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Short and long-term behavior of structural concrete with recycled concrete aggregate

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ABSTRACT

Recycling concrete construction waste is a promising way towards sustainable construction. Coarse recycled concrete aggregates have been widely studied in recent years, however only few data have been reported on the use of fine recycled aggregates. Moreover, a lack of reliable data on long-term properties of recycled aggregate concrete has to be pointed out.

In this paper the effects of both fine and coarse recycled concrete aggregates on short and long-term mechanical and physical properties of new structural concrete are investigated. The studied concrete mixes have been designed by adjusting and selecting the content and grain size distribution of concrete waste with the goal to obtain medium–high compressive strength with high content of recycled aggregates (ranging from 27% to 63.5% of total amount of aggregates).

Time-dependent properties, such as shrinkage and creep, combined with porosity measurements and mechanical investigations are reported as fundamental features to assess structural concrete behavior.

1. Introduction

It is well known that concrete industry largely contributes to the environment impoverishment. For this reason, the less natural aggregates are used in concrete production, the lower the impact of the concrete industry on the environment. Aggregates are the major components of concrete and have a significant effect on engineering properties of the final product [1]. Natural resources are remarkably affected by their extensive use due to the increasing demand of structures. Therefore, the use of construction and demolition waste (C&DW) as alternative aggregates for new concrete production gains importance to preserve natural resources and reduce the need for disposal. Indeed, the deposition of demolition waste has an environmental impact and it strongly contributes to landfill saturation.

Maximizing the amount of recycled materials among concrete components is a very effective and promising approach toward sustainable construction [2–9]. In fact, aggregates represent almost 80% of concrete, thus their replacement with recycled materials can really help to transform traditional concrete into a sustainable material.

Available experimental data concerning concrete made with recycled aggregate (recycled aggregate concrete, RAC) are highly variable since the quality of RAC mostly depends on the quality of original demolished concrete used for recycling. Even if some results are contradictory, some general conclusions can be drawn about the effects of coarse recycled aggregate. For example, RAC with low to medium compressive strength can be easily obtained irrespective of the specific quality of recycled aggregates [5,10–14]. Moreover, it is not uncommon to demolish relatively young structures (for instance 15 years old or less), because their functional features do not suit any longer the new technical and social needs [10]. This type of waste represents a very good choice for recycling high grade concrete in new concrete structures.

The physical properties of recycled aggregates strongly depend on the adhered mortar quality and amount [11,15]. Adhered mortar is a porous material and its porosity depends on the water/cement ratio (w/c) originally adopted. In general, the quantity of adhered mortar increases with the decrease of the recycled aggregates size [11,15,16]. The crushing procedure also has an influence on the amount of adhered mortar. Due to the adhered mortar, recycled concrete aggregates have a lower density and higher water absorption, compared to natural aggregates. The actual concrete compressive strength varies with the compressive strength of the original concrete used as recycled aggregates and the adopted w/c. Moreover, the presence of potentially un-hydrated cement on the surface of recycled concrete aggregate can further affect the concrete properties [17].

All the mentioned reasons explain why the quality of the recycled aggregates is a key point in the production of new concrete and how the comparison between RACs properties coming from literature data can be directly affected by this issue.

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So far, most of the research carried out focused on the use of coarse recycled aggregates in new structural concrete [5,10–14], whereas the use of fine recycled fraction [18,19] is still poorly investigated because it can significantly impair some concrete properties. The utilization of fine recycled aggregates in structural RAC is generally not recommended [5]. However, during the last decade the use of fine recycled aggregates has achieved great international interest, mainly because of economic implications related to the shortage of natural sands suitable for concrete production [19–21]. Indeed, the use of recycled aggregates of all grades is strongly recommended to increment the recycling process of C&DW.

The novelty of this paper is that the effects of both fine and coarse recycled concrete aggregates on short and long-term mechanical and physical properties of new structural concrete are investigated. The current study has been carried out with an integrated approach involving mechanical characterizations and porosimetric analysis.

Although in the past, several studies were focused on the relations between cement matrix pore size distribution and extent of shrinkage/creep in traditional concrete structures, less research in this direction has been carried out on recycled aggregate concretes [20,24–26]. RACs have been studied extensively from the point of view of environmental impacts [4,5], mix-design [11,20,26] and short-term mechanical performances [5,10–14], but a lack of widespread and reliable data on long-term properties is evident. Thus, time-dependent properties combined with porosity measurements can be considered as the original features of the present paper, besides the fact that all the types of recycled aggregates derive from the same demolished structures.

Concrete waste deriving from the demolition of concrete buildings located in Punta Perotti (Bari, Italy) was crushed and properly assorted to create grain size distributions suitable to produce high quality concrete for structural applications. Aggregates play a fundamental role in determining workability, strength, dimensional stability and durability of concrete. Exploiting previous studies in this field [22,23], the investigated concrete mixes have been designed adjusting and selecting the content and grain size distribution of concrete waste with the goal to obtain medium–high compressive strength with high content of recycled aggregates (fine and coarse).

Five concrete mixes with a large content of recycled concrete aggregates (ranging from 27% to 63.5% of total volume of aggregates) replacing natural ones (fine and/or coarse) have been designed and characterized at the fresh and hardened state by physical–mechanical tests in order to obtain a full description of their short and long-term behavior. The experimental results are discussed and correlated with the determined porosity data (total porosity and pore size distribution), in order to highlight their effects on the macroscopic behavior of new concrete mixes. A control concrete mix, prepared with natural aggregates and the same cement amount and w/c ratio as those prepared with recycled concrete aggregates, is reported for comparison.

Finally, this work attempts to strengthen the concept of sustainability in civil constructions combining the use of coarse and fine recycled concrete aggregates to produce structural concrete with a low environmental impact.

2. Experimental investigation

2.1. Materials

Cement type CEM II-A/LL 42.5 R, according to UNI EN 196-1 [27], was used as binder.

Sand (*S*, 0–6 mm), fine gravel (*FG*, 6–16 mm) and gravel (*G*, 16–25 mm) (Cave Pederzoli, Bologna, Italy) were used as natural aggregates (*N*) in concrete mixes. Two cumulative grain size distributions were prepared following Fuller distribution, with maximum diameter of 16 and 25 mm, respectively: *N 16* (*S* 60 vol% and *FG* 40 vol%) and *N 25* (*S* 48 vol%, *FG* 25 vol% and *G* 27 vol%) (Fig. 1).

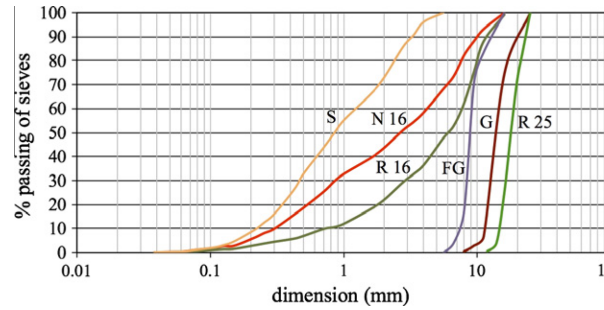

Fig. 1. Grain size distribution of natural (*S*, *FG*, *N 16*, *G*) and recycled (*R 16*, *R 25*) aggregates.

Concrete waste coming from the demolition of Punta Perotti building (2006, Bari, Italy) [22,23] was used as recycled aggregates. Punta Perotti building represents a typical Italian example of structures built in a natural protected area without planning permissions (Fig. 2). The construction started in 1995 and was stopped by the Italian court after 2 years, thus the building was never completed with interior partitions, technological apparatus, etc. It took 11 years of legal debates to reach the final decision of complete structures demolition. From the scientific point of view, the demolition waste of Punta Perotti building has been considered as very interesting as constituted by concrete and steel only. After demolition, steel was removed and recycled, whereas a large part of the concrete waste was disposed to landfill. Fortunately, a minor part of the demolished concrete was also collected by the University of Bologna and used for scientific purposes.

Compressive tests made on concrete cores of the original building showed medium–high compressive strength ($f_{cm} \approx 36$ MPa), thus making the relevant demolition waste very attractive for the production of new structural concrete. Indeed, concrete waste coming from Punta Perotti building has been considered completely stable at the moment of the demolition as the relevant concrete was cast 15 years before.

The demolished concrete underwent on-site crushing in two different stages. The first crushing treatment, used to separate concrete from steel, was made with clamp mechanical excavators and

Fig. 2. Punta Perotti structure (Bari, Italy) before demolition.

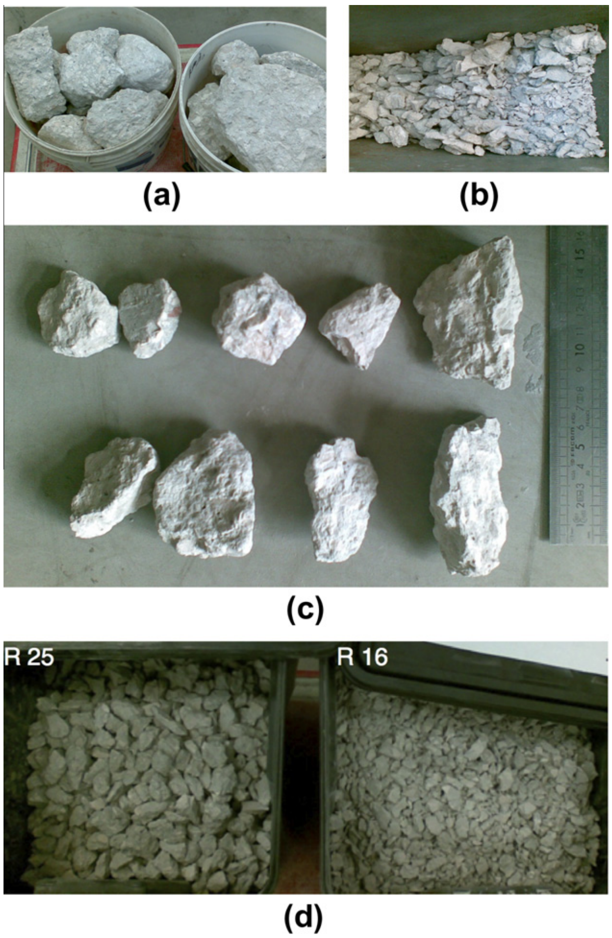

Fig. 3. C&DW before (a) and after (b–d) the laboratory jam crusher.

jackhammers immediately after demolition of the building. Then, C&DW was treated on site with a mobile crusher (secondary crushing treatment) and jaw crusher (maximum sieve open: 9 cm) to obtain a nearly homogeneous material (Fig. 3a). Furthermore, two crushing treatments were made with laboratory jaw crushers (maximum sieve open: 29 mm and 20 mm respectively) to obtain chunks with size comparable to natural aggregates (Fig. 3b).

In particular, after the first laboratory crusher, C&DW aggregates (Fig. 3c) were divided in two groups on the basis of 25 mm dimension. C&DW with an average size >25 mm was subjected to a second jam crusher, thus obtaining a fraction named as *R 16* (Fig. 3d), with a cumulative grain size distribution curve similar to that prepared with the natural aggregates *N 16*. C&DW with an average size ⩽25 mm was further sieved to select only the fraction 16–25 mm. This fraction, named as *R 25* (Fig. 3d), shows a grain size distribution similar to that one of natural gravel *G*. Fig. 1 reports the comparison between the investigated natural and recycled aggregates distributions used for concrete mix-design.

Table 1
Physical properties of natural and recycled aggregates (*WA* = water absorption; ρ_{rd} = dry bulk density; ρ_{ssd} = saturated surface-dried density).

Properties	Natural aggregates (*NA*)			Recycled aggregates (*RA*)		
	S	*FG*	*G*	*R 16*		*R 25*
WA (%)	2.2	1.4	1.2	9.0[a]		7.0
ρ_{rd} (Mg/m^3)	2.63	2.54	2.54	2.10[b]	2.26[c]	2.10
ρ_{ssd} (Mg/m^3)	2.68	2.57	2.57	2.32[b]	2.43[c]	2.25

[a] For 0–4 mm, *WA* = 10.0% and 4–16 mm, *WA* = 7.7%, according to UNI EN 1097-6 [28].
[b] For 0–4 mm, according to UNI EN 1097-6 [28].
[c] For 4–16 mm, according to UNI EN 1097-6 [28].

The main physical properties (water absorption *WA*, dry bulk density ρ_{rd} and saturated surface-dried density ρ_{ssd}) of natural and recycled aggregates are reported in Table 1. The recycled aggregates are similar in appearance to the natural crushed aggregates, however their texture is rougher due to the adhered mortar, thus presenting higher water absorption and lower density than natural aggregates [24].

An acrylic based superplasticizer (*SP*) was used for all the concrete mixes.

2.2. Samples preparation

In order to study the effect on concrete properties of both coarse and fine aggregates substitution, five different concrete mixes were investigated. Natural and recycled aggregates content in the concrete mixes and relevant mix design data are reported in Tables 2 and 3, respectively.

Cement content (350 kg/m^3), *w*/*c* ratio (0.48) and D_{max} (25 mm) were constant for all the formulations. The reference concrete mix, named *CC*, was prepared with 100% of natural aggregates with *N 25* grain size distribution. In order to investigate the effects of 100% coarse aggregate substitution on the concrete properties, *RC1* was prepared replacing all the natural gravel (*G*) with the recycled fraction *R 25*. A further concrete mix, named *RC2*, was prepared starting from *RC1* and replacing half the volume of the natural aggregate fraction 0–16 mm with the recycled fraction *R 16*. In particular, 24% of *S* and 100% of *FG* were substituted with *R 16*. The total volume of recycled aggregates (both *R 16* and *R 25* fractions) in *RC2* is equal to 63.5%.

In order to investigate the effect of the fine aggregate substitution on the concrete properties, two further mixes were prepared keeping constant the volume as natural gravel. In more details, *RC3* was prepared with the same volume as *R 16* fine recycled aggregates as *RC2*, 36.5% and 27% of natural aggregates (*S* and *G* fraction, respectively). The total volume of recycled aggregates in *RC3* is equal to 36.5% and corresponds to 50% of the fine fraction substitution. Finally, *RC4* was prepared starting from *RC3* and operating a different amount of replacement for *S* and *FG*. In particular, half the volume of natural sand and fine gravel was replaced with recycled aggregates (Table 2).

Natural and recycled aggregates were used in wet condition. For each type of aggregates, the total moisture content was determined immediately before the mixing procedure. The surface/free moisture content was determined by subtracting the moisture in saturated-surface dry condition from the total moisture.

The mixes were prepared in a laboratory concrete mixer (190 L volume) according to the following procedure: first, aggregates (gravel, fine gravel and sand) were added and mixed for about 5 min. Then, cement, water (75%) and superplasticizer along with the remaining water were added and mixed for further 3 min. For all the investigated mixes, superplasticizer was dosed to ensure a slump between 10–20 cm (S3 or S4). *RC1*, *RC2* and *RC4* required a slightly higher amount of superplasticizer than *CC* and *RC2* (Table 3). Slump test was performed to measure concrete workability, according to UNI EN 12350-2 [29], and relevant results are reported in Table 3.

2.3. Samples characterization

For each formulation at least 16 cylindrical concrete samples (diameter: 12 cm, height: 24 cm) as well as 2 prisms (10 × 10 × 40 cm) and 2 cubic samples (15 × 15 × 15 cm) were prepared and cured for 28 days at 20 ± 1 °C and R.H. >95%, for physical and mechanical tests. Bulk density (*D*) measurement

Table 2
Natural and recycled aggregates content (vol%) in the investigated concrete mixes (*S* = sand; *FG* = fine gravel; *G* = gravel).

Mix	Natural aggregates (*NA*)				Recycled aggregates (*RA*)		
	S (vol%)	*FG* (vol%)	*G* (vol%)	Total (vol%)	*R 16* (vol%)	*R 25* (vol%)	Total (vol%)
CC	48.0	25.0	27.0	100.0	0.0	0.0	0.0
RC1	48.0	25.0	0.0	73.0	0.0	27.0	27.0
RC2	36.5	0.0	0.0	36.5	36.5	27.0	63.5
RC3	36.5	0.0	27.0	63.5	36.5	0.0	36.5
RC4	24.0	12.5	27.0	63.5	36.5	0.0	36.5

Table 3
Concrete mix-design.

	CC	*RC1*	*RC2*	*RC3*	*RC4*
Water/cement ratio	0.48	0.48	0.48	0.48	0.48
Cement (kg/m^3)	350	350	350	350	350
Water (kg/m^3)	168	168	168	168	168
Total amount of aggregate (kg/m^3)[a]	1800	1750	1699	1758	1749
NA (kg/m^3)[a]	1800	1331	675	1154	1144
RA (kg/m^3)[a]	0	419	1024	604	604
Superplasticizer (%)[b]	1.0	1.2	1.0	1.2	1.2
Slump (cm)	19	10	20	21	13

[a] Saturated surface-dried (ssd) condition.
[b] Mass% on cement amount.

(determined by mass/volume ratio) and water absorption (w_a) test at atmospheric pressure were performed on 2 cubic concrete samples, according to UNI 7699 [30].

Concrete strength tests were performed using a universal testing machine (4000 kN). Compressive strength (f_{cm}) was determined according to UNI EN 12390-3 [31] on four concrete cylindrical samples per mix, tested at 7 (f_{cm}@7d) and 28 (f_{cm}@28d) days of curing. Secant elastic modulus (E) was also measured, according to UNI 6556 [32], on cylindrical samples at 28 days of curing: two samples for every mix were considered. Tensile splitting strength (f_{ct}) was determined on 2 concrete cylindrical samples, according to UNI EN 12390-6 [33]. Three-point flexural strength (f_{cf}) was determined on 2 concrete prisms, according to UNI EN 12390-5 [34].

Moreover, the long-term behavior of the recycled aggregates concretes was investigated by creep and shrinkage tests. Two cylinders for each mix were subjected to creep test, according to ASTM C512/C512M-10 [35] standard and two cylinders were subjected to shrinkage test starting after 2 days from casting. All the tests were performed in a climate chamber at 20 ± 1 °C and 60% R.H. for more than 1 year with specimens in drying conditions. The longitudinal strain variation with time of each cylinder was measured by using electrical strain gauges connected to a digital acquisition system [36,37]. For creep tests, a compression stress of about 30% of the strength at the time of loading (i.e. within stress limit of linear viscoelasticity) was applied at 28 days.

Pore size distribution was investigated by mercury intrusion porosimeter (MIP, Carlo Erba 2000), equipped with a macropore unit (Fisons 120) on samples obtained by concrete cylinders. Porosimeter samples, about 1 cm^3, were cut by a diamond saw, dried under vacuum and kept under P_2O_5 in a vacuum dry box till testing. Porosimeter samples were observed by optical microscopy before MIP test in order to ensure that they were representative of the cement mortar between coarse aggregates.

3. Results and discussion

3.1. Fresh state behavior

In accordance with literature data [11,24], *RC1* characterized by 100% of coarse recycled aggregates has shown a considerable reduction in workability compared to the reference *CC* (Table 3). Indeed, a noteworthy slump reduction has been observed in *RC1* even if a higher amount of superplasticizer was used (the upper limit suggested by the producer was met).

Compared to *CC*, similar and even better workability was observed for *RC2* and *RC3*, where the recycled fraction *R 16* was used in combination with 100% of coarse recycled aggregates and 100% of natural coarse aggregates, respectively. *RC4*, where *R 16* replaced 50% of natural fine gravel and 50% of natural sand (thus enriching the fineness content compared to *RC2* and *RC3*) has shown a lower slump than *CC*, but higher than that exhibited by *RC1*.

The mentioned results clearly indicate that when the *R 16* fraction is used as sand replacement, concrete workability is higher than the reference samples, since *R 16* is characterized by a smaller content of fines with respect to natural sand. On the contrary, when the replacement includes aggregate fractions greater than sand, workability decreases and this reduction becomes more significant when all coarse aggregates are completely replaced. Indeed, since the water/cement ratio used was the same for all the mixes (0.48), workability is strongly affected by the shape and texture of coarse aggregates surface.

3.2. Hardened state behavior

In the hardened state (Table 4), *CC* shows the highest value of bulk density (D) as well as the lowest value of water absorption (w_a), among the investigated concretes. Anyway, D and w_a of *RC1* are very similar to the values of the reference concrete, thus highlighting that the characteristics of *RC1* mix design are promising. Indeed, a low w_a is very important since it means low porosity and, hence, high concrete durability. *RC2*, with the highest amount of total recycled aggregates (63.5%) shows the lowest values of D and the highest values of w_a. As general trend, replacing natural fine aggregates with recycled ones leads to an increase in concrete water absorption. Such an increase is more significant when both a part of sand and all fine gravel fractions are replaced (*RC3*), than when half percentage of both sand and fine gravel fractions are substituted (*RC4*).

Fig. 4 and Table 4 show the compressive strength of the investigated concrete samples at 7 and 28 days of curing. As expected, concrete strength (f_{cm}) increases with curing time for all the mixes and the increase is higher for RACs than for *CC* with natural aggregates (15% gain *vs* 11%, respectively). Such an increase might be ascribed to a later reaction of unhydrated cement of the adhered mortar present on the surface of recycled aggregates and/or retarded absorption of water by recycled aggregates thus producing a slightly smaller effective water/cement ratio.

After 28 days of curing all the RACs show higher values of f_{cm} compared to the reference *CC* concrete and, in particular, *RC1* shows the highest compressive strength value (52 MPa), about 27% higher than *CC*. The high quality of the recycled concrete aggregates used in the present work has a positive effect on the compressive strength of the new mixes. This effect becomes stronger as the dimensions of the replaced aggregates increase. In fact, *R 25* has been used in *RC1* and *RC2*, which show the highest values of

Table 4
Physical and mechanical properties of the investigated concrete mixes (D = bulk density; w_a = water absorption; f_{cm}@7d and f_{cm}@28d = compressive strength at 7 and 28 days of curing; E = secant elastic modulus; f_{ct} = tensile splitting strength; f_{cf} = three-point flexural strength).

Mix	D (g/cm^3)	w_a (%)	f_{cm}@7d (MPa)	f_{cm}@28d (MPa)	E (GPa)	f_{ct} (MPa)	f_{cf} (MPa)
CC	2.38	6.1	36.7	41.3	31.4	3.8	6.4
RC1	2.32	6.2	44.9	51.4	30.3	3.2	5.8
RC2	2.20	9.3	39.5	45.6	24.9	3.0	4.9
RC3	2.27	9.0	34.5	44.7	26.9	4.1	4.8
RC4	2.30	7.8	36.1	41.9	30.6	3.3	5.7

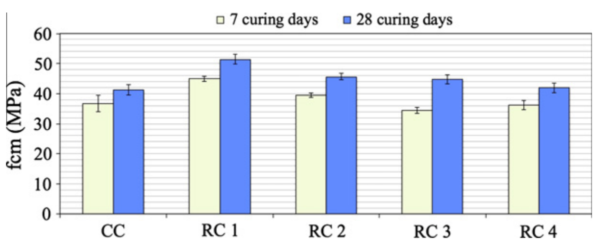

Fig. 4. Concrete compressive strength at 7 and 28 days of curing (vertical bar represents standard deviation).

f_{cm}, whereas when only *R 16* has been adopted (*RC3* and *RC4*), lower values of compressive strength have been determined. Such results were qualitatively expected since it is known that replacement of smaller size aggregates can be responsible of greater reductions in the mechanical properties; nevertheless, the extent of such reduction was very limited and encouraging towards a future widespread adoption of this type of recycled aggregate (actually restricted in Italy).

The elastic modulus (E) for the investigated mixes is reported in Table 4. *CC*, *RC1* and *RC4* show values around 30 GPa, whereas *RC2* and *RC3* show the lowest values (≈25–27 GPa), in accordance with their lower density and higher water absorption; in this case, the positive effect of a reduced effective water/cement ratio (due to a retarded water absorption by recycled aggregates) was counterbalanced by weakening of the solid skeleton and by an increase in porosity due to replacement of *FG* with *R 16*. For the same reasons, three-point flexural strength (f_{cf}) values (Table 4) follow the same trend as elastic modulus. Indeed, *CC*, *RC1* and *RC4* have very close values, whereas *RC2* and *RC3* show the lowest flexural strength, in good agreement with their physical properties. Finally, the tensile splitting strength (f_{ct}) for all the investigated mixes is in the range of 3–4 MPa without significant difference among the mixes (Table 4), thus indicating that the use of recycled aggregates has no significant influence on this property. This result agrees with the conclusions reported by other authors [13,16]; nevertheless, disregarding the results from *RC3* where some anomalies occurred during the test, the same trend of E and f_{cf} can be observed again, even if to a smaller extent. The observed good performances in terms of tensile strength of recycled aggregates are indicative of a good adhesion between aggregates and mortar matrix. Thus, the mechanism of failure of RAC elements would be expected to be similar to traditional concrete one.

The results of the short-term mechanical properties collected so far prove that the investigated mixes with recycled aggregates are equivalent to the reference concrete with natural aggregates.

3.3. Long-term behavior

Fig. 5 shows the long-term behavior of all the mixes tested for more than 1 year. In particular, shrinkage strains (autogenous and drying contributions) are reported in Fig. 5a and specific creep (creep strain per unit of applied stress, basic and drying contributions together) in Fig. 5b.

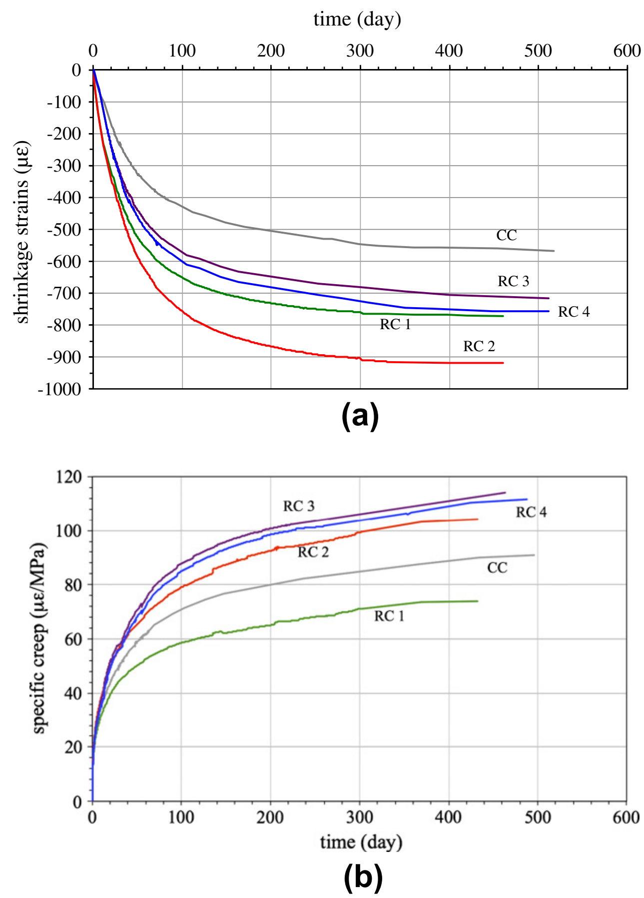

Fig. 5. Shrinkage strains (a) and specific creep (b) for the investigated mixes.

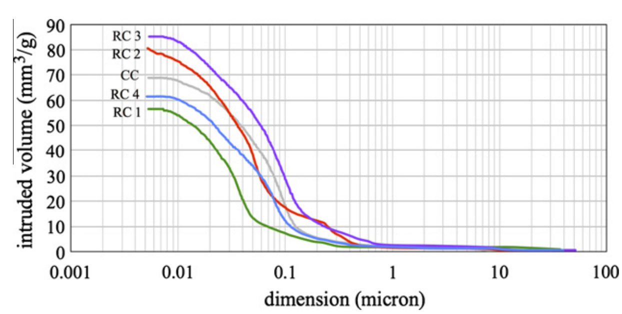

Fig. 6. Pore size distribution of the investigated samples.

Regarding the shrinkage behavior, *CC* shows the smallest strains, while *RC2* exhibits the largest ones, the latter being the mix with the largest amount of recycled aggregates. The other mixes, with intermediate percentages of natural aggregates replacement, provide intermediate shrinkage values. From a

Table 5
Classification of porosity in the investigated samples according to IUPAC pore size classification.

Designation	Porosity range (nm)	*CC* (mm^3Hg/g)	*RC1* (mm^3Hg/g)	*RC2* (mm^3Hg/g)	*RC3* (mm^3Hg/g)	*RC4* (mm^3Hg/g)
Micropores	<1.25	N.d.	N.d.	N.d.	N.d.	N.d.
Mesopores	1.25–25	10.6	17.6	20.7	16.3	14.5
Macropores	25–5000	57.1	37.0	58.7	66.6	45.7
Directly accessible large pores	5000–50,000	1.2	1.8	1.3	2.4	1.3

qualitative point of view, all curves are similar showing a rapid shrinkage strain increase in the first 3 months. The slope of the curves decreases with time, becoming almost flat after 10 months. The elastic properties of the aggregates normally determine the degree of restraint offered. The influence of the aggregate is confirmed by a correlation between shrinkage and the modulus of elasticity of concrete, which depends on the compressibility of the aggregate used [1]. RAC usually leads to higher shrinkage, because the recycled aggregates, having a lower elastic modulus than natural ones, offer less restraint to the potential shrinkage of the cement paste.

However, in order to properly explain the reasons leading to small or large shrinkage values, the raw percentage of natural aggregate replacement is not sufficient; indeed, shrinkage is mainly driven by capillary tensions generated inside the mesopore structure of cement matrix [38]. Accordingly, the porosity and its distribution play a fundamental role for each mix and further remarks are reported in Section 3.4, where MIP results are discussed.

Specific creep curves are reported in Fig. 5b: the slope of all the curves (reference included) is still appreciable after 1 year, meaning that the creep phenomenon is still quite active and not strictly related to the presence of recycled aggregates. *RC3* and *RC4* exhibit the highest creep, according to the large presence of *R 16* recycled aggregate characterized by high water absorption (*WA*% = 9). *RC2*, containing the highest content of recycled aggregates, also including the coarser fraction *R 25*, shows a lower creep than *RC3* and *RC4*, but still higher than reference mix. The total replacement of the natural gravel with *R 25* leads to a positive effect on RACs creep. This effect becomes more evident for *RC1*, which shows the lowest creep values among all the investigated mixes.

The result of *RC1* is somehow unexpected since it has been reported that the adhered mortar on the surface of recycled aggregates together with the new cement matrix contributes to increased creep [24,26]. However, the magnitude of creep strain depends not only on cement matrix microstructure, but also on the composite nature of the concrete, thus including aggregates (shape, grain size distribution, modulus of elasticity) and interface zone between aggregate and cement matrix, where localized stresses and micro-cracks can occur [38,39].

The lowest creep value detected for *RC1* agrees with the highest compressive strength and low value of water absorption determined for this mix. Indeed, *RC1* appears to be a very dense concrete where localized stresses and micro-cracks are minimized at the interface between aggregate and matrix.

3.4. Porosity

Fig. 6 reports the cumulative pore size distributions, determined by MIP, for the investigated samples representative of the cement matrix porosity between coarse aggregates. All samples exhibit a negligible porosity for pores greater than 1 μm, whereas significant differences in pore size distribution curves are evident for pores dimension <1 μm. *RC1* shows the lowest total open porosity, as well as the lowest cumulative pore volume and mean pore radius (0.035 μm) among the investigated samples. This result agrees with the good performances of the concrete observed during mechanical and creep tests. Increasing the content of recycled aggregates up to 36.5%, porosity slightly increases for *RC4*, still remaining lower than the one showed by *CC*. However, *RC3*, containing 36.5% of recycled aggregates, exhibits the highest porosity and intruded volume combined with the largest mean pore radius (0.073 μm). Such results highlight the importance of a proper selection of natural aggregates to be replaced. Indeed, when all fine gravel aggregates and a small part of natural sand are replaced by recycled aggregates (*RC3*), the relevant cement matrix is more porous than when half of both the sand and the fine gravel natural aggregates are substituted (*RC4*). *RC2*, which contains recycled aggregates up to 63.5%, shows a larger porosity compared to *CC*, but still lower than *RC3*.

MIP measurements, although only referred to cement mortar samples, provide results confirming the previously described macroscopic properties.

Table 5 reports the IUPAC classification of the pore size and the relevant data of porosity determined in the investigated samples. As previously stated, shrinkage is strongly influenced by the amount of mesopores [39,40]. The measured amount of mesopores (1.25–25 nm pore radius range) decreases as follows: *RC2* > *RC1* > *RC3* > *RC4* > *CC*. This trend confirms the shrinkage results previously reported (Fig. 5a), except for *RC3* and *RC4*, which have a very similar mesopore content. In general, for all the investigated samples, shrinkage strain increases with the increasing content of mesopores.

4. Conclusions

The results of this research can be summarized as follows:

- at the fresh state, concrete workability is more influenced by the shape, texture and grain size distribution of the recycled aggregates than by their total amount;
- among the investigated RACs, *RC1* and *RC4* exhibit the highest compressive and flexural strength, elastic modulus and the best physical features (density and water absorption), thus highlighting that a proper assortment of fine and coarse concrete waste can lead to good structural concrete as using only coarse recycled aggregates;
- concrete shrinkage strain is negatively influenced by the use of recycled concrete aggregates, whereas specific creep results showed that *RC1* recycled aggregate concrete exhibits even better performance than the reference concrete;
- porosity data and pore size distribution fully agree with the mechanical properties determined for the investigated samples, thus confirming that the use of recycled concrete aggregates can lead to very dense microstructures.

Indeed, properly assorted concrete waste may be used in the production of structural concrete. Their size and content can have different consequences on short and long-term mechanical properties, however an integrated investigation able to take into account microstructure parameters, as well as macroscopic features, can be a useful tool for designing optimized mixes with performances equivalent to those usually exhibited when natural aggregates are used. Moreover, the present investigation proved the feasibility of introducing fine and coarse recycled aggregates together inside a new concrete without negatively affecting the mechanical performances, both in the short and long-term. The obtained data can be used to better understand cement mortar porosity, especially when fine recycled aggregates are added, and how it can affect the mechanical behavior of RACs. Indeed, in the near future even this fraction of recycled aggregates might be included in Codes prescriptions, since only coarse fraction is usually allowed.

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