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Self-compacting concrete with recycled concrete aggregate: study of the long-term properties

Stefania Manzi*, Claudio Mazzotti, Maria Chiara Bignozzi

Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna,
Viale Risorgimento 2, 40136 Bologna, Italy
stefania.manzi4@unibo.it; claudio.mazzotti@unibo.it; maria.bignozzi@unibo.it

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* Corresponding author:
Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna,
Viale Risorgimento 2, 40136 Bologna, Italy
Tel.: +39 051 2090329; fax: +39 051 2090322
E-mail address: stefania.manzi4@unibo.it (S. Manzi)

Abstract

This paper investigates the shrinkage and creep of self-compacting concrete prepared with coarse and fine recycled concrete aggregates (up to 40% of total amount of aggregates). Physical properties and porosity measurements are studied and related to the mechanical properties. Results highlight that self-compacting characteristics are maintained when recycled aggregates are utilized and their good quality promotes high mechanical properties. Creep behavior and pores size distributions are more influenced by the content and assortment of recycled aggregates, although their effect is more limited compared to what occurs in traditional concrete with recycled aggregates.

Keywords

Self-compacting concrete; concrete construction and demolition waste; recycled concrete aggregate; porosity measurements; long-term properties

1. Introduction

In the last decade the study of new methods for reusing concrete waste from construction and demolition (C&DW) has turned into large attractiveness in order to decrease the environmental impact due to natural aggregates exploitation and waste disposal [1-6]. Nowadays European Standards and Eurocodes [7-8] allow the use of C&DW in the mix design of new concrete, when preparatory adequate characterizations are made. Indeed, the good quality of the aggregates is a crucial issue for new structural concrete applications [9-10]. Moreover, it is well known that the introduction of self-compacting concrete (SCC) has improved both the concrete technology and the working safety and health conditions due to the removal of mechanical compaction in the construction sites [11-15].

The present work falls within the framework of circular economy strategy, one of the main ambitions of Europe, which wants to move towards a recycling society with a high level of resource efficiency. The art. 11.2 of the Waste Framework Directive (2008/98/EC) [16] stipulates that "(EU) member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste shall be prepared for re-use, recycled or undergo other material recovery". Although the level of recycling and material recovery of C&DW varies greatly in Europe, the effort to strengthen the concept of sustainability in civil constructions needs to be pursued not only preparing recycled conglomerates suitable for low cost operations such as backfilling and embankments, but also developing innovative recycled aggregate concrete that can be exploited for structural applications.

SCC prepared with recycled concrete aggregate has not been extensively studied yet. In particular, in the last few years some researches have been made using C&DW in SCC [17-36], particularly with coarse recycled concrete aggregates [18-21, 23-27, 30, 33, 35-36], thus showing the interest toward this topic, but there are no data on the long-term behavior of SCC with C&DW. On the contrary, some studies are present on the long-term properties of structural concrete with C&DW [3-4, 37-43].

Following a previous research where the long-term behavior of structural concrete containing coarse and fine and C&DW was studied [3], the aim of this work is to extend the study to the long-term properties of SCC replacing both coarse and fine natural aggregates with recycled ones. Accordingly, the effects of different formulations are studied in relation to the SCC properties at both fresh and hardened states to determine the practicability of SCC with good mechanical resistance.

Comparing this research with the most recent state of the art of the use of C&DW in SCC, the important issues highlighted in this paper are (i) the evaluation of the contemporary use of both fine and coarse concrete recycled aggregates on fresh behavior; (ii) the mechanical characterization at long-term (i.e., shrinkage and creep); (iii) the integrated approach involving microstructure-physical-mechanical parameters in explaining the strengthening mechanisms occurring in the new mixes; (iv) the comparison with traditional concrete prepared with the same C&DW.

As in the previous work [3-4, 44-45], the recycled concrete aggregate hail from the destruction of a never completed concrete construction in Italy (e.g., buildings of Punta Perotti, Bari, Italy) where masonry and gypsum were totally absent, thus constituting an adequate selection for the reuse of medium-high compressive strength concrete in new structures. C&DW was suitably crushed and combined with appropriate grain size distributions to obtain structural SCC.

Three SCC mixes were designed with an amount of C&DW varying from 25 to 40% of total volume of aggregates in substitution of natural coarse and fine aggregates. With the aim of a complete characterization of the long-term properties of the SCC mixes, the time-dependent properties such as shrinkage and creep were studied and associated with the other essential properties of the SCC materials such as the characteristic at the fresh state, as well as the physical and mechanical properties and the porosity measurements (total porosity and pore size distribution). For comparison, the same characterizations were performed on a reference SCC mix, prepared with 100% natural aggregates.

2. Experimental investigation

2.1 Materials

Cement type CEM II-A/LL 42.5 R, in accordance with EN 197-1 [46], and calcium carbonate with an average grain size of 7.5 µm, were used as binder and filler, respectively. An acrylic based superplasticizer and a biopolymer based viscosity modifying agent were used as admixtures in all the SCC mixes.

As natural aggregates (*N*, Fig. 1), sand (*N0-6*, 0-6 mm) and gravel (*N6-16*, 6-16 mm) (Cave Pederzoli, Bologna, Italy) were used. Following previous studies [3-4, 44-45], a cumulative grain size distribution curve (called *NA16*) was prepared according to Fuller distribution, setting the aggregate maximum diameter equal to 16 mm: it was made of *N0-6* at 60 vol% and *N6-16* at 40 vol% (Fig. 1).

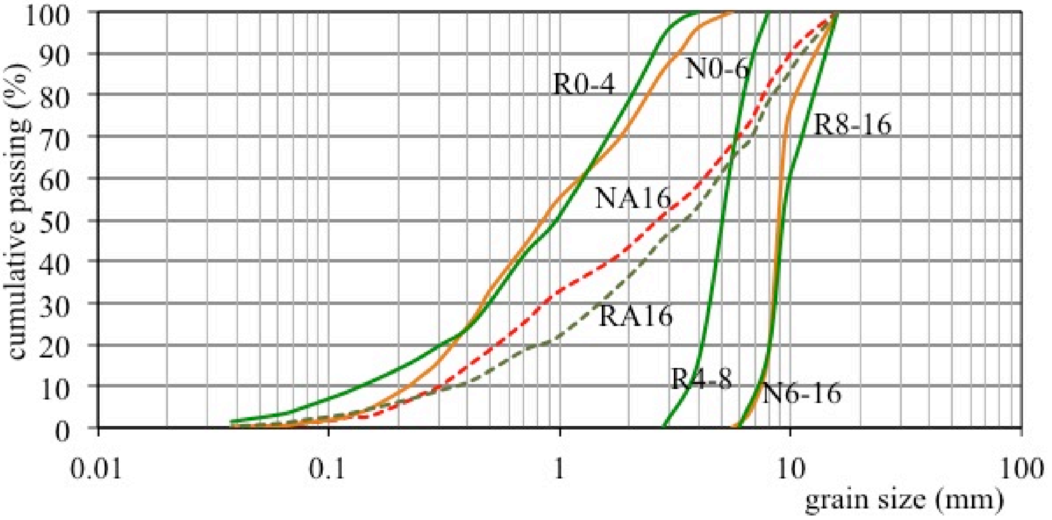
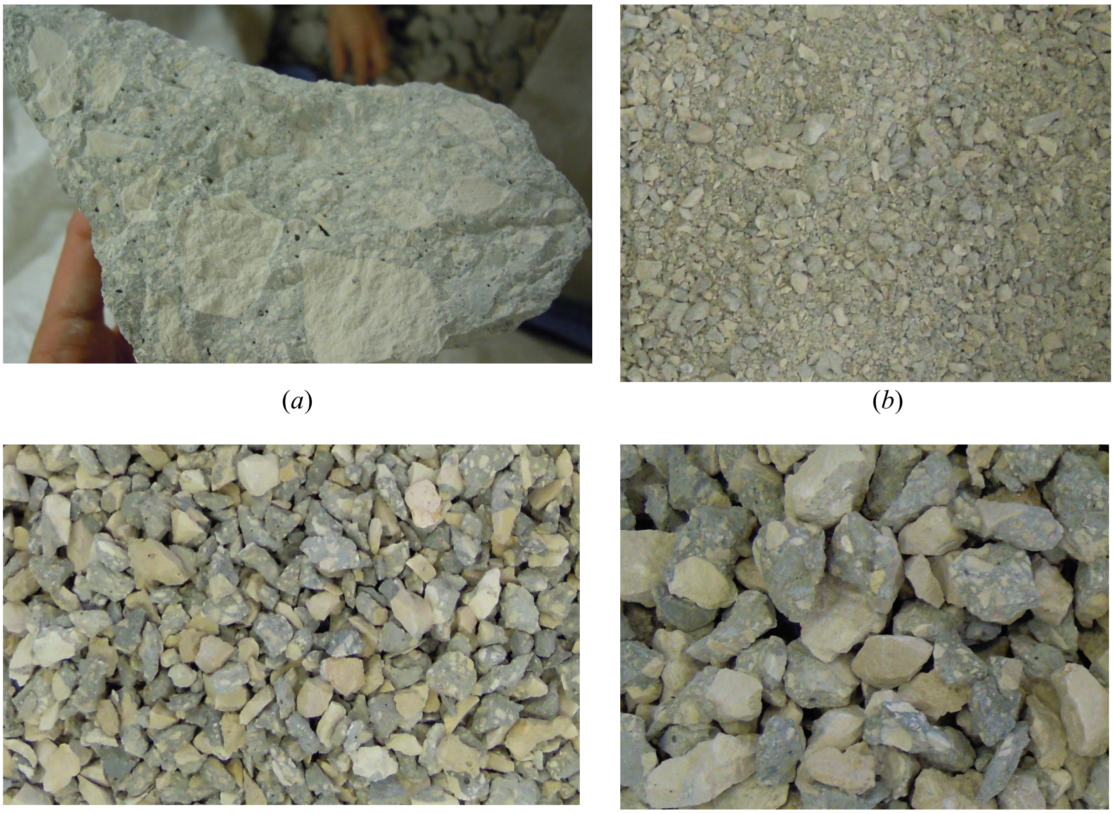


Fig. 1. Grain size distribution of natural (*N*: *N0-6, N6-16, NA16*) and recycled (*R*: *R0-4, R4-8, R8-16, RA16*) aggregates.

As recycled aggregates (*R*, Fig. 1), C&DW of good quality coming from the demolition of an Italian concrete building started in 1995 and never finished was used (2006, Bari, Italy) [3].

Concrete cores extracted form the original construction showed a compressive strength of about 36 MPa.

After demolition, a large part of the concrete waste was disposed to landfill and the University of Bologna collected a part of it for scientific purpose [3-4, 44-45], after on-site crashing procedure and steel detachment. Hereinafter, further crushing procedures were made in the laboratory to produce three different fractions (Fig. 1 and 2) named as *R0-4* (0-4 mm), *R4-8* (4-8 mm) and *R8-16* (8-16 mm). In order to obtain a cumulative grain size distribution curve of aggregate similar to that one of *NA16*, 47 vol% of *R0-4* + 21 vol% of *R4-8* + 32 vol% of *R8-16* were mixed. The resulting grain size distribution was named *RA16*.



(*a*) (*b*)

(*c*) (*d*)

Fig. 2. C&DW before the laboratory jam crusher (*a*) and *R0-4* (*b*), *R4-8* (*c*) and *R8-16* (*d*) recycled aggregates.

Tab. 1 reports the physical properties of natural and recycled aggregates, determined according to EN 1097-6 [47]: dry bulk density (ρ_{rd}), saturated surface-dried density (ρ_{ssd}) and water absorption (*WA*). *R* aggregates present dry bulk density values lower than *N* aggregates and, correspondingly higher values of water absorption, according to previous studies [3-4, 44-45]. In particular, *R0-4* fraction shows the lowest values of dry bulk density (i.e., 2.1 g/cm^3) and similarly the highest values of *WA* (i.e., 10%).

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

Properties	ρ_{rd} (Mg/m^3)	ρ_{ssd} (Mg/m^3)	*WA* (%)
N0-6	2.6	2.7	2.2
N6-16	2.5	2.6	1.4
R0-4	2.1	2.3	10.0
R4-8	2.3	2.4	7.7
R8-16	2.3	2.4	7.7

2.2 Concrete samples preparation

Three new SCC mixes were studied starting from a reference mix-design (named *R0*) with 100% of natural aggregates and varying the amount of recycled aggregates between 25 and 40 vol% over the total content of aggregates (Table 2).

A concrete mix, named *R25,* was obtained substituting 25 vol% of natural aggregates (coarse and fine) with recycled aggregates. *R25* contains 45 vol% of *N0-6*, 30 vol% of *N6-16*, 12 vol% of *R0-4*, 5 vol% of *R4-8* and 8 vol% of *R8-16*.

Two different mixes were obtained substituting 40 vol% of natural aggregates. In the mix named *R40* both coarse and fine natural aggregates were partially substituted with recycled aggregates. *R40* contains 36 vol% of *N0-6*, 24 vol% of *N6-16*, 19 vol% of *R0-4*, 8 vol% of *R4-8* and 13 vol% of *R8-16*.

In the mix named *CR100* the total volume of gravel (i.e., *N6-16*) was replaced by the two fractions *R4-8* and *R8-16* of recycled aggregates. Thus, *CR100* contains 60 vol% of *N0-6*, 16 vol% of *R4-8* and 24 vol% of *R8-16*.

Table 2. Natural and recycled aggregates content (vol%) in the investigated self-compacting concrete mixes.

	Natural aggregates (*N*)			Recycled aggregates (*R*)			
Mix	*N0-6* (vol%)	*N6-16* (vol%)	*N* total (vol%)	*R0-4* (vol%)	*R4-8* (vol%)	*R8-16* (vol%)	*R* total (vol%)
R0	60	40	100	0	0	0	0
R25	45	30	75	12	5	8	25
R40	36	24	60	19	8	13	40
CR100	60	0	60	0	16	24	40

Table 3 shows the investigated mixes. For all the SCC formulations, cement content (350 kg/m^3), filler content (220 kg/m^3), D_{max} (16 mm) and viscosity modifying agent were kept constant. Similar water/cement (*w/c*) ratio (i.e., 0.50 ± 0.01) and superplasticizer amount (i.e., 1.1 ± 0.1%) were utilized for all the SCC formulations. The small increase in the superplasticizer amount of both *R25* and *R*40, compared to *R0*, compensates for their lower water content (i.e., 172 instead of 179 kg/m^3). For this reason, fresh state results are comparable.

All aggregates were utilized in wet condition and their total moisture content was directly established before the mixing procedure: the surface/free moisture value was obtained by subtracting from the total moisture the moisture in saturated-surface dry condition. SCC is more easily influenced by the initial humidity of aggregates than traditional concrete [48-49]. Even if the water content of the aggregates is compensated in all the mixes, different initial aggregates humidity, as well as the real amount of water compensated in every mix, can contribute to a change of the fresh state behavior of the SCC mixes. For this reason, in this study the initial humidity of the aggregates was the same for all the mixes. In particular, aggregates (both natural and recycled ones) were previously treated in order to have wet condition almost identical to their ssd condition, with the only exception of natural sand that was stoked in sealed plastic bags at an almost constant humidity of 6%. For this reason in each mix the water was always adjusted by decreasing its amount.

The SCC mixes were obtained by using a laboratory concrete mixer (190 L volume) introducing gravel and sand. After 5 minutes of mixing, cement, water (75%), superplasticizer and viscosity modifying agent with the remaining water (25%) were introduced and mixed for further 3 minutes.

Table 3. Concrete mix-design.

	R0	*R25*	*R40*	*CR100*
Water/cement ratio	0.51	0.49	0.49	0.51
Cement (kg/m^3)	350	350	350	350
Water (kg/m^3)	179	172	172	179
Filler (kg/m^3)	220	220	220	220
N0-6 (kg/m^3)$^{(a)}$	975	731	585	975
N6-16 (kg/m^3)$^{(a)}$	623	467	374	0
R0-4 (kg/m^3)$^{(a)}$	0	165	264	0
R4-8 (kg/m^3)$^{(a)}$	0	77	124	233
R8-16 (kg/m^3)$^{(a)}$	0	118	189	356
Total N (kg/m^3)$^{(a)}$	1598	1198	959	975
Total R (kg/m^3)$^{(a)}$	0	360	577	589
Total aggregate (kg/m^3)$^{(a)}$	1598	1558	1536	1564
Superplasticizer (%)$^{(b)}$	1.0	1.1	1.1	1.2
VMA (%)$^{(b)}$	0.4	0.4	0.4	0.4

$^{(a)}$ saturated surface-dried (ssd) condition; $^{(b)}$ mass % on cement amount.

2.3 Concrete samples characterization

In the fresh state, the slump-flow (*SF*) and the flow rate (t_{500}) when the concrete has flowed to a diameter of 500 mm were determined according to EN 12350-8 [50]. A visual observation of the slump-flow diameters at the end of the flowing was made to verify the uniform distribution of the particles, the lack of segregation, and confirm the SCC behavior of the mixes.

The J-ring test (SF_J) was used to assess the passing ability of SCC to flow through tight opening, according to EN 12350-12 [51]. The bulk density in the fresh state was determined by mass/volume ratio (M/V), according to EN 12350-6 [52].

For physical and mechanical tests, 16 cylindrical concrete samples (diameter: 12 cm, height: 24 cm) as well as 2 prisms (10 x 10 x 40 cm) and 2 cubic samples (15 x 15 x 15 cm) were obtained for each formulation. Samples were cured for 28 days at 20 ± 1°C and R.H. > 95%. Bulk density (D) and water absorption (w_a) at atmospheric pressure were obtained in accordance with UNI 7699 [53] on 2 cubic concrete samples.

Concrete strength tests were determined by means of a 4000 kN universal testing machine. Compressive strength (f_{cm}) was obtained in accordance with EN 12390-3 [54] on 4 concrete cylindrical samples for every mix after 5 ($f_{cm}@5d$) and 28 ($f_{cm}@28d$) days of curing. Secant elastic modulus (E) was measured in accordance with UNI 6556 [55], tensile splitting strength (f_{ct}) was determined in accordance with EN 12390-6 [56], and three-point flexural strength (f_{cf}) was determined in accordance with EN 12390-5 [57]: two concrete cylindrical samples were used per mix for every test.

The pore size distribution of samples obtained from concrete cylinders after 28 days of curing (about 1 cm^3) was studied by mercury intrusion porosimeter (MIP, Carlo Erba 2000), equipped with a macropore unit (Fisons 120). Before MIP test, porosimeter samples were investigated by optical microscopy to confirm that they were characteristic of the cement mortar around coarse aggregates.

The long-term properties of the SCC were studied by shrinkage and creep tests performed for about two years in a climate chamber at 20 ± 1°C and 60% R.H. with specimens in drying conditions.

For shrinkage test, two cylinders were used for every mix starting after two days from casting.

For creep test, two cylinders were used for every mix, in accordance with ASTM C512/C512M-10 [58] Standard: a compression stress of about 30% of the actual strength at the time of loading (i.e., within stress limit of linear viscoelasticity) was applied after 28 days from casting.

Electrical strain gauges attached to a digital acquisition system [59-60] were used to study the longitudinal strain variation with time of each cylinder.

3. Results and discussion

3.1 Fresh state behavior

Properties of the SCC mixes in the fresh state are reported in Table 4. The higher the slump-flow (*SF*) diameter is, the higher the material deformability is, thus indicating the ability of the material to reach area distant from the concrete introduction point in the formwork. All the mixes showed *SF* > 600 mm, which is the lower limit of flowability for SCC [61]. Moreover, both *R25* and *R40* mixes with coarse and fine recycled aggregates showed values of *SF* higher than the reference mix *R0*, even if a slightly lower *w/c* ratio was used (i.e., 0.49 instead of 0.51 for *R0*).

This increase in slump-flow diameter can be ascribed to the high water absorption capacity of the fine recycled aggregates compared to natural sand (i.e., *WA* = 10.0% instead of 2.2%) that needs a higher amount of water in the mix in order to be in the saturated surface-dried condition. This amount of water could not be held initially by the aggregates, thus increasing the flowability of the mix [17]. Indeed, the slightly higher amount of superplasticizer used in *R25* and *R40* than in *R0* (i.e., 1.1 instead of 1.0%) is compensated by a slightly lower water amount (i.e., 172 instead of 179 kg/m^3). Moreover, aggregates initial humidity was the same for all the mixes, as well as water was always adjusted by decreasing its amount, thus avoiding the presence of other variables not constant involved in the mixes.

CR100 mix, with 100 vol% of coarse recycled aggregates, showed the lowest value of *SF* diameter among the investigated mixes. In this mix, the negative effect on flowability due to the more irregular and rougher texture of the coarse recycled aggregates compared to natural ones prevailed on the delay of absorbing water observed for *R25* and *R40*, thus contributing to decrease the *SF*.

Table 4. Properties of the investigated mixes at the fresh state (*SF* = slump-flow; t_{500} = flow rate when the concrete has flowed to a diameter of 500 mm; SF_J = J-ring test; *M/V* = bulk density).

Mix	*SF* (mm)	t_{500} (s)	SF_J (mm)	$SF\text{-}SF_J$ (mm)	*M/V* (g/cm^3)
R0	700	11	660	40	2.34
R25	780	11	730	50	2.28
R40	745	5	690	55	2.28
CR100	635	5	610	25	2.22

The flow rate t_{500} corresponds to the time when the concrete has flowed to a diameter of 500 mm. It is a measure of the speed of flow and an indication of the relative viscosity of the SCC and resistance to segregation. All the investigated mixes showed values of t_{500} within 12", in accordance with SCC specifications [61]. No differences were observed between *R0* and *R25* mixes, while *R40* and *CR100* mixes, both obtained substituting 40 vol % of natural aggregates, showed the same value of t_{500}, even if lower than the reference mix (i.e., 5" instead of 11"): this can be probably correlated to the high amount of recycled aggregates in the mixes.

The visual observation of the slump-flow diameters at the end of the flowing showed a uniform distribution of the particles in the mixes, confirming the lack of segregation and the regularity of the SCC behavior.

The J-ring (SF_J) test (Table 4) is used to assess the passing ability of SCC to flow through tight openings, including spaces between reinforcing bars and other obstructions, without segregation or blocking effect. According to UNI Standard [61], the difference between the confined slump-flow (i.e., SF_J) and the slump-flow in absence of obstacles (i.e., *SF*) should be equal or lower than 50 mm. *R40* slightly exceeded the recommended value (i.e., 55 mm), while all the other mixes fulfilled the limit (Table 4). Moreover, the visual observation of the slump-flow diameters at the end of the flowing through obstacles showed again a uniform distribution, without segregation, according to SCC Standards [61].

The results of all the 3 tests highlight how the use of recycled aggregates of high quality, even in a large amount, does not seem to compromise the self-compacting properties of SCC. A further study could be to check if these self-compacting properties could still be maintained for a very long period of time [28], in case of difficult and exceptional situations in the construction site.

Finally, the bulk density (*M/V*) in the fresh state of the SCC with recycled aggregates is lower than the reference with natural aggregates (Table 4), according to the lower density of recycled aggregates (Table 1). In general, an increase in C&DW content corresponds to a decrease in *M/V* as also found elsewhere [3-4].

3.2 Hardened state behavior

Fig. 3 shows the cross-section images of the 4 investigated self-compacting concretes. Natural (*N*) and recycled (*R*) aggregates are easy to distinguish because the latter are lighter in color (pale gray) than the former. Moreover, the parent aggregates can be easily detected inside the recycled aggregates being lighter than the adhered mortar (Fig. 2a).

The physical and mechanical properties of the mixes after 28 days of curing are reported in Table 5. *R0* shows the highest value of bulk density (*D*), as well as the lowest value of water absorption (w_a) among the investigated mixes. Anyway, only slight variations can be observed in the physical properties of SCC mixes with recycled aggregates. As a general trend, the higher the amount of recycled aggregate is, the higher the w_a is. The comparison between *R40* and *CR100* (both containing 40 vol% of recycled aggregates) highlights that the presence of the fine fraction (*R0-4*) leads to the highest water absorption.

Table 5 shows the compressive strength (f_{cm}) at 5 and 28 days of curing. As expected, strength increases with curing time for all the SCC. At 5 days of curing, *R40* and *CR100* show the highest values of f_{cm} (i.e., 37.1 and 36.6 MPa, respectively), about 23% higher than *R0*. *R25* shows a f_{cm} value only slightly lower than *R0* at early age of curing, while it shows the highest increase in f_{cm} with time (i.e., 58%), so that at 28 days all the SCC mixes with C&DW show f_{cm} values higher than that of *R0* containing only natural aggregates. The higher the recycled aggregate amount in the mix-design is, the higher the SCC compressive strength is, regardless the recycled aggregates dimensions. Indeed, comparing the compressive strength values of *R40* and *CR100*, it is evident that the presence of fine recycled aggregates does not play a detrimental role from the mechanical point of view.

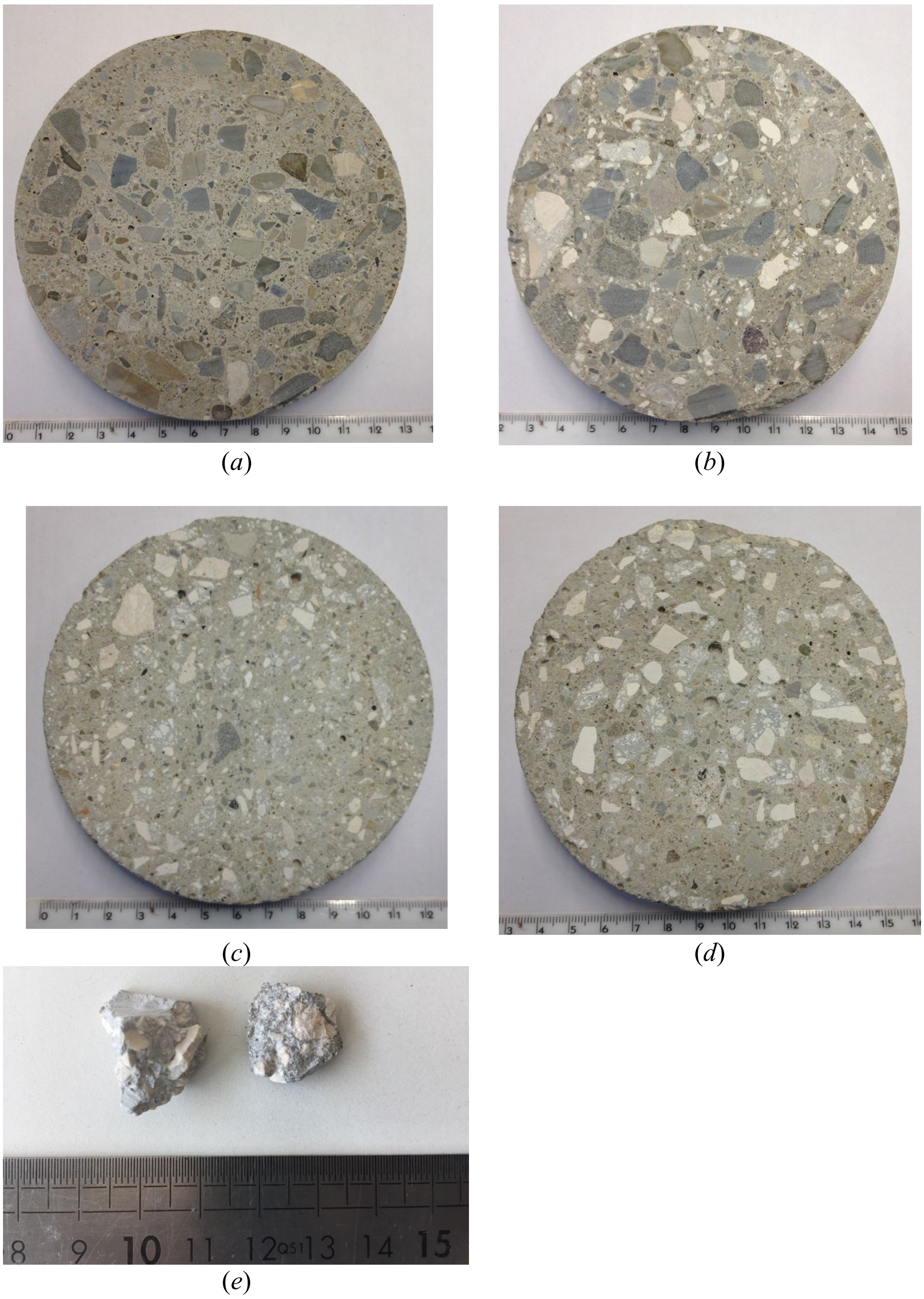


Fig. 3. Cross-section images of the 4 investigated self-compacting concrete: *R0* (*a*), *R25* (*b*), *R40* (*c*), *CR100* (*d*), and a detail of coarse recycled aggregates (*e).*

The high values of f_{cm} found for the SCC containing recycled aggregates can be related to a good adhesion between the new mortar and the adhered mortar of the recycled aggregates, but also to the high quality of the recycled aggregates. As previously reported [3-4], an increase in compressive strength up to 20% was determined for traditional structural concrete prepared with the same recycled aggregates, confirming their remarkable effect.

Table 5. Physical and mechanical properties of the investigated concrete mixes (D = bulk density; w_a = water absorption; $f_{cm}@5d$ and $f_{cm}@28d$ = compressive strength at 5 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 (%)	$f_{cm}@5d$ (MPa)	$f_{cm}@28d$ (MPa)	E (GPa)	f_{ct} (MPa)	f_{cf} (MPa)
R0	2.15±0.02	6.8±0.1	29.9±0.5	43.8±1.9	26.1±0.2	3.3±0.4	4.0±0.3
R25	2.12±0.01	7.8±0.3	28.7±1.8	45.4±1.1	25.2±0.4	3.2±0.3	3.8±0.2
R40	2.11±0.01	8.4±0.0	37.1±0.7	50.3±1.9	28.6±0.8	2.5±0.2	3.0±0.3
CR100	2.06±0.01	7.8±0.4	36.6±1.2	51.1±1.8	27.3±0.2	3.1±0.3	4.1±0.6

The elastic modulus (E) for the investigated mixes is reported in Table 5. In accordance with the compressive strength, *R40* and *CR100* samples show the highest values of E (i.e., ≈ 28 GPa), whereas *R25* samples show E values slightly lower than *R0*. In this study, the presence of different content of recycled aggregates does not have a strong effect on the elastic modulus, highlighting a good adhesion between the old and the new mortar.

The tensile splitting strength (f_{ct}) and three-point flexural strength (f_{cf}) (Table 5) are about 3.2 and 4 MPa, respectively, for all the mixes, thus indicating that the use of recycled aggregates has no great influence on these properties. These results agree with those obtained with traditional concrete [3, 62]. Only *R40* mix exhibits slightly lower values (i.e., 2.5 and 3 MPa, respectively) in accordance with the highest water absorption.

3.3 Porosity

Table 6 reports the IUPAC classification of the pores size and the relevant data of porosity determined by MIP on samples representative of the cement matrix between coarse aggregates. The total specific volume of intruded Hg is also reported as a measurement of the total open porosity. *R25* and *R40* present similar specific volume of Hg (i.e., 86-90 mm^3 Hg/g), higher than those exhibited by *R0* and *CR100* (i.e., ≈ 76 mm^3 Hg/g) prepared with a higher water/cement ratio. Such a difference might be ascribed to the presence in *R25* and *R40* of the fine recycled aggregate fraction *R0-4* (i.e., 12 and 19%, respectively) that is totally absent in *R0* and *CR100.*

Table 6. Classification of porosity in the investigated samples according to IUPAC pore size classification (percentage of porosity over the total specific volume of Hg is reported in brackets).

Designation	Porosity range (nm)	*R0* (mm^{3}Hg/g)	*R25* (mm^{3}Hg/g)	*R40* (mm^{3}Hg/g)	*CR100* (mm^{3}Hg/g)
Micropores	< 1.25	n.d.	n.d.	n.d.	n.d.
Mesopores	1.25 - 25	18.6 (24.5)	20.9 (24.4)	32.9 (36.7)	26.0 (34.0)
Macropores	25 - 5000	50.6 (66.6)	64.1 (74.7)	50.0 (55.8)	44.3 (58.0)
Directly accessible large pores	5000 - 50000	6.8 (8.9)	0.8 (0.9)	6.7 (7.5)	6.1 (8.0)
Total porosity		76.0 (100)	85.8 (100)	89.6 (100)	76.4 (100)

Examining the different porosity ranges, it can be observed that (i) all the mixes exhibit about the same content of directly accessible large pores, except *R25*; (ii) the amount of macropores is strongly influenced by the variation of recycled aggregates content; (iii) mesopores amount increases when 40% of recycled aggregates is added.

The low content of directly accessible large pores detected for *R25* is in agreement with the highest workability measured at the fresh state for this mix (Table 4). As for macropores content, which also includes capillary porosities of cement matrix, a clear trend can not be determined. Comparing *R0* and *R25*, according to the increase in total open porosity (i.e., 76 and 86 mm^3 Hg/g, respectively), a relevant increase in macropores content is observed. Comparing *R25* and *R40*, showing about the same total porosity (i.e., 86 and 89 mm^3 Hg/g, respectively), the macropores content decreases with the increase of recycled aggregates, thus suggesting that a better adhesion between recycled aggregates/cement matrix/natural aggregates occurred when the natural aggregates replacement was equal to 40%. Comparing *R40* and *CR100*, both containing 40% of recycled aggregates, a decrease in total open porosity was registered (i.e., 89 and 76 mm^3 Hg/g, respectively) which was almost uniformly distributed in the range 0.004-0.1 μm of pores size, as reported in Fig. 4. Finally, comparing *CR100* and *R0*, exhibiting the same total porosity (i.e., 76 mm^3 Hg/g), macropores content decreases in *CR100*, promoting the formation of a larger amount of mesopores, which has a minor detrimental effect on mechanical properties, as previously observed (Table 5).

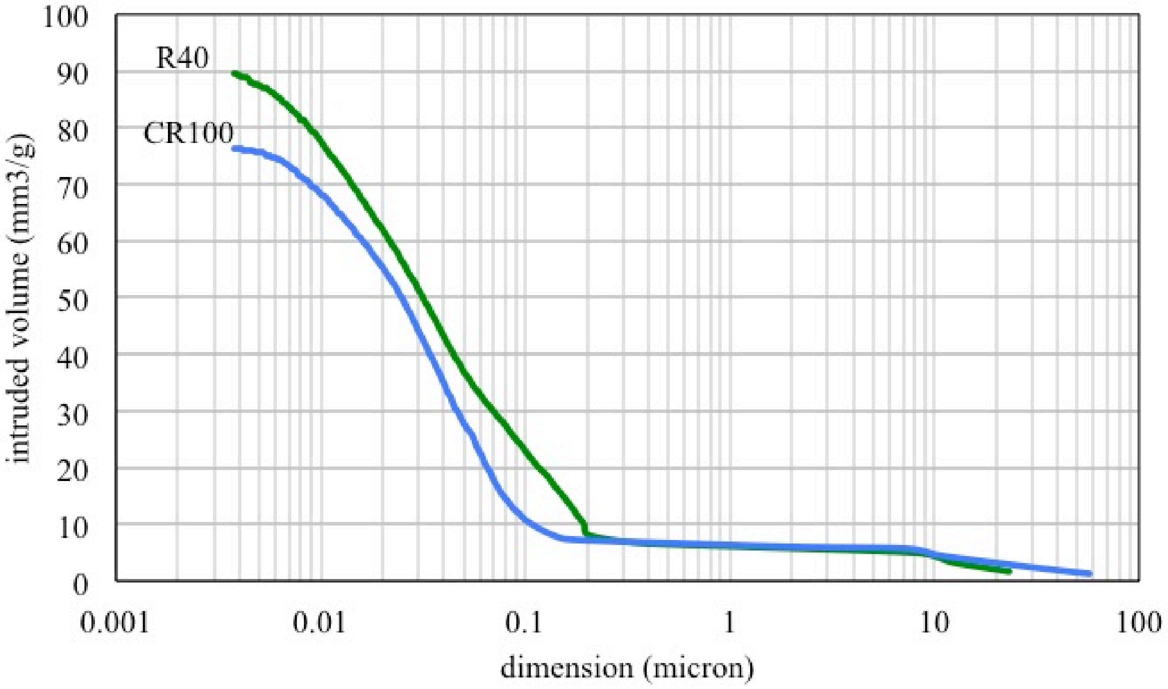
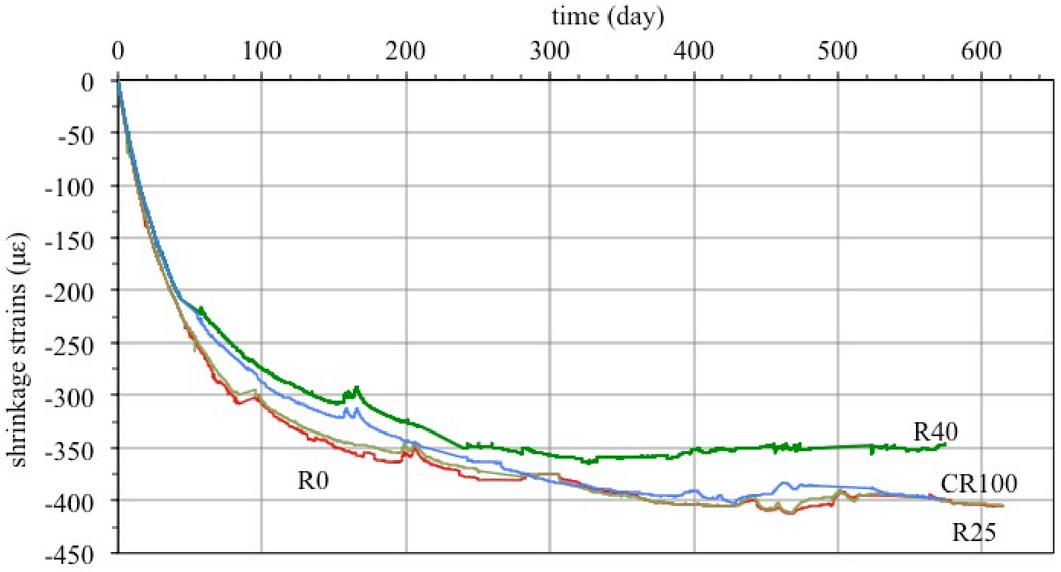


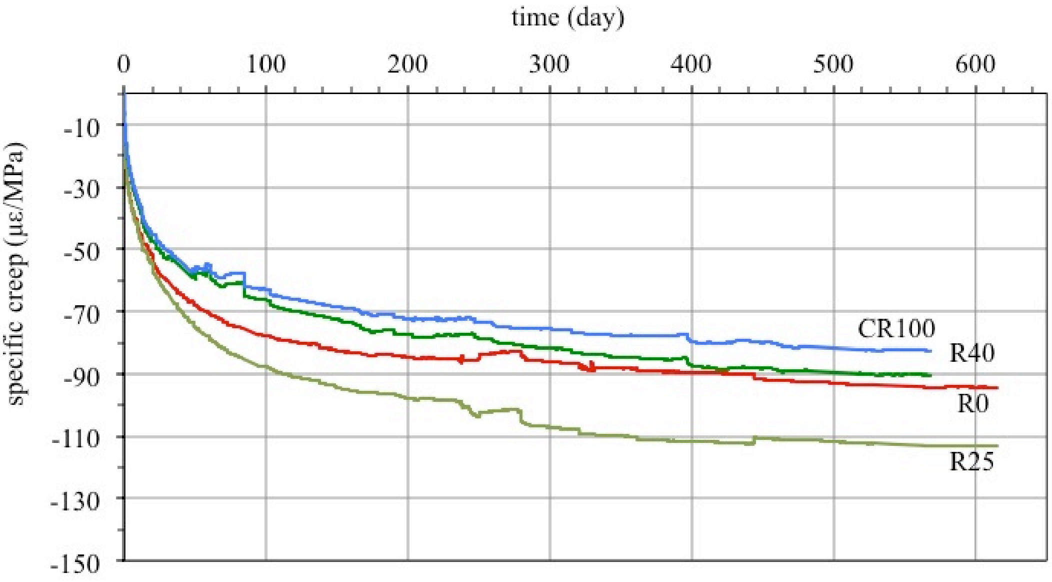
Fig. 4. Pore size distribution of *R40* and *CR100* samples.

3.4 Long-term behavior

Fig. 5 shows the long-term properties of all the SCC mixes tested for nearly 2 years. In particular, shrinkage strains (autogenous and drying contributions) are reported in Fig. 5*a*, while specific creep (creep strain per unit of applied stress, basic and drying contributions together) in Fig. 5*b*.



(*a*)



(*b*)

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

Regarding the shrinkage behavior (Fig. 5*a*) all curves are similar, showing a rapid shrinkage strain increase in the first three months. The slope of the curves decreases with time, becoming almost flat after ten months. Such behavior was also detected in the traditional concrete containing the same recycled aggregates previously studied [3-4], even if for SCC mixes the determined shrinkage strain is in the range of 350-400 με compared to values in the range of 550-900 με reported for the traditional concrete. The detected low shrinkage for the investigated SCC, which does not appear particularly affected by the presence and amount of recycled aggregates, is due to the strong reduction of the water/powder (*w/p*) ratio (from 0.48 for traditional concrete to approximately 0.31 for SCC). In more details, the increase of the amount of paste volume for SCC leading to an increment of the shrinkage [63] is largely compensated by the effect of its reduction due to the smaller *w/p* ratio [64]. When dealing with SCC shrinkage, the role played by the aggregates elastic modulus can be considered smaller than that for traditional concretes.

Specific creep curves are reported in Fig. 5*b*: all the curves have a qualitative similar behavior. The slope of the curves decreases with time and after about 5 months the creep phenomenon is less active. As for the shrinkage, the detected creep behavior of SCC differs from that previously observed for traditional concrete with the same type of recycled aggregates [3-4]. Even if the extent of the creep is similar for both traditional concrete and SCC, in all the investigated SCC mixes the initial rate of creep strain increase is larger than that of traditional concrete, while after one year of loading this rate is strongly reduced, showing a limited long-term activity. This behavior can be ascribed to the smaller pore size usually shown by SCC leading to faster water movement.

Comparing the different curves reported in Fig. 5*b*, it can be observed that (i) *CR100* exhibits a lower creep than *R0* even if they have the same water/cement ratio (i.e., 0.51); (ii) *R40* (with a water/cement of 0.49) shows a trend very similar to *R0* but lower than *CR100*; (iii) *R25* shows the worst behavior even if it was prepared with a water/cement ratio of 0.49 and a content of recycled aggregates equal to 25%.

Although the magnitude of creep strain depends not only on cement matrix microstructure, but also on the composite nature of the concrete, thus including aggregates (e.g., shape, grain size distribution, modulus of elasticity) and interface zone between aggregate and cement matrix, where localized stresses and micro-cracks can occur [65-66], the obtained results are in good agreement with the compressive strength and porosity results. Indeed, comparing *R40* and *CR100*, both having 40% of recycled aggregates, the lowest creep is determined for *CR100* featuring the highest compressive strength (Table 5) and lowest pore size distribution (Fig. 4).

R25, nevertheless containing only 25% of recycled aggregates, exhibits the worst behavior in terms of creep according to its high cumulative porosity and lowest elastic modulus, suggesting that this mix is characterized by a microstructure less compact than the ones exhibited by the other investigated mixes.

4. Conclusions

Based on the results of this experimental investigation, the following conclusions are drawn:

1. It is feasible to produce SCC with coarse and fine recycled concrete aggregates up to 40 vol% in the mix design.
2. Mechanical properties (i.e., elastic modulus, compressive, flexural, tensile splitting strength) of the SCC containing recycled concrete aggregates of high quality can be equal or even higher than the reference mix with 100% natural aggregates because of the development of a more compact microstructure.
3. For time-dependent characteristics, creep behavior is more influenced by the presence of recycled aggregates than shrinkage, although its variations are rather limited compared to what occurs in traditional concrete. The best creep behavior among the investigated mixes has been determined for *CR100* according to its highest compressive strength and lowest pore size distributions.
4. Porosity investigations have highlighted that the microstructure of the investigated mixes is influenced by the content and assortment of recycled aggregates promoting different pores size

distributions (i.e., macropores and mesopores content), which in their turn influence the mechanical properties at short and long-term.

This work strengthens the concept of sustainability in civil constructions. SCC can be designed combining the use of coarse and fine recycled concrete aggregates highlighting that concrete waste, properly assorted and characterized, can be a useful resource for structural applications.

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