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Influence of granular fraction and origin of recycled concrete aggregates on their properties

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ABSTRACT
Large quantities of construction and demolition wastes are produced each year. In order to make good use of recycled concrete aggregates (RCA) in concrete, it is very important to study the influence of the granular fraction and the origin of RCA on their properties. In this study, RCA from industrial produced blocks (RCA_Blocks) and slabs (RCA_Slabs) were crushed and then separated into four granular fractions (0/2, 2/6.3, 6.3/14, 14/20 mm). Each granular fraction of RCA was physically characterised. Real RCA from recycling plant were also used for comparison. The results showed that recycled sands offered significantly higher cement paste content (higher bound water content) than coarse recycled aggregates. The fine RCA had therefore a higher water absorption coefficient compared to coarser fractions of RCA. The water absorption of finer fraction of RCA could be extrapolated precisely from the relationship between water absorption and cement paste content (or bound water content) of three coarse fractions of RCA. The values of hardened cement paste content obtained for the RCA_Blocks were lower than those measured on the RCA_Slabs, which was due to a smaller amount of initial cement paste content in blocks. The results showed that RCA_Slabs were more angular than RCA_Blocks.

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KEYWORDS
Recycled concrete aggregates; granular fraction; cement paste content; water absorption; shape

1. Introduction

Large quantities of construction and demolition wastes are produced each year. So far, only a small fraction of these concrete wastes are reused as aggregate for concrete production (Etxeberria, Vázquez, Marí, & Barra, 2007). To optimise the use of recycled concrete aggregates (RCA) in new concrete, it is very important to precisely determine the properties of RCA and the influence factors such as granular fraction and origin of RCA on their properties (Hansen & Narud, 1983).

Recycled concrete aggregates are composed of a mix of natural aggregates and hardened adherent cement paste. The latter is usually much more porous than natural aggregates (Zhao, Remond, Damidot, & Xu, 2013) and leads to a large water demand which makes RCA harder to recycle into concrete (Courard, Michel, & Delhez, 2010; Evangelista & de Brito, 2014). Properties of RCA such as water absorption, porosity and shape can deeply influence the properties of fresh concrete as well as mechanical properties and durability of concrete made with RCA (Hansen & Boegh, 1985; He, Le, & Stroeven, 2012; Khatib, 2005; Poon, Shui, Lam, Fok, & Kou, 2004; Xiao, Fan, & Tam, 2015).

The hardened cement paste content and its properties have a decisive influence on the properties of RCA, such as density, porosity and water absorption (Zhao, Remond, Damidot, & Xu, 2015). The

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determination of adherent cement paste and mortar is, however, difficult to carry out experimentally. Thermal treatment is difficult to carry on with small particles (de Juan & Gutiérrez, 2009). Chemical treatment with a solution of hydrochloric acid cannot be used with limestone aggregates and filler (Nagataki, Gokce, Saeki, & Hisada, 2004). Image analysis method is suitable for quantification of residual mortar in RCA, but the distinction between fine aggregates and cement paste is more difficult to carry out (Abbas et al., 2009). However, De Juan (de Juan & Gutiérrez, 2009) pointed out that the adherent mortar content estimation was varying with the different methods described here above. Many authors showed that the size of granular class of RCA had an important influence on adherent mortar content (Topcu & Sengel, 2004). They presented that the adherent mortar content was lower for larger size RCA. But, some authors reported that mortar content increased as the grain sizes increased, which was contradictory to other studies (Yagishita, Sano, & Yamada, 1994). Some authors pointed out that the properties of RCA depended on that of the original concrete (Padmini, Ramamurthy, & Mathews, 2009; Tam, Wang, & Tam, 2008), whereas some authors concluded that there was no or little effect of the original concrete (Limbachiya, Marrocchino, & Koulouris, 2007). However, as most of the research programmes were carried out on laboratory-produced original concrete ("labcrete"), only a few researches were based on the industrial produced original concrete ("realcrete").

The objectives of this paper are the following:

(1) develop a simple method for the measurement of CPC of RCA;
(2) relate the properties of original industrial produced concrete to the different physical properties of RCA such as cement paste content, water absorption, shape and resistance to wear as a function of four different granular classes (0/2, 2/6.3, 6.3/14, 14/20 mm), and compare them with real RCA from recycling plant.

In this study, RCA from industrial produced blocks (RCA_Blocks) and slabs (RCA_Slabs) were crushed by laboratory jaw crusher and then separated into four granular fractions (0/2, 2/6.3, 6.3/14, 14/20 mm). Each granular fraction of RCA was characterised in order to study the influence of granular fraction and the origin of recycled concrete aggregates on their properties. Real RCA from recycling plant were also used to compare with these two laboratory-produced RCA from industrial concretes.

2. Materials

Two concretes reference Slabs and Blocks were collected from Prefer Company (Belgium) and then crushed in a laboratory jaw crusher retaining the same jaw opening for all products. Concretes were produced with two cements and crushed limestone natural aggregates (Table 1). About 320 kg/m^3 of CEM I 52.5 N and water to cement ratio of 0.52 were used for slabs (C40/50: the class of slabs, the characteristic cylindrical compressive strength of slabs after 28 days curing in water is 40 MPa and the characteristic cube compressive strength is 50 MPa); 200 kg/m^3 of CEM III/A 42.5 and water to cement ratio of 0.56 were used for blocks (C8/10: the class of blocks, the characteristic cylindrical compressive strength of blocks after 28 days curing in water is 8 MPa and the characteristic cube compressive strength is 10 MPa). After crushing, RCA_Blocks and RCA_Slabs were separated into four granular fractions (0/2, 2/6.3, 6.3/14, 14/20 mm). The recycled concrete aggregates produced in recycling plant (RCA_Trade) were also used to compare with the laboratory-produced RCA. RCA_Trade (0/20 mm) were provided by

Table 1. Original concrete compositions produced by Prefer (for 1 m^3 of fresh concrete)

Components	Slabs	Blocks
Cement (kg)	320 (CEM I 52.5 N)	200 (CEM III/A 42.5)
Sand 0/2 (kg)	800	760
Aggregate 2/6 (kg)	–	460
Aggregate 2/8 (kg)	880	650
Aggregate 6/14 (kg)	320	–
Water (kg)	165	112

Table 2. Constituents of industrial coarse recycled aggregates (RCA_Trade) according to EN 933-11 (%).

Fractions (mm)	Description	2/6.3	6.3/14	14/20
Rc	Concrete, conrete products, mortar	90.4	93.1	90.0
Ru	Unbound aggregate, natural stone	6.0	3.0	6.5
Rb	Clay masonry units (i.e. bricks and tiles)	0.5	1.2	2.2
Ra	Bituminous materials	2.9	2.3	1.1
X	Others: Cohesive (i.e. clay and soil); metals; wood; plastic	0.2	0.4	0.2

the Tradecowall Company and the recycling plant Valorem in Mont-Saint-Guibert (Belgium). The constituents of RCA_Trade were classified according to EN 933-11 (2009). RCA_Trade is mainly composed of concrete and concrete products, but it also contaminated with other materials such as the bricks and bituminous materials (Table 2).

3. Experimental programme

3.1. Measurement of cement paste content

A method based on salicylic acid dissolution was developed for the characterisation of cement paste content in RCA (Zhao et al., 2013). Salicylic acid allows the dissolution of most phases contained in OPC cement paste (C_2S, C_3S, ettringite, portlandite and C–S–H, for example) but not of the main phases contained in natural aggregates and, especially limestone.

The experimental protocol used is as follows (Zhao, Remond, Damidot, & Xu, 2014):

(1) A representative sample was dried at 105 °C, then grinded until passing 0.2-mm sieve (M_1);
(2) About 0.5 g of dried representative sample was immersed in a solution of 14 g of salicylic acid in 80 ml of methanol, and stirred during 1 h;
(3) The solid fraction was filtered on glass filter (Pyrex N°4, pores: 10–16 μm) and washed four times using methanol (2–3 mm high on top of filter);
(4) The solid residue was dried in the oven at 70 °C for 30 min (M_2);
(5) The cement paste content (CPC) was then calculated as follows (Equation (1)):

$$\text{CPC}\ (\%) = (M_1 - M_2)\big/M_1 \times 100 \quad (1)$$

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

3.2. Bound water content

Thermogravimetric analysis of RCA (Zhao, 2014) showed that the peak at 150–175 °C corresponds to a loss of water in C–S–H. The peak at 450 °C corresponds to the loss of water in portlandite. The decarbonation of carbonated hydrates can start from 500 °C. Therefore, a thermal method was used to determine the bound water content (BWC) at 475 °C of the cement paste in RCA. This BWC correlates the dehydration of hydrated phase of hardened cement paste. Three samples of each granular class of RCA were measured to obtain the average value. The experimental protocol used is as follows (Zhao, 2014):

(1) Representative samples were grinded until passing 0.2 mm sieve and the grinded representative samples (about 5 g) were pre-dried in the oven at 105 °C until constant mass (1 day, noted as M_{105});
(2) Dried samples were put in the oven at 475 °C until constant masse (1 day, noted as M_{475});
(3) The bound water content (BWC) is calculated from the mass loss between 105 and 475 °C (Equation 2):

$$\text{BWC}\ (\%) = (M_{105} - M_{475})\big/M_{105} \times 100 \quad (2)$$

3.3. Water absorption

The water absorption coefficient of three coarse fractions for both studied RCA was determined according to EN 1097-6 (EN 1097-6, 2013). Zhao et al. (2014) showed that the standard EN 1097-6 was not adapted for measuring the water absorption coefficient of the fraction less than 0.63 mm. The water absorption coefficient of the fraction 0/2 mm of RCA was therefore determined on the basis of the relationship between water absorption and cement paste content as explained in section 4.4. The water absorption of the fraction 0/2 mm was also measured in accordance with the standard EN 1097-6 and IFSTTAR method (IFSTTAR, 2011) for the comparison.

3.4. Shape

The shape of RCA was measured by image analysis with the software from Occhio Company (Michel & Courard, 2014). Representative particles were dispersed on a plate which is positioned between a camera and a light source. The software then measured the size and shape of each particle individually (Califice, Michel, Dislaire, & Pirard, 2013). Selected parameters may be separated into two categories: the width (l) and length (L). The elongation factor q is determined by $q = l/L$. For each granular fraction, between 2000 and 10,000 particles were measured in several minutes.

The RCA shape index was also measured by caliper for the three coarse fractions. The thickness (e), the width (l) and the length (L) of each particle were measured with caliper on the basis of 200 representative particles ($L \geq l \geq e$). British Standard BS 812-105 (BS 812-105, 1989) characterised the shape by four categories: cubic, flat, elongated, elongated and flat (Figure 1). These four categories were defined by the flakiness coefficient p ($p = e/l$) and the elongation coefficient q ($q = l/L$).

3.5. Resistance to wear (micro-Deval)

The resistance to wear of RCA was determined by the micro-Deval coefficient which corresponds to the percentage of original sample reduced to a size smaller than 1.6 mm during rolling (EN 1097-1, 2011). Three coarse fractions of RCA (2/6.3, 6.3/14, 14/20 mm) were tested in dry condition without addition

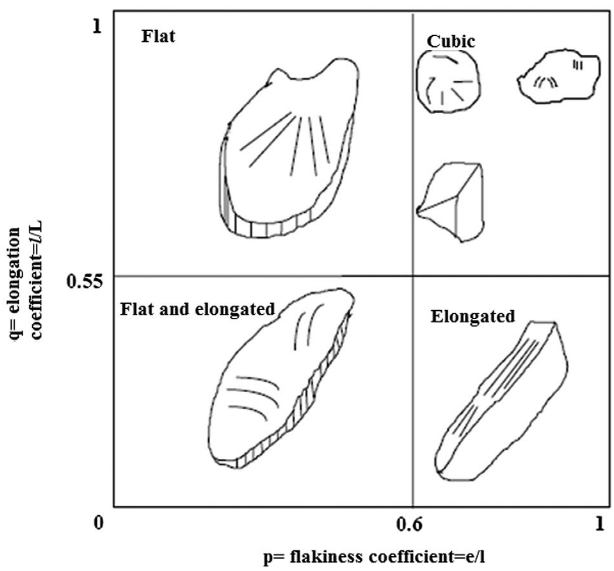

Figure 1. Shape categories according to the flakiness coefficient and elongation coefficient (Lab., Laboratoire de Géotechnologie, Université de Liège, 2015).

Table 3. Mass of ball load used for the different fractions.

Fractions (mm)	Mass of ball load (g)
2/6.3	2000 ± 5
6.3/14	4400 ± 5
14/20	5500 ± 5

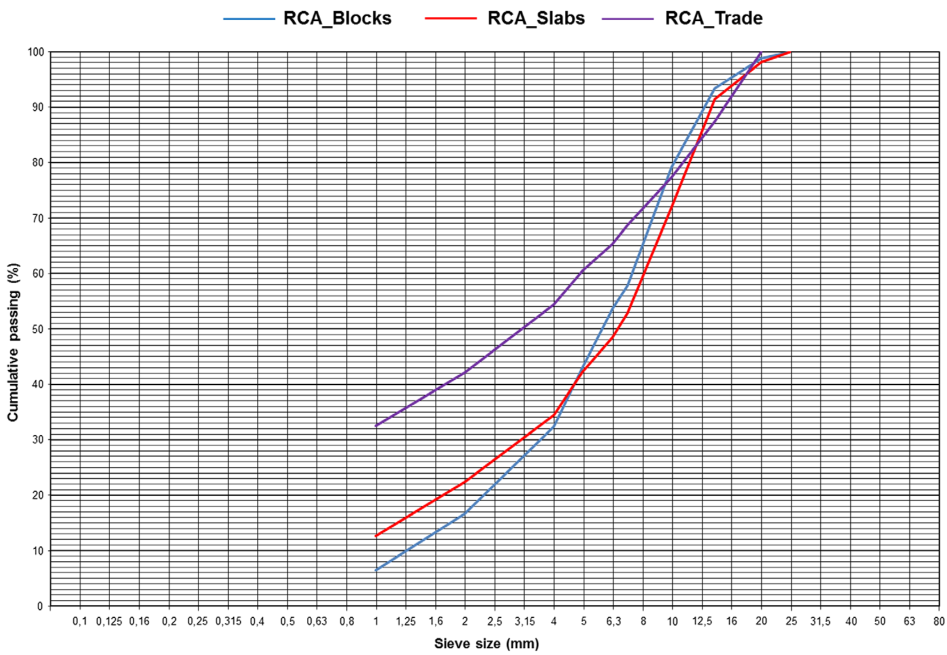

Figure 2. Particle size distributions of RCA manufactured in the laboratory and from recycling plant ("Trade").

of water. The mass of ball loads were amended to suit the different aggregates fractions (Table 3). The drum within samples (pre-dried in the oven at 105 °C, noted as M_a) and ball loads were rotated at a speed of (100 ± 5) rounds per minute for (12,000 ± 10) revolutions. After the rotation, the materials were collected and washed carefully on the 1.6 mm sieve and then dried in the oven at 105 °C until constant mass (noted as M_b). The micro-Deval coefficient (MD) is calculated as follows (Equation 3):

$$\text{MD}\ (\%) = (M_a - M_b)/M_a \times 100 \tag{3}$$

4. Results and discussions

4.1. Particle size distribution

Figure 2 shows the particle size distribution curves of RCA. This figure shows that for RCA made in the laboratory and for the same jaw crusher opening, the grain size distribution curves were similar. RCA_Trade had a greater amount of fine particles (less than 1 mm) than other RCA. RCA_Slabs showed a higher amount of fines (less than 1 mm) than RCA_Blocks, which could be due to the initial composition of slab containing a larger amount of cement paste.

4.2. Cement paste content of RCA

Figure 3 shows the cement paste content as a function of granular fraction. As described in Figure 3, for all studied RCA, CPC of fraction 0/2 mm was larger compared with the three coarse fractions of RCA,

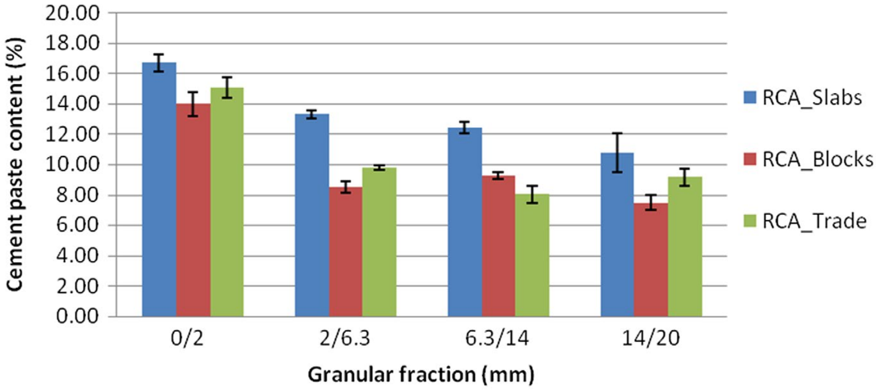

Figure 3. CPC as a function of granular fraction.

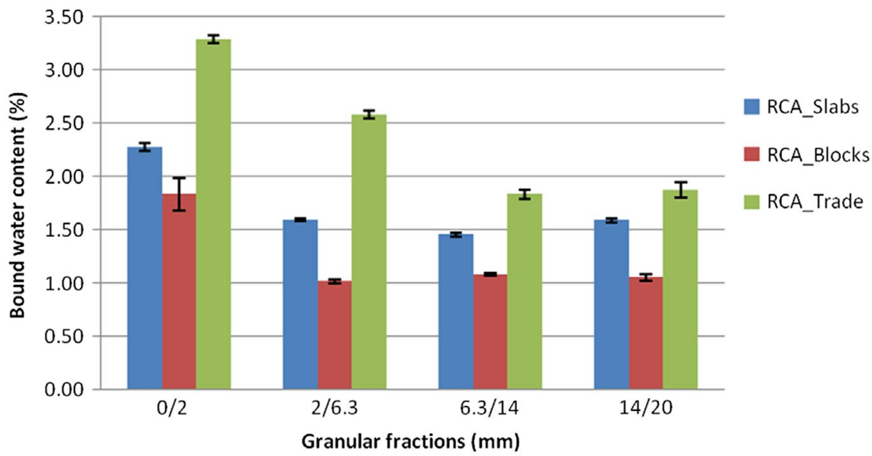

Figure 4. Bound water content as a function of granular fraction.

while the values obtained for the three coarser fractions were similar. Recycled sands thus possessed higher cement paste contents than the coarse recycled aggregates, which may heavily penalise their use properties comparing with coarse recycled aggregates. CPC values obtained for RCA_Blocks were lower than that of RCA_Slabs, which might be due to the lower quantity of initial cement paste in blocks (theoretically 19.5% for slabs and 14% by weight for blocks, on the basis of the initial cement paste content calculated from the fresh state of original concrete). The CPC values obtained for both RCA_Blocks and RCA_Slabs were lower than these theoretical values. In the theoretical calculation, the entire amount of water was taken into account from the fresh state of original concrete, while the CPC of hardened concrete only concerned the bound water by hydration, which was lower than the entire amount of water. It might also be due to some phases such as AFm, slag and carbonated products that are not dissolved, thus underestimating CPC (Zhao, Damidot, Remond, & Courard, 2015). CPC values obtained for the RCA_Trade might also be underestimated as the RCA from the recycling plant contains some non-dissolved phases such as AFm, slag and carbonated products.

4.3. Bound water content of RCA

Figure 4 shows the bound water content as a function of granular fraction. As can be seen, the bound water content of fraction 0/2 mm was larger compared with the three coarse fractions of RCA, while

Table 4. Extrapolated water absorption of fraction 0/2 mm.

	$WA_{RCA\ Extra}$ by CPC (%)	$WA_{RCA\ Extra}$ by BWC (%)	$WA_{RCA\ EN}$ (%)	$WA_{RCA\ IF}$ (%)
RCA_Slabs 0/2	6.0	6.5	3.4	9.8
RCA_Blocks 0/2	7.8	8.3	2.8	8.5
RCA_Trade 0/2	16.2	15.2	7.8	16.1

the values obtained for the three coarser fractions were similar (except for the fraction 2/6.3 mm of RCA_Trade). Recycled sands thus possessed higher bound water content than that of the coarse recycled aggregates, which confirmed the results of cement paste content for all studied RCA. The higher bound water content (higher cement paste content, higher porosity) may heavily penalise their use properties comparing with coarse recycled aggregates. BWC values obtained for RCA_Blocks were lower than those measured on RCA_Slabs, which might be due to the lower quantity of initial cement paste in block; it confirmed the results of cement paste content.

4.4. Water absorption of RCA

The water absorption of recycled aggregates depends on the water absorption of natural aggregates (WA_{NA}), water absorption of adherent cement paste (WA_{CP}) and their relative proportions. For a given original concrete composition, the water absorption of natural aggregates and of cement paste does 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 (4). Here, we assumed that the water absorption of NA was negligible ($WA_{NA} = 0$) compared to the water absorption of cement paste: WA_{CP} and CPC can be calculated from the average values of water absorption for the three coarse fractions of RCA (the values obtained for water absorption and CPC were similar for the three coarse fractions of RCA). Then, WA_{RCA} of fraction 0/2 mm can be calculated with Equation (4). As the BWC is proportional to CPC (CPC = BWC × K), the above assumption is also suitable in the case of Equation (5), WA_{RCA} of fraction 0/2 mm can also therefore be extrapolated from the average values of water absorption and BWC of the three coarse fractions (Equation 5). Table 4 shows the extrapolated water absorption of fraction 0/2 mm from two methods. As expected (Zhao et al., 2013), the value of water absorption of finer fraction for both extrapolation methods were similar and were comprised between the value obtained by the standard EN ($WA_{RCA\ EN}$) and IFSTTAR ($WA_{RCA\ IF}$) methods.

$$WA_{RCA} = WA_{CP} \times CPC + WA_{NA} \times (1 - CPC) \tag{4}$$

where CPC is the CPC of the considered granular fraction.

$$WA_{RCA} = WA_{CP} \times BWC \times K + WA_{NA} \times (1 - BWC \times K) \tag{5}$$

where BWC is the BWC of the considered granular fraction.

Figure 5 presents the water absorption as a function of the granular fraction for all studied RCA: the fraction 0/2 mm of RCA revealed a larger value of water absorption in comparison with the three coarse fractions of RCA, while the values obtained were similar for the three coarser fractions. The recycled sand had a higher water absorption comparing with the coarse recycled aggregates. The values obtained on RCA_Trade were larger than the laboratory produced RCA, which might due to the complex constituents of different origin of old concrete (low quality) and other contaminations such as bricks and bituminous materials.

4.5. Shape of RCA

Figure 6 shows the elongation coefficient of RCA as a function of granular fraction by image analysis (q). For all the fractions of RCA, RCA_Slabs had a lower elongation coefficient than RCA_Blocks, which might probably be related to the different compressive strength of the original concrete.

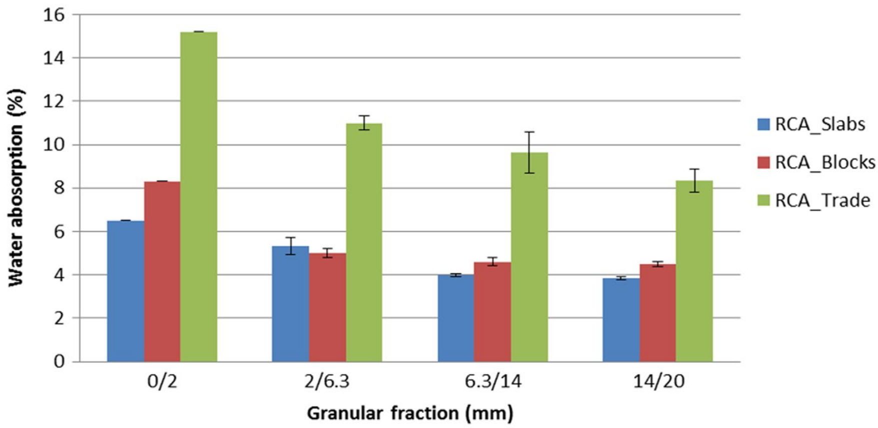

Figure 5. Water absorption as a function of granular fraction for all studied RCA (Note: the values obtained for the fraction 0/2 mm are based on the extrapolation method from BWC).

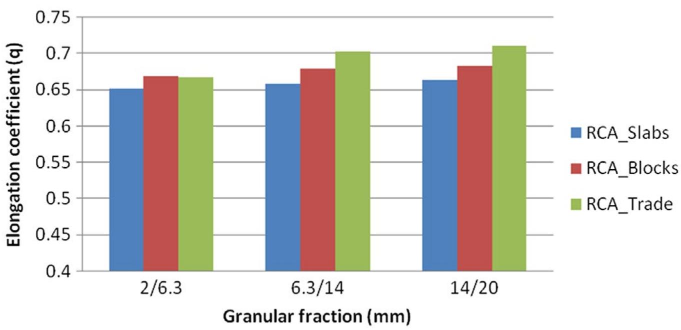

Figure 6. Elongation coefficient of RCA determined by image analysis as a function of granular fraction.

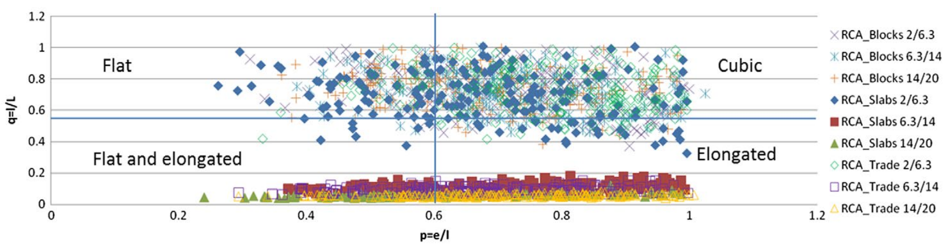

Figure 7. Shape categories measured by caliper according to the elongation coefficient and flakiness coefficient of three coarse fractions for all studied RCA.

Figure 7 shows the shape categories measured by caliper according to the flakiness coefficient and elongation coefficient of three coarse fractions of all studied RCA. RCA_Blocks had a greater percentage of cubical grains than that of RCA_Slabs (Table 5). RCA_Slabs had a greater amount of flat-shaped particles (confirmed the results of image analysis). The shape of RCA might be due to the different compressive strengths of original concrete. It could also be due to the maximum granular size of aggregate used (Dmax of slabs was 14 mm, while it was 8 mm for the blocks). The interface between aggregates and cement paste in the blocks was much easier to break and it contributed to much more cracking during the crushing. Meanwhile, for the slabs, the cement paste was well adhered to the natural aggregate.

Table 5. Shape distribution determined by caliper according to flakiness coefficient and elongation coefficient (%).

Fractions (mm)	Cubic	Flat	Elongated	Flat and Elongated
RCA_Slabs 2/6.3	51	31	13.5	4.5
RCA_Slabs 6.3/14	0.0	0.0	71	29
RCA_Slabs 14/20	0	0	57.5	42.5
RCA_Blocks 2/6.3	65.5	22.5	11	1
RCA_Blocks 6.3/14	70.5	17	11.5	1
RCA_Blocks 14/20	62	31.5	6	0.5
RCA_Trade 2/6.3	77.5	12	10	0.5
RCA_Trade 6.3/14	0	0	67.5	32.5
RCA_Trade 14/20	0	0	76.5	23.5

Table 6. Micro-Deval coefficient of RCA (%).

Fractions (mm)	2/6.3	6.3/14	14/20
RCA_Slabs	24.4	14.8	13.2
RCA_Blocks	27.0	8.3	8.6
RCA_Trade	19.0	11.1	14.5

Fractions 6.3/14 and 14/20 mm of RCA_Trade had a greater percentage of flat-shaped particles than the fraction 2/6.3 mm.

4.6. Resistance to wear of RCA

Table 6 shows the resistance to wear of three coarse fractions of all studied RCA. For the fractions of 6.3/14 and 14/20 mm, RCA_Blocks had a lower coefficient than that of RCA_Slabs, and better resistance to wear, which might be due to the lower cement paste content on the surface, and, on the contrary, higher aggregate content (calcareous aggregate had well resistance to wear than cement paste). RCA_Slabs had a greater percentage of flat-shaped particles, which might induce higher mass loss by the wear. For the fraction of 2/6.3 mm, RCA_Slabs showed better resistance to wear comparing with RCA_Blocks, which might probably be related to the different compressive strength of the original concrete (predominant effect).

5. Conclusions

In this study, recycled concrete aggregates from blocks (RCA_Blocks) and slabs (RCA_Slabs), and real RCA from recycling plant were characterised in order to study the influence of granular fraction and origin of recycled aggregates on their properties. The adherent hardened cement paste content of RCA was measured by dissolution in salicylic acid. The results showed that recycled sands possessed significantly higher cement paste content than coarse recycled aggregates. Thus, recycled sand had a higher water absorption coefficient compared with coarse recycled aggregates. The values of hardened cement paste content obtained for RCA_Blocks were lower than those measured on RCA_Slabs (also confirmed by the bound water content measurement by the mass loss between 105 and 475 °C), which might due to the lower quantity of initial cement paste in blocks. The water absorption of finer fraction of RCA could be extrapolated precisely from the relationship between water absorption and cement paste content (or bound water content) of three coarse fractions of RCA.

The shape of RCA was measured by image analysis and calipers. The results showed that for all fractions of RCA, RCA_Slabs had a lower elongation coefficient than RCA_Blocks. The shape of RCA measured by caliper showed that RCA_Slabs had a greater percentage of flat-shaped particles. The shape of produced RCA was related to the original concrete composition and quality of original concrete. The results obtained in this study are only valid for the studied concrete and used crusher: it is possible that another type of crusher (e.g. hammer or percussion) give other shapes and other fine contents. The resistance to wear of RCA was also well related to the original concrete composition and quality of original concrete.

These results are notably important for the fresh properties of concrete made of RCA. The design of new concrete made of RCA will be studied and physical parameters determined as here above will be taken into account for explaining results.

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Disclosure statement

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