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ORIGINAL ARTICLE

Performance of mortars containing recycled fine aggregate from construction and demolition waste

Amnon Katz · Daniele Kulisch

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Abstract Waste from construction and demolition accumulates in large quantities in the modern world. Recycled coarse aggregates derived from this waste can replace virgin aggregates used in the production of new concretes but the studies on the effect of using the fine fraction of this waste on the properties of new concrete have not yet led to clear conclusions. The present study evaluated the properties of recycled fine aggregates derived from two recycling plants using two different waste treatment procedures, as well as their effects on the properties of fresh and hardened mortars prepared using these aggregates at two water-to-cement ratios and three replacement ratios. It was found that the recycled aggregates were more porous than the natural aggregates and may have contained some organic matter. Setting times were longer when recycled aggregates replaced natural aggregates and strength and durability were reduced as well. Partial replacement of the fine aggregate is possible if an appropriate compensation of the water to cement ratio is applied.

Keywords Recycled fine aggregate · Durability · Strength · Recycled concrete

A. Katz (✉) · D. Kulisch
Faculty of Civil and Environmental Engineering, National Building Research Institute, Technion – Israel Institute of Technology, Haifa, Israel
e-mail: akatz@technion.ac.il

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1 Introduction

Construction and demolition waste (C&DW) accumulates in large quantities in many countries and thus requires special attention. The European Commission, for example, set a target of 70% recycling by the year 2020 [1]. A report prepared for the European Commission [2] estimates the amount of mineral waste at 40–80% of the total C&DW. Similarly, Katz, Baum [3] found that granular material comprises ~50% of construction waste accumulated during the construction of structural frames of residential buildings, a figure that decreases to ~20% during finishing works. This granular waste material can be recycled to produce aggregates for civil works and most of the waste is indeed used as aggregates in infrastructure works such as road construction [2]. Its use in concrete as a replacement for natural aggregates is more challenging due to some detrimental effects on the properties of the new concrete.

The use of coarse recycled aggregate as a replacement for natural aggregate has been studied extensively in past years [4–10]. In general, it was found that replacing 10–20% of the virgin aggregate with recycled coarse aggregate is possible without it having a significant effect on the properties of the new concrete. RILEM published recommendations for the use of recycled aggregates in the production of new concrete [11], and similar recommendations can be found in current standards, e.g. EN 206 [12].

Recycling the fine fraction of C&DW (<∼5 mm) is more problematic since this fraction affects the water requirements for a given workability, changes the cohesiveness, and affects the control of segregation and bleeding [13]. Fine recycled aggregates are also more susceptible to contamination with foreign materials than is the coarse fraction, resulting in negative effects on the new concrete [4]. Rodrigues et al. [14] found that the fraction of particles smaller than 0.063 mm contains harmful materials such as gypsum and clay, and therefore its removal can improve the quality of the recycled aggregates.

Many studies were done using artificial recycled aggregates, i.e. aggregates from concrete that was manufactured solely for those specific studies [15–17] while others used mixed waste from C&DW recycling plants that, in many cases, contained both old concrete and old clay bricks [18–20].

Conflicting results were obtained in the abovementioned studies regarding properties at both the fresh and the hardened states. Some reported improved workability, compressive strength or durability, or at least, no negative effects, whereas others observed a decline in these properties. It appears that the method used to determine the absorption of water into the recycled aggregate during mixing and the way in which that water should be taken into account when designing the mix of new concrete have significant effects on the properties of the new concrete. This may partially explain the conflicting results found in the literature.

In the study presented here, we investigated the properties of fine aggregate manufactured from local C&DW processing and recycling plants and recorded the effects of aggregate replacement on a number of important fresh and hardened properties of new mortar made with these aggregates, for several replacement ratios. Mortars were selected for this study to focus on the fine aggregate without effects that may arise from the interaction with the coarse fraction.

2 Experiment

2.1 Materials

2.1.1 Recycled fine aggregate

Samples of 'as is' construction and demolition waste were collected from two treatment plants that represent two significantly different waste streams: Plant A is located in a dense and highly populated area and is equipped with advanced sorting and treatment facilities; Plant B is located in a less populated area and is equipped with basic sorting and treating facilities.

The waste stream arriving at both plants undergoes initial inspection and sorting but the process at plant A is more stringent, and so harmful materials, such as leaves and other organic matter, are better removed from the stream. After this initial sorting, the waste streams pass through a crushing and sieving process that separates the stream into two sub-streams of coarse and fine particles (larger and smaller than ∼5 mm). Aggregates RA-3 and RA-4 are obtained from the fine portion of the waste, as described above, from Plants A and B, respectively.

Aggregate RA-3 (Plant A) was further treated by additional crushing and separation into two fractions: larger and smaller than 1.18 mm. The smaller particles were then subjected to intensive washing and scrubbing processes commonly used in aggregates treatments to remove clay and other deleterious materials from stones crushed to the size of sand, yielding RA-1, whereas the fraction of larger particles, denoted RA-2, was stored on-site. The exact treatment was not exposed by the manufacturer as a trade secret. The number in the aggregate's name represents the level of expected properties after the cleaning process.

2.1.2 Natural crushed fine aggregate

Natural crushed fine aggregate, rather than natural sand, was used as a reference aggregate since its size distribution and shape are closer to those of the recycled fine aggregate. Also, from a practical point of view, natural sand sources are diminishing whereas crushed aggregate is widely used nowadays in the concrete industry.

2.1.3 Cement

Ordinary Portland cement CEM I 52.5 N conforming to EN 197 was used.

2.2 Experimental program

The experimental program was divided into three steps:

- Characterization of the aggregates.
- Preparation of mortars containing recycled aggregates. Mortars were prepared with two water/cement ratios (0.40 and 0.60) and three replacement ratios (0, 30 and 100% by weight). Mixes with 0% replacement ratio served as reference.
- Characterization of the fresh and hardened mixes.

Mortar compositions: All mortars were prepared with a constant cement:fine-aggregate weight ratio of 1:2 and so the final cement:water:sand compositions were either 1:0.4:2 or 1:0.6:2. Comparison with a single reference sand enables preserving constant water to cement ratios (0.40 and 0.60) throughout partial and full replacement of the aggregates, while monitoring the effects on the fresh and hardened properties.

Adjusting the water content to compensate for the increased absorption by the porous aggregates is widely discussed in the literature with respect to lightweight aggregate concrete [21, 22] or recycled aggregate concrete [7, 16]. Neville [21] stated that "major part of the 30-minute absorption takes place in 2 min from wetting". Water absorption at the first 30 min from wetting was, thus, determined for each aggregate. The aggregates and the adjusted mixing water content were mixed for a few seconds and allowed to rest for 3 min before adding the other ingredients to allow absorption of the excess water, thus maintaining the desired water/cement ratios.

2.3 Characterization techniques

Aggregates:

- Particle size distribution.
- Fines content (particles smaller than 75 μm).
- Presence of organic impurities based on colorimetric test (ASTM C40).
- Absorption capacity (ASTM C128).
- Specific gravity at oven-dry and saturated surface-dry conditions (ASTM C128).
- Thermal gravimetric analysis (TGA) up to 1000 °C at a constant rate of 10 °C/min.; decomposition of various phases is expressed as weight loss at certain and characteristic temperatures.
- Scanning electron microscopy (SEM).

Fresh mortar:

- Density.
- Consistency as per the flow table in ASTM C1437 but using 15 drops only.
- Air content as per the air pressure gauge method (ASTM C231) using a 1-liter container.
- Setting time as per the penetration resistance method (proctor needle as in ASTM C403); this test was performed for 0 and 100% replacement ratios only.

Hardened mortar:

- Compressive strength on 50 mm cubes (ASTM C109) or section of beams used for flexural strength (EN 196-1). Testing age was 3, 7 and 28 days. All specimens cured in water up to the testing age.
- Flexural strength using 40 × 40 × 160 mm prisms tested at 3, 7 and 28 days as per the three-point flexural test method (EN 196-1).
- Capillary absorption as per the principles set out in EN 13057 using discs 200 mm in diameter and 50 mm thick cured in water for 7 days following 21 days in laboratory air. The specimens then dried to a constant weight at 60 °C and all surfaces are sealed except for the one in contact with water.
- Air permeability test using the Torrent device [23]. Test was done on discs, 200 mm in diameter and 50 mm thick, that were cured in water for 7 days following 21 days in the lab environment, and then dried at 60 °C until reaching a constant weight (~7 days) before testing.
- Accelerated carbonation test: specimens used for the air permeability tests were placed for 7 days in a carbonation chamber with 5% CO_2 concentration, at 30 °C and 50% R.H. This test was used as a sample test only to assess the mortars' sensitivity to carbonation.

Three specimens were used to calculate the average result of each test.

3 Results

3.1 Aggregates

Figure 1 presents the sieve analysis of all tested aggregates together with the reference (natural crushed) aggregate. Table 1 presents data on other properties of the aggregates.

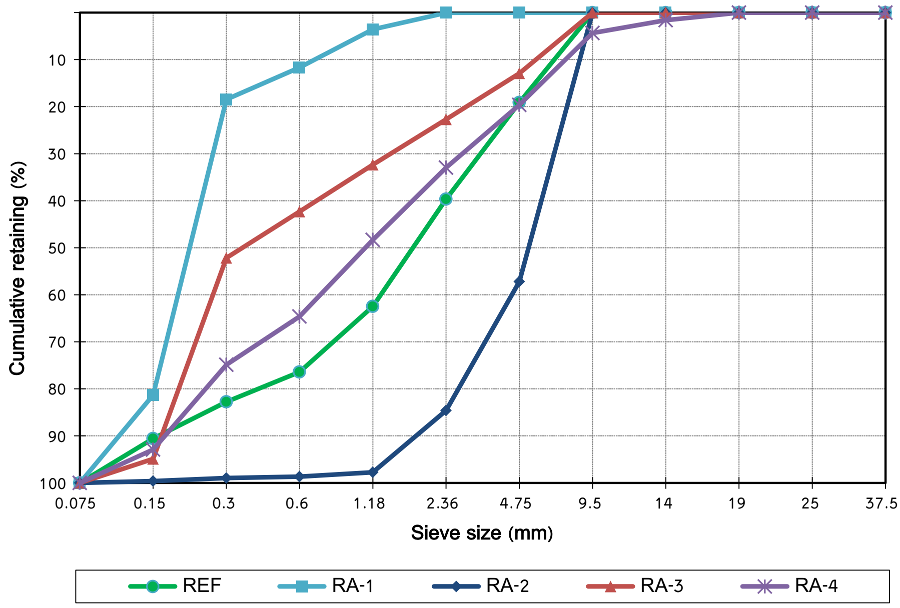


Fig. 1 Sieve analysis of the tested aggregates

Table 1 Properties of recycled and reference aggregates

	RA-1	RA-2	RA-3	RA-4	Crushed sand (REF)
Content of material finer than 75 µm (%)	7.6	0.85	18.2	25.1	12.4
Organic impurities	Lighter	Lighter	Lighter	Darker	–
Absorption capacity (%)	2.5	6.6	8.7	7.8	2.4
Specific gravity—OD	2.48	2.22	2.13	2.17	2.6
Specific gravity—SSD	2.55	2.37	2.32	2.34	2.65
Fineness modulus	1.15	5.37	2.57	3.38	3.71
Natural moisture content (%)[a]	1.5	1.5	0.6	0.56	1.4

[a] Natural moisture content (determined in air-dried conditions) is used for the mortar mix design

It seems that the size distribution of aggregate RA-4 (Plant B) is similar to that of the reference aggregate whereas the aggregate from Plant A, RA-3, contains a much larger quantity of particles that are smaller than 0.3 mm. When RA-3 was further treated, it was divided to a fraction of smaller particles, RA-1, mostly <0.3 mm, and a fraction of coarser particles, RA-2, >1.18 mm. The content of particles finer than 75 µm ('fines') is quite high for both plants, and is 18 and 25% for aggregates RA-3 and RA-4, respectively, compared with 12% in the natural crushed sand. The additional cleaning process of aggregate RA-3 significantly reduced the fines content to 7.6% in RA-1 and 0.8% in RA-2. Note that the fines content was determined using wet sieving, while regular sieving (Fig. 1) is done on the dry material that is not sufficiently accurate for very fine particles. Thus, a discrepancy in results may be seen between the two methods.

The absorption capacity of the recycled aggregates is relatively high, at 8.7 and 7.8% for aggregates RA-3 and RA-4, respectively, compared with only 2.4% for the crushed natural sand. Further treatment of RA-3 yielded the RA-1 fraction that is less porous and denser, values that are close to those of natural aggregate, and another fraction, RA-2, that is both more porous and less dense. It is, however, interesting to note that RA-2 is denser and less porous than RA-3 from which it was processed, probably due to additional crushing of the old paste that adhered to the particles in RA-3. Increased density upon reduction of aggregate size due to crushing is a known phenomenon in lightweight aggregate technology as well [22].

Tests for the presence of organic matter were conducted using the colorimetric method (ASTM C40) in which a clear solution of NaOH darkens due to the presence of organic matter. Only RA-4 presented indication of the presence of organic matter (Table 1) but TGA showed peaks at ~50 °C that may be attributed to the presence of volatile compounds in RA-2 and RA-3 as well (Fig. 2).

TGA also showed the expected phases in C&DW, such as calcium carbonate (~700 °C) and C-S–H (~900 °C). In the analysis of RA-3, a peak was identified at 378 °C and attributed, with high probability, to the presence of a polymer that was not clearly identified by other methods. It is interesting to note that only a small peak at ~420 °C, attributed to calcium hydroxide, was identified in RA-1 and RA-2, indicating extensive carbonation of the aggregates upon exposure to the atmosphere while undergoing processing at the recycling plants.

Chemical analysis of the recycled aggregates further demonstrated the difference between the sources of the two waste samples (RA-3 vs. RA-4) as well as the separation of RA-3 into two different fractions (RA-1 vs. RA-2) (Table 2). Aggregate RA-3 is manufactured from the waste generated in an area where the use of natural quartz sand is quite common, both in new and old concretes, while crushed limestone fine aggregate is more common in the area where RA-4 was manufactured. This difference is demonstrated by the higher contents of SiO_2 seen in RA-3 compared with RA-4 (52 and 24%, respectively). The additional treatment of RA-3 yielded the RA-1 fraction characterized by a high content of SiO_2 (67%) compared with only 29% in RA-2. These results are in line with the loss-on-ignition (LOI) results, which demonstrated much higher values for RA-2 than

Table 2 Chemical composition of the recycled aggregates

d.b. (wt%)	RA-1	RA-2	RA-3	RA-4
CaO	13.48	25.37	20.76	34.43
SiO_2	67.20	28.65	51.94	24.13
Al_2O_3	1.68	3.53	2.12	2.22
Fe_2O_3	0.73	2.24	0.90	0.74
MgO	1.89	7.40	3.50	6.92
TiO_2	0.14	0.33	0.20	0.12
K_2O	0.36	0.40	0.34	0.29
Na_2O	0.27	0.23	0.22	0.30
P_2O_5	0.02	0.10	0.03	0.04
Mn_2O_3	0.02	0.05	0.02	0.02
SO_3 ICP	0.45	0.67	1.17	0.74
LOI 950 °C	12.94	31.44	19.79	29.22

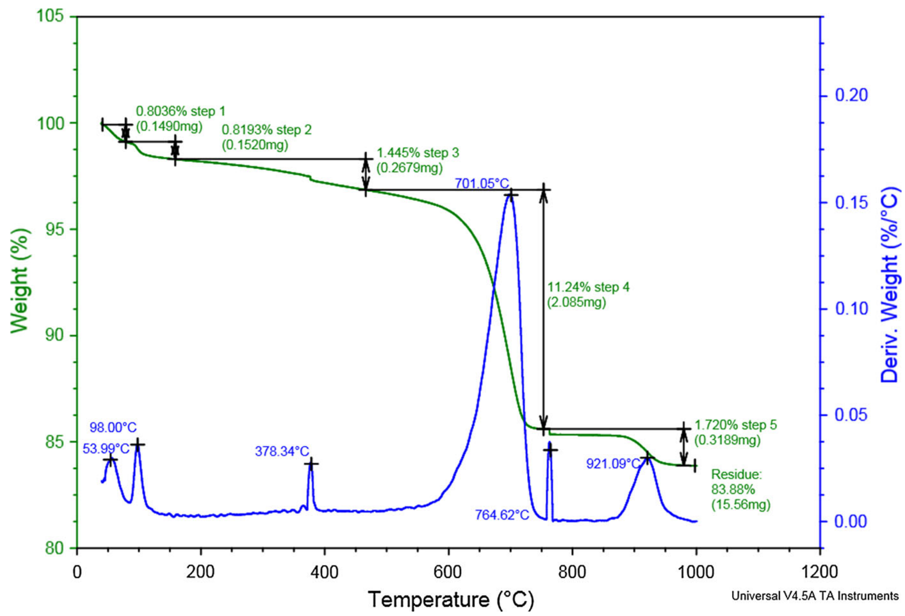


Fig. 2 Representative TGA results (RA-3)

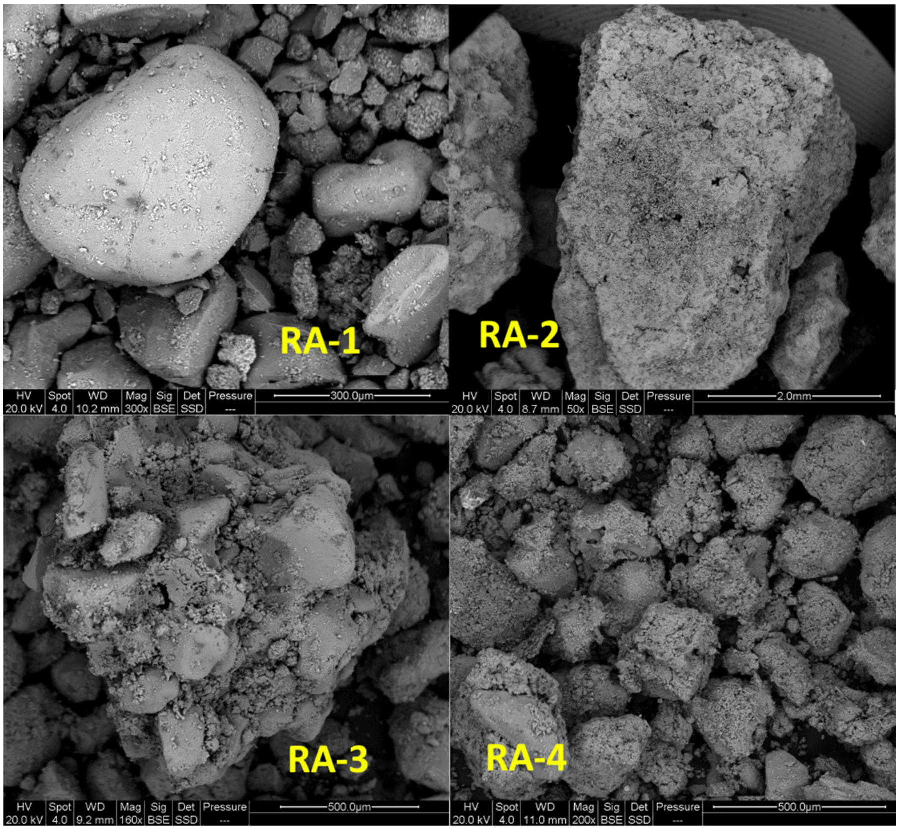


Fig. 3 SEM images of the recycled aggregates

for RA-1 (31 vs. 13%), indicating larger amounts of old cement paste in RA-2.

Additional support for these finding can be seen in the typical SEM images taken of the aggregates (Fig. 3). Cleaner and more rounded aggregates were identified in RA-1, consistent with the shape of quartz aggregates, while RA-2 demonstrated aggregates that are more porous. RA-3 and RA-4 contained agglomerates of natural aggregates bound by porous cement paste.

3.2 Fresh mortar

Table 3 presents the properties of the fresh mixes.

3.2.1 Density

Fresh mortar mixes containing recycled aggregates exhibited lower density, as was expected due to the lower density of the recycled aggregates; this reduction was naturally greatest when all of the natural aggregate was replaced. A pronounced reduction in mortar density is seen for RA-3 and RA-4 at w/c = 0.6 and 100% replacement, resulting probably from the increased air entrapment in these mixes.

3.2.2 Air content

Air content was relatively stable in most of the mixes: ~4.5% at low w/c and ~2.5% at high w/c. The thicker mixes with low w/c entrapped more air, probably due their higher consistency, as identified also by the consistency test. Such mixes that contain porous aggregates are expected to exhibit high variability since the pressure method (ASTM C231) is affected by the presence of some air in the open pours of the recycled aggregate. Nevertheless, a significantly large volume of trapped air was identified when aggregates RA-3 and RA-4 were used at a maximum replacement ratio of 100% and high w/c (0.6). Somewhat increased air content was detected for aggregate RA-4 also at 30% replacement ratio and

Table 3 Properties of fresh mixes

	Replacement ratio (%)	Aggregate type	Consistency (mm)	Density (kg/m^3)	Air content (%)	Setting time (h:min)	
						Initial	Final
w/c = 0.4	0	REF	144	2269	4.0	2:10	3:48
	30	RA-1	149	2232	4.7	÷	÷
		RA-2	158	2230	5.2	÷	÷
		RA-3	152	2194	4.4	÷	÷
		RA-4	136	2205	4.4	÷	÷
	100	RA-1	148	2116	6.1	2:35	3:58
		RA-2	176	2079	4.8	2:40	4:01
		RA-3	155	2021	4.8	3:02	5:02
		RA-4	121	2037	4.6	3:32	5:26
w/c = 0.6	0	REF	229	2172	0.8	4:38	6:20
	30	RA-1	232	2153	2.2	÷	÷
		RA-2	232	2134	2.6	÷	÷
		RA-3	231	2128	2.7	÷	÷
		RA-4	214	2077	3.7	÷	÷
	100	RA-1	241	2040	2.4	5:29	7:46
		RA-2	242	1991	2.4	5:33	8:40
		RA-3	243	1909	4.2	5:33	8:20
		RA-4	229	1862	5.2	6:38	9:50

same w/c of 0.6, but not for RA-3. High results of air content were also observed for RA-1 at w/c = 0.4 and 100% replacement and similar values obtained when calculated based on the density of the fresh mortar and its ingredients (ASTM C185). The reason for these exceptional high values is unclear and requires further investigation.

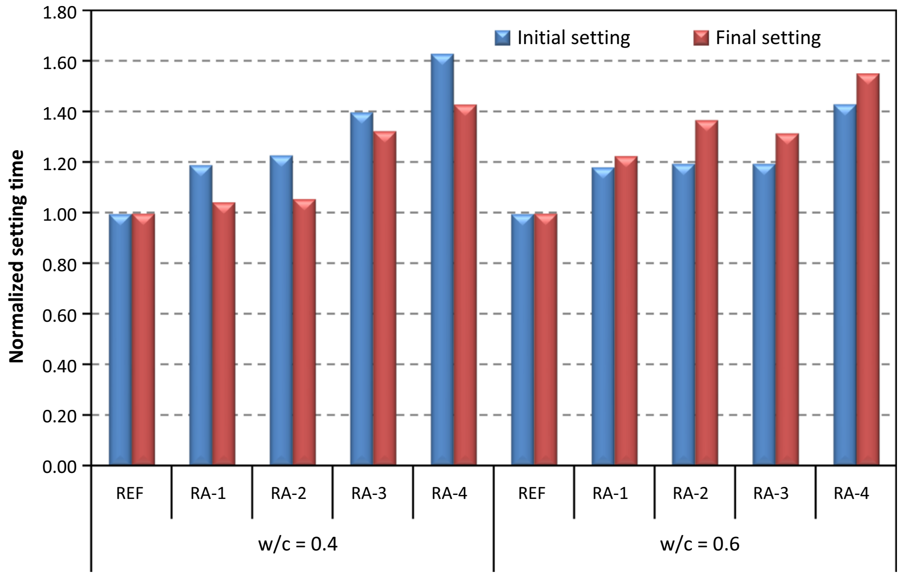
3.2.3 Consistency

Consistency of fresh mixes is affected by several parameters: (1) total amount of free water; (2) ratio between water and fine particles (including cement and aggregate fines); and (3) roughness of aggregate surface. All of the mixes tested were prepared at a constant weight ratio and so the use of lower-density aggregates increased their relative volume in each unit volume of fresh mortar (e.g. 1 m^3) while reducing the relative amount of the other ingredients (cement and water) in this unit volume. Calculation of the water content per 1 m^3, based on the results of mortar unit weight (ASTM C185), shows that when RA-3 replaced 100% of the reference aggregate, the amount of free water decreased from 267 to 238 kg/m^3 at w/c = 0.4, and from 362 to 318 kg/m^3 at w/c = 0.6 (note that the cement content changed accordingly in order to maintain a constant w/c). A certain decrease in the consistency of the mixture is expected with such reduction of water content, but the effect on consistency, if any, was moderate, indicating that the combined effect of the above mentioned parameters is complex and the exact behavior cannot be predicted accurately.

3.2.4 Setting time

Setting time increased for all mixtures in which recycled aggregates were used. Table 3 presents absolute values of initial and final setting times, and Fig. 4 presents normalized values with respect to mixes containing natural aggregate (REF). The initial setting time for RA-1 and R-2 increased by 20% at both w/c ratios, while for RA-3 and RA-4 it increased, respectively, by 40 and 63% at w/c = 0.4 and by 20 and 43% at w/c = 0.6. The effect on the final setting time was smaller for the low w/c ratio and greater for the high w/c ratio. This retarding effect is probably due to the presence of organic matter, which was clearly identified by the colorimetric method in RA-4, the mix

Fig. 4 Normalized setting times (with respect to REF) of the various mixes



that exhibited the greatest delay in setting time, and in the other aggregates by TGA only. It is possible that the colorimetric method may not be sensitive enough to identify the presence of contaminants identified by a more complex method such as TGA.

3.3 Hardened mortar

3.3.1 Compressive strength

Compressive strength of the hardened mortar samples was tested at 3, 7 and 28 days and the results are shown in Table 4 and Fig. 5. Table 4 also presents the relative effect on strength with respect to the reference mix at each w/c ratio.

3.3.2 Low replacement ratio

A small effect, ranging from +10 to −9%, was noticed at early age (3 and 7 days) for the high w/c ratio and low replacement ratio. At the lower w/c ratio, early age and low replacement ratio, the effect was larger—up to 27% reduction for RA-4. At the later age of 28 days, the effect was dominant and all mixes with partial replacement ratio exhibited lower strength. The decrease in strength was, however, quite small when aggregate RA-1 and RA-2 were used (3 and 15% for the low w/c mixes and 9 and 7% for the high w/c mixes, respectively). When aggregates RA-3 and RA-4 partially replaced the virgin aggregates, the reduction was significant: 25 and 29% for the low w/c mixes and 15 and 29% for the high w/c mixes, respectively.

3.3.3 High replacement ratio

Full replacement of the natural aggregate with recycled aggregate yielded a significant reduction in the compressive strength of all aggregates tested and at all ages. The reduction was as high as 60% for aggregate RA-4 and ~20 and ~35% for aggregate RA-1 at the high and low w/c ratios, respectively. It was evident that the effect of replacing natural aggregate with recycled aggregate was smaller in mixes with higher w/c ratios while in the low w/c mixes, the differences between the mechanical properties of the new paste and of the aggregate were substantial, leading to a remarked decline in the mechanical properties of the mortar. As expected, this effect was more pronounced when full replacement of the aggregates was made, as was observed also by Limbachiya et al. [8] for coarse recycled aggregate. This behavior resembles that of lightweight aggregate concrete, in which aggregate mechanical properties are inferior to that of the paste, and so an increase in paste strength does not always lead to a similar increase in concrete strength [24].

It is interesting to note that the compressive strength of the low w/c mix with 100% replacement with RA-1 was similar to that of the reference mix with the high w/c ratio (Fig. 5). This implies that the detrimental effect of using 100% recycled aggregate

Table 4 Compressive strength of mixes at 3, 7 and 28 days

	Compressive strength (MPa)			Change (%)		
	3 days	7 days	28 days	3 days	7 days	28 days
w/c = 0.4						
REF	56.5	64.6	73.8	–	–	–
RA-1 30%	43.7	63.6	71.7	−23	−2	−3
RA-1 100%	35.0	42.6	48.8	−38	−34	−34
RA-2 30%	42.4	52.6	62.5	−25	−19	−15
RA-2 100%	23.8	32.0	39.7	−58	−50	−46
RA-3 30%	42.1	51.4	55.5	−26	−20	−25
RA-3 100%	23.0	30.0	40.3	−59	−54	−45
RA-4 30%	41.5	48.3	52.7	−27	−25	−29
RA-4 100%	22.2	25.0	34.4	−61	−61	−53
w/c = 0.6						
REF	24.6	33.3	47.2	–	–	–
RA-1 30%	22.4	33.3	42.9	−9	0	−9
RA-1 100%	19.2	26.6	38.2	−22	−20	−19
RA-2 30%	27.0	35.3	43.7	+10	+6	−7
RA-2 100%	13.7	19.3	30.1	−44	−42	−36
RA-3 30%	25.0	31.9	40.2	+2	−4	−15
RA-3 100%	13.7	15.9	25.9	−44	−52	−45
RA-4 30%	23.7	31.4	33.5	−4	−6	−29
RA-4 100%	12.0	14.4	22.0	−51	−57	−53

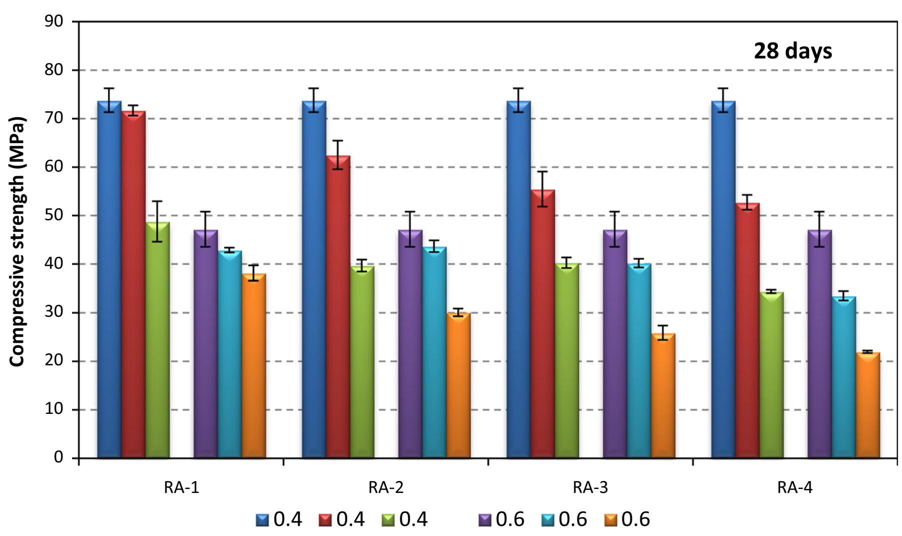


Fig. 5 Compressive strength of the mixes at 28 days

can be improved by lowering the water-cement ratio, in this case from 0.6 to 0.4. This conclusion applies, however, to aggregate RA-1 only; it seems that when RA-2 aggregate is used, the water-cement ratio must be reduced to values lower than 0.4, since the compressive strength of the reference mix at w/c = 0.6 was 47.2 MPa while that of RA-2 at w/c = 0.4 and full replacement was only 39.7 MPa. Thus, a further reduction in the w/c ratio is needed to preserve the mix's compressive strength.

Figure 6 presents the effect of using recycled fine aggregate on the rate of development of compressive

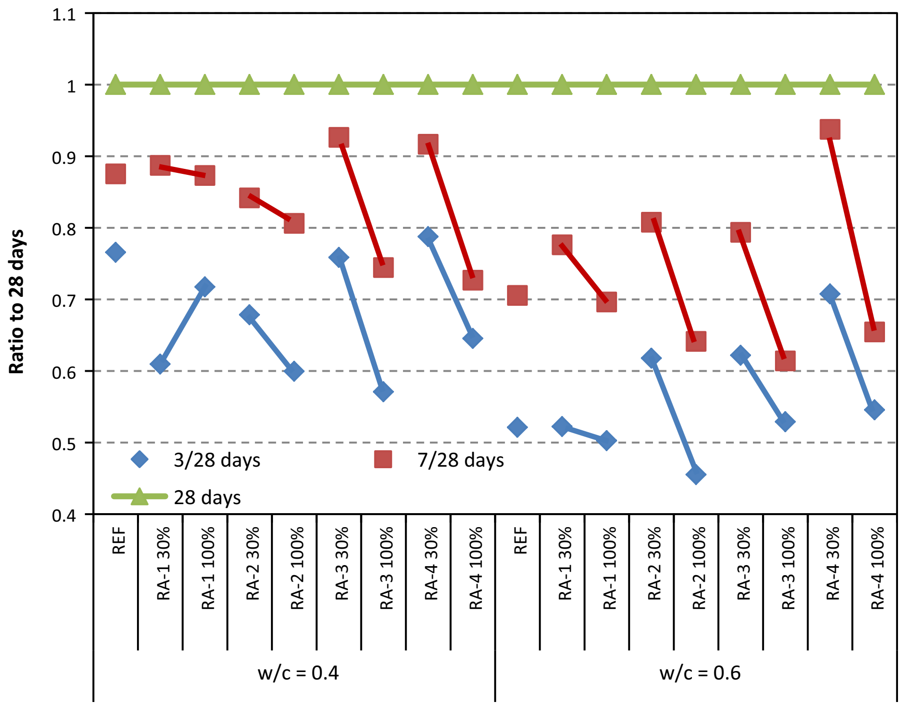


Fig. 6 Ratio between strength at 3 days and at 7 days to strength at 28 days

strength. The figure shows the ratio between the strength at 3 or 7 days to the strength at 28 days. Increasing the replacement ratio from 30 to 100% reduced the 3-to-28 or 7-to-28 ratio, which is represented by the line connecting between the two replacement ratios of each aggregate. The reduction was minor for RA-1, only a few percent, but significant for the other aggregates, mainly RA-3 and RA-4. The only exception was RA-1 at w/c = 0.4, where the ratio to strength at 28 days increased by 11% when the replacement ratio increased from 30 to 100%. It seems that increasing the replacement ratio slows the rate of strength development in addition to the apparent effect on the absolute value of strength itself. This finding is also in agreement with the slower rate of setting described in the section on fresh properties.

3.3.4 *Flexural strength*

Flexural strength was tested at 3, 7 and 28 days and the results are presented in Table 5. Using recycled fine aggregate as replacement for natural aggregate led to a decrease in the flexural strength of all mixes prepared at the low w/c ratio. Partial replacement led to a moderate strength reduction at early age and to a more significant reduction of ~30% at 28 days, except for RA-1 for which a reduction of only 10% was observed. With full aggregate replacement, the reduction was significant for all types of aggregates ranging from 30% for RA-1 to 67% for RA-4. At an early age of 3 days, partial replacement of aggregates led to only a moderate strength reduction but to severe reduction at full replacement.

At the higher w/c ratio, the effect of aggregate replacement was small at partial replacement and in some cases, a slight increase in the flexural strength was observed. At full replacement ratio, the reduction was more pronounced, 20–40% at age 28 days for aggregates RA-2 to RA-4, but no reduction was observed for RA-1.

It is possible that two phenomena act simultaneously: reduction due to the effect of aggregates with inferior properties on the one hand, and an improved interlocking effect known to affect flexural strength due to the increased roughness of the aggregates compared with natural aggregates.

3.3.5 *Capillary absorption*

Capillary absorption results are presented in Fig. 7 for the various mixes. Different trends were identified at

Table 5 Flexural strength of mixes at 3, 7 and 28 days

	Flexural strength (MPa)			Change (%)		
	3 days	7 days	28 days	3 days	7 days	28 days
w/c = 0.4						
REF	10.5	11.3	13.1	0	0	0
RA-1 30%	9.5	7.1	11.9	−9	−38	−10
RA-1 100%	7.4	9.2	9.0	−30	−19	−32
RA-2 30%	9.2	10.1	9.1	−12	−11	−31
RA-2 100%	5.7	7.0	8.3	−46	−38	−37
RA-3 30%	9.4	11.2	10.0	−10	−1	−24
RA-3 100%	5.4	6.3	5.3	−48	−45	−59
RA-4 30%	7.9	9.4	9.2	−25	−17	−30
RA-4 100%	4.2	6.0	4.4	−60	−47	−67
w/c = 0.6						
REF	6.1	8.1	8.6	0	0	0
RA-1 30%	5.4	6.4	9.4	−12	−21	+10
RA-1 100%	4.9	7.8	8.9	−20	−3	+4
RA-2 30%	6.2	8.3	9.4	+1	+4	+10
RA-2 100%	4.1	4.2	6.8	−33	−48	−21
RA-3 30%	6.6	8.5	9.4	+8	+6	+10
RA-3 100%	3.2	4.4	5.9	−47	−45	−31
RA-4 30%	6.1	5.8	7.3	0	−28	−14
RA-4 100%	2.7	3.5	5.2	−55	−56	−40

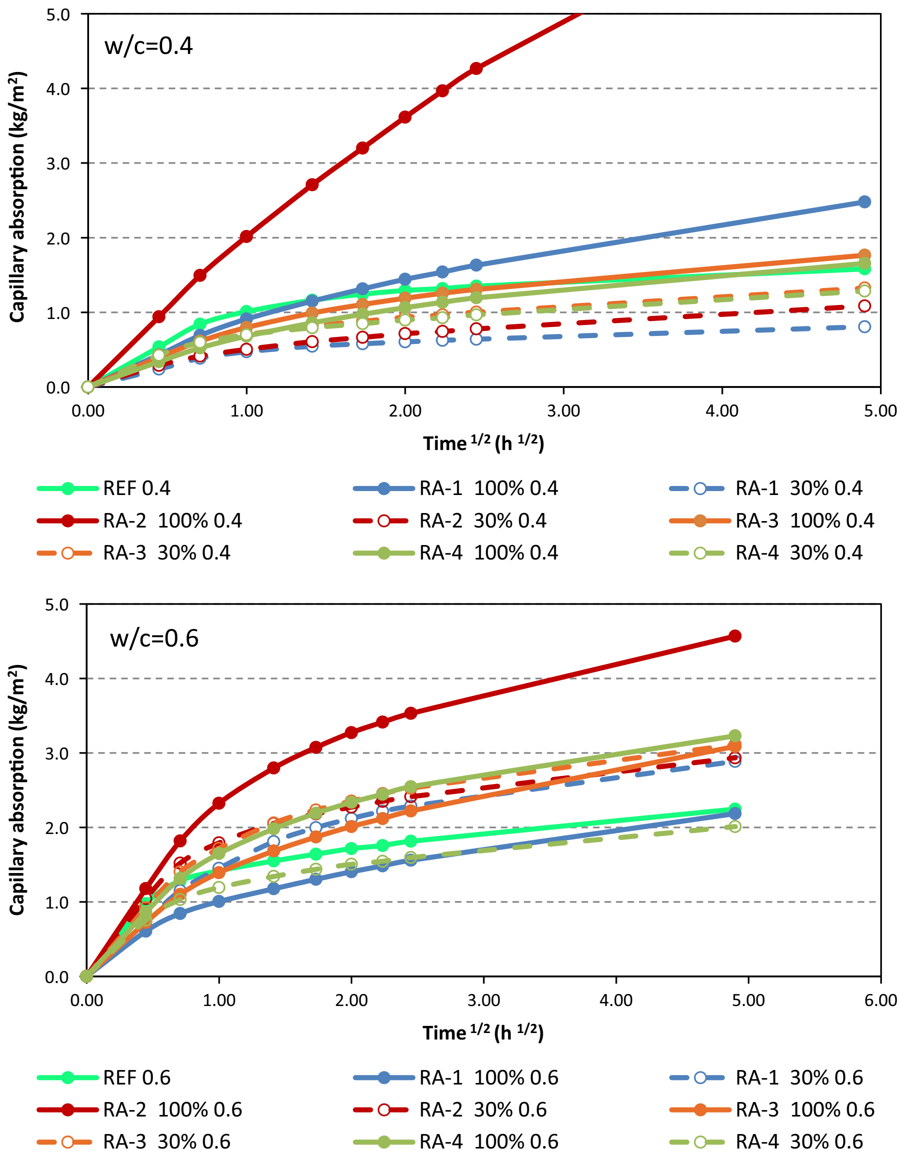
the two w/c ratios tested. At the low w/c ratio, all mixes containing 30% recycled aggregates exhibited lower absorption values compared with the reference mix. At 100% replacement, RA-3 and RA-4 exhibited somewhat lower absorption values, mainly at the initial stage of the test, while the more treated aggregates, RA-1 and RA-2, showed higher and much higher values, respectively. At the higher w/c ratio, only RA-1 at 100% replacement and RA-4 at 30% replacement exhibited lower absorption values compared with the reference mix. Somewhat higher values were obtained for all other mixes, regardless of the aggregate type or replacement ratio, except for RA-2 that, at a 100% replacement rate, exhibited higher values, but not as high as at the lower w/c ratio.

It should be noted that attempts to calculate the samples' sorptivity values according to common standards (e.g. ASTM C1585 or EN 13057) or as proposed by Hall [25], failed due to large deviations from the expected theoretical curve.

It seems that several parameters influence the capillary absorption process, including the composition and content of fines in the recycled aggregates and the differences between the pore structure of the new cement paste and that of the recycled aggregates, which is likely affected by the presence of old paste. These parameters may influence the connectivity and tortuosity of the pores in the new mortars, thus leading to a wide variation in the results. Using the very porous aggregate, RA-2, at a 100% replacement ratio and low w/c ratio led to significant differences between the aggregates and the new paste, which together with a low content of fine particles led to very high absorption values. At the higher w/c ratio, the difference between the pore structure of the recycled aggregate and that of the new paste is smaller and so absorption values are lower for this aggregate.

This complex behavior is probably a result of using aggregates from recycling plants that treat mixed waste. Such behavior was not observed when recycled aggregates were derived from artificial concrete that was produced in the lab (Evangelista, Brito [15]) thus the abovementioned assumption should be checked in a different study.

Fig. 7 Capillary absorption of the tested mixes



3.3.6 Air permeability

Air permeability was measured using the Torrent method [23] and results are presented in Table 6 together with the change relative to the reference mix at each w/c ratio tested. It appears that in all cases, using recycled aggregates increased the coefficient of air permeability. Larger replacement ratio led to higher air permeability values except for RA-1 at w/c = 0.6, for which similar values were obtained at both replacement ratios. Again, it seems that one of the controlling mechanisms is the difference between the properties of the new paste and the paste present in the recycled aggregates. Air permeability of RA-2 at w/c = 0.4 and 100% replacement ratio was seven times higher than that of the reference mix. At the higher w/c ratio, the coefficient was only three times higher than that of the reference. These results are in line with the results of the capillary absorption tests.

Also, similar values were obtained for mixes RA-2 and RA-4 at 100% replacement ratio and the high w/c ratio ($\sim 51 \times 10^{-16}$ m^2), while different values obtained at the low w/c: 30×10^{-16} m^2 for RA-2, and 7×10^{-16} m^2 for RA-4, both at 100%

replacement. These two aggregates are quite similar in terms of their porosity but differences in their fines contents may affect the density of the matrix around the aggregates as was found by Ye et al. [26] for pates prepared at low w/c ratio. It is possible that this effect on air permeability is minor when porous pastes are involved, as in the case of high w/c ratio.

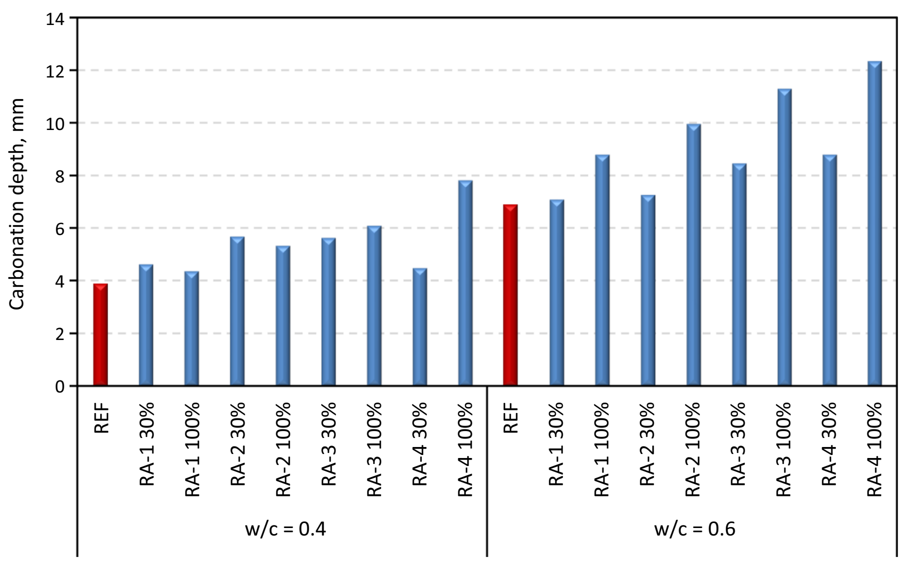
Table 6 Torrent air permeability of mixes

	Air permeability (10^{-16} m^2)	Change (%)
w/c = 0.4		
REF	4.26	0
RA-1 30%	5.60	+31
RA-1 100%	7.46	+75
RA-2 30%	7.742	+82
RA-2 100%	29.64	+596
RA-3 30%	5.82	+37
RA-3 100%	10.51	+147
RA-4 30%	4.91	+15
RA-4 100%	7.49	+76
w/c = 0.6		
REF	17.37	0
RA-1 30%	21.31	+23
RA-1 100%	20.74	+19
RA-2 30%	22.54	+30
RA-2 100%	50.93	+193
RA-3 30%	21.00	+21
RA-3 100%	37.11	+114
RA-4 30%	23.03	+33
RA-4 100%	51.86	+198

3.3.7 Carbonation

Sensitivity of the mixes to carbonation was initially assessed after the air permeability tests, using the same specimens. Figure 8 presents the results (reference mixes are presented in red to emphasize the differences). Greater carbonation depths were observed for all mixes containing recycled aggregates, regardless of the replacement ratio. At the low w/c ratio, increasing the replacement ratio yielded similar carbonation depths for all aggregates except for RA-4. At the high w/c ratio, however, increasing the replacement ratio increased the carbonation depths for all aggregates tested. It seems that at a low w/c ratio, the quality of the new paste has a major effect on carbonation whereas the higher permeability of the high w/c paste led to a combined effect of both the paste and aggregates. It is interesting to compare these results with the results of the air permeability test. The influence of aggregate replacement on air permeability was much larger than on carbonation although we used the same specimens in both cases and both tests are related to gas diffusion (air vs. CO_2). Small amounts of calcium hydroxide were identified in the recycled aggregates in the TGA test. It is possible, thus, that

Fig. 8 Carbonation depth of mixes after 7 days of accelerated carbonation



chemical binding of CO_2 to both the new and old paste, during diffusion, led to these differences, by moderating the progress of the carbonation front compared with net air diffusion.

4 Discussion

Figure 9 presents the relationship between the compressive strength of the mixes and their flexural strength. It seems that although the reduction in compressive strength due to aggregate replacement led to a correlated reduction in flexural strength, values obtained for high w/c mixes were higher than those obtained for low w/c mixes. For example, at compressive strengths of ~35 and ~40 MPa, low w/c mixes exhibited flexural strengths of 4.4 and 5.3 MPa, respectively, whereas higher values (7.3 and 9.4 MPa, respectively) obtained at high w/c mixes with similar compressive strengths. Etxeberria et al. [27] also found that the flexural strength of concrete prepared with recycled aggregates was higher than the reference concrete prepared with virgin aggregates. They attributed this phenomenon to absorption of cement paste to the recycled aggregate surface thus improving the bond between the new paste and the recycled aggregates. In the current study, the aggregates were pre-soaked in water for a few minutes before other ingredients were added, thus eliminating suction of cement particles to the surface of the aggregates. It is possible, thus, that better interlocking effect is obtained when the new matrix is weaker and closer to the properties of the recycled aggregates.

Durability aspects are also related to w/c ratio and so all standards limit the w/c ratio for certain environmental exposures. The European standard for concrete, EN 206, also recommends a minimal strength class for each exposure class. Figure 10 presents the relationship between compressive strength and the following durability parameters: air permeability, carbonation and initial and late capillary water absorption, as defined by the slope of the curves in Fig. 7. All values are normalized to the reference mix prepared with natural aggregates at w/c = 0.4. Correlation to a second order polynomial is also presented in the figure with their R^2 values.

Although large variation can be seen in the results, correlation between the compressive strength and carbonation and air permeability is reasonable. Note that carbonation is presented on the left y-axis in the figure and air permeability—on the right y-axis, thus these two properties are correlated with compressive strength, but at different ratios. It appears that compressive strength alone cannot represent durability parameters related to gas permeability. The rate of both initial and late water absorption exhibited no correlation with the compressive strength. It is possible that durability parameters that are related to water penetration, such as chloride diffusion, behave differently, but this finding should be tested specifically.

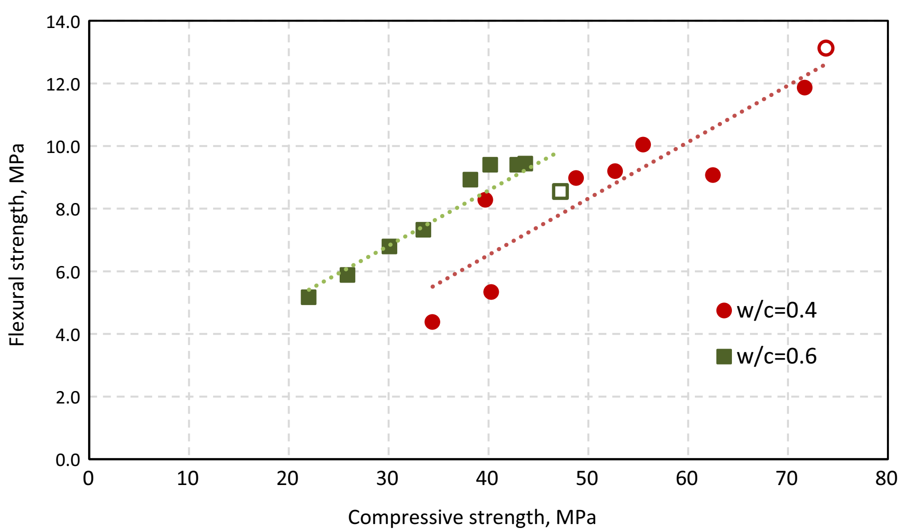


Fig. 9 Relationship between compressive and flexural strengths at 28 days. *Open symbols* represent reference mixes

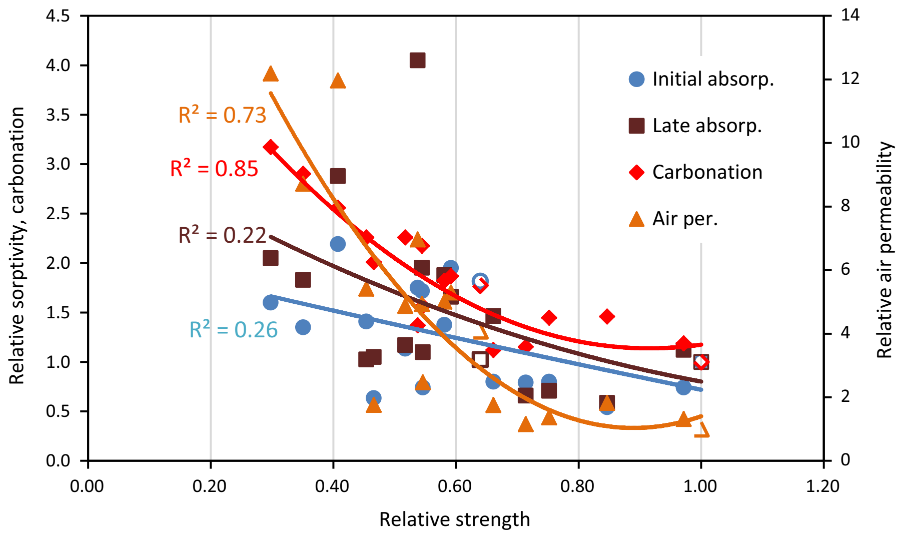


Fig. 10 Relationship between durability parameters and compressive strength, normalized to the reference mix at w/c = 0.4. *Open symbols* represent reference mixes

5 Summary and conclusions

Fine fractions of aggregates produced by two construction and demolition waste recycling plants were studied as potential sources for aggregates in the production of new concrete. The fine fractions were taken from the waste streams after initial crushing and separation. One of the aggregate fractions was further treated to produce two types of cleaner aggregates. The most rigorous cleaning process, which included additional crushing, separation washing and scrubbing, yielded aggregate that was quite clean from old paste and other foreign matter other than natural mineral (in this case, quartz). The other aggregate, derived from the same stream, was clean from fine particles (<0.075 mm) but contained significant amounts of old cement paste, which was identified by large absorption values, lower density, and SEM micrographs. The presence of organic matter was identified by TGA in all aggregates, but the colorimetric method (ASTM C40) indicated that only one aggregate contained organic matter. The colorimetric method is, probably, sensitive enough to identify residues of humus but not industrial organic contamination.

Mortar mixes were prepared at two cement:water:aggregate weight ratios (1:0.4:2 and 1:0.6:2) and at three aggregate replacement levels (0, 30, and 100%). The fresh mix properties of all mixes were quite similar to those of the reference mixes except for setting times, which were longer for all mixes with recycled aggregates (only 100% replacement level was tested) indicating the presence of contaminant that affects the setting time, most likely the organic matter identified in the aggregates. The effect of slower strength development (i.e. 3 to 28-day or 7 to 28-day compressive strength) was identified also when the replacement ratio increased from 30 to 100%.

A minor effect on the compressive strength of the cleanest aggregate was identified at a replacement ratio of 30%. However, a reduction of ~35 and 20% was seen at 100% replacement ratio of this aggregate at low and high w/c ratios, respectively. The reduction in compressive strength when using the other aggregates was even greater for both low and high replacement ratios. Reduced properties were identified also for flexural strength, air permeability, capillary water absorption, and carbonation.

Inconsistent relationships were found between compressive strength and other properties. Flexural strength decreased with the decrease in compressive strength due to the effect of aggregate replacement but this occurred to a different extent for each type of aggregate and replacement ratio. Similar behavior was observed for carbonation and air permeability. No correlation was found between compressive strength and parameters of capillary water absorption. It seems that the damping effect that recycled aggregate has on various properties of the mortar can be compensated for by lowering the water/cement ratio; however, the extent to which it should be lowered differs for the different properties under consideration. A limited replacement ratio of natural fine aggregate with RA-1 in concrete without damaging its properties seems possible at an extent that will be determined in a different study.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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