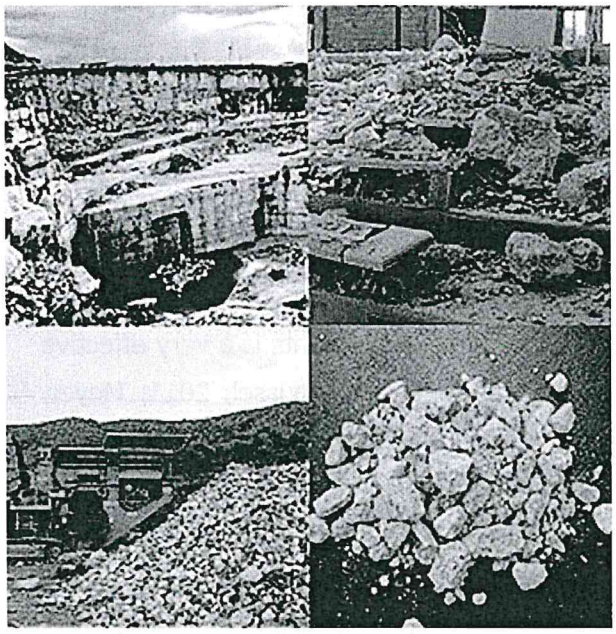

RECYCLED AGGREGATES

MECHANICAL PROPERTIES AND ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT

This paper highlights the possibility of using structural concrete debris, also with modest mechanical performances (Rck ≤ 20 MPa), in order to obtain coarse recycled concrete aggregates to produce new structural concrete with higher performances. A specific case study concerned the recycling of the debris deriving from the total demolition of Cagliari football stadium concrete structures, to obtain coarse aggregates to produce new concrete. The results of the study point out the possibility of organizing recycling plants of secondary raw materials to produce coarse recycled aggregates deriving from onlyconcrete, with the same size distribution of natural aggregates, without necessarily having additional performance information of the parent concrete. The alternative use of recycled aggregates in place of natural ones for concrete production aims to preserve natural resources and, in consequence, to reduce the extension of landfills.

KEYWORDS

Recycled Aggregates; Mechanical Properties; Recycling

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1 INTRODUCTION

It is well known that construction industries consume annually huge amount of aggregates, contributing to significant environmental losses. For this reason, the use of construction and demolition waste (C&DW) as alternative aggregate to produce new concrete limits the exploitation of natural resources and the extension of landfills.

Maximizing the amount of recycled materials among concrete components is a very effective and promising approach toward sustainable construction (Kovler & Roussel, 2011; Meyer, 2009; Rao et al., 2007). Available experimental data concerning concrete made with recycled concrete aggregate (RA) are highly variable and some authors (Padmini et al., 2009; Shi-cong Kou & Chi-sun Poon, 2015) claim that the quality of RA 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, a recycled concrete (RC) with low to medium compressive strength can be easily obtained irrespective of the specific quality of recycled aggregates (Ajdukiewicz & Kliszczewicz, 2002; Etxeberria et al., 2007; González-Fonteboa & Martínez-Abella, 2008; Rahal, 2007; Tabsh & Abdelfatah, 2009).

The physical properties of RA strongly depend on the adhered cement mortar quality and amount (Etxeberria et al., 2007; Sánchez de Juan & Alaejos Gutiérrez, 2009). In general, the quantity of adhered mortar increases with the decrease of the recycled aggregate size (Etxeberria et al., 2007; Sánchez de Juan & Alaejos Gutiérrez, 2009). The crushing procedure also has an influence on the amount of adhered mortar. Due to the adhered mortar, RA has a lower density and higher water absorption, compared to natural one. Moreover, the presence of potentially un-hydrated cement on the surface of RA can further affect the concrete properties (Katz, 2003).

This paper shows that is possible to obtain structural concrete of strength class C30/37, using coarse RA obtained by crushing structural concrete with low compressive strength (Rck $\leq$ 20 MPa).

In this study, RA derives from concrete structures (foundations and cantilever beams) of the old football stadium located in Cagliari (Sardinia, Italy, construction year 1968). Before demolishing these concrete structures, tests were carried out to evaluate the mechanical performance of concrete. Part of foundations and cantilever beams have been demolished and crushed separately, to obtain two types of coarse RA, both with size 4 - 16 mm.

RC mixes have been produced using three different replacement percentage (30%, 50% and 80%) of natural aggregates with RA. A total of six RC mixes were produced, using separately the two types of coarse RA. In comparison an additional mix of normal concrete (NC) with

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only natural aggregates (NA) was produced. Further tests were carried out in order to obtain a full description of physical and mechanical properties of new made concretes, RC and NC. The final goal of this work is to strengthen the concept of sustainability in civil constructions combining the use of coarse RA to produce structural concrete with a low environmental impact.

2 EXPERIMENTAL INVESTIGATION

2.1 QUALITY OF PARENT CONCRETE

In the first phase of the research, the integrity and mechanical behavior of Cagliari football stadium concrete were analyzed. In a near future, the stadium will be demolished and created a new stadium with a modern design. The concrete structures chosen for the preliminary analysis are the cantilever beams and the foundation blocks. A total of 12 cored specimens were collected from both the foundation and the beams, respectively named C. Found and C. Beam. A preliminary visual inspection performed on the cored specimens did not highlight any abnormalities. In Tab. 1 the mean values of the tests conducted on the cored specimens are reported.

	DEPTH OF CARBONATATION (mm)	DENSITY (kg/m^3)	COMPRESSIVE STRENGTH (MPa)	ELASTICITY MODULUS (MPa)	TENSILE STRENGTH (MPa)
C. Found	10	2314	27.9	25335.3	2.04
C. Beam	31	2270	21.0	18041.6	1.49

Tab. 1 Mechanical performances of parent concrete

The experimental data show that the beams and foundations were made with two types of concrete and differ by mechanical properties, carbonatation state and composition. The mechanical behavior and the carbonatation state of the foundation are better than that of the beam. Moreover, definite compositional differences between the two materials are confirmed from petrographic analyses on thin sections. Under the polarizing microscope, the conditions of the concrete in both samples appear overall good. The samples are characterized by the presence of several types of aggregates, embedded in a fine cement matrix, which may be distinguished both by mineralogical composition and by size distribution. Polarized light microscopy analysis performed on sample C. Found revealed, in the fine cement matrix, the presence of a coarse fraction entirely made of centimetric angular fragments of micritic (cryptocrystalline) limestone. This component contrasts with a very varied siliciclastic fine-grained (millimetric to sub-millimetric) fraction, made of granite and metamorphic rock

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fragments, with quartz and feldspar free crystals; all the fragments are sharp-edged. Analyses on sample C. Beam indicate a more homogeneous siliciclastic composition, with a millimetric-centimetric fraction prevalently made of angular fragments of granite rocks with various types of metamorphic rocks (quartzites to metavolcanics), and a fine-grained, sub-millimetric fraction consisting of the same materials associated to free crystals of quartz, feldspars and biotite.

2.2 RECYCLED AGGREGATES

Two types of RA have been produced, called respectively recycled aggregate found (RA_F), obtained from crushed foundation blocks, and recycled aggregate beam (RA_B), obtained from crushed cantilever beams, both with size 4-16 mm. The two types of RA were subjected to all the tests complying with UNI EN 12620: 2008 and UNI 8520-1: 2015. In Tab. 2 the results are shown and in Fig. 1 RA size distribution is reported.

The analysis carried out showed that RA, even if obtained by crushing two different concretes, have very similar characteristics. In Tab. 2 it can be observed that only four parameters (Shape Index, Percentage of fines, Content of acid-soluble sulfate, Content of water-soluble sulfates) out of twenty-one are slightly different.

2.2.1 RESIDUAL MORTAR CONTENT IN RECYCLED CONCRETE AGGREGATES

In RA the adhered cement mortar to the original natural aggregate particles (RMC) influence significantly physical properties, workability, mechanical performances and durability of RC (Otsuki et al., 2003; Pani et al., 2011; Pani et al., 2013; Pani et al., 2013; Sánchez de Juan & Alaejos Gutiérrez, 2009).

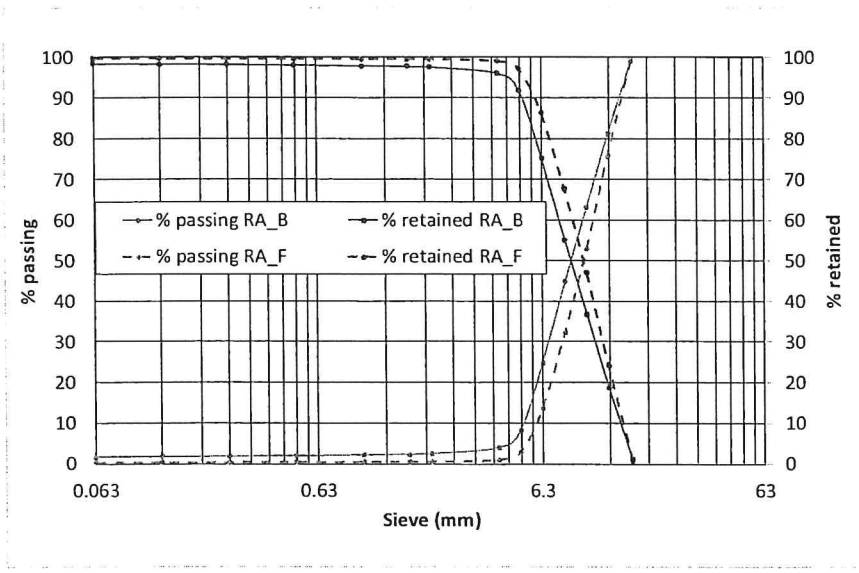

Fig. 1 Recycled aggregates size distribution

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Previous studies have attributed the reduction in compressive strength of RC (Tavakoli & Soroushian, 1996) and in modulus of elasticity (Salem & Burdette, 1998), compared to NC, to the presence of old mortar adhered.

The determination of the RMC is of critical importance to better understand/evaluate the properties of concrete incorporating RA. However, there is currently no standard method for the RMC determination.

The method used in this research, proposed by Abbas et al. in 2007, consists in submitting representative samples of the RA to daily cycles of freezing and thawing in a solution of sodium sulphate. The RMC obtained in RA_F and RA_B, divided into two fraction sizes (retained by 4 mm and 10 mm sieve), is shown in Tab. 3. The test shows that RMC is significantly similar for RA_F and RA_B.

PROPERTY	RA_F	RA_B
Size designation	4/16	4/16
Category grading	G_C 90/15, G_T 17.5	G_C 90/15, G_T 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	ρ_b = 1.23 Mg/m^3 v% = 45	ρ_b = 1.14 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 RCA	X = 0; R_c = 74%; R_u = 27%; R_b = 0; R_a = 0; R_g = 0	X = 0; R_c = 78%; R_u = 22%; R_b = 0; R_a =0; R_g = 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	WA_{24} = 7.0	WA_{24} = 6.7
Resistance to freezing and thawing	41%	42%
Resistance to magnesium sulphate	2.56%	0%
Presence of humus	absent	absent

Tab. 2 Recycled aggregate test results

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RESIDUAL MORTAR CONTENT IN %	RA_F	RA_B
Sieve Retained 4 mm	55.81%	49.67%
Sieve Retained 10 mm	45.82%	45.65%

Tab. 3 Residual mortar content

2.3 CONCRETE

CEM II/A-LL 42,5 R was used in all concrete mixes. Coarse natural and coarse recycled aggregates were used. Crushed natural granite was used as the natural aggregate. Two type of recycled aggregates (RA_F and RA_B) were used. Natural sand was used as the fine aggregate in all concrete mixes. A super plasticizer based on polycarboxylate was used in all the concrete mixtures. RC mixes were produced using different replacement percentages (30%, 50% and 80%) of coarse RA replacing coarse NA.A total of six RC mixes were produced, using separately the two types of coarse RA. In comparison an additional mix of NC with only NA was produced.

In Tab. 4 the proportions for each mix produced are shown. The mix of RC was designated to include type of coarse RA and aggregate replacement ratio. For example, the designation RC_F 30% represents a mix containing RA_F with replacement percentage 30% and RC_B 80% represents a mix containing RA_B with replacement percentage 80%.

	w/c RATIO	CEMENT (kg/m³)	WATER (l/m³)	FINE NA (kg/m³)	COARSE NA (kg/m³)	COARSE RA_F (kg/m³)	COARSE RA_B (kg/m³)	ADDITIVE (kg/m³)	DENSITY (kg/m³)
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

Tab. 4 Mix proportions of concretes

2.4 CONCRETE TESTS

The workability of the fresh concrete was measured using the standard slump test procedure. Test were performed soon after the mixing process was completed and then after 30 minutes. Values are shown in Fig. 2.Slump values of the RC mixes are very similar to NC. Compressive

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and splitting tensile strengths test wereperformedaccording to UNI EN 12390-3: 2009 and UNI EN 12390-6: 2010. The compressive strength test for each mix was determined at 14 and 28 days, while splitting tensile strength and modulus of elasticity were determined at 28 days.

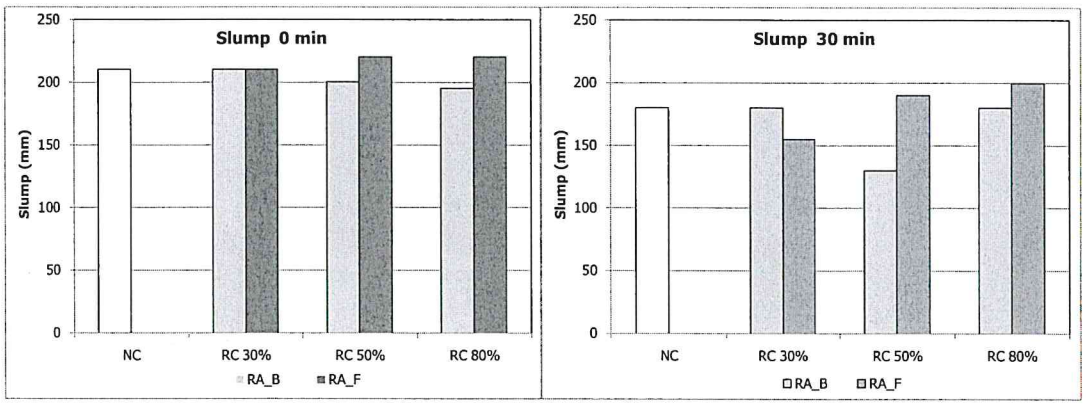

Fig. 2 Slump test immediately and 30 min after

The results of the average compressive strength at 14 and 28 days (Fig. 3) show optimal performance even when the percentage of coarse RA reaches 80%.

It should also be noted that the compressive strength of RC does not appear to be influenced by the parent concrete. Rather it results that, in some cases, the compressive strength of RC is higher than NC. Splitting tensile strength (Fig. 4) is greater or equal for all RC, compared to NC. This result was expected and can be explained by the greater roughness of RA, that produces an increase in tensile strength of concrete.

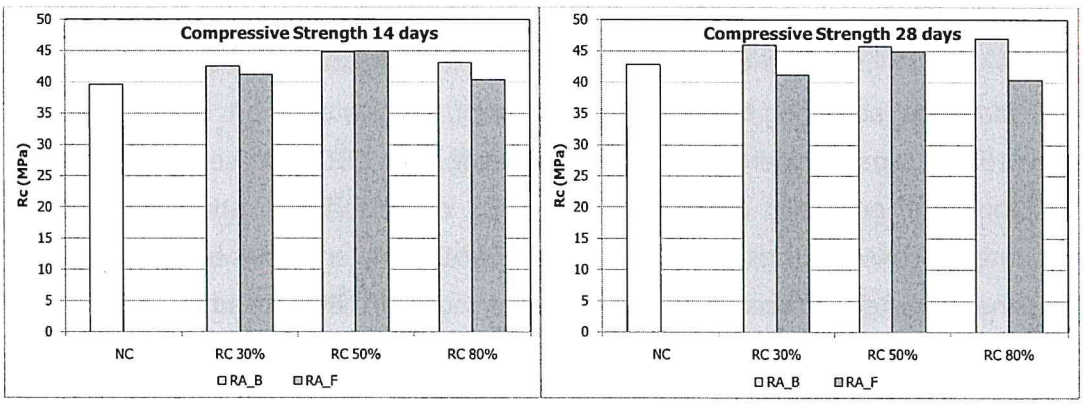

Fig. 3 Compressive strength of concrete at 14 and 28 days

The secant modulus of elasticity in compression (Fig. 5) appears slightly lower (limited to a maximum of 10%) for RC compared to NC. This result was expected and mainly due to the adherent mortar (Salem & Burdette, 1998). The durability tests on concrete are in progress.

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The first results obtained confirm the optimal performance of RC even when the replacement percentage reaches 80%.

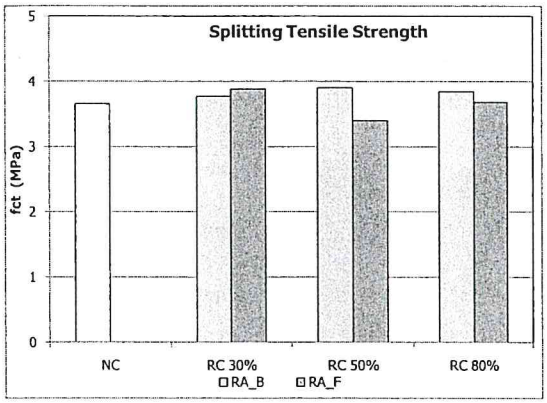

Fig. 4 Splitting tensile strength of concrete

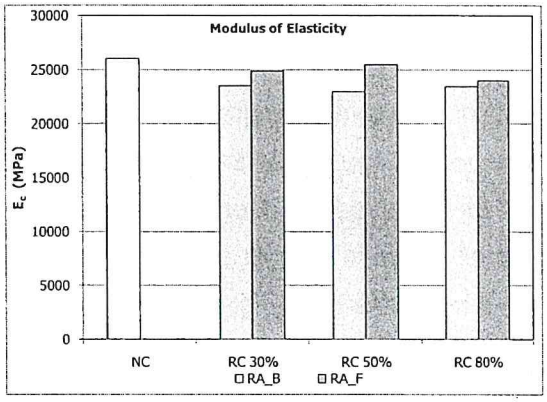

Fig. 5 Modulus of elasticity of concrete

3 ENVIRONMENTAL SUSTAINABILITY IN CIVIL CONSTRUCTIONS

C&DW materials, according to the Italian Legislation and stated in art.184 of the Legislative Decree 152/06, are considered part of special waste. The C&DW possess great potential for reuse, but are generally disposed in landfills, or abandoned abusively with serious environmental consequences. In Italy, the use of C&DW materials has been limited, after the processing of waste from secondary raw materials, loose fill material and for road foundations. In other European countries the resistive and profitable: they are in fact used for more nobleusessuchas structural concrete. The composition of C&DW is extremely variable depending by many factors: local building techniques, economic activity and technological development of the area, the type of raw materials locally available are factors that influence the composition of debris. The cost of waste disposal, although varying from area to area,

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depends strongly on the distance between the demolition site and the storage facility and is continuously increasing, given the progressive decrease in the number of landfills.
The recycling of the demolished material meets, therefore, both the needs of the operators in the sector, whose the possibility of inserting into the production process what was initially a waste, eliminating the cost of disposal, and the needs of the Public Administrations, facing the environmental issue. It is not possible to accurately identify the differences in price between RA and NA, normally the price of RA is about half of NA.
During demolition, generally, an undifferentiated stream of debris is produced, consisting of heterogeneous fractions, that make difficult any type of recovery operations and compromise a possible use for manufacturing concrete. In this perspective, the strategic role of waste mapping to allow maximum recovery of demolition materials (Baiani & Altamura, 2018) and a preliminary separation of the materials can be convenient, for a future re-use of waste. It would therefore be very useful to advise waste mapping and selective demolition techniques. The resulto the RC characteristics produced with RA (Francesconi et al., 2016; Stochino et al., 2017) must encourage recycling plants to offer different iated materials immediately marketable, concrete production plants to supply RC to guaranteed performance and the Public Administrations to draw up Specifications for both RA and RC.

4 CONCLUSIONS

The present research has highlighted that:

- recycled concrete produced with coarsere cycled aggregates has shown equivalent mechanical performances then those of normal concrete, evenwhen the natural aggregates replacement percentage reaches 80%.
- the performance of recycled concrete is not related to the parent concrete mechanical characteristics.
- the results evidenced that the care in the study of the design of the concrete mix is fundamental for competitive recycled concretes.
- the durability tests on recycled concrete are in progress; preliminary results show the optimal performance of recycled concrete even in the long term.
- waste mapping and selective demolition should be promoted and enforced wheneve rpossible. These are: 1) absolute necessities in order to obtain RA for its use in construction, and 2) good practices for environmental sustainability.
- following the results presented and the extensive international literature on the topic, Public Administrations must produce specifications that allow the use of recycled concretes.

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