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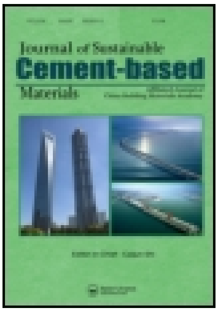

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Influence of hardened cement paste content on the water absorption of fine recycled concrete aggregates

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Influence of hardened cement paste content on the water absorption of fine recycled concrete aggregates

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A linear relationship was found between the mean size of four granular classes (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm) of different laboratory-made fine recycled concrete aggregates (FRCA) and their hardened cement paste content (CPC). A method based on salicylic acid dissolution was specifically developed for the measurement of CPC. Results showed that bound water and density of FRCA were strongly correlated with their CPC. Identically, the water absorption coefficient also followed a linear trend as a function of the CPC but only for the three coarser granular classes. Indeed, the water absorption coefficient of the finer fraction of FRCA (0/0.63 mm) cannot be correctly measured using European standard method EN 1097-6 or method no. 78 of IFSTTAR; but it can be obtained by extrapolation from the previous linear trend. As a consequence, the accurate total water absorption of FRCA (fraction 0/5 mm) can be estimated.

Keywords: cement paste; recycled concrete aggregates; water absorption; salicylic acid; granular class; porosity

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1. Introduction

With the rapid development of construction industry, lots of construction and demolition wastes (C&DW) are generated yearly in the world.[1–4] Meanwhile, good quality natural aggregates (NA) are in shortage. Up to now, only a small proportion of C&DW is reused. Components of C&DW typically include concrete, wood, metals, gypsum, asphalt, bricks, and other materials.[5–7] Old concrete is the most abundant material among various types of C&DW. The use of recycled concrete aggregates (RCA) crushed from old concrete to replace or partially replace the NA has become more common.

RCA are mainly composed of an intimate mix between NA and cement paste and the complete separation between these two phases seems to be a difficult task. Cement paste generally presents a much larger porosity than NA; the content and the physicochemical properties of cement paste, therefore, have a large influence on the properties of RCA. The coarse fraction of RCA (CRCA), essentially composed of natural gravel, generally possesses satisfying properties for the reuse as concrete aggregates. Lots of studies [8–11] have been dedicated to their characterization and to the study of properties of concretes containing CRCA. However, the fine fraction of RCA (FRCA), containing a larger content of mortar and cement paste, possesses a large water demand which makes it harder

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to recycle into concrete. Concrete manufactured with FRCA generally presents a lower workability, a lower strength, and a lesser durability than similar concrete composed of NA.[12–15] However, much less studies have been dedicated to FRCA, and there is in particular no general study on the quantitative influence of cement paste content (CPC) on the other properties of FRCA.[16]

Up to now, there is no standard test to measure CPC in RCA; however, different methods have been found in the literature:

- Thermal treatment [17]: this method is based on several cycles of soaking in water and heating of the aggregates, which allows detaching progressively adherent mortar from coarse aggregates surface because of micro-cracks occurring at the interface between aggregates and mortar. This method is only suitable for CRCA because the removal of mortar necessitates "brushing" the RCA, which is difficult with small particles.
- Treatment with a solution of hydrochloric acid [18]: this method is based on the dissolution of cement paste in a solution of hydrochloric acid. Unfortunately, it cannot be used with limestone aggregates and filler, which is also dissolved by hydrochloric acid.
- Image analysis [19]: image analysis is used to quantify the amount of residual mortar on flat polished section. This method is suitable for quantification of residual mortar in CRCA, but the distinction between fine aggregates and cement paste is more difficult to carry out. Moreover, this method is long to perform as a statistical approach is needed.

None of the above-mentioned methods seems to be adapted to the characterization of CPC in FRCA, especially for RCA containing calcareous aggregates. However, CPC in FRCA is closely related to the water absorption of FRCA that plays an important role in the manufacture of concrete. Indeed, it has to be measured precisely in order to determine the efficient water content in concrete. However, the methods used to measure the water absorption coefficient of fine aggregates are generally not accurate for materials containing large fractions of fine particles.[20–21]

The objectives of this paper are the following:

(1) develop a simple method for the measurement of CPC of FRCA;
(2) relate the CPC to different physical properties such as the water absorption coefficient as a function of four different granular classes (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm; here, for example, 0.63/1.25 mm stands for the minimum and maximum particle sizes, respectively, 0.63 and 1.25 mm of the granular class); and
(3) propose a new method for determining the water absorption coefficient of the finer fraction of FRCA.

This study is based on laboratory-made FRCA produced from three concretes that have been prepared in the laboratory with two water–cement ratios (W/C) and two paste volumes. As a consequence, the original concrete composition was known and also FRCA were not subjected to weathering during storage.

2. Materials and methods

2.1. Materials

Three original concretes with two different W/C ratios and volumes of paste

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were designed and manufactured for production of FRCA. Table 1 shows the details of original concrete compositions. OC1 and OC2 had the same W/C ratio and OC2 and OC3 had the same volume of cement paste. The cement used in this study was a white OPC (CEM I 52.5 "superblanc") provided by Lafarge company whose mineralogical composition is shown in Table 2. Crushed calcareous sand and calcareous coarse aggregates sourced from Tournai (provided by Holcim France Benelux) were used for production of all original concretes. After 28 (RCA-28) and 90 (RCA-90) days curing in water, original concretes have been crushed in the laboratory by using a jaw crusher with the same opening size (10 mm). After crushing, RCA have been dried in the oven at 105 °C. The cumulated and partial particle size distributions (PSD) of all the crushed RCA are given in Figures 1 and 2. These figures show that, with the same jaw crusher opening, very similar PSD can be obtained for all the concretes produced in the laboratory, whatever their properties and compositions. Nevertheless, RCA-90 for the three concretes were coarser than RCA-28. All the crushed RCA have been separated into CRCA and FRCA. In this study, we focus on the properties of FRCA (0/5 mm). FRCA have then been separated by sieving in four different granular classes (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm) in order to study the influence of granular class on the properties of recycled aggregates. In the following, each granular class is represented by its average particle size, corresponding to the average value of the minimal and maximal particle sizes of the granular class. Each class has been tested for CPC, water absorption, density, porosity, and bound water content.

2.2. Experimental methods

2.2.1. Cement paste content

A method based on salicylic acid dissolution has been developed for the characterization of CPC in FRCA. Salicylic acid has been chosen because it allows the dissolution of most phases

Table 1. Original concrete compositions made in the laboratory (1 m^3).

Type of original concrete	OC1	OC2	OC3
Aggregate (kg)	1138.3	1040.7	1018.9
Sand (kg)	756.4	691.5	677.0
Cement (kg)	298.8	375.7	474.8
Efficient water(kg)	179.3	225.4	189.9
Absorbed water(kg)	17.2	15.7	15.4
Total water(kg)	196.5	241.1	205.3
Coarse aggregate/sand	1.505	1.505	1.505
W/C ratio	0.6	0.6	0.4
Volume of cement paste (dm^3)	278	350	347
Density of fresh concrete(kg/m^3)	2390	2349	2376
Slump (cm)	5.8	20.3	5.6
fc_{28} (MPa)	41.1	40.8	51.0
fc_{90}(MPa)	47.3	46.4	57.6

Table 2. Mineralogical composition of cement determined by XRD-rietveld.

	C_3S	C_2S	C_3A	C_4AF	Anhydrite	Calcite	Periclase
CEM I 52.5 superblanc (%)	73.90	21.87	1.46	–	0.52	1.53	0.72

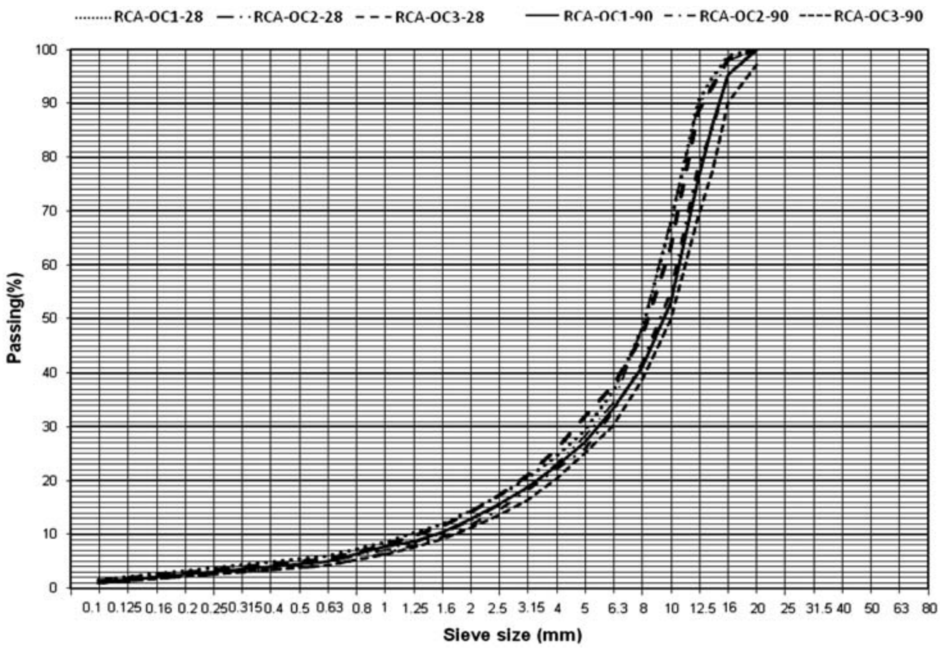

Figure 1. Cumulated PSD of crushed RCA.

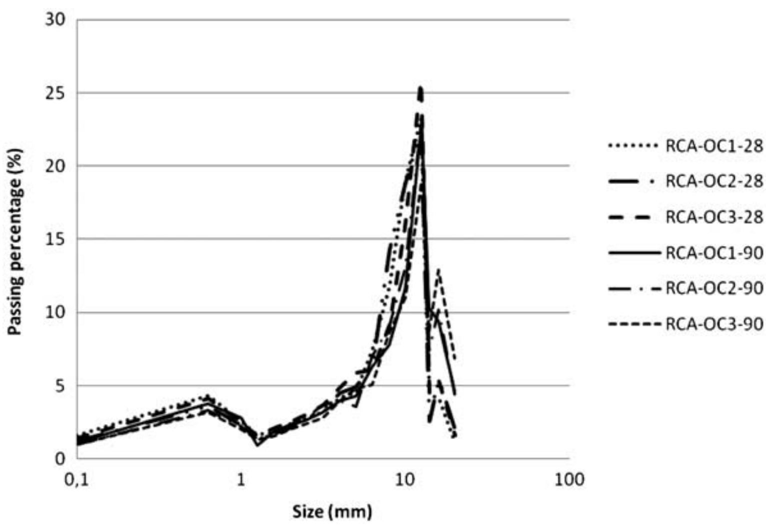

Figure 2. Partial PSD of crushed RCA.

contained in OPC cement paste but not of the main phases contained in NA and especially limestone (Table 3).[22–26] Three samples of each granular class of FRCA have been measured to obtain an average value of the CPC.

The experimental protocol used is as follows:

(1) a representative sample has been dried at 105 °C, then grinded until passing 0.2 mm sieve;

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Table 3. Insoluble and soluble phases in salicylic acid and methanol.

Insoluble phases	Soluble phases
C_3A, C_4AF	C_2S, C_3S
Quartz, Dolomite	CaO, $Ca(OH)_2$
Calcite (limestone)	C–S–H
C_3AH_6, calcium monosulfoaluminate hydrate	Ettringite

(2) 0.5 g of dried representative sample has been immersed in a solution of 14 g of salicylic acid in 80 ml of methanol, and stirred for 1 h;
(3) the solid fraction has been filtered on glass filter (Pyrex No. 4, pores: 10–16 μm) and washed four times using methanol (2–3 mm high on top of filter);
(4) the solid residue has been dried in the oven at 70 °C for 30 min; and
(5) the CPC is then calculated as follows:

$$\mathrm{CPC}(\%) = \frac{M_1 - M_2}{M_1} \times 100 \qquad (1)$$

where M_1 is the mass of dried material before dissolution and M_2 is the mass of dried filtrate.

In order to validate this method, preliminary tests have been carried out with NA and a pure cement paste having a W/C ratio of 0.5. The cement paste was manufactured with the same white cement CEM I 52.5 "Superblanc" used for the rest of the study. Two kinds of NA were used: a crushed calcareous aggregate from Tournai (the same as that used for the production of concretes OC1, OC2 and OC3) and a siliceous sand complying with standard EN 196-1 [27]. Table 4 presents the results after dissolution. As can be seen, 95.6% of the cement paste was dissolved while only 0.83% of siliceous aggregate and 3.21% of calcareous aggregates were dissolved. A small deviation is observed for all materials that confirms the robustness of the method.

2.2.2. *Bound water content*

A thermal method has been used to determine the bound water content at 600 °C of the cement paste in FRCA. Three samples of each granular class of FRCA have been measured to obtain the average value. The experimental protocol used is as follows:

(1) representative samples have been grinded until passing 0.2 mm sieve;
(2) the grinded representative samples have been pre-dried in the oven at 105 °C until constant mass (1 day);
(3) dried samples were put in the oven at 600 °C until constant mass (1 day);
(4) the bound water content is calculated from the mass difference between 105 and 600 °C.

In order to validate this method, thermogravimetric analysis (TGA) of cement paste, calcareous sand, siliceous mortar, and calcareous mortar have been carried out (Figure 3). This figure shows

Table 4. Results of preliminary tests with salicylic acid dissolution-1 h (mass dissolved %).

	Test 1	Test 2	Test 3	Average value	Standard deviation value
Cement paste	95.46	96.35	94.89	95.57	0.74
Siliceous sand	0.76	0.86	0.88	0.83	0.06
Calcareous sand	3.42	3.03	3.18	3.21	0.20

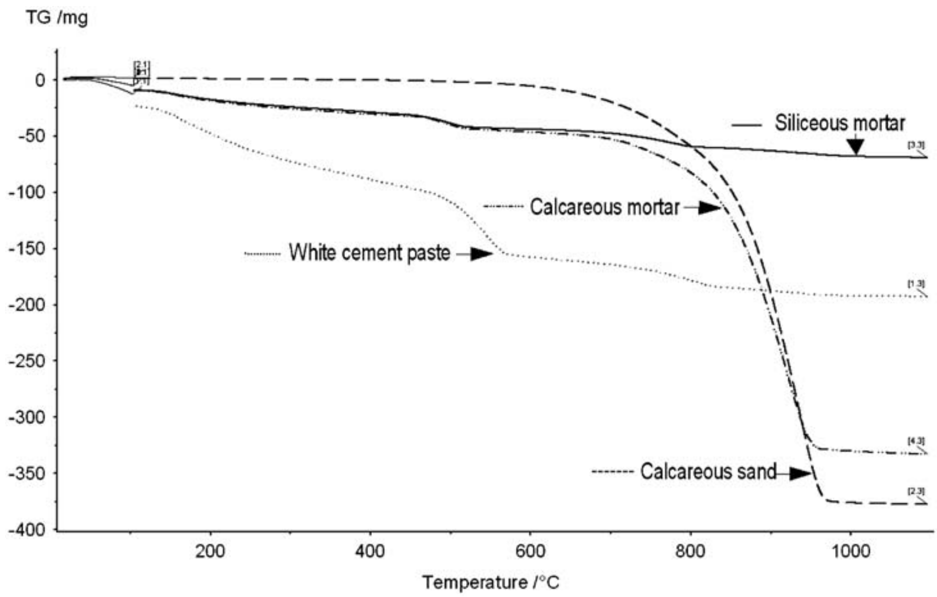

Figure 3. TGA results obtained on cement paste, calcareous sand, siliceous mortar, and calcareous mortar.

that calcareous sand and mortar decarbonize over 600 °C whereas most of the pure cement paste is dehydrated below 600 °C. Indeed, several authors [28–30] have shown that the dehydration of C–S–H is about 180–300 °C and the dehydration of CH (Portlandite) is about 450–550 °C. Therefore, a heating at 600 °C has been chosen for the measurement of bound water content as it allows avoiding the decarbonation of aggregates. The mass loss at 600 °C comes only from the dehydration of cement paste hydrates, and not from aggregates, it is, therefore, a good indicator of the CPC in the material.

2.2.3. *Water absorption*

The water absorption coefficient of each granular class of the FRCA has been measured with two different methods: the European standard method EN 1097-6 [31] and the method no. 78 of IFSTTAR. [32] Three samples of each granular class of FRCA have been measured to obtain the average value.

The principle of these methods is similar: in both cases, samples are saturated for 24 h in water and then the water absorption coefficient is determined based on the water content at saturated surface dry (SSD) state. However, the drying method and the way to identify the SSD state are totally different. In the standard method (EN 1097-6), saturated aggregates are exposed to a gentle current of warm air to evaporate surface moisture and to reach the SSD state. The latter is identified using a slump test on the drying sample, which allows detecting the existence of cohesion forces due to surface moisture. A metal cone mould is filled with the drying sample and lifted gently to let the aggregate flow under the effect of gravity. The shape of the aggregate cone obtained after lifting allows identifying the SSD state (Figure 4). In the IFSTTAR method, the aggregates are dried progressively with different sheets of colored absorbent paper until no trace of water can be seen on the paper (the surface of each sheet of colored absorbent paper was wiped carefully with a

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Figure 4. Shape of cone corresponding to the SSD state (EN 1097-6 method).

brush to ensure that no fine particles remain attached on the paper). In that state (SSD state), no moisture remains at the surface of particles (third sheet of paper on Figure 5).

2.2.4. *Density*

For each RCA and each granular class, representative samples have been pre-dried in the oven at a temperature of 105 °C, and then specific density has been measured by using helium pycnometer (Micromeritics AccuPyc 1330).

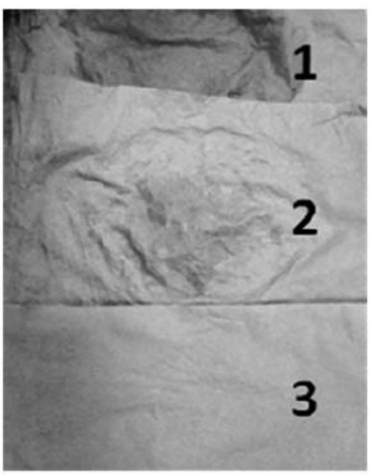

Figure 5. Trace of water after successive dryings with absorbent paper (IFSTTAR method).

2.2.5. *BET specific surface area and BJH porosity*

The specific surface area of each granular class of each FRCA has been measured by using Brunauer–Emmett–Teller (BET) analysis using N_2 adsorption (Micromeritics ASAP 2010). Representative samples have been pre-dried in the oven at a temperature of 105 °C and then cooled down in desiccators to room temperature. These samples have then been used in the BET analysis. Barrett–Joyner–Halenda (BJH) analysis has been employed to determine pore area and specific pore volume on desorption isotherms.[33]

3. Results and discussion

3.1. Cement paste content

Figure 6 presents the variation of CPC as a function of granular class for all the FRCA studied. As can be seen in Figure 6, CPC is higher as the average particle size decreases. A reasonable linear relation between CPC and granular class is obtained. The correlation

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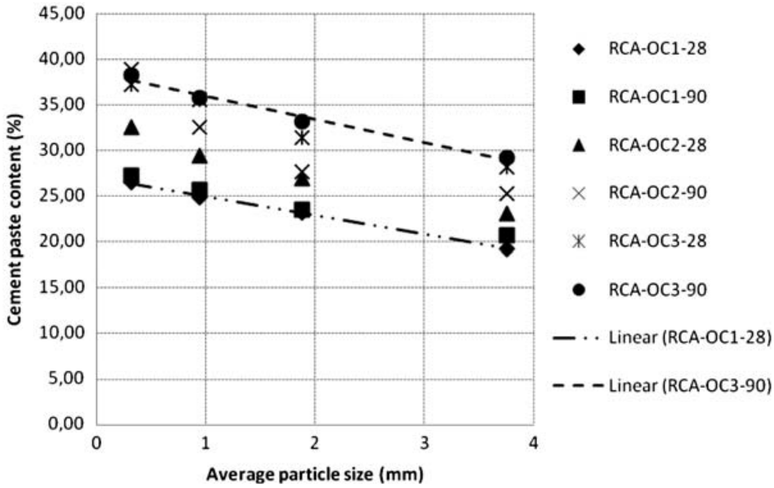

Figure 6. CPC as a function of the average size of the four different granular classes considered (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm).

coefficients obtained (R^2) range from 0.8189 to 0.9985. For all the FRCA, the larger values obtained for RCA-90 comparatively to RCA-28 can be attributed to the longer curing time in water. The longer the curing in the water, the higher degree of hydration of cement paste, and then the higher the CPC in the parent concrete. Indeed, the mass of hydrated cement paste is higher than the mass of initial anhydrous cement, because an additional quantity of water is added to the initial anhydrous cement during hydration. The larger values obtained for RCA-OC2 comparatively to RCA-OC1 can be attributed to the higher volume of cement paste in the original composition. Similarly, the larger values obtained for RCA-OC3 comparatively to RCA-OC2 can be attributed to a lower W/C ratio in the original composition, leading to a denser cement paste and, therefore, to a larger mass of cement paste for a similar paste volume. Therefore, the CPC of FRCA is influenced by the W/C ratio and the cement paste volume of the original concrete.

Bound water content is connected with the degree of hydration and CPC. Figure 7 shows the bound water content of FRCA as a function of granular class. As can be seen, the bound water content increases as the average particle size decreases for all FRCA. A reasonable linear relation between bound water content and granular class is obtained, which confirms that the CPC varies quasi linearly with the four granular classes that were used.

3.2. *Water absorption*

Figures 8 and 9 show the variation of water absorption coefficient of RCA-28 and RCA-90 measured with the two methods (EN1097-6 and IFSTTAR). The results obtained for RCA-OC1 and RCA-OC3 are very similar, whatever the granular class. On the contrary, the water absorption coefficients obtained with all the granular classes of RCA-OC2 are significantly larger than those obtained with RCA-OC1 and RCA-OC3. The larger values obtained for RCA-OC2 comparatively to RCA-OC1 can be attributed to the higher volume of cement paste in the original composition. Similarly, the larger values obtained for

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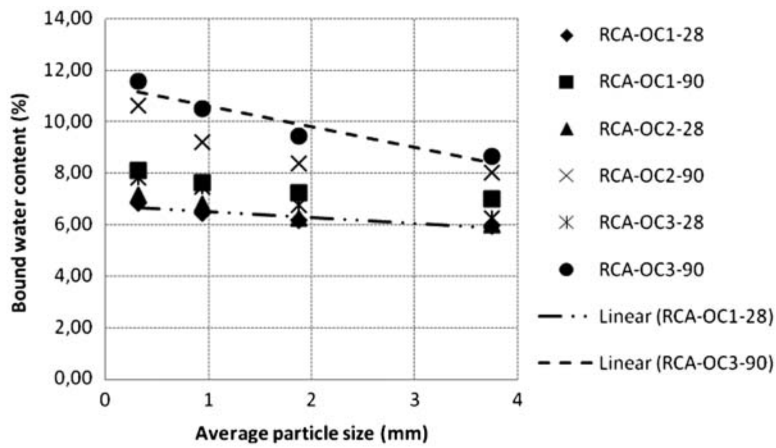

Figure 7. Bound water content as a function of the average size of the four different granular classes considered (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm).

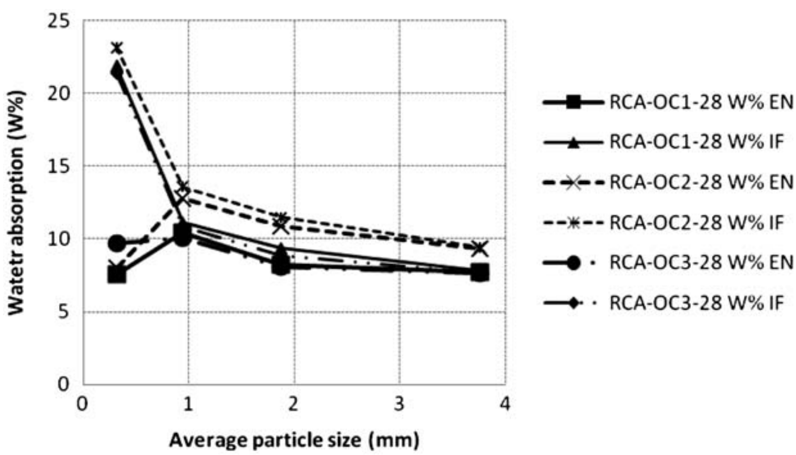

Figure 8. Water absorption of RCA-OC-28 measured by EN1097-6 and IFSTTAR methods as a function of the average size of the four different granular classes considered (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm).

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RCA-OC2 comparatively to RCA-OC3 can be linked to a larger W/C ratio in the original composition, leading to a greater porosity of the cement paste.

The results obtained with the two experimental methods (EN1097-6 and IFSTTAR) were very close from one to another except for the smaller fraction (0/0.63 mm). For all FRCA tested in our study, the water absorption coefficient increased when the average particle size decreased except for the fraction 0/0.63 mm with the standard EN1097-6. For the smaller fraction, the standard method does not allow to identify precisely the SSD state. Indeed, for very small angular particles (like those obtained from crushed concrete), the sand can present some cohesion even if all the water at the surface of particles has been removed, preventing the sand cone to collapse [34]. The standard method,

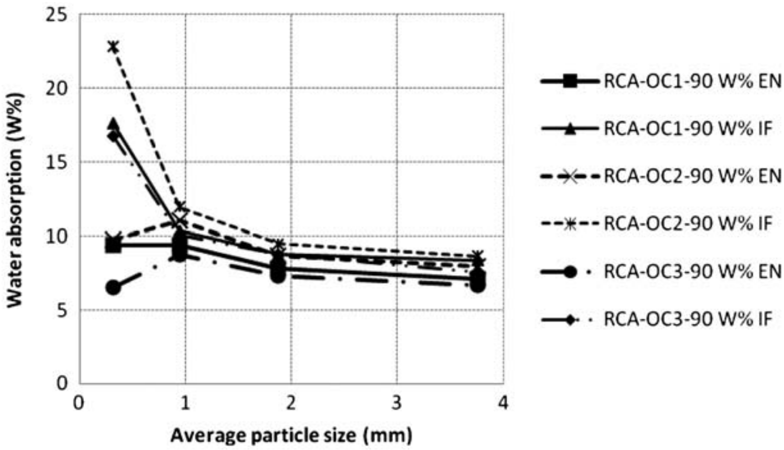

Figure 9. Water absorption of RCA-OC-90 measured by EN1097-6 and IFSTTAR methods as a function of the average size of the four different granular classes considered (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm).

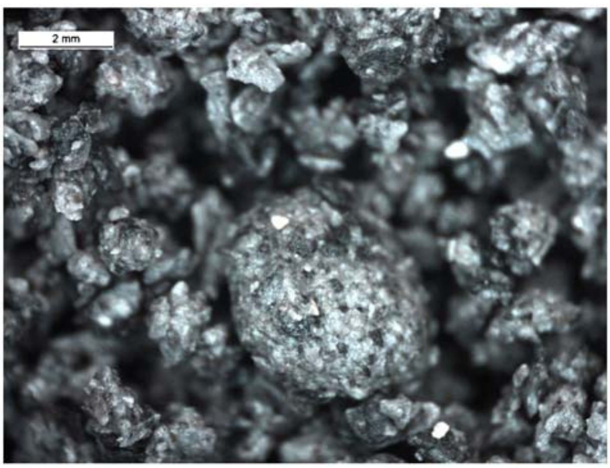

Figure 10. Optical microscopy of fraction 0–0.63 mm of RCA-OC1-28 at SSD state by the IFSTTAR method.

therefore, underestimates the water absorption coefficient for small particles. On the contrary, with IFSTTAR method, the water absorption coefficient increases a lot for the smaller fraction. Figure 10 presents an optical microscopy image of the fraction 0–0.63 mm of RCA-OC1-28 at SSD state with IFSTTAR method. As can be seen, agglomerates larger than 2 mm (much larger than the maximum particle size of 0.63 mm) are present. This result is due to the fact that very small particles tend to agglomerate during drying because of capillary forces. Absorbent paper allows drying the surface of these agglomerates, but the method used does not allow breaking them. IFSTTAR method, therefore, overestimates the water absorption coefficient of the finer fraction.

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3.3. Density and porosity

Figure 11 presents the variation of density measured with the helium pycnometer as a function of granular class. The density of all the fractions of FRCA is lower than that of NA (2.67 g/cm^3). This is due to the cement paste surrounding NA, whose density is smaller than that of natural calcareous aggregates. Figure 11 also shows that the density of FRCA increases as the average particle size increases.

Figure 12 shows the BJH porosity of all the granular classes of FRCA. The porosity of FRCA increases as the average particle size of FRCA decreases. The larger values obtained for RCA-OC2 comparatively to RCA-OC1 can be attributed to the higher volume of cement paste in the original composition of OC2 (same W/C ratio). Similarly, the larger values obtained for RCA-OC2 comparatively to RCA-OC3 can be attributed to a larger W/C ratio in the original composition of OC2 (same volume of cement paste), leading to a larger porosity of the cement paste. So, as expected, the porosity of FRCA is influenced by the W/C ratio and the cement paste volume of the original concrete. Generally, the porosity

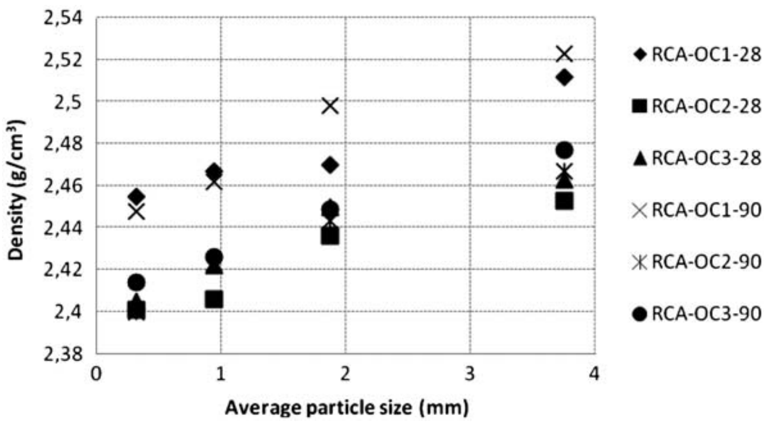

Figure 11. Density of FRCA as a function of the average size of the four different granular classes considered (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm).

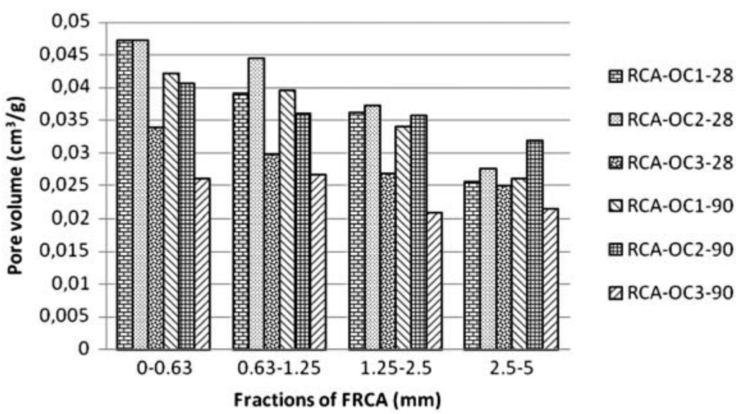

Figure 12. BJH porosity of FRCA as function of the average size of the four different granular classes considered (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm).

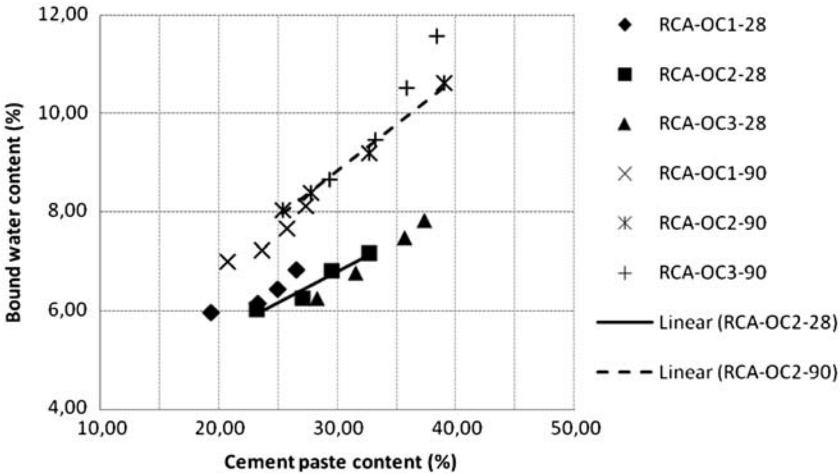

Figure 13. Bound water vs. CPC.

of RCA-90 is lower than RCA-28 which is due to higher hydration degree of cement paste (except for the fractions 0.63–1.25 and 2.5–5 for RCA-OC1 and for the fraction 2.5–5 for RCA–OC2).

3.4. Relationships between CPC and the other studied properties

Figure 13 shows the variation of bound water content as a function of CPC. For a given original concrete composition and a given hydration degree, the bound water content increases linearly with the CPC (R^2 ranges from 0.867 to 0.9978). Table 5 shows that the slope of bound water to cement paste is similar for RCA-OC1 and RCA-OC2, and the slope of RCA-OC 90 is higher than RCA-OC 28. Indeed, the mass dissolved in salicylic acid and the mass loss at 600 °C both depend closely on the cement paste proportion in the material. However, salicylic acid leads to the dissolution of both anhydrous phases (except C_4AF) and hydrates whereas heating at 600 °C only leads to the decomposition of hydrates but does not affect the anhydrous phases. Therefore, when comparing two cement pastes having different hydration degrees like in Figure 13, the mass loss at 600 °C will be larger for the cement paste having the larger hydration degree. Indeed, for a given CPC (measured by the mass dissolved in salicylic acid), the paste with the larger hydration degree contains more hydrates than the one with the lower hydration degree.

Figure 14 shows the variation of specific density as a function of CPC. When CPC increases, specific density decreases linearly. The density of RCA directly depends on density of cement paste and of NA and on the proportion of cement paste. For a given RCA, if ρ_{NA} is the density of NA and ρ_{CP} is the density of cement paste, then the density of a given granular fraction of RCA (ρ_{RCA}) can be calculated with Equation (2):

Table 5. Coefficients of the linear relationships between bound water content and CPC ($y = ax + b$).

	a	b	R^2
RCA-OC1-28	0.1134	3.684	0.867
RCA-OC2-28	0.1265	3.0191	0.9448
RCA-OC3-28	0.1722	1.3674	0.9978
RCA-OC1-90	0.1699	3.3695	0.9262
RCA-OC2-90	0.1895	3.1609	0.9919
RCA-OC3-90	0.3246	−1.0356	0.9688
RCA-OC-28	0.1025	3.77	0.8573
RCA-OC-90	0.2387	1.741	0.9516

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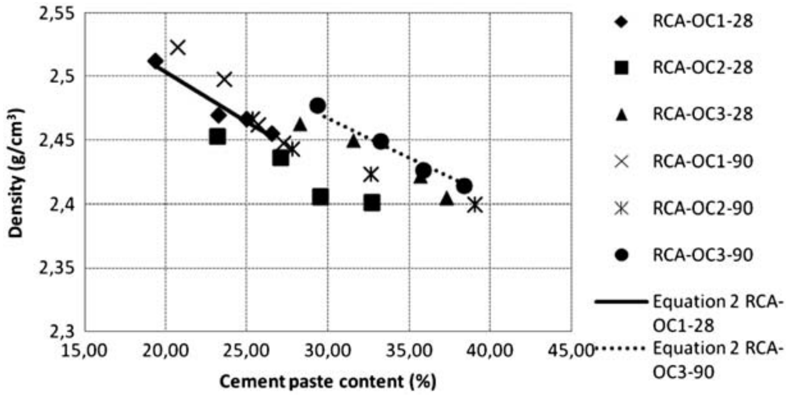

Figure 14. Correlation between cement paste and specific density.

Table 6. Density of cement paste calculated by the correlation between density and cement paste Equation (2).

	RCA-OC1-28	RCA-OC2-28	RCA-OC3-28	RCA-OC1-90	RCA-OC2-90	RCA-OC3-90
Density	2.002	1.962	2.068	2.035	2.038	2.095
R^2	0.9533	0.9230	0.9728	0.9805	0.9615	0.9926

$$\rho_{RCA} = \frac{\rho_{NA}}{1 + CPC \times \frac{\rho_{NA} - \rho_{CP}}{\rho_{CP}}} \qquad (2)$$

where CPC is the CPC of the considered granular fraction.

The density of each cement paste can then be obtained by fitting Equation (2) with our experimental results (Table 6). Table 6 shows that the densities of cement paste in RCA-OC1-28 and RCA-OC2-28 (similarly for RCA-OC1-90 and RCA-OC2-90) are similar as expected. Indeed, cement paste of RCA-OC1 and RCA-OC2 have the same W/C ratio. Moreover, the larger values obtained for RCA-OC3 comparatively to RCA-OC1 and RCA-OC2 can be attributed to the lower W/C in the original composition. As the hydration degree of original concrete increases (from RCA-28 to RCA-90), the density of cement paste increases. Table 6 also shows that the correlation coefficients obtained between calculated and experimental value (R^2) range from 0.9230 to 0.9926.

Figure 15 presents the variation of water absorption (IFSTTAR method) with the CPC: when CPC increases, the water absorption increases too. As can be seen, the water absorption of all FRCA varies linearly with the CPC for the three coarser average particle sizes of RCA. On the contrary, as discussed previously, the water absorption measured by standard or IFSTTAR method for the finer fraction seems to be either underestimated or overestimated, respectively (example for RCA-OC3-90 shown on Figure 15). The water absorption of RCA directly depends on the water absorptions of cement paste and of NA and on the proportions of cement paste. For a given original concrete composition, the water absorption coefficients of NA (WA_{NA}) and of the cement paste (WA_{CP}) do not depend on the granular fraction considered. Therefore, the water absorption of a given granular fraction of RCA (WA_{RCA}) can be calculated with Equation (3) (see Table 7).

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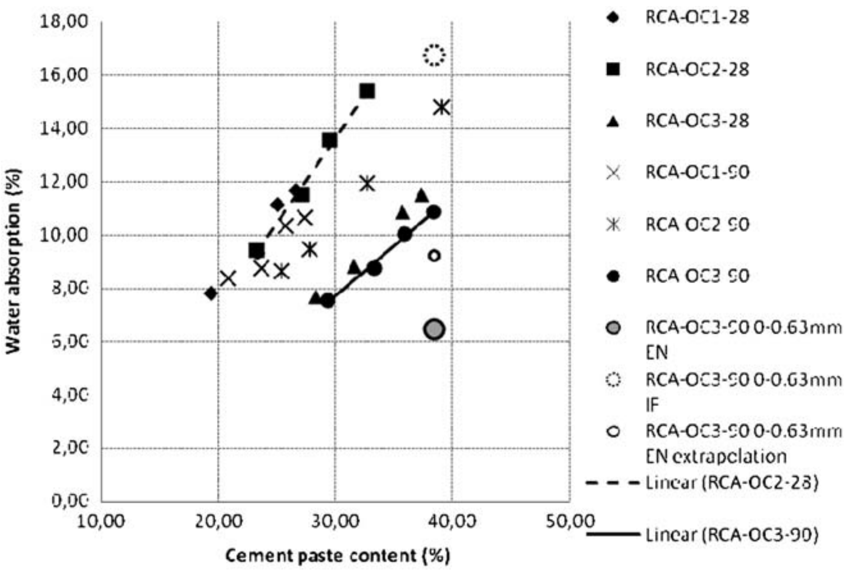

Figure 15. Correlation between water absorption (IFSTTAR method) and CPC.

Table 7. Coefficients of the linear relationships between water absorption (IFSTAAR method for three coarse fractions) and CPC ($y = ax + b$).

	a	b	R^2
RCA-OC1-28	0.5567	−3.0928	0.9318
RCA-OC2-28	0.6408	−5.51	0.9829
RCA-OC3-28	0.433	−4.6383	0.991
RCA-OC1-90	0.3825	0.235	0.8265
RCA-OC2-90	0.4581	−3.0639	0.9925
RCA-OC3-90	0.3775	−3.5786	0.9801

$$\mathrm{WA_{RCA}} = \mathrm{WA_{CP}} \times \mathrm{CPC} + \mathrm{WA_{NA}} \times (1 - \mathrm{CPC}) \quad (3)$$

where CPC is the CPC of the considered granular fraction.

Equation (3) shows that the water absorption coefficient of RCA has to vary linearly with the CPC. Therefore, the water absorption coefficient of the finer fraction (0/0.63 mm) can be obtained by linear extrapolation of the relation between WA and CPC determined with the three coarser fractions of RCA. Extrapolation carried out using both standard and IFSTTAR methods gives similar values for the water absorption coefficient of the finer fraction (Table 8); the average difference between these two values obtained for the six FRCA is 1.06%. As expected, the value of water absorption coefficient of finer fraction obtained is between the value obtained by the standard and IFSTTAR methods. In Figure 15, the water absorption coefficients of the smaller granular classes (0–0.63 mm) correspond to the extrapolated values from experimental results with IFSTATAR method. The values obtained by the standard and IFSTTAR methods are also reported for RCA-OC3-90 to demonstrate that these values are not appropriate.

Therefore, we propose the following method to estimate the water absorption coefficient of the finer fraction (0–0.63 mm) of FRCA. FRCA first have to be separated in different granular classes. In our study, the four classes, 0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm, have been retained because they allowed separating the FRCA into classes representing significant proportions of the aggregate.

Table 8. Extrapolated water absorption coefficient of Fraction 0–0.63 mm from standard and IFSTTAR.

	Tested value of IFSTTAR (%)	Tested value of EN 1097-6 (%)	Extrapolated value of IFSTTAR (%)	Extrapolated value of EN 1097-6 (%)	Difference of two extrapolated values (%)
RCA-OC1-28	21.9	7.61	11.68	10.50	1.19
RCA-OC2-28	23.18	8.05	15.42	15.87	−0.45
RCA-OC3-28	21.44	9.74	11.52	10.43	1.09
RCA-OC1-90	17.66	9.42	10.67	9.82	0.85
RCA-OC2-90	22.84	9.77	14.81	13.67	1.14
RCA-OC3-90	16.79	6.52	10.90	9.28	1.62

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However, depending on the particle size distribution of the FRCA, different granular classes could be chosen. First, the CPC of each granular class have to be determined using the salicylic acid dissolution method described in this paper. Then, the water absorption coefficients of the three coarser fractions of FRCA have to be measured either with European standard EN 1097-6 or IFSTTAR method no. 78. Finally, the water absorption coefficient of the finer fraction (0/0.63 mm) can be obtained by a linear extrapolation between WA and CPC of the three coarser classes. The accurate total water absorption of FRCA used (fraction 0/5 mm) can be determined by knowing the proportion and water absorption coefficient of each fraction.

Additionally, drawing the water absorption coefficient as a function of the CPC can be a very convenient method to differentiate different sources of RCA for which the original concrete composition is generally unknown. Changes of the slope of this regression can also be used to estimate the effect of the weathering or some specific treatment after RCA being crushed. Indeed, for a given RCA, the presence of insoluble phases of the cement paste (Table 3) will impact similarly all the four particle size classes. Thus, the linear relationship between the CPC and the average size of the four different granular classes will be kept. On the other hand, insoluble phases will impact the coefficients of the linear regression of the water absorption coefficient as a function of CPC as this latter will decrease with an increase of the content of insoluble phases.

4. Conclusions

Some of the major properties of FRCA produced in the laboratory from the crushing of concretes of known composition have been related to the CPC. A method based on the dissolution of the major part of the cement paste contained in FRCA by salicylic acid has been developed for the measurement of CPC. The method was applied to concrete manufactured with a white OPC to obtain the most reliable results. However, it can be applied to grey OPC as the presence of insoluble phases of the cement paste will impact similarly all the particle size classes.

Main conclusions obtained are as follows:

(1) For the FRCA used in this study, the CPC decreases linearly with the average particle size of four different granular classes (0/0.63, 0.63/1.25, 1.25/2.5, 2.5/5 mm). This result has been confirmed by studying the variation of bound water content of FRCA (mass loss at 600 °C) as a function of average particle size. However, different relations could be obtained between CPC and parti-

cle size for other types of RCA. A study performed on industrial RCA of various origins is in progress.

(2) The properties of FRCA including specific density, water absorption, and porosity are strongly correlated to the CPC. The higher the CPC, the higher the water absorption and porosity, and the lower the specific density at the exception of the absorption coefficient measured by EN 1097-6 standard for the smaller fraction (0/0.63 mm).

(3) For particle sizes larger than 0.63 mm, EN 1097-6 and IFSTTAR methods gave similar results, which suggest that these methods are relevant for the measurement of water absorption coefficient of FRCA (larger than 0.63 mm). For these fractions, a linear relation is found between the water absorption coefficient and the particle size; the former decreasing with the latter. However, for the smaller particle size (<0.63 mm), IFSTTAR method seems to overestimate the water absorption coefficient, and standard method (EN 1097-6) seems to underestimate it. The characterization of water absorption coefficient of very fine particles is known to be a difficult task, especially for FRCA. As the water absorption displays a linear relationship with CPC of the three coarser granular classes, the absorption coefficient could be estimated with good accuracy for very fine RCA by extrapolating the relationship obtained between water absorption and CPC with coarser granular class. The total water absorption of FRCA (fraction 0/5 mm) can, therefore, be determined precisely which is very important in the mixture proportioning of recycled concrete.

(4) The water absorption coefficients of the FRCA studied range between 6.7 and 15.9%, which is much larger than the water absorption coefficient of common NA. The presence of cement paste, much more porous than the NA used, is responsible for these large absorption values.

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