

Article

Effect of Parent Concrete on the Performance of Recycled Aggregate Concrete

Luisa Pani, Lorena Francesconi, James Rombi , Fausto Mistretta, Mauro Sassu  and Flavio Stochino * 

Department of Civil, Environmental Engineering and Architecture, University of Cagliari, 09123 Cagliari, Italy; lpani@unica.it (L.P.); lorenafrancesconi@libero.it (L.F.); james.14@tiscali.it (J.R.); fmistret@unica.it (F.M.); msassu@unica.it (M.S.)

* Correspondence: fstochino@unica.it; Tel.: +39-070-675-5115

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Abstract: Recycling concrete construction waste is a promising way towards sustainable construction. Indeed, replacing natural aggregates with recycled aggregates obtained from concrete waste lowers the environmental impact of concrete constructions and improves natural resource conservation. This paper reports on an experimental study on mechanical and durability properties of concretes casted with recycled aggregates obtained from two different parent concretes, belonging to two structural elements of the old Cagliari stadium. The effects of parent concretes on coarse recycled aggregates and on new structural concretes produced with different replacement percentages of these recycled aggregates are investigated. Mechanical properties (compressive strength, modulus of elasticity, and splitting tensile strength) and durability properties (water absorption, freeze thaw, and chloride penetration resistance) are experimentally evaluated and analyzed as fundamental features to assess structural concrete behavior. The results show that the mechanical performance of recycled concrete is not related to the parent concrete characteristics. Furthermore, the resistance to pressured water penetration is not reduced by the presence of recycled aggregates, and instead, it happens for the chloride penetration resistance. The resistance to frost–thawing seems not related to the recycled aggregates replacement percentage, while an influence of the parent concrete has been assessed.

Keywords: concrete; recycled concrete; durability; recycled aggregate

1. Introduction

The environmental impact of concrete constructions is huge. For this reason, recycling concrete construction waste to obtain recycled concrete aggregate can lower the environmental impoverishment. Indeed, the use of Construction and Demolition Waste (C&DW) as alternative aggregates for new concrete production improves natural resource preservation, reduces landfill disposal, and promotes construction sustainability [1].

The physical properties of Recycled Aggregates (RA) depend on the quality and amount of the adhered cement mortar [1,2]. Actually, the quantity of adhered mortar increases with the decrease of the RA size [1,2]. Furthermore, the crushing procedure modifies the amount of adhered mortar. Due to this mortar, RA have higher water absorption and lower density in comparison to natural ones. In addition, the un-hydrated cement on the RA surface can modify the properties of concrete [3] and crack propagation [4,5].

It is observed that the mechanical properties (compressive strength, splitting tensile strength, and modulus of elasticity) of concrete with recycled concrete aggregates decrease with the increase of the replacement percentages of Natural Aggregates (NA) [6–8]. The different mechanical performances

can be explained considering the different stress distribution and failure mechanisms caused by the different micro-structures of concrete with RA in comparison to the ones with NA. The failure mechanism of the concrete with RA is complex and it is influenced by the geometrical and mechanical properties of the aggregates but also by two different interfacial transition zones. Indeed, one is located between the original NA and the old mortar and the other one is between the old and the new mortar. Clearly, the situation is different in the case of normal concrete with NA where there is only one interfacial transition zone [9].

Often, RA have been used for concrete block pavements [10,11], but other research [9,12–14] has shown how it is possible to produce structural concrete with RA. Limbachiya et al. [14] found that flexural strength and modulus of elasticity of concrete containing recycled aggregates are similar to the ones of concrete made with NA. Recently, many researchers have investigated the influences of polymer additives on Self Compacting Concrete (SCC) cast with recycled and natural aggregates [15]—see [16] for a review—proving how it is possible to employ RA in the production of structural elements casted with SCC.

The durability properties of concrete with RA (chloride diffusion, freeze thaw resistance, and abrasion resistance) are still under investigation, since a wide variability in the results is reported [17]. The durability of concrete with recycled concrete aggregates is generally lower in comparison with traditional concrete [17–21]. Pereira et al. [22] suggest that the concrete containing recycled concrete aggregates should be avoided in aggressive environments. Actually, the adhered mortar that remains attached to the recycled concrete aggregates also influences the durability properties of concrete [19]. Saravanakumar and Dhinakaran [23] show that resistance to chloride ion penetration, water absorption, and acid attack resistance of concrete decrease with addition of recycled concrete aggregates. Kwan et al. [24] report that using recycled concrete aggregates as partial replacement of NA yields to low Water Absorption (WA) and low intrinsic permeability compared to the control concrete mix. Medina et al. [25] show that concrete with higher ratios of RA have higher freeze–thaw resistance. This can be explained considering the high mechanical quality of RA and the intrinsic properties of the new aggregates. Olorunsogo and Padayachee [26] reveal that the durability characteristics of concrete with RA are reduced by the increase in RA content. However, the durability of concrete with recycled concrete aggregates can be improved by the addition of pozzolanic materials, such as superfine phosphorus slag and ground granulated blast-furnace slag [27]. Xiao et al. [28], considering a Chinese experimental database, summarizes that the resistance of chloride penetration of Recycled Aggregate Concrete (RAC) is lower compared to that of Normal Concrete (NC), and that the resistance of chloride penetration of RAC decreases with the increase of RA replacement percentage. Similar studies confirm these conclusions; see [29,30]. Kurda et al. [31], considering both literature experimental data and their new experimental campaign, show that water absorption increases, and the electrical resistivity decreases with increasing replacement percentage of RA. An opposite result is obtained if fly ash is added to concrete for both tests. The reduction of water absorption is higher in mixes with both RA and fly ash in comparison to the mixes with only RA or fly ash. In addition, the benefit of incorporating fly ash and RA in concrete increases even more when superplasticizers are used. In addition, Lima et al. [32] prove that the presence of fly ash in the mixture improves the concrete workability, and compressive and tensile strengths.

In order to develop the marketing of recycled aggregates and the management of recycling plants, it is important to know whether their chemical, physical, and mechanical characteristics are influenced by parent concrete and also whether it influences the properties and performance of the concrete with RA. The experimental data representing the properties of RAC are characterized by high dispersion [33]. According to some authors [34,35], the quality of RA is mostly influenced by the quality of original demolished concrete. Even if more research is needed, some general statements can be drawn. For example, RAC with low to medium compressive strength can be produced independently from the characteristics of parent concrete [1,36–39]. On the other hand, Tabsh and Abdelfatah [40] state that the influence of the parent concrete is more significant in a weak concrete than in stronger

one. Actually, this can be explained considering that the strength of concrete depends on both coarse aggregates and cement. Therefore, if more cement is used, then the effect of the coarse aggregate is reduced.

Given that non conclusive statements have been proved on this issue, in this paper, an extensive experimental campaign was carried out to evaluate the mechanical performance and durability of concrete with coarse recycled concrete aggregates obtained through the demolition of concrete with quite low compressive strength ($R_{ck} \leq 20$ MPa). In this case, the old football stadium located in Cagliari (Italy) has been used as an artificial “quarry”. Indeed, in the future, the stadium will be demolished and rebuilt with a modern design. Thus, the RA are obtained from its concrete cantilever beams and foundations. Tests were carried out to evaluate the concrete mechanical performance of these concrete structures. Parts of cantilever beams and foundations have been separately demolished and crushed in order to obtain two types of coarse RA with a size range between 4 and 16 mm. Three different replacement percentages (30, 50, and 80%) of NA with RA have been used to produce different six concrete mixes. Three of them were casted using the RA obtained from the beams and the others were produced using the RA obtained from the foundations. An additional mix of NC with only NA was produced as a benchmark. Further tests were carried out to obtain a full description of physical and mechanical properties and durability of these concretes.

The aim of this work is twofold: to verify the feasibility of using concrete debris of the old Cagliari stadium for new structural concrete and to investigate the influence of the parent concrete on the new concrete obtained with RA.

After this brief introduction, Section 2 presents the experimental program, while Section 3 describes the characteristics of the RA. Section 4 deals with the mechanical and durability properties of the concrete with RA, discussing the influence of the parent concrete. Some discussions and conclusive remarks are presented in Section 5.

2. Experimental Program

The mechanical characteristics of concrete structures of the old Cagliari football stadium (built between 1965 and 1970, as shown in Figure 1) were investigated in the first step of the experimental program. Beams and foundation blocks (see blue elements in Figure 2) were chosen as the sources of the recycled concrete.

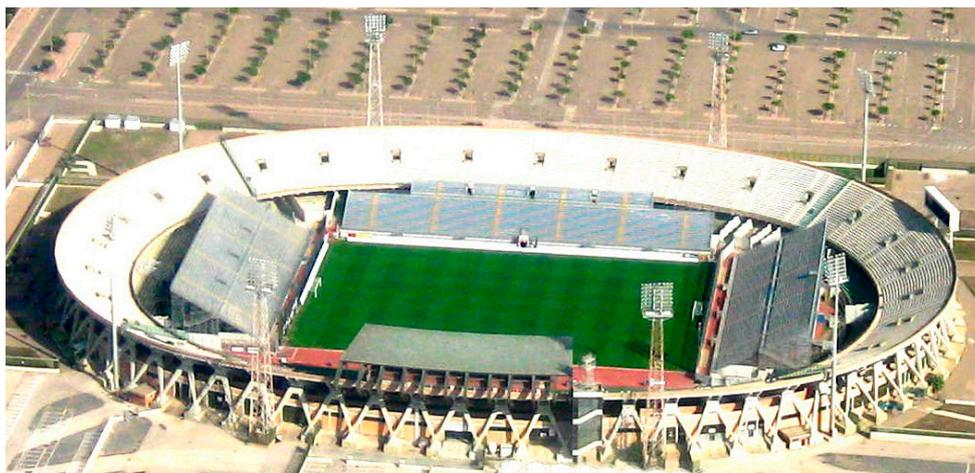


Figure 1. Aerial view of old Cagliari football stadium, cropped version of the File: “Stadio_Sant’Elia_Cagliari_Italy_230Octo2008.jpg” posted to Flickr by Cristiano Cani, license CC 2.0.

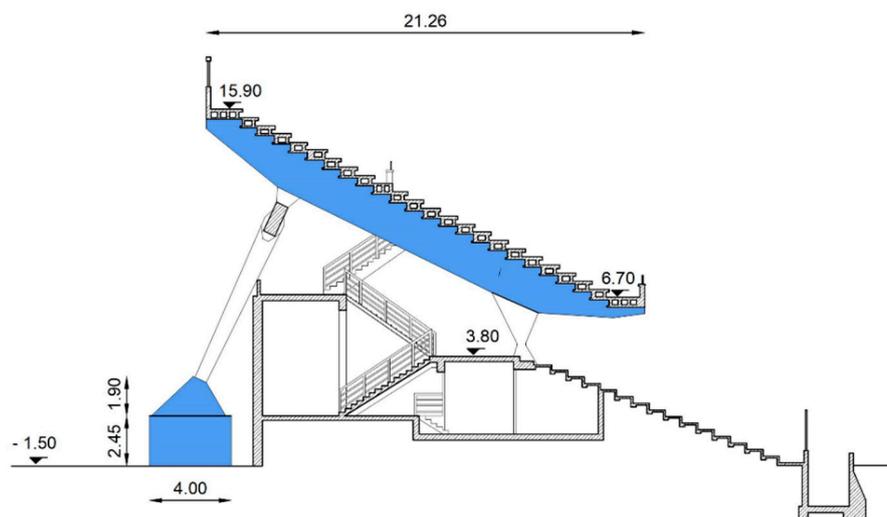


Figure 2. Cross section of reinforced concrete structures of old Cagliari football stadium. The analyzed structures are highlighted in blue (measures are in m).

Parent Concrete Quality

Twelve core samples were extracted from both the beams and the foundations, respectively labelled C. Beam and C. Found. Table 1 presents the average values of parent concrete mechanical characteristics and carbonation depth. These experimental results prove that concrete used to cast the beams is different from the ones used for the foundations. Indeed, different mechanical properties and carbonation depth were assessed. The mechanical performances and the carbonation depth of foundations concrete are better than those of the one used for beams.

Table 1. Properties of parent concrete.

Identification	Carbonation Depth (mm)	Density (kg/m ³)	Compressive Strength (MPa)	Elasticity Modulus (MPa)	Tensile Strength (MPa)
C. Found. 1	30	2299	26.8	24,470	-
C. Found. 2	30	2334	32.2	27,751	-
C. Found. 3	0	2283	24.7	23,785	-
C. Found. 4	0	2345	-	-	2.04
C. Found. 5	0	2298	-	-	1.83
C. Found. 6	0	2327	-	-	2.28
C. Found. Average	10	2314	27.9	25,335	2.05
C. Beam 1	50	2271	22.2	19,744	-
C. Beam 2	0	2315	22.1	18,537	-
C. Beam 3	60	2233	18.7	15,845	-
C. Beam 4	0	2295	-	-	1.50
C. Beam 5	40	2248	-	-	1.58
C. Beam 6	40	2259	-	-	1.40
C. Beam: Average	32	2270	21.0	18,042	1.49

Petrographic analysis on thin sections of the cores highlights differences in the composition of the two materials C. Found and C. Beam. The polarizing microscope detects a fine cement matrix with different kinds of aggregates. Size distribution and mineralogical composition allow us to distinguish them. C. Found is characterized by centimetric fragments of micritic limestone. The presence of a varied siliciclastic, fine-grained, millimetric and sub-millimetric, fraction of metamorphic rock and granite fragments, with feldspar free crystals and quartz was also detected. All the fragments

are characterized by sharp edges. C. Beam presents a quite homogeneous siliciclastic composition. Millimetric-centimetric fraction of granite rocks, angular fragments, and various types of metamorphic rocks can be seen with a fine-grained, sub-millimetric fraction of the same materials and free crystals of feldspars, biotite, and quartz.

3. Recycled Aggregates

Taking into account that two different parent concretes have been considered, two kinds of RA have been produced: Recycled Aggregates obtained from crushed Foundations (RA_F), and Recycled Aggregates obtained from crushed Beams (RA_B). In both cases, the aggregates size range is 4–16 mm.

The tests following the indications of UNI EN 12620: 2008 [41] and UNI 8520-1: 2015 [42] have been performed on both types of RA. Table 2 presents the main test results while Figure 3 depicts the RA size distribution. It is interesting to point out that both RA types have very similar characteristics even if they have been obtained by crushing two different concretes. Indeed, only four parameters (content of acid-soluble sulfate and water-soluble sulfates, percentage of fines, shape index) out of twenty-one are different.

The physical properties, workability, mechanical performances, and durability of concrete with RA is strongly influenced by the Residual Mortar Content (RMC) attached onto the original NA particles [2,29,43–47]. Indeed, previous studies have proved that the reduction in compressive strength of concrete with RA [43–48] and in modulus of elasticity [49] are related to the presence of RMC. Thus, in order to evaluate the properties of concrete with RA, the determination of the RMC is critical. However, currently no standard method is available. In this research, the authors follow the strategy proposed by Abbas et al. in [50]. RA samples were exposed to daily cycles of freezing and thawing in a sodium sulphate solution. Table 3 presents the RMC obtained in RA_F and RA_B considering two fraction sizes (retained by a 4 and 10 mm sieve) and it highlights that RMC is almost similar for RA_B and RA_F.

Table 2. Recycled aggregate properties.

Property	RA_F	RA_B
Size designation	4/16	4/16
Category grading	GC 90/15, GT 17.5	GC 90/15, GT 17.5
Flakiness Index	4	4
Shape Index	59	34
Saturated surface-dried particle density	2.39 Mg/m ³	2.38 Mg/m ³
Loose bulk density and voids	$\rho_b = 1.23 \text{ Mg/m}^3$ $v\% = 45$	$\rho_b = 1.14 \text{ Mg/m}^3$ $v\% = 49$
Percentage of fines	0.15%	0.59%
Percentage of shells	absent	absent
Resistance to fragmentation	39	39
Constituents of coarse RA	X = 0; Rc = 74%; Ru = 27%; Rb = 0; Ra = 0; Rg = 0	X = 0; Rc = 78%; Ru = 22%; Rb = 0; Ra = 0; Rg = 0
Content of water-soluble chloride salts	0.005%	0.005%
Content of acid-soluble chloride salts	0.325%	0.325%
Content of acid-soluble sulphate	0.43%	0.26%
Content of total sulfur	S < 0.1%	S < 0.1%
Content of water-soluble sulphates	SS = 0.148%	SS = 0.068%
Lightweight contaminator	absent	absent
Water absorption	WA24 = 7.0%	WA24 = 6.7%
Resistance to freezing and thawing	41%	42%
Resistance to magnesium sulphate	2.56%	0%
Presence of humus	absent	absent

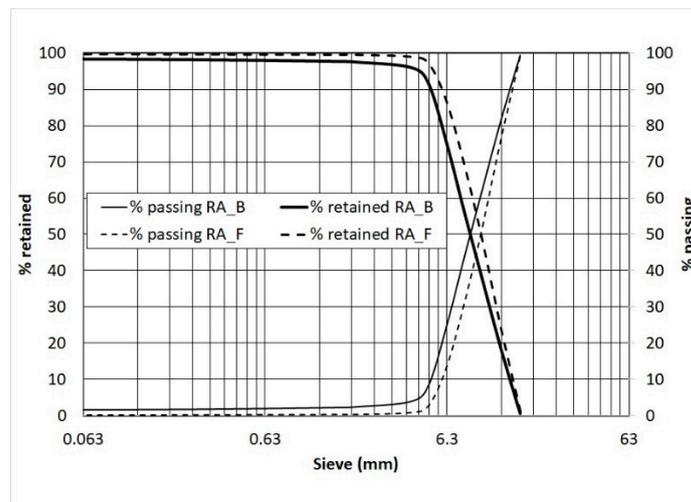


Figure 3. Recycled Aggregates (RA) size distribution.

Table 3. Residual mortar content.

Residual Mortar Content (%)	RA_F	RA_B
Sieve Retained 4 mm	55.81%	49.67%
Sieve Retained 10 mm	45.82%	45.65%

4. Concrete

Cement CEM II/A-LL 42,5 R was adopted for each concrete mix. Sand is the fine aggregate while the coarse aggregates are crushed granite and the two kinds of recycled aggregates (RA_F and RA_B). In addition, a super plasticizer based on polycarboxylate was also used. Different replacement percentages (30, 50, and 80%) of coarse RA belonging to RC_B (Reinforced Concrete of the Beams) and to RC_F (Reinforced Concrete of the Foundations) were considered. Thus, the label RC_B_X% represents a mix with X% replacement percentage using RC_B. In addition, a normal mix of concrete without RA and with only NA was produced and labelled NC. Table 4 presents the characteristics of each mix.

Table 4. Mix proportions of concretes per m³.

Notation	w/c Ratio	Cement (kg/m ³)	Water (l/m ³)	Fine NA (kg/m ³)	Coarse NA (kg/m ³)	Coarse RA_F (kg/m ³)	Coarse RA_B (kg/m ³)	Additive (kg/m ³)	Density (kg/m ³)
NC	0.463	400	185	847.49	880.06	-	-	2.91	2322
RC_B 30%	0.463	400	185	821.8	616.04	-	263.69	3.31	2293
RC_F 30%	0.463	400	185	821.8	616.04	263.69	-	3.31	2287
RC_B 50%	0.463	400	185	802.97	440.03	-	440.27	3.31	2298
RC_F 50%	0.463	400	185	802.97	440.03	440.27	-	4.00	2283
RC_B 80%	0.463	400	185	778.15	176.01	-	703.96	4.00	2268
RC_F 80%	0.463	400	185	778.15	176.01	703.96	-	4.00	2229

4.1. Concrete Mechanical Properties

The standard slump test UNI EN 12350-2:2019 [51] was used to measure the fresh concrete workability. Two tests were performed for each mix at different times: immediately after the mixing process and after 30 min. Figure 4 presents the obtained values. It is interesting to highlight that slump values of the mixes with RA are very similar to NC.

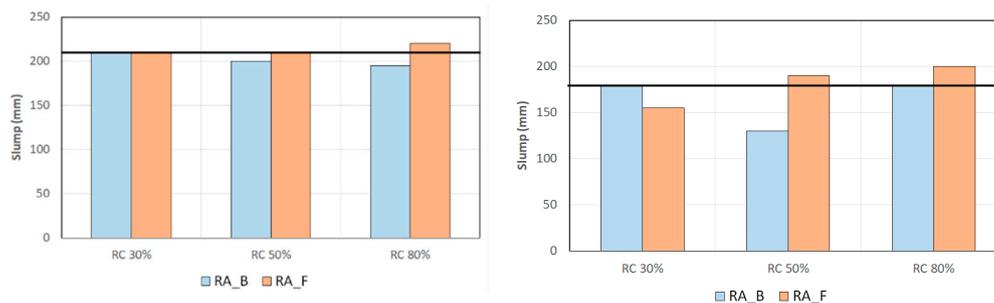


Figure 4. Slump test immediately (left) and 30 min after (right) mixing. The horizontal black line represents the slump value of Normal Concrete (NC).

Compressive strength and secant modulus of elasticity in compression tests were performed, respectively, according to UNI EN 12390-3: 2019 [52] and UNI EN 12390-13: 2013 [53], while splitting tensile strength was obtained following UNI EN 12390-6: 2010 [54].

After 14 and 28 days from the casting date, the compressive strength was measured, while modulus of elasticity and splitting tensile strength were obtained after 28 days. Table 5 presents the above-mentioned mechanical tests results. The average compressive strength at 14 and 28 days is quite high even when the percentage of coarse RA reaches 80%. Indeed, the compressive strength of concrete with RA seems not influenced by the parent concrete. Actually, some tests show how the compressive strength of concrete with RA is higher than NC. The splitting tensile strength of concrete with RA is almost equal or slightly higher than NC. Actually, the greater roughness of RA improves the aggregate interlocking, which produces an increase in tensile strength of concrete. As already shown in other research [49,55], the secant modulus of elasticity of concrete with RA is slightly lower than the one of NC.

The results shown in Table 5 prove that concrete with RA can be considered as a structural concrete, even when the replacement percentage reaches 80%. It is also important to point out that the performance characteristics of the parent concrete do not affect the performance of concrete with RA while the mix design plays a very important role [56].

4.2. Concrete Durability Properties

The durability of concrete is due to degradation phenomena that are produced by chemical and electro-chemical or physical causes [18]. The chemical and electro-chemical causes are related to reactions between aggressive fluids coming from the external environment and the ingredients or hydration products of the cement. The physical causes are determined by the temperature variations and relative humidity gradients, but they are also generated by static and dynamic loads acting on the structure and by abrasive actions. In this work, the durability properties related to the cementitious matrix characteristics have been analyzed in order to assess the concrete water permeability, the freeze–thaw resistance, and resistance to chloride penetration.

4.2.1. Permeability of Concretes

In general, concrete is not very permeable, and the higher the quality, the lower the permeability. Actually, permeability is an important parameter capable of assessing both the ability to avoid liquid loss, in the case of structures designed to contain liquids, and the material durability. The method currently used to estimate the permeability of concrete is based on the resistance to pressurized water penetration. The result of this test is the measurement of the water penetration depth in a cubic specimen (non-steady-state, without water permeation), due to the effect of pressure acting on the specimen for the test time.

Table 5. Mechanical properties of concrete with RA and NC, $R_{c,14d}$ represents the cubic compressive strength at 14 days, $R_{c,28d}$ represents the cubic compressive strength at 28 days, f_{ct} is the splitting tensile strength, while E_c is the secant elastic modulus.

Notation	N.	$R_{c,14d}$ (MPa)	$R_{c,28d}$ (MPa)	f_{ct} (MPa)	E_c (MPa)
NC	1	37.4	41.7	3.53	26,601
	2	41.1	41.4	3.71	25,473
	3	40.3	45.2	3.75	26,037
	Average Value	39.6	42.8	3.66	26,037
RC_B 30%	1	44.4	45.5	3.46	24,138
	2	41.7	47.3	3.83	23,553
	3	41.5	44.8	4.06	22,846
	Average Value	42.5	45.9	3.78	23,512
RC_F 30%	1	43.1	44.2	3.87	25,081
	2	38.5	46.3	3.95	25,081
	3	42.0	43.1	3.87	24,543
	Average Value	41.2	44.5	3.89	24,902
RC_B 50%	1	45.5	43.9	3.70	23,383
	2	44.9	41.8	4.04	22,976
	3	43.9	47.5	3.95	22,675
	Average Value	44.8	44.4	3.90	23,011
RC_F 50%	1	45.5	48.6	3.19	25,796
	2	45.3	46.3	3.26	23,842
	3	44.0	48.9	4.60	26,889
	Average Value	44.9	47.9	3.68	25,509
RC_B 80%	1	43.4	45.6	4.10	25,314
	2	42.8	47.9	3.59	22,602
	3	43.1	48.1	3.87	22,541
	Average Value	43.1	47.2	3.85	23,486
RC_F 80%	1	39.4	42.6	3.77	25,398
	2	41.0	43.5	3.47	23,415
	3	40.6	47.3	3.84	23,315
	Average Value	40.3	44.5	3.69	24,043

The standard considered for this test is UNI EN 12390-8: 2009 [57]. Water pressure of 500 kPa is applied for 72 h, as shown in Figure 5a, to the specimen. During the test, the presence of water on the specimen surfaces not exposed to water pressure was periodically observed. The pressure was applied for 72 h and then the specimen was split in half. The cutting surface was perpendicular to the face on which the water pressure was applied, as shown in Figure 5b. The water penetration front could be clearly seen on the split face and then it was marked, as shown in Figure 5c, and measured.

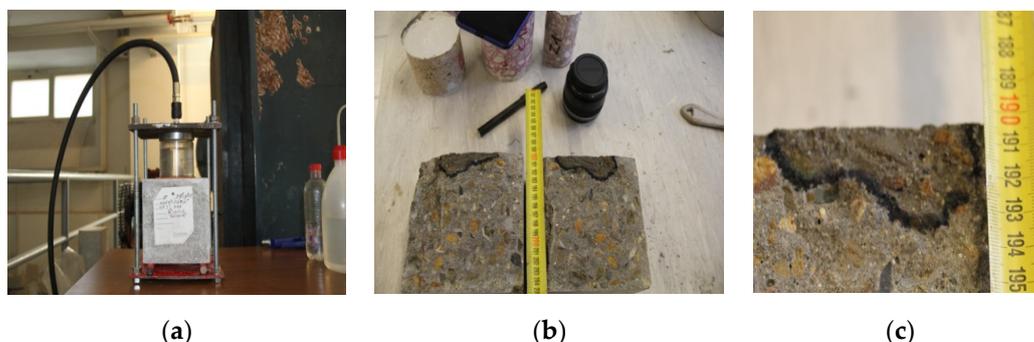


Figure 5. Test of penetration of water under pressure: (a) apparatus to apply water under pressure; (b) split specimen; (c) marked waterfront.

Figure 6 presents the maximum penetration depth measured on the marked waterfront. It was found that NC presents a greater permeability compared to concrete with RA. The RC with RA_B has higher permeability than RC with RA_F. The influence of parent concrete in recycled concrete with 30% and 50% replacement percentage was also highlighted. Concrete made with RA_F shows less permeability. When the percentage of substitution is 30%, the depth of penetration of pressurized water is greater (1.5 times) in RC with RA_B than in RC with RA_F. The difference in penetration depth between RC with RA_B and with RA_F tends to disappear as the percentage of substitution increases. Thus, the permeability of concrete with RA was lower than the one of NC.

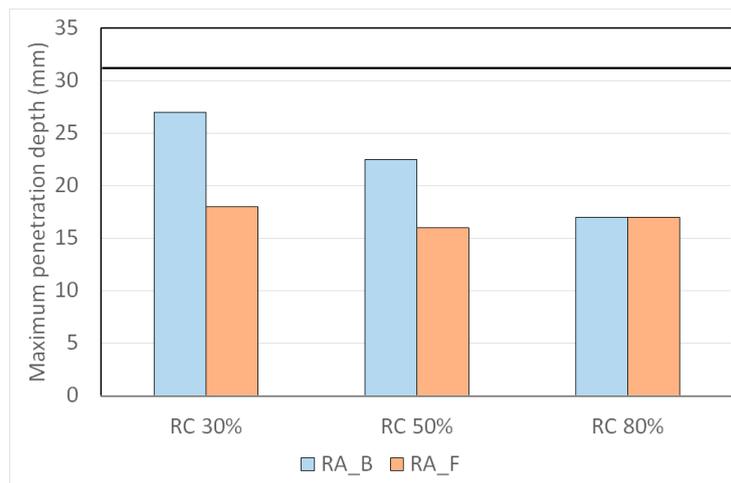


Figure 6. Maximum penetration depth of water under pressure. The black horizontal line represents the penetration depth of water under pressure for NC.

4.2.2. Resistance to Chloride Penetration

The resistance to chloride penetration has been measured following the international standard UNI EN 12390-11: 2015 [58]. Seven cube specimens have been casted and cured for a period of 28 days. Each specimen was divided into two sub-specimens: a “profile specimen” that was used to determine the chloride profile after exposure to unidirectional chloride ingress, and an initial chloride sub-specimen that was used to determine the initial chloride level, C_i . The profile specimen was vacuum saturated with demineralized water, coated on all sides but one, and then the uncoated face was exposed to a chloride solution (3% mass sodium chloride (NaCl) solution) by complete immersion. After 90 days of exposure, 8 layers parallel to the chloride exposed surface but with different depths were ground. The acid-soluble chloride content of each layer and the average depth of the layer from the surface of concrete exposed to the chloride solution were determined. The initial chloride content was also determined by grinding a sample from the other sub-specimen and the acid soluble chloride content determined.

By non-linear regression analysis using the least squares approach, the surface chloride constant (C_s) and the non-steady state chloride diffusion coefficients (D_{nss}) were determined. The regression is necessary to find the parameters C_s and D_{nss} , which minimize the differences between the measured experimental data and the solution to Fick’s 2nd law:

$$C_x = C_i + (C_s - C_i) \left(1 - \operatorname{erf} \left[\frac{x}{2 \cdot \sqrt{D_{nss} \cdot t}} \right] \right) \quad (1)$$

Table 6 presents the experimental data related to the initial chloride level C_i (% by mass of concrete), acid-soluble chloride content C_x (% by mass of concrete), and related average depth, x (mm), of the layer from the surface of concrete exposed for an exposure period of 90 days, and the parameters C_s (% by mass of concrete), D_{nss} (mm^2/days), and the coefficient of determination R^2 .

Table 6. Experimental chloride penetration parameters.

Concrete		NC	RC_F30%	RC_F50%	RC_F80%	RC_B30%	RC_B50%	RC_B80%
	C_i (%)	0.007	0.016	0.012	0.010	0.011	0.006	0.007
Layer 1	x (mm)	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	C_x (%)	0.176	0.074	0.274	0.157	0.272	0.130	0.108
Layer 2	x (mm)	2.310	2.690	2.950	2.520	3.000	2.800	2.810
	C_x (%)	0.060	0.061	0.075	0.070	0.070	0.083	0.099
Layer 3	x (mm)	4.190	4.950	4.930	4.740	5.000	4.450	4.940
	C_x (%)	0.055	0.052	0.063	0.057	0.058	0.077	0.080
Layer 4	x (mm)	7.270	7.060	6.720	6.950	7.500	6.600	7.200
	C_x (%)	0.040	0.044	0.055	0.050	0.048	0.060	0.060
Layer 5	x (mm)	9.930	9.180	10.97	10.90	10.46	10.11	9.960
	C_x (%)	0.038	0.040	0.038	0.038	0.032	0.054	0.050
Layer 6	x (mm)	13.35	13.50	14.10	14.83	14.17	13.87	14.39
	C_x (%)	0.020	0.021	0.030	0.026	0.028	0.038	0.015
Layer 7	x (mm)	16.63	17.23	17.80	17.67	17.17	17.78	17.67
	C_x (%)	0.013	0.007	0.009	0.020	0.020	0.017	0.013
Layer 8	x (mm)	20.06	21.14	20.40	21.75	20.73	21.88	21.95
	C_x (%)	0.011	0.006	0.006	0.009	0.009	0.012	0.007
	C_s (%)	0.071	0.075	0.090	0.083	0.085	0.099	0.128
	D_{nss} (mm ² /days)	0.787	0.516	0.731	0.711	0.649	1.019	0.496
	R^2	0.953	0.961	0.998	0.993	0.980	0.970	0.970

The resistance of concrete to chloride penetration can be defined by three parameters: initial chloride content in concrete, C_i ; surface chloride content in concrete after exposure to chlorides, C_s ; and diffusion coefficient, D_{nss} . Although the adopted exposure solution does not simulate an actual condition produced by seawater or thawing salts, it is nevertheless useful to reduce the problem of durability to a single parameter. To this end, the time T necessary for the chlorides to destroy the protective film was obtained using Equation (1). The calculation was done with reference to a particular level of concentration of chlorides critical C_{cr} and a depth x equal to the reinforcement depth. In this case, $C_{cr} = 0.05$ (% by mass of concrete) and $x = 40$ mm have been considered. Figure 7 presents the theoretical service life T (in years) of concretes.

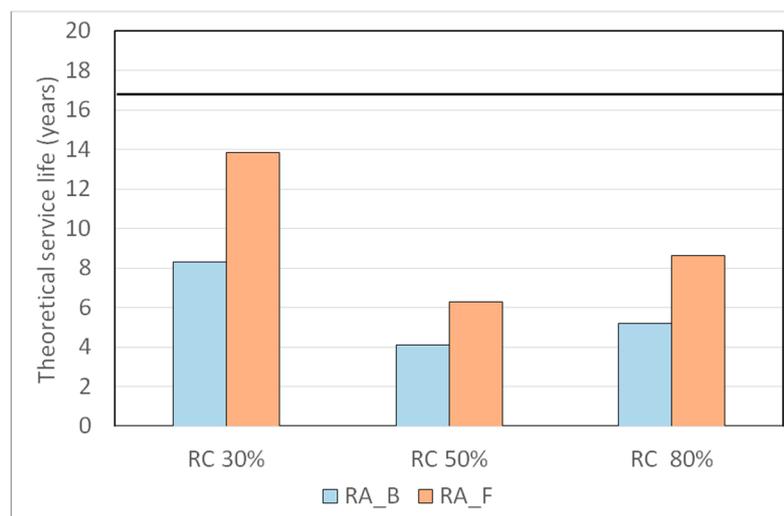


Figure 7. Theoretical service life of concretes. The horizontal black line represents the theoretical service life of NC.

The theoretical service life is not the actual service life of these concretes but is indicative for their chloride penetration resistance. The chloride penetration resistance of concrete with RA is lower than that of NC. When 30% of the aggregates were replaced by RA_F, a decrease of 20% in the theoretical service life was observed when compared to the control mix NC, decreasing up to 50% when 30%

of the aggregates were replaced by RA_B. The chloride penetration resistance of RC appears to be influenced by the parent concrete of RA. On average, the theoretical service life of RC with RA_F is 40% higher than that of RC with RA_B.

4.2.3. Freeze–Thaw Resistance of Concrete

Concrete elements frequently exposed to water, to high relative humidity (more than 75%), and to low environmental temperature ($-5\text{ }^{\circ}\text{C}$ or lower), can be subjected to deterioration caused by frost and thaw. This damage allows the penetration of aggressive external agents (such as sulphates and chlorides) and consequently the rebars corrosion is started. It consists mainly of micro- and macro-cracking of the cement matrix and also of spalling of the exposed surface [25,59,60]. In order to investigate this aspect, frost and thaw resistance tests were developed on the different concrete mixes, as shown in Table 4. The standard test procedure UNI CEN/TS 12390-9: 2017 [61] was adopted to assess the frost and thaw resistance of concrete in the presence of a sodium chloride solution. The test does not fully reproduce any possible real field condition, as that can be extremely variable and can be influenced by random parameters as the chemical composition of the environment surrounding the concrete. Indeed, real concretes can be exposed to different types of pollution, chemical aggression, and freezing and thawing cycles at the same moment. In addition, the porosity of the test specimens can be different from the porosity of real concrete elements that is influenced by the presence of reinforcing bars, different casting methods, etc. However, the test is useful to compare the behavior of different concrete mixes with and without RA in given conditions.

Four cubic specimens (150 mm side length), for each concrete mix, were packed and cured for 28 days under standard thermo-hygrometric conditions. From each cube, a prismatic specimen of size $150 \times 150 \times 50$ mm was obtained using a water-cooled diamond saw. A rubber coating was glued to each face of the specimen except for the test surface, which coincides with the sawdust surface. A silicone cord was applied around the entire perimeter of the test surface between the concrete and the rubber coating. The individual specimens were placed in polystyrene honeycomb plastic boxes to ensure thermal insulation on all surfaces except for the test surface, as shown in Figure 8.



Figure 8. Samples exposed to freeze–thaw cycles.

All 28 samples (4 specimens for 7 concretes mixes, as shown in Table 4) were placed in the freezing chamber and subjected to repeated freezing and thawing cycles. The temperature of the freezing liquid in one specimen was monitored continuously and Figure 9 shows the temperatures measured over a 24 h cycle of freezing and thawing for a representative sample.

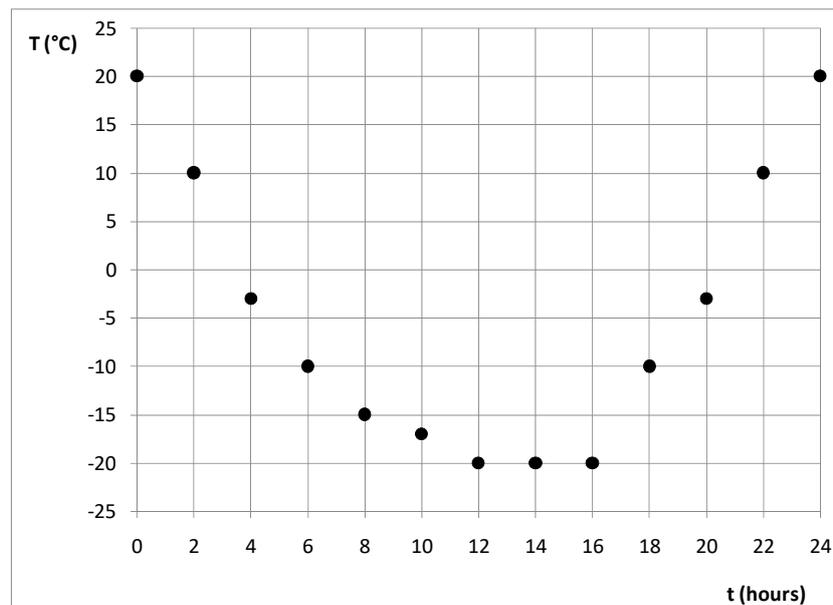


Figure 9. Temperature time history for a 24 h freezing and thawing cycle.

After 14, 28, 42, and 56 freezing and thawing cycles, the specimens were subjected to flaking. The flakes of material detached from the test surface were collected by rinsing and brushing. The collected material was subjected to 110 °C in an oven in order to be dried and then weighed.

Figure 10 shows the cumulative quantity of dried flakes per unit area (S_n) for the different concrete mixes. It is interesting to point out that the concretes with RA_B have the same qualitative and quantitative trend regardless of the percentage of recycled aggregates replacement percentage. The mass value of the cumulated flakes is always higher than the one of the NC for all the monitored freezing and thawing cycles. Instead the concrete with RA_F has a lower, or at most the same, cumulative flake mass values of the NC. Looking at Figure 10 there is no obvious link between the percentage of substitution and S_n .

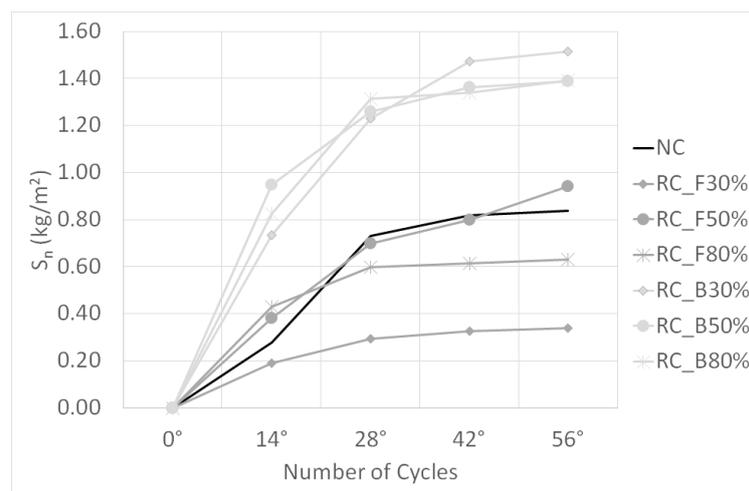


Figure 10. S_n versus number of freeze-thaw cycles.

After 56 freeze-thaw cycles, the cumulative quantity of dried material flakes per unit area of S_n (kg/m^2) and the average value of the four samples for each concrete mix was evaluated and reported in Table 7. It can be stated that the resistance to the frost-thawing cycle, measured using the S_n parameter, is higher in concrete with RA_B. However, the S_n value of the concrete RA_F is lower

or approximately equal to the value of the NC. The obtained results do not show any relationship between the replacement percentage of recycled aggregates and the resistance to frost and thaw.

Table 7. Cumulative quantity of flakes of dried material per unit area (S_n) after 56 cycles of frost and thaw.

Concrete	Sample	S_n (kg/m ²)	$S_{n, average}$ (kg/m ²)
RC_B30%	1	1.39	1.52
	2	0.76	
	3	1.71	
	4	2.20	
RC_B50%	1	1.97	1.39
	2	1.00	
	3	0.66	
	4	1.93	
RC_B80%	1	1.03	1.39
	2	2.60	
	3	0.79	
	4	1.16	
NC	1	1.12	0.88
	2	0.21	
	3	1.17	
	4	1.00	
RC_F30%	1	0.20	0.34
	2	0.21	
	3	0.63	
	4	0.31	
RC_F50%	1	0.97	0.94
	2	0.94	
	3	1.27	
	4	0.57	
RC_F80%	1	0.36	0.63
	2	0.70	
	3	0.86	
	4	0.60	

5. Discussion and Conclusions

In this paper, an experimental campaign has been developed in order to assess the mechanical and durability properties of concrete with recycled concrete aggregates. Two different parent concretes have been used to produce the recycled aggregates. In this way, it was possible to investigate what is the influence of the parent concrete on the performance of recycled concrete. RC_F and RC_B denote the concrete with recycled concrete aggregates respectively obtained from the foundation and the beam of the old Cagliari Stadium. The foundation concrete showed better mechanical performance in comparison to the beams one. The following conclusions can be drawn from the results:

- Recycled concrete produced with coarse recycled aggregates has shown similar mechanical performances to normal concrete produced with natural aggregate, even when the natural aggregates replacement percentage reaches 80%.
- The mechanical performance of recycled concrete is not related to the parent concrete mechanical characteristics.
- Concerning the durability, experimental results show that:
- The resistance to pressured water penetration is not reduced by the presence of recycled aggregates.

- The chloride penetration resistance of concrete with RA is lower than that of normal concrete (NC). In addition, it appears to be influenced by the parent concrete. Indeed, the theoretical service life of RC_F is 40% higher than that of RC_B, regardless of the percentage of recycled aggregate replacement.
- The resistance to the frost–thawing cycle is higher in concrete with RA_B. Instead the S_n value of the concrete with RA_F is lower or approximately equal to the value of the normal concrete NC. The results obtained do not show a relationship between the replacement percentage of recycled aggregates and the resistance to frost and thaw.

These results highlight the importance of the mix design that can allow the obtaining of structural concrete even with concrete demolition waste with different mechanical characteristics.

Recycled aggregates can represent an efficient way to lower the buildings' impact on the environment, improving their sustainability. At the same time, RA can create new opportunities for the companies that re-design their production workflow. For instance, the processing scraps of precast concrete elements should be used to create recycled aggregates, reducing losses and maximizing earnings with a beneficial effect on the environment.

Actually, the transportation costs of construction materials have a paramount relevance in the economic analysis. Thus, recycled aggregates can be very effective when the source of the parent concrete is near the location of the construction, as happens in the case of demolition and re-building, or in the case of retrofitting of existing structures and infrastructures (see [62,63]). Finally, it should be considered that if the environmental impact of the retrofitting intervention is taken into account (see [64,65]), the equivalent CO₂ cost is reduced by the use of RA. Furthermore, the combined use of RA and alternative bio-natural aggregate [66] and structures [67] represent an effective approach to lower the environmental impact of constructions.

Further developments of this work are expected considering whole structural elements like those presented in [68–71].

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