is 2.44 g/cm^3 (calculated value from the 1 m^3 composition given in Table 1). Thus, the used process of crushing and screening provides a powder whose composition should be close to the one of the original concrete. We note that RCCF specific area is higher than those measured for the limestone filler and the cement. The results of the particle size distribution confirm this observation with a median diameter D_{50} lower than those of both other studied materials. The RCCF preparation process is effective to obtain a high fineness powder.

Table 3 Mortars compositions (in kg per cubic meter of mortar)

	Ref	RCCF			LF		
		25	50	75	25	50	75
Sand 0/4	1431	1431	1431	1431	1431	1431	1431
CEM I 52.5 N La Couronne	499	374	249	125	374	249	125
Mineral addition	0	99	197	296	109	219	328
Water	299	299	299	299	299	299	299
W/C	0.60	0.80	1.20	2.40	0.80	1.20	2.40
W/(A + C)	0.60	0.63	0.67	0.71	0.62	0.64	0.66

with A mineral addition, i.e. RCCF or Limestone Filler (LF)

Table 4 Density, specific area, median diameter and water demand of the studied materials

Material	Density (g/cm^3)	Specific area (cm^2/g)	D_{50} (μm)	Water demand (%)
RCCF	2.45	6200	8.8	22
LF	2.72	4700	11.8	19
CEMI 52.5 La Couronne	3.19	4100	15.4	25

Moreover, Fig. 1 shows a multimodal particle size distribution with four distinct peaks at 0.2, 2.8, 13 and 40 μm. Compared to the cement, the RCCF present two finer size modes. The difference in size distribution could stem from the crushing process contributing to different sizes of grain and shape (as opposed to grinding used for cement). Note also that the size distribution of RCCF is much closer to the one of the tested limestone filler.

The particle size distribution of RCCF may have some benefit in the partial replacement of cement by these fines in concrete mixtures. Indeed, it could complete the particles arrangement of cement and thus improve its packing density (filler effect).

3.1.2 *Mineralogical composition*

The mass fraction of $CaCO_3$ was determined by TGA for the RCCF and for the aggregates of APPLET concrete (the latter were crushed prior to TGA). Figure 2 gives the obtained DTG curves. We have to note that the portlandite content measured by TGA was realized from the average of three specimens (Fig. 2). We found portlandite content at 2.4 % with standard deviation 0.1.

The $CaCO_3$ fraction of the aggregates was measured equal to 95 %. If we assume that the $CaCO_3$ in APPLET concrete comes only from the limestone aggregates, the $CaCO_3$ content of APPLET concrete is then equal to 73 %. The presence of $CaCO_3$ in the concrete could also result from an eventual carbonation. However, this is quite unlikely since previous studies have shown that this concrete has very slow carbonation kinetics, even in accelerated carbonation conditions [19].

The $CaCO_3$ fraction in RCCF was found by TGA equal to 73 %. Since RCCF and APPLET concrete have the same $CaCO_3$ content, we can conclude that RCCF have the same composition than the original concrete and thus the same cement content, i.e. 13 %.

DTG of RCCF reveals also peaks related to the dehydrate of C-S-H, ettringite and Portlandite (Fig. 2). From 25 °C up to 200 °C, the free water and a part of the bound water of hydrated products escape such as calcium silicate hydrate (C-S-H) [28–30], and the decomposition of ettringite take place [31], and from 400 °C up to 470 °C, associated with dehydroxilate of portlandite ($Ca(OH)_2$) [32, 33]. The measured content of Portlandite is 2.4 ± 0.1 %.

Both density and mineralogical composition of RCCF are very close to those of the source concrete.

3.1.3 *Anhydrous cement content and residual reactivity*

The degree of cement hydration at long term (α_u) can be assessed by the model proposed by Schindler which takes into account both W/C ratio and FA content [34]:

$$\alpha_u = \frac{1.031 \times W/C}{0.194 + W/C} + 0.5 \times \frac{FA}{C + FA} \tag{1}$$

where W, C and FA are the masses of water, cement and fly ash, respectively. This model is an improvement of Mills model [35] taking into account the effect of fly ash on cement hydration.

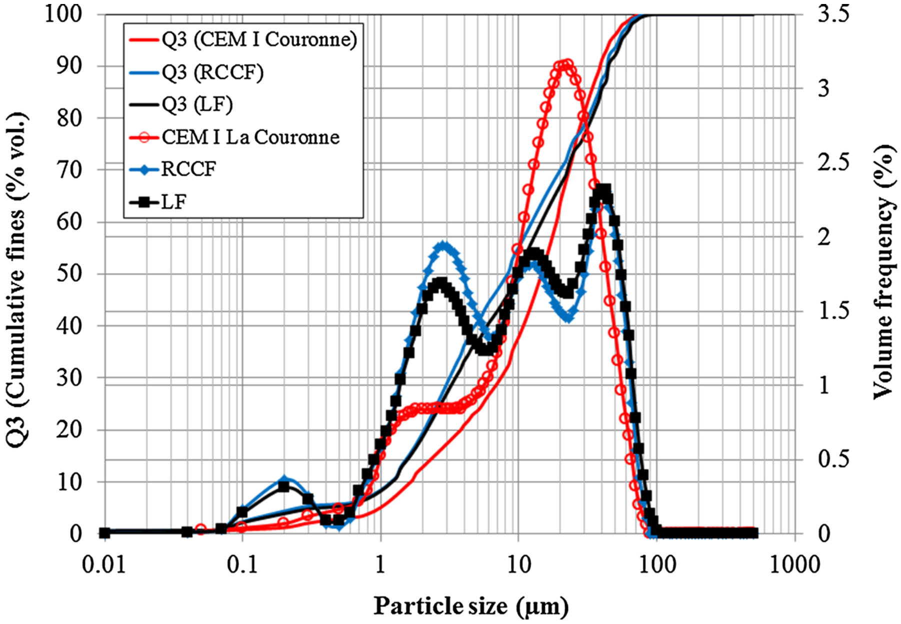
Using Eq. 1, the degree of hydration is found equal to 0.82 for $FA/(C + FA) = 0.19$ and $W/C = 0.45$ (mix ratios from Table 1). As shown previously, RCCF have the same composition than the APPLET concrete. Thus, from the calculated α_u, the expected Portlandite content of APPLET concrete (α_{CH}) can be estimated by Eq. (2):

$$\alpha_{CH} = 0.29\alpha_u C \tag{2}$$

where C is the cement content (equal to 13 %). In Eq. (2), the mass ratio Portlandite/cement for a complete hydration is assumed to be 0.29 [36]. α_{CH} is found equal to 3.2 %. The Portlandite content measured by TGA is lower (2.4 %). This difference can be explained by the consumption of Portlandite by fly ash due to pozzolanic reactions (the original concrete is 5 years old).

Assuming that $\alpha_u = 0.82$, the anhydrous cement content of RCCF should be $\alpha_{AC} = (1 - 0.82) \times 13\ \% = 2.3\ \%$. In order to evaluate the residual

Fig. 1 Particle size distributions measured by laser granulometry



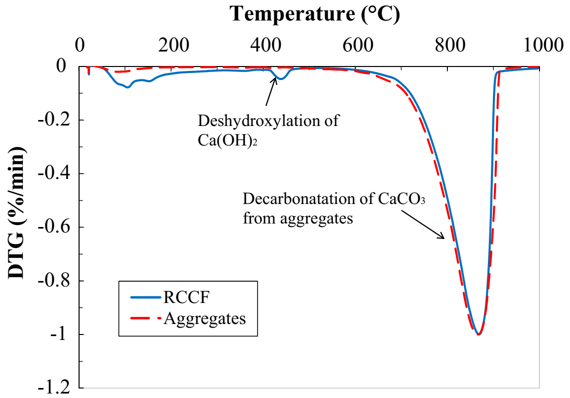


Fig. 2 DTG recycled crushed concrete fines (RCCF) and APPLET concrete aggregates

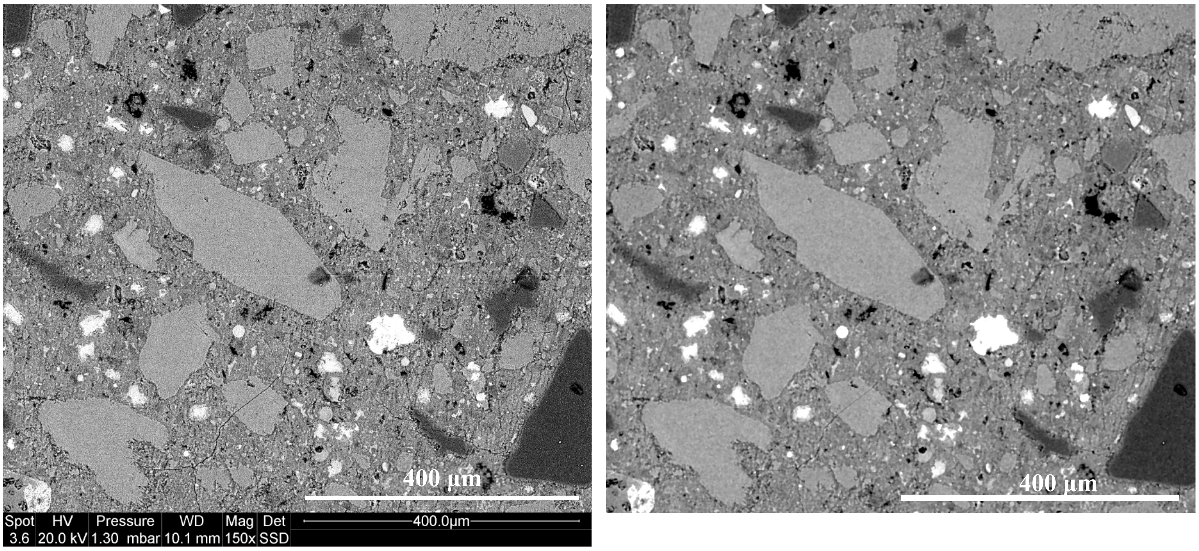
reactivity of RCCF due to the presence of anhydrous cement, calorimeter tests were carried out on mixes prepared with water/RCCF mass ratio of 0.45. At the end of the tests, the total heat was found to be lower than 15 J per g of RCCF. Hydration of APPLET concrete cement (CEMI 52.5 N Dannes) should release 350 J per g of cement according to the technical data from the manufacturer. Thus, the heat release from RCCF is equal to less than 4 % of the one of the cement. From this rough assessment, we confirm that the anhydrous cement content of RCCF (α_{AC}) should be close to the value estimated from the theoretical α_u and the cement content.

To go further, investigations were carried out by means of SEM to confirm the presence of anhydrous cement in RCCF. It should be recalled that SEM images was not obtained on the RCCF but on the raw material, i.e. polished samples of APPLET concrete.

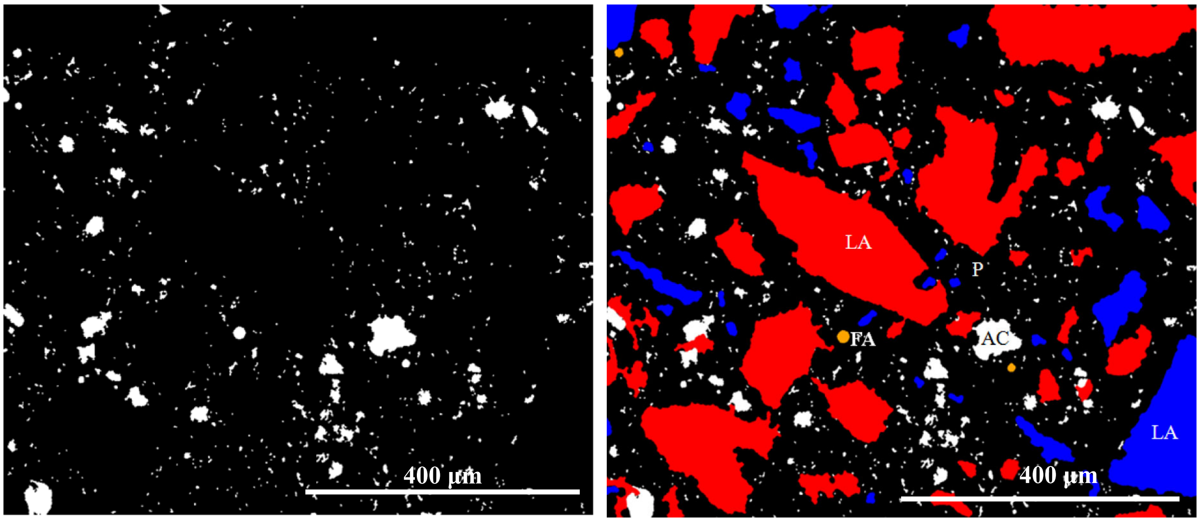
Figure 3 gives an example of the image treatment process that allowed us to determine the surface fractions of the different phases, from aggregates to anhydrous cement. Anhydrous cement clearly appear on the obtained images (the densest phases shown in white in Fig. 3). Fly ash particles can be also detected due to their spherical shape.

In order to quantify the phase contents, the surface fractions obtained from the image processing are assumed to be equivalent to volume fractions [37]. Moreover, the volume of anhydrous cement has to be related to the volume of paste (i.e. total concrete volume minus aggregates volume). Indeed, SEM images are not representative of the overall concrete. According to the used magnification, only the finest aggregates (lower than 400 µm) are visible, what represents 15.5 % of the total granular matrix. The volume ratio of anhydrous cement and paste (p_{AC}) and the volume ratio of anhydrous fly ash and paste (p_{FA}) are first calculated:

$$p_{AC} = A_{AC}/A_P \text{ and } p_{FA} = A_{FA}/A_P \qquad (2)$$



(a) SEM of APPLET concrete **(b)** Filtered image of APPLET Concrete



(c) Binary image of anhydrous cement phase (AC) **(d)** reconstructed image

Fig. 3 Treatment of SEM image in BES mode with ×150 of magnification (APPLET concrete sample)

where A_{AC}, A_{FA} and A_p are the volumes of anhydrous cement, fly ash and paste, respectively, deduced from SEM images.

Secondly, in order to obtain the anhydrous cement content and the unreacted fly ash content (i.e. mass ratios α_{AC} and α_{FA} respectively), the following calculations are done:

$$\alpha_{AC} = p_{AC} \times \rho_C \times \frac{V_P}{M_{tot}} \quad \text{and} \quad \alpha_{FA} = p_{FA} \times \rho_{FA} \times \frac{V_P}{M_{tot}} \tag{3}$$

where ρ_c and ρ_{FA} are the densities of cement and fly ash respectively; V_p and M_{tot} are the paste volume and the concrete mass, respectively, for 1 m^3 of concrete (Table 1).

Based on the SEM images, α_{AC} and α_{FA} was found equal to 1.6 and 0.1 % respectively. This confirms that the residual anhydrous phases exist with contents lower than 4 %.

Furthermore, according to the SEM images, anhydrous particles contained in the original concrete are smaller than 80 µm. Since the preparation of the RCCF by crushing and sieving results in a powder with a lower median diameter ($D_{50} = 8.8$ µm), anhydrous phases are likely to be accessible to water. Thus, if used as partial substitute of cement in a concrete mixture, RCCF may contribute to the hydraulic reactions. Of course, the hydraulic reactivity of RCCF should be relatively low given the low content of anhydrous cement (as shown also by our calorimetry tests on RCCF). Moreover, their very low content of residual fly ash makes any pozzolanic reaction even less likely.

The next section presents the effect of RCCF on the behavior of fresh and hardened mortars.

3.2 Properties of mortars prepared with RCCF

Slumps and compressive strengths of mortars are given in Table 5.

3.2.1 Influence of RCCF on mortars consistency

Slumps of mortars made with RCCF or Limestone Filler (LF) are higher than in the case of the reference, whatever the substitution level. First, this could be surprising since RCCF and LF have higher fineness than cement. However, the water demands were measured lower for RCCF and LF than for cement (respectively 22, 19 and 25 %). Given this result, we can also state that water absorption of RCCF is low.

In order to evaluate the influence of the powder properties on mortars workability, the packing density of mixes made with various substitution levels of cement by RCCF or LF was calculated using the software called “René LCPC” developed by De Larrard and Sedran [25]. The input parameters are: specific weight, water demand and size distribution. For more details on the model, the reader is referred to [38]. As shown in Fig. 4, the calculated packing density tends to increase with the cement substitution for either RCCF or LF. This may be explained by a better arrangement of the solid particles. This result is in good concordance with tendencies observed for slump. In fact, with an increasing packing density, the amount of water needed to fill the porosity decreases and more water is available to make the mortar fluid [24].

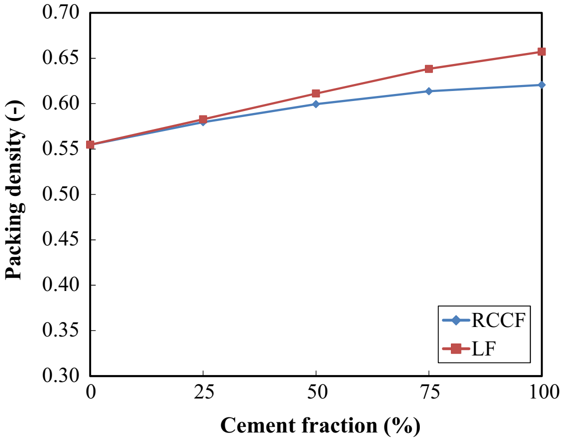


Fig. 4 Calculated packing densities of mixes of cement and fines (RCCF or LF)

Contrary to usual binary blend, Fig. 4 does not show any optimal packing density for a given mix. The optimization of the cement/RCCF ratio cannot be done from the packing density evolution.

3.2.2 Hydration kinetics

Calorimetry tests reveal that RCCF play a role in cement hydration. Figure 5 and Fig. 6 give the time-evolution of the heat release rate Q’ (h-1) related to the total heat Qtot (J) measured at the end of the calorimetry tests. The higher the substitution level is, the earlier the peak of heat rate is (see also Table 6).

Table 5 Properties of mortars (Ref, RCCF, LF)

	Ref	RCCF			LF		
		25	50	75	25	50	75
Slump (cm)	6.1 ± 0.15	8.5 ± 0.13	8.3 ± 0.19	8.0 ± 0.08	6.9 ± 0.18	7.5 ± 0.22	8.1 ± 0.15
f_c 2 days (MPa)	26.6 ± 0.89	24.8 ± 1.32	10.7 ± 0.14	2.5 ± 0.05	20.7 ± 1.14	10.7 ± 0.25	1.0 ± 0.63
f_c 7 days (MPa)	36.8 ± 0.26	32.7 ± 0.27	14.0 ± 0.06	5.7 ± 0.23	30.3 ± 0.69	14.8 ± 1.81	3.5 ± 0.04
f_c 28 days (MPa)	45.8 ± 1.45	38.4 ± 0.46	16.4 ± 0.19	4.2 ± 0.19	34.6 ± 1.31	18.1 ± 0.23	4.5 ± 0.23
f_c 90 days (MPa)	52.0 ± 2.15	38.7 ± 2.24	17.3 ± 0.91	4.6 ± 0.91	37.9 ± 1.82	21.6 ± 0.43	4.5 ± 0.05

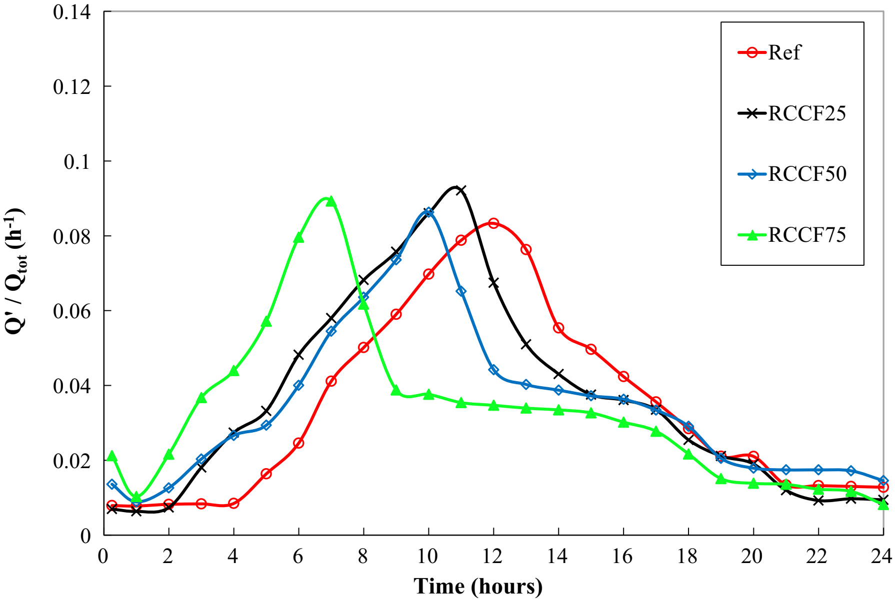


Fig. 5 Rate of heat evolution of mortars with RCCF

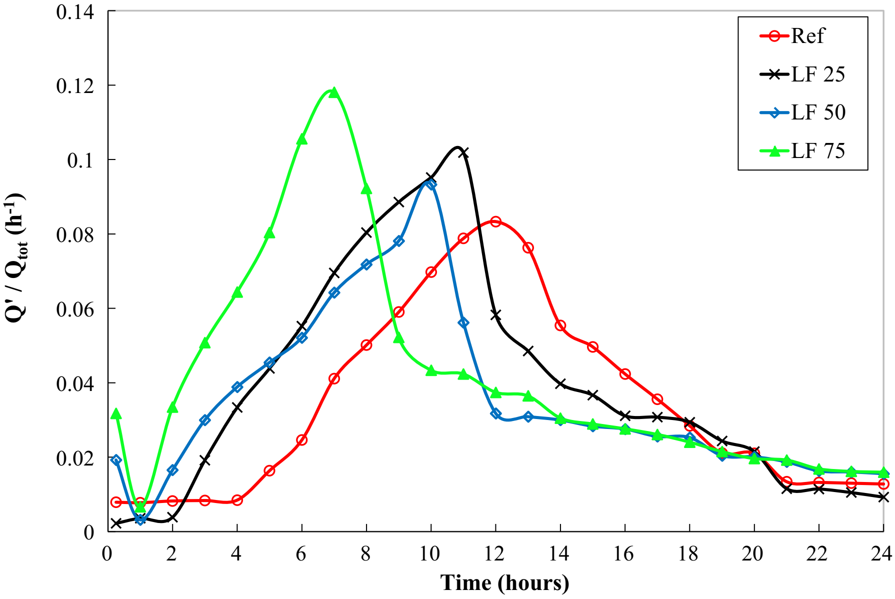


Fig. 6 Rate of heat evolution of mortars with LF

This acceleration of cement hydration is usually explained by the increase of surface available for the nucleation of C-S–H, which is confirmed by the higher specific area of RCCF and LF than cement (Table 3) [39–41]. However, recently Berodier and Scrivener [42] have revealed that this effect of surface provided for nucleation by mineral addition is not enough to explain the acceleration of hydration. Adding fineness addition decreases the interparticle distance and therefore increases the shear between the particles during mixing and thus enhances the dissolution of ions into the solution. Finally, the nature and mineralogical structure of limestone additions increases more or less the nucleation effect. It seems that the calcite promotes this effect compared to aragonite.

As shown previously, RCCF contains anhydrous cement which could participate to the heat release.

Table 6 Results from Langavant calorimetry tests (time of maximum heat rate and total heat Q_{tot}), calculated heats and calculated hydration degree (details in Sect. 3.2.2)

	Ref	RCCF			LF		
		25	50	75	25	50	75
Time of maximum heat rate (h)	12	11	10	6.75	11	10	7
Measured total heat Q_{tot} (J)	125,005	108,283	77,132	42,522	98,485	74,867	37,405
Heat released by RCCF Q_{RCCF} (J)	0	1123	2214	3330	0	0	0
Heat released by RCCF (% of total heat)	0	1	2.9	7.9	0	0	0
Heat released by cement Q_c (J)	125,005	107,160	74,919	39,192	98,485	74,867	37,405
Heat released by cement (J/g of cement)	344	378	399	415	347	392	384
Hydration degree of cement (%)	0.69	0.76	0.80	0.83	0.69	0.78	0.77

Table 6 gives the total heat Q_{tot} obtained from Langavant tests and the heat Q_{RCCF} potentially released by RCCF (LF was assumed not to release heat). Q_{RCCF} was calculated from the RCCF content of mortars and assuming that 1 g of RCCF released 15 J (see Sect. 3.1.3). Of course, this is a rough estimation since the latter value was obtained for W/RCCF = 0.45, ratio different from that used in the studied mortars. However, the so-calculated heat from RCCF appears to be negligible compared to the total heat (except in the case of the mortar with 75 % of cement substitution level). It can be concluded that the measured heat is mainly due to the cement hydration.

The heat released by hydration cement was then assessed by subtracting the heat from RCCF from the total heat ($Q_c = Q_{tot} - Q_{RCCF}$). Expressed in J per g of cement, the so-obtained values show that the heat release rate increases with the cement substitution. The substitution of cement by RCCF has not only an acceleration effect on hydration but it also increases the degree of hydration of cement. In Table 5, degrees of hydration were calculated as the ratio of the heat released by cement and the maximum heat for a complete hydration, i.e. 500 J/g of cement (values obtained using the mineralogical composition and model of Schindler and Folliard [43]). The increase in hydration degree can result from the presence of RCCF but also from the increase of *W/C* ratio consecutive to the substitution (Eq. 1).

These results show that the influence of RCCF on cement hydration is similar to that commonly observed for limestone filler.

3.2.3 Compressive strength

Figures 7 and 8 show the relative compressive strength of mortars containing RCCF and LF compared to the reference mortar, depending on time and level of substitution.

The higher the level of substitution, the lower relative compressive strength of mortars is, whatever the curing time. However, for a given substitution level, the relative compressive strengths are higher at 2 and 7 days than at 28 or 90 days. This confirms the effect of acceleration and increase of the hydraulic reactivity of cement due to RCCF.

As for the substitution level, it must obviously be limited because the loss of mechanical performance is too high when it reached 50 %. Note that, according to

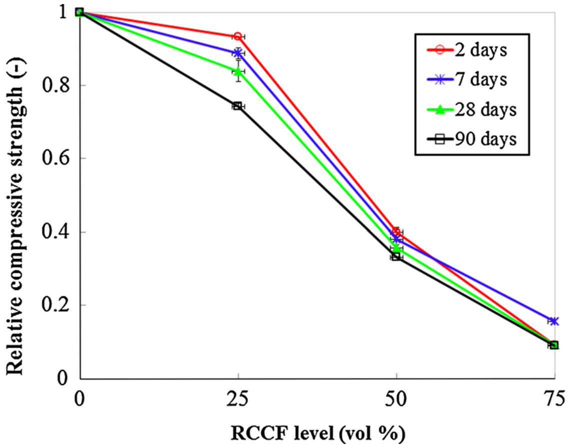


Fig. 7 Effect of RCCF on relative compressive strength of mortars

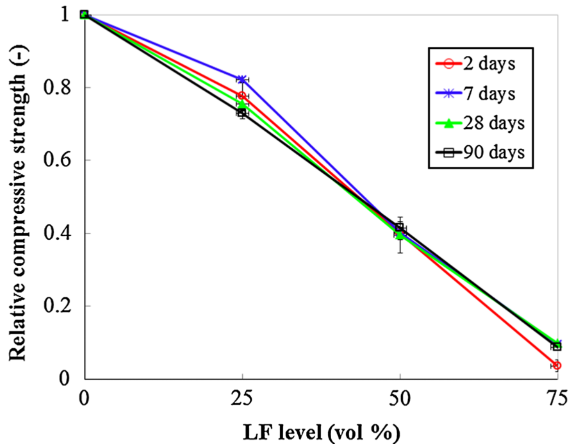


Fig. 8 Effect of LF on relative compressive strength of mortars

the European standard EN 206-1, the maximum substitution level of cement by LF is 25 %. The relative compressive strengths at 28 days of RCCF mortars are at least equal to those of LF mortars. Especially, it is quite possible to substitute 25 % of cement by RCCF to obtain the same performance than in the case of LF.

Based on the approach proposed in [12], activity coefficients of RCCF and LF were deduced from the compressive tests using the Bolomey formula (Eq. 4). For a given aggregate type, the parameter K_B depends only on the cement activity. The activity coefficient χ_B gives equivalence between the mass of mineral addition and the mass of cement. K_B was calculated using strengths f_c measured for the reference mortar (Eq. 5). χ_B was calculated using results for RCCF and LF mortars (Eq. 6).

$$f_c(t) = K_B(t)\left(\frac{C+\chi_B(t)A}{W+V} - 0.5\right) \tag{4}$$

$$K_B(t) = f_c(t) \Big/ \left(\frac{C}{W+V} - 0.5\right) \tag{5}$$

$$\chi_B(t) = \left[\left(\frac{f_c(t)}{K_B(t)} + 0.5\right)(W+V) - C\right] \Big/ A \tag{6}$$

where $f_c(t)$ is the compressive strength at the age t; $K_B(t)$ and $\chi_B(t)$ are the constant of Bolomey and the coefficient of activity at t, respectively; C, A and W are the masses of cement, mineral addition (RCCF or LF) and water, respectively; V is the mass of water equivalent to the volume occupied by the air entrained in the mixture.

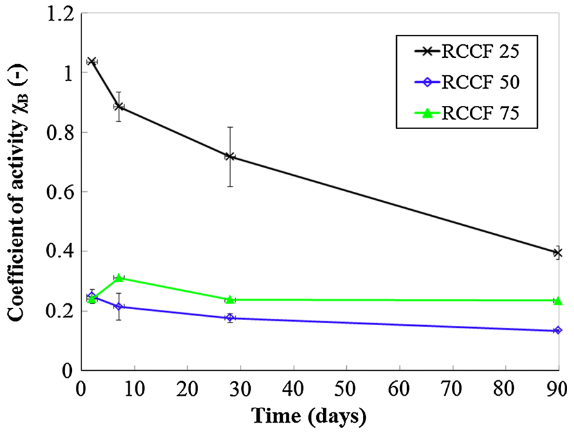


Fig. 9 Time-evolution of coefficients of activity for RCCF

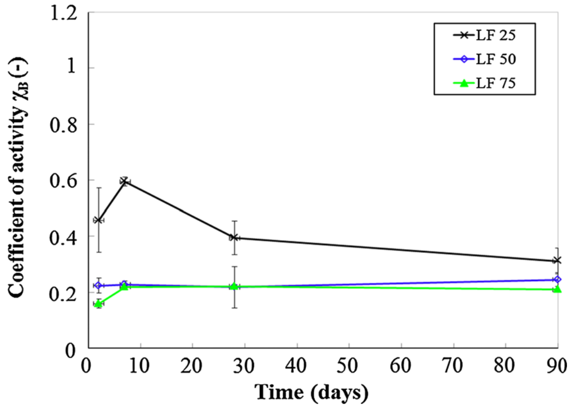


Fig. 10 Time-evolution of coefficients of activity for LF

Figures 9 and 10 show the evolution of the activity of RCCF and LF at different ages.

It is interesting to note that the coefficient of activity of RCCF is non-zero regardless of age and substitution level. Compared to LF, RCCF has a higher activity coefficient, especially at early age for substitution level of 25 %. At long term, RCCF and LF tend to have the same activity.

4 Conclusion

Compared to LF, We have highlighted that the studied RCCF (Recycled Crushed Concrete Fines) have very similar properties than LF, i.e.: accelerating and increasing the cement hydration. Particularly, we note that:

- slumps of mortars with RCCF are higher than those of OPC mortar,
- compressive strengths of mortars with RCCF are at least equal to those of LF mortars,
- activity coefficients of RCCF are higher at the early age than those of LF, especially for a cement substitution of 25 %.

The studied RCCF contains anhydrous cement which is likely to react because of the high fineness of the powder but also filler effect. However, theoretical assessments completed by measurements (from SEM images analysis) highlight that the anhydrous cement content of the RCCF is low (less than 4 %). Thus, our RCCF are little hydraulic, what was confirmed by calorimetry tests.

Moreover, our experimental campaign was carried out in the case of a particular source concrete, made with limestone aggregates.

Our results are encouraging for new ways of recovering of concrete from demolition sites. Moreover, the use of RCCF as a substitute of limestone filler may be a practical solution to reduce quarrying and CO_2 emissions of concrete resulting from clinker.

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