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Properties of concrete made with recycled aggregate from partially hydrated old concrete

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Abstract

Concrete having a 28-day compressive strength of 28 MPa was crushed at ages 1, 3 and 28 days to serve as a source of aggregate for new concretes, simulating the situation prevailing in precast concrete plants. The properties of the recycled aggregate and of the new concrete made from it, with nearly 100% of aggregate replacement, were tested. Significant differences were observed between the properties of the recycled aggregates of various particle size groups, while the crushing age had almost no effect. The properties of the concrete made with recycled aggregates were inferior to those of concrete made with virgin aggregates. Effects of crushing age were moderate: concrete made with aggregates crushed at age 3 days exhibited better properties than those made with aggregates of the other crushing ages, when a strong cement matrix was used. An opposite trend was seen when a weaker cement matrix was used. Some latent cementing capacity was seen in the recycled aggregates crushed at an early age.

Keywords: Recycled aggregates; Waste management; Hydration; Mechanical properties; Fresh concrete

1. Introduction

The use of construction waste as a source of aggregate for the production of new concrete has become more common in the recent decade. The increasing charges for landfill, on the one hand, and the scarcity of natural resources for aggregate, on the other hand, encourage the use of waste from construction sites as a source for aggregates. Some successful projects have lately been reported, in which waste from the demolition of old structures was recycled into a new one [1–3]. RILEM Committee 121-DRG [4] has published recommendations for the use of recycled aggregates, classifying them into three groups: Group I: aggregates that stem mainly from masonry rubble; Group II: aggregates obtained mainly from concrete rubble; and Group III: a mixture of natural aggregates (>80%) and rubble from the other two groups (with up to 10% of Group I). Group III can be used for the production of all types of concrete, whereas restrictions limit the applications of the other two groups. This classification highlights one of the major difficulties in the recycling of demolished waste, namely the variable and unsteady quality of the recycled aggregates. In highway replacement for example [2], a uniform source of recycled aggregate is guaranteed (from the demolition of the old pavement). However, when the aggregate source is a center for recycling of construction waste, the rubble is collected from various origins and the properties of the aggregate are not uniform. This leads to difficulties in the application of the resulting aggregates for the production of new concrete [5,6].

Apparently, no problem should exist in making recycled concrete using waste derived from the industry of construction products such as precast concrete or brick plants. The various products are routinely made from the same type of concrete and, therefore, the problem of variability in the properties of the rubble should not exist. A reduction of up to 10% in the compressive strength was reported by van-Acker [7], when up to 10% of recycled aggregate made from high-strength concrete replaced virgin aggregate in a new concrete of the same quality (28-day compressive strength of 75.4 MPa). The replacement ratio strongly affects the properties of the new concrete and a reduction of almost 20% was reported for a higher replacement ratio

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Table 1
Composition and properties of the old concrete

Component	Quantity (kg)
Coarse aggregate (12–25 mm)	5.415
Midsize aggregate (2.36–9.5 mm)	1.415
Fine aggregate (1.2–0.15 mm)	3.120
Portland cement	1.800
Water	1.080
Compressive strength (MPa) at[a]	
1 day	7.4 (0.9)
3 days	14.4 (1.2)
28 days	28.3 (3.1)

[a] Number in parenthesis: standard deviation.

(25%). Mansur et al. [8] reported similar properties of concretes in which coarse granite aggregate was replaced by high strength clay bricks (compressive strength of 153 MPa) that rejected during manufacturing.

Despite the belief that all concrete waste from one precast plant is of a constant quality, products are often rejected during the manufacturing process; thus, concrete of such elements may contain some unhydrated cement that could affect the properties of the recycled aggregate and of the new concrete made with it. This paper reports the effect of partially hydrated waste concrete on the properties of aggregate made from it and the resulting properties of new concrete made with these recycled aggregates.

2. Experimental program

The overall experimental program consisted of two stages: (1) a comprehensive study of the properties of new concrete made with recycled aggregate that was prepared by crushing partially hydrated old concrete; (2) a study of the effect of recycled fines only on the properties of new concrete. This paper presents the results of Stage 1 of the study.

In the following, the term "old concrete" refers to the waste concrete used to produce the recycled aggregates, while "recycled concrete" denotes the new concrete prepared with the recycled aggregates. "Recycled aggregate" is the aggregate produced by crushing old concrete, whereas "natural aggregate" refers to new aggregate obtained by crushing natural stone.

The old concrete is made up of concrete elements used for standard tests in the process of quality assurance in cement manufacturing. Ordinary Portland cement (OPC) from the cement plant is produced continuously and its compressive strength is tested routinely by mixing the cement with standard aggregates in a standard process. Table 1 lists the mix composition and compressive strength of the old concrete.

The old concrete was in the form of 120-mm cubes and it was tested for compressive strength at ages of 1, 3 and 28 days, as part of the standard procedure. Immediately after the compression tests, the cubes were crushed by a mini jaw crusher and dried in an oven at 105 °C to inhibit any further hydration. Uniform old concretes were obtained despite being cast on different dates, as can be seen from the small values of the standard deviation (Table 1).

The new concrete was prepared by using all the aggregates obtained by crushing the old concrete, with the addition of some natural sand that was needed to maintain good workability. In addition, a reference new concrete was prepared by using natural aggregates in the same mixing ratio as the recycled concrete. The composition of the new concretes is listed in Table 2. Two types of cement were used in the preparation of the new concrete: white Portland cement (WPC) and OPC. The white cement was initially used in the new concrete in order to enable visual distinction between the new cement matrix and the old one (which adhered to the recycled aggregate) in the new concrete. However, it was found later that it is impossible to define, even under the microscope, a clear boundary between the new cement matrix and the recycled aggregate, despite the differences between the cements. It should be noted, however, that the OPC was weaker than the white cement (a 28-day compressive strength of 34.6 MPa compared with 42.1 MPa for the white cement, when comparing the reference concretes).

The crushed concrete was divided into fractions of the following sizes: coarse (larger than 9.5 mm), medium (smaller than 9.5 mm but larger than 2.36 mm) and fine (smaller than 2.36 mm). This was done so the effect of aggregate size on its properties could be studied. Each size group was tested for size distribution, bulk density, bulk-specific gravity, water absorption, crushing value (of the

Table 2
Composition of the new concrete (kg/m^3)

	WPC				OPC			
	Reference	1 day[a]	3 days[a]	28 days[a]	Reference	1 day[a]	3 days[a]	28 days[a]
Crushed aggregate (9.5–25 mm)	896				907			
Crushed aggregate (2.36–9.5 mm)	448				454			
Crushed sand	212				215			
Natural sand	421	254	219	238	427	259	217	240
Recycled aggregate		1440	1484	1457		1453	1460	1456
Water	161	160	165	162	163	166	168	163
Cement	294	293	302	296	298	298	300	298

[a] Crushing age of the old concrete.

coarse fraction only, in accordance with British Standard 812:1990) and cement content (following the procedure in ASTM C1084-97).

The 100-mm cubes and 70 × 70 × 280-mm prisms were prepared from the new concrete. The cubes were cured in water for 7 days at 21 °C and then air cured (21 °C and 60% RH) until the testing day. The prisms were cured in water at 21 °C until the testing day. Compressive strength was determined on the cubes at ages of 7, 28 and 90 days. The prisms were tested at age 28 days for four-point bending strength, splitting strength and modulus of elasticity. The rate of capillary absorption of water (according to DIN 52617-87) and the total water absorption were tested on mature concrete at 180 days of age or higher. Drying shrinkage was tested on beams that had been placed in an environmentally controlled room (20 °C, 60% RH) starting at age 7 days and up to 6 months. After the drying shrinkage tests, the specimens were used to determine the depth and rate of carbonation in a carbonation chamber (30 °C, 60% RH and 5% of CO_2) for 3 and 7 days. At least three samples were used for each test. All the tests conformed to the relevant ASTM standard unless otherwise specified.

3. Results

3.1. Properties of the aggregates made from crushed concretes

Size distribution curves of the aggregates prepared from the old concretes crushed at various ages are presented in Fig. 1. The three curves shown in the figure exhibit the same size distribution. It appears that, as long as the jaw crusher is set at a specific opening, there is no significant change in the grading of the aggregates despite the differences in the strengths of the concrete they are made from (Table 1). The crack path of normal-strength concrete, in the range of strengths of the old concrete, is known to propagate through the cement matrix [9]. Therefore, crack development in the cement matrix only led to concrete fracture when the old concrete was crushed, resulting almost the same size distribution of the aggregates despite the different crushing ages (Fig. 1). Visual examination of the crushed concrete showed no sign of new planes of fracture in the natural aggregate, validating this explanation.

Table 3
Properties of the recycled aggregates

Crushing age		Bulk-specific gravity	Bulk density (kg/m^3)	Absorption (%)	Crushing value (%)	Cement content (%)
1 day	coarse	2.59	1462	3.2	25.4	6.9
	medium	2.35	1220	9.7	N/A	15.8
	fine	2.23	1324	11.2	N/A	26.6
3 days	coarse	2.60	1433	3.4	25.3	6.1
	medium	2.38	1234	8.1	N/A	15.2
	fine	2.25	1342	11.4	N/A	25.4
28 days	coarse	2.55	1433	3.3	24.3	6.8
	medium	2.32	1278	8.0	N/A	13.2
	fine	2.23	1321	12.7	N/A	24.5

The aggregates were divided into three size fractions (coarse, medium and fine) in order to distinguish between properties that might be related to their particle size. Table 3 presents the bulk-specific gravity, bulk density, absorption, crushing value and cement content in the recycled aggregates of the different size groups and crushing ages. Normalized values were calculated relative to the value of the coarse fraction crushed at age 28 days (Fig. 2).

A comparison of the three size groups shows significant differences between the groups; however, variations within the same size group, but of a different crushing age, are minor. The differences between the size groups seem to be a result of the relative amounts of cement paste in the crushed material regardless of its age at crushing. As seen in Table 3, the amount of cement (hydrated and nonhydrated) increases significantly from approximately 6.5% in the coarse fraction to approximately 25% in the fine fraction.

The porosity of the recycled aggregates, expressed by absorption values (Table 3), ranged from ~3.2% to ~12% for the coarse and the fine fractions, respectively. The

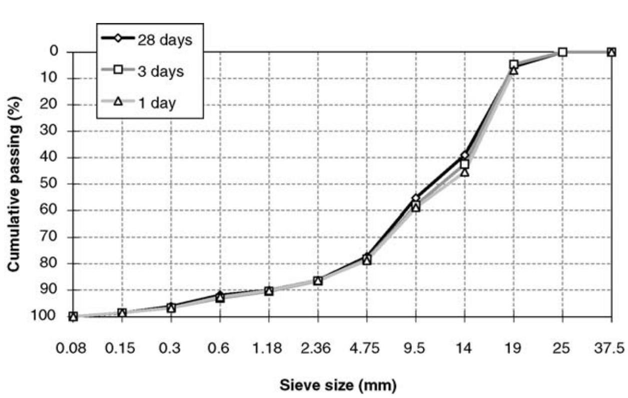

Fig. 1. Grading of the recycled aggregates crushed at various ages.

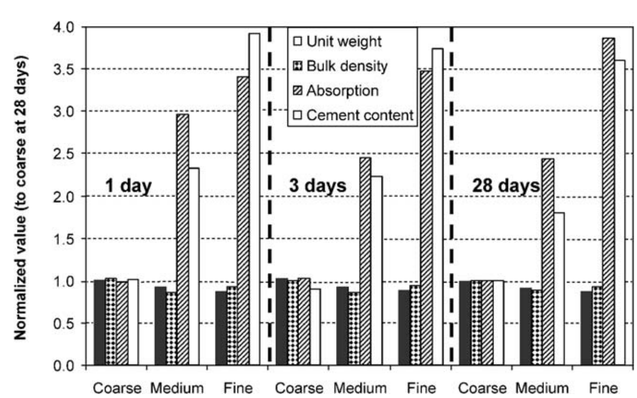

Fig. 2. Properties of the recycled aggregates normalized to the coarse fraction crushed at age 28 days.

porosity of the natural aggregates used in the production of the old concrete was relatively low (0.5–1.5%). Therefore, the high porosity of the recycled aggregates appears to be mainly related to the residues of cement paste that is still adhered to the natural aggregates. The porosity of cement paste with a water-to-cement ratio of 0.6 varies theoretically between 45% and 60%, for degrees of hydration of 25% and 100%, respectively [10], assuming these values correspond to the degrees of hydration at ages 1 and 28 days. Therefore, the porosity of the recycled aggregates increases significantly when the amount of cement paste is increased (i.e., when the aggregate size is smaller), but insignificantly with the crushing age. Other parameters, such as bulk-specific gravity and bulk density, which are related to the properties of both the natural aggregates and the cement paste, change only moderately with particle size, since the cement paste forms only a minor part of the recycled aggregate (up to 25% for the smaller aggregate size).

The bulk-specific gravity of the recycled aggregates ranged from 2.23 to 2.60 for the fine to the coarse fractions, respectively. The bulk-specific gravity of the natural aggregate was approximately 2.70 and the reduced weight of the former is probably a result of the residues of cement paste that remained adhering to the natural aggregate after crushing. The bulk density of the recycled aggregates was relatively low, approximately 1300 kg/m^3. The bulk density of the medium-size aggregate was lower than that of the fine aggregates (approximately 1240 compared with 1330 kg/m^3, respectively) despite the lower bulk-specific gravity of the latter. This finding is probably a result of the better grading of the fine aggregate fraction over a larger range of sizes (Fig. 1), leading to a denser packing of the particles in this range.

The variation in the properties within each fraction of the aggregates crushed at different ages is not significant (Table 3). This suggests that the amount of cement paste that was still adhered to the natural aggregates in each size fraction was constant, regardless of the crushing age. The mechanical properties of the cement matrix, at the level of strengths studied here, probably exert only a minor effect on the mode of crushing of the old concrete, leading to uniform recycled aggregate properties despite the different crushing ages.

Considering the similarity of the size distributions and other parameters of the aggregates crushed at different ages, it was decided that separation of the recycled aggregates into different size fractions is unnecessary for the production of the new concrete. Thus, the recycled concrete was added in its entirety to all the mixes (see Table 2).

The relatively high values of absorption demanded special care during the preparation of the new concrete. Therefore, to ensure a uniform mixing procedure, the aggregates were firstly mixed with the water for a period of 15 min before continuing with the mixing procedure.

3.2. Properties of new concrete made from recycled aggregates

3.2.1. Fresh concrete

Properties of the new concrete are listed in Table 4. The bulk density of fresh concrete made with natural aggregates, as the reference material, was in the typical range of normal concrete (approximately 2400 kg/m^3), whereas the concrete made with recycled aggregates was significantly lighter, approximately 2150 kg/m^3, regardless of the type of cement or the crushing age. That lower density is the result of the lower bulk-specific density of the aggregates discussed before (2.60, 2.30 and 2.20 for the coarse, medium and fine crushed aggregates, respectively, compared with 2.63–2.74 for the natural aggregates). In addition, an increased air content was observed, leading to an additional reduction in the density of the fresh concrete.

Air content was calculated by the gravimetric method (ASTM C138). The results indicated a normal air content for the reference concrete, but a higher one (4–5.5%) for the new concrete made with recycled aggregate. The air in the aggregate's voids is taken into account through the bulk-specific gravity of the aggregate; thus, the values above represent additional air entrapped in the concrete. The cause of the increased air content is not clear. Further study is needed in order to better understand this phenomenon. It

Table 4
Properties of the fresh and hardened new concrete

	WPC				OPC			
	Reference	1 day[a]	3 days[a]	28 days[a]	Reference	1 day[a]	3 days[a]	28 days[a]
Bulk density (kg/m^3)	2462	2146	2170	2153	2463	2175	2145	2156
Slump (mm)	170	170	155	185	140	180	175	135
Calculated air content (%)	1.3%	5.4%	4.1%	5.0%	N/A	4.8%	5.4%	5.6%
Compressive strength (MPa)								
7 days	36.8	19.0	23.4	20.0	21.6	18.3	17.0	17.1
28 days	42.1	24.1	30.5	29.1	34.6	26.6	25.8	26.8
90 days	58.9	28.9	38.7	35.2		33.0	28.7	30.6
Flexural strength (MPa)	6.7	4.7	5.3	4.6	6.1	6.1	5.4	5.4
Splitting strength (MPa)	5.0	3.1	3.6	2.7	3.3	3.4	2.9	3.1
Modulus of elasticity (GPa)	23.1	11.4	13.7	11.5	22.7	14.2	13.3	11.3

[a] Crushing age of the old concrete.

should be noted that determination of the air content by the gravimetric method is very sensitive to minor changes in the bulk-specific gravity of the aggregate or of the fresh concrete. Minor errors in their determination may lead to large changes in the calculated air content. Accurate determination of the bulk-specific gravity is difficult, however, due to difficulties in the determination of the saturated surface dry (SSD) state of the recycled aggregates resulted from their high porosity. Therefore, the general trends of increased air content should be considered rather than its apparently exact values, since the latter may include an error of about ± 1%. Increased air content is also known to occur in lightweight aggregate concrete [11], which exhibits some similarities with concrete made with recycled aggregates from crushed concrete.

The slump of almost all the mixes was in the range of 135–185 mm (mostly ~175 mm). The similar slump was obtained with comparable quantities of free water (see Table 2), indicating that the water requirement for a given slump is not affected by the type of aggregates or by the crushing age. It should be noted, however, that due to the insufficient amount of fines in the recycled aggregates, some quantities of natural sand were still needed in order to maintain proper workability and cohesivity.

3.2.2. Hardened concrete

3.2.2.1. Compressive strength. The compressive strengths of the various mixes are shown in Table 4 for ages of 7, 28 and 90 days. The difference in the quality of the two types of cement is clearly seen when comparing the 28-day compressive strengths of the reference concretes; the one made with OPC was 18% weaker than the WPC concrete. The use of recycled aggregates led to a reduction in the compressive strength of the concrete, whether WPC or OPC was used (see Fig. 3). Loss of strength of 30–40% was seen in recycled concrete made with white cement; the maximum reduction was observed in the concrete made from recycled aggregates crushed at 1 day. The loss of strength of the recycled OPC concrete was more moderate, approximately 24%.

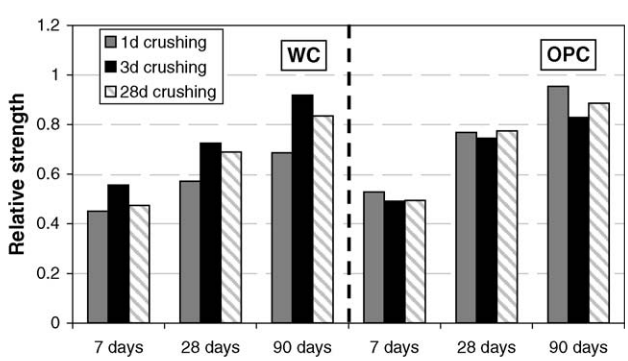

Fig. 3. The compressive strength of recycled concrete crushed at different ages relative to the reference concretes.

Crushing age seems to have a significant effect on the compressive strength of the recycled WPC concrete, which with recycled aggregates crushed at 1 day exhibited lower strength compared with the other crushing ages. The recycled aggregates crushed at 3 days produced the highest strength at all the tested ages. The effect of crushing age was quite moderate when the new concrete was tested at age 7 days and became more pronounced at later ages. At the age of 7 days, the concrete that was made with recycled aggregates crushed at 3 days was 19% stronger than the concrete with recycled aggregates crushed at 1 day. The difference grew to 25% at a testing age of 90 days.

For the recycled OPC concrete, this effect was different. The effect of the crushing age was much smaller; the differences between the lower and the higher strengths were 7% and 13% at testing ages of 7 days and 90 days, respectively. A slightly higher compressive strength was observed in recycled OPC concrete made with aggregates crushed at age of 1 day, and there was no significant difference between crushing ages of 3 and 28 days.

3.2.2.2. Flexural and splitting strength. The flexural and splitting strengths of the new concrete are listed in Table 4. The ratios of the flexural and the splitting strengths to the compressive strength were in the ranges of 16–23% and 9–13%, respectively. Although these values are within a reasonable range, according to Ref. [10], they are relatively high when comparing them with the recommendations found in ACI 363R. The following equations are recommended by ACI 363R for the relationships between the compressive strength (f_c') and the flexural (f_r') and splitting (f_{sp}') strengths, for concrete of a compressive strength in the range of 21–83 MPa:

$$f_r' = 0.94\sqrt{f_c'} \tag{1}$$

$$f_{sp}' = 0.59\sqrt{f_c'} \tag{2}$$

The relationships between the compressive strength and the flexural and splitting strengths are shown in Fig. 4, together with the lines representing the ACI relationships noted above. The higher values of the flexural and splitting strengths relative to the predicted ones are clearly seen in the figure, especially for the OPC recycled concrete. Smaller values than the predicted ones are expected for lightweight aggregate concrete [12], which has some similarities with the concrete made with the recycled aggregates tested here. The higher values compared with the predicted ones require additional attention.

3.2.2.3. Modulus of elasticity. Relatively low values of modulus of elasticity (E_c) were obtained for the tested concretes (Table 4), both the reference and the recycled concrete. After application of a corrective factor for the compressive strength of air-dry cubes relative to saturated cylinders, the values of the reference concretes become

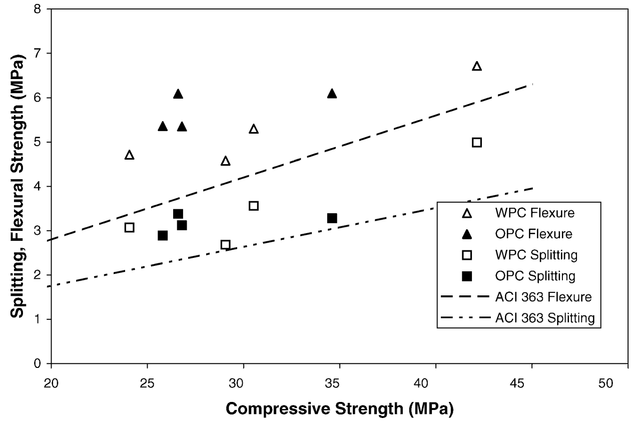

Fig. 4. Flexural and splitting strengths vs. compressive strength.

closer to the values calculated using Eq. (3) (adopted from ACI 318). However, the values for the recycled concretes, corrected for their lower density (W_c), are still lower by approximately 25% than the values predicted by Eq. (3).

$$E_c = 0.043 W_c^{1.5} \sqrt{f'_c} \tag{3}$$

3.2.2.4. Rate of absorption and total absorption. The rate of absorption and the total absorption are presented in Fig. 5 and Table 5, respectively. The rates of absorption of the reference concretes made with OPC and with WPC are closely similar to each other. The rates of absorption of the recycled concretes were much larger with only a small effect of the crushing age (Fig. 5). Recycled WPC concrete with aggregates crushed at 3 days has a lower rate of absorption relative to the other crushing ages (Table 5). The recycled OPC concretes showed absorption rates that were quite similar; slightly higher rate was seen for the concrete with a crushing age of 3 days, contrary to the findings for the recycled WPC concrete.

No significant difference was found between the total absorptions of the recycled concretes made with either of the two types of cement (Table 5). The absorption was approximately 3.8% for the reference concretes and approximately 7.2% for the recycled concrete. The higher porosity of the recycled concrete is a result of the higher porosity of the recycled aggregate (Table 3). No significant effect of the crushing age on the total absorption of the new concrete was observed, similar to the insignificant difference between the absorption of the recycled aggregates crushed at different ages (Table 3).

The rate of absorption, rather than the total absorption, is mainly affected by the structure and size distribution of the pores in the concrete. A paste with a finer pore structure is stronger and exhibits a higher absorption rate compared with a paste having the same total porosity but a coarser pore structure. Differences between the fineness of the hardened cement paste of WPC and that of OPC, which is further affected by the presence of unhydrated cement in the recycled aggregates, can explain the differences in the rates of absorption of the various recycled concretes, despite the similarity of their total absorption (Table 5 and Fig. 5).

3.2.2.5. Drying shrinkage. The results of drying shrinkage tests are presented in Fig. 6. The shrinkage of the recycled OPC concretes at the age of 90 days was 0.7–0.8 and 0.55–

Table 5
Absorption of the tested concretes after an extended curing time (>180 days)

	Reference	Crushing age		
		28 days	3 days	1 day
	Total absorption			
WPC concrete	3.8%	7.3%	7.1%	7.6%
OPC concrete	3.9%	7.3%	7.5%	6.9%
	Coefficient of capillary absorption (kg/m^2/$\sqrt{h}$)			
WPC concrete	0.58	1.42	1.11	1.44
OPC concrete	0.63	1.00	1.11	1.06

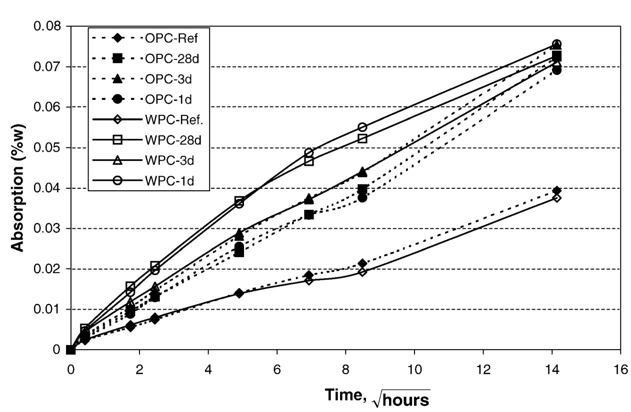

Fig. 5. Absorption rate of the recycled concretes and reference concrete.

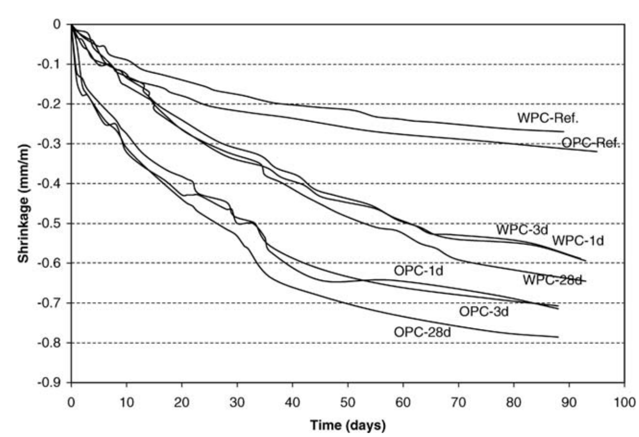

Fig. 6. Shrinkage of the new concrete made from white cement (WPC) and ordinary cement (OPC).

Table 6
Depth of carbonation (mm) of the recycled and reference concretes after 3 and 7 days of testing

Measuring location	Duration of test (days)	WPC concrete				OPC concrete			
		Reference	Crushing age			Reference	Crushing age		
			28 days	3 days	1 day		28 days	3 days	1 day
Top	0	3.1	4.9	4.5	4.4	2.7	5.8	5.3	5.5
	3	6.3	10.2	9.2	8.9	8.8	13.2	14.4	13.2
	7	7.4	13.3	12.0	12.8	13.8	17.0	17.9	17.7
Bottom	0	0.7	3.0	1.7	4.1	1.5	5.0	2.6	2.6
	3	4.5	8.4	7.9	9.1	6.6	11.7	12.2	11.5
	7	5.9	10.1	9.7	12.3	10.8	17.0	18.2	14.7
Sides	0	1.5	4.6	2.2	3.1	2.3	5.7	5.2	5.6
	3	6.2	9.9	8.9	9.9	10.9	13.8	14.2	12.7
	7	7.3	11.9	10.5	13.1	12.8	16.3	17.0	17.1

0.65 mm/m for the WPC concrete. The shrinkage of the reference concretes at that age was much lower, 0.27 and 0.32 mm/m, respectively. The shrinkage values of the reference concrete are similar to those known for ordinary concretes of different strengths, while the values obtained for the recycled concretes are similar to those of lightweight aggregate concrete made with scoria aggregates having an open porosity [13,14]. Shrinkage of concrete with lightweight aggregate is known to be up to 50% greater than that of normal weight concrete of the same compressive strength [12]. The same compressive strength is achieved in lightweight aggregate concrete by lowering the water/cement ratio; therefore, higher values are expected for weaker concretes that have the same water/cement ratio, similar to the ones in this study.

For both types of cement, the shrinkage of the new concrete made from aggregates crushed at age 28 days was larger than that with aggregates crushed at earlier ages, but no significant change could be seen when comparing crushing ages of 1 and 3 days.

3.2.2.6. Carbonation. The depth of carbonation through the sides of the tested prisms before starting the carbonation test (approximately 6 months after casting, cured in air) and after 3 and 7 days in the carbonation chamber is shown in

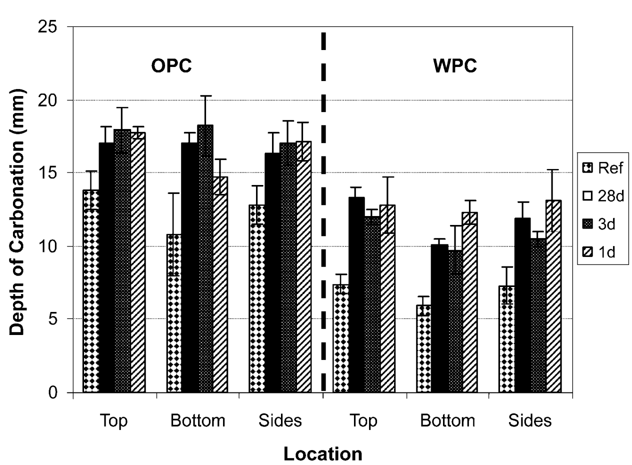

Fig. 7. Depth of carbonation at the different sides of the tested prisms after 7 days in the carbonation chamber.

Table 6. Fig. 7 presents the values obtained after 7 days of testing. The depth of carbonation of the recycled concrete was 1.3–2.5 times greater than that of the reference concrete and higher values were observed in the recycled OPC concrete compared with the WPC concrete. Lower carbonation depths were measured in the recycled WPC concrete made with aggregates crushed at 3 days (Fig. 7). No clear effect of the crushing age was seen when comparing the recycled OPC concretes made with aggregates crushed at different ages.

3.2.3. Latent cementing properties (concrete and mortar)

In order to examine the latent cementing properties that may have been left in the recycled aggregates after crushing, another set of experiments was undertaken. Concrete, similar to the one from which the recycled aggregates were made (Table 1), was prepared and crushed at ages 1, 3 and 28 days to produce recycled aggregates. New concrete and mortar were made from these recycled aggregates without any addition of cement. The mortar was made from the fraction of aggregate that passed a 2.36-mm sieve. Some water had to be added in order to obtain reasonable workability, as well as natural sand (only for the concrete mixes). The compositions and compressive strengths of these mixes are listed in Table 7. The 100-mm cubes were prepared from the concrete and 25-mm cubes from the mortar. The specimens were stored in humid air for 28 days.

A relatively high compressive strength (9.5 MPa) was found for the mortar made from recycled aggregate crushed

Table 7
Composition and strength of the recycled concrete and mortar made without cement

	Concrete	Mortar
Recycled aggregate	9.18 kg	575 g
Natural sand	2.96 kg	
Water	1.09 kg	140 g
28-day compressive strength	Crushed at 1 day: 1.26 MPa	Crushed at 1 day: 9.5 MPa
	Crushed at 3 days: 0.49 MPa	Crushed at 3 days: 0.36 MPa
	Crushed at 28 days: N/A[a]	Crushed at 28 days: N/A[a]

[a] Cubes were not hardened.

at 1 day (Table 7). When the crushing age was 3 days, the strength was only 0.4 MPa and, at a crushing age of 28 days, the crushed material had become completely inert and had gained no strength. A similar trend was observed in the concrete, but with different values resulting from the differences in the mix compositions.

4. Discussion

The difference between the qualities of the new cement matrix and of the old cement matrix adhering to the recycled aggregates seems to be the major parameter governing the properties of the recycled concrete. Two opposing mechanisms appear to control the properties of the recycled aggregates: (1) their mechanical properties when crushed at different ages and (2) the residual cementing capacity of the unhydrated cement that remained in the recycled aggregates. The properties of the recycled aggregates are superimposed on those of the new cement matrix to produce different effects on the new concrete at different ages. These effects are depicted schematically in Fig. 8.

The mechanical properties of the recycled aggregates crushed at different ages were not uniform indicated by the compressive strength of the old concrete they were made from (Table 1). At an early age the recycled aggregate is weak, but it rapidly gains strength with age. Additional hydration of the old cement in the recycled aggregates may somewhat improve their properties when they are embedded in the new concrete, mainly of those crushed at age 1 day. The latent cementing properties of the recycled aggregate crushed at 1 day was clearly seen in the second series of specimens made only from recycled aggregates (Table 7). The cementing potential of the recycled aggregates diminishes rapidly with time and almost disappears after three days. Therefore, the recycled aggregate crushed at one day is weak but still maintains some cementing potential, while, when crushed after 28 days, it is stronger but without cementing potential (Fig. 8). The overall effect depends on the properties of the new cement matrix and it is best seen in the case of a matrix that is much stronger than the aggregate, as in the recycled WPC concrete to be discussed in the following.

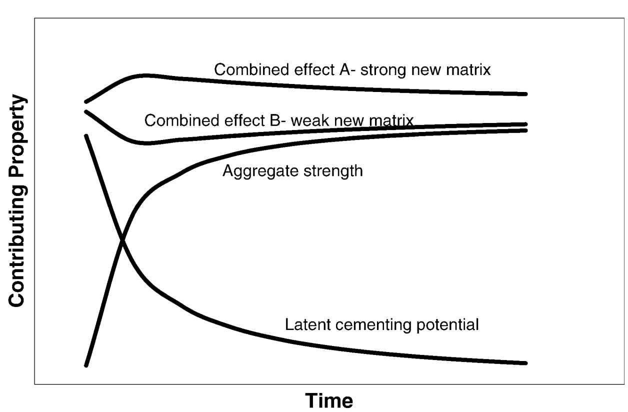

Fig. 8. Schematic presentation of the combined effects of cementing potential and strength of the recycled aggregates and their combined effects in different new concretes.

At the age of 7 days, when the matrix of the new cement is still relatively weak, there was no significant difference between the strengths of the recycled WPC concretes whether made with aggregate crushed at age 1 day or 28 days. At greater ages (28 and 90 days), the new cement matrix became much stronger and the differences between the properties of the new matrix and the aggregates turned out to be more significant. At age 90 days, the new concrete made with recycled aggregates crushed at age 1 day was 18% weaker than the concrete made with aggregates crushed at age 28 days. The low strength of the aggregate crushed at age 1 day has a stronger effect than the latent cementing capacity at that age. Recycled aggregate, crushed at age 3 days, combines the benefits of both strength and cementing capacity resulting in stronger recycled WPC concrete as compared with the WPC concretes made with recycled aggregates crushed at age 1 or 28 days (line A in Fig. 8).

The cement matrix of the new OPC concrete was relatively weak, thus, the effect of the crushing age was more moderate. The properties of the old cement matrix and of the new matrix were close to each other. Therefore, the contribution of cementing capacity (crushing age of 1 day) or a better old matrix (crushing age of 28 days) could yield a better concrete than the one made with aggregate crushed at 3 days (line B in Fig. 8).

5. Summary and conclusions

1. The properties of the recycled aggregates crushed at different ages were quite similar. The size distribution of the aggregates was the same for the three ages of crushing, as well as other properties such as absorption, bulk-specific gravity, bulk density, cement content and crushing value of the coarse fraction. These observations indicate that at these strength levels and structure of the old concrete the aggregates that are made of it have quite similar properties. However, some additional cementing capacity still remains in the aggregates crushed at 1 day, but it rapidly decreases within a few days.

2. Concrete made with 100% recycled aggregates was weaker than concrete made with natural aggregates at the same water to cement ratio. When the new concrete was made from the same type of OPC and the same water to cement ratio as the old concrete, the strength reduction was ~25%, regardless of the crushing age of the old concrete. With white cement, the reduction was 30–40%, depending on the crushing age of the old concrete (the white cement provides with 20% higher compressive strength than the OPC concrete at the same water to cement ratio prepared with natural aggregate). Other properties, such as flexural and splitting strengths, absorption and absorption rate,

drying shrinkage and depth of carbonation, exhibited similar trends.

3. The properties of recycled WPC concrete made with recycled aggregate crushed at age 3 days were significantly better than those of concretes made with aggregate crushed at age 1 or 28 days. Opposing trends were seen in recycled OPC concrete in which the new cement matrix was weaker than that of the WPC concrete at the same water to cement ratio.

4. Two opposing mechanisms seem to affect the properties of the new concrete: the physical properties of the old concrete and the presence of unhydrated cement in the recycled aggregate. These effects are prominent when the new cement matrix is significantly stronger than the one in the old concrete. In such concrete, the combination of strength and cementing capacity of the recycled aggregates crushed at 3 days provides better strength over crushing ages of 1 or 28 days. In a weaker new cement matrix, this effect is reversed and the new concrete made from recycled aggregates crushed at 3 days was slightly weaker than concrete made from aggregates crushed at 1 or 28 days.

5. The properties of aggregates made from crushed concrete and the effect of the aggregates on the new concrete (strength, modulus of elasticity, etc.) resemble those of lightweight aggregate concrete, and similar considerations apply when dealing with this type of aggregates.

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