Sustainable Concrete with Recycled Aggregates: experiences and perspective

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ABSTRACT: The recycling of concrete construction and demolition wastes to obtain coarse recycled aggregates for structural concrete production represents an interesting strategy fostering circular economy in the construction sector. In this work, the effects of parent concretes on coarse recycled aggregates and on new structural concretes produced with different replacement percentages of recycled aggregates have been investigated. The quality of parent concrete seems not directly related to the mechanical properties of the concrete prepared with recycled aggregates, while the mix design plays a key role. In addition, tests on concrete specimens (i.e. plinths) have been carried out to demonstrate the feasibility of structural elements with recycled aggregates concrete. In the manuscript we present an overview of these results, highlighting pros and cons of using concrete with recycled aggregates for future developments of the concrete construction market, also stressing the influence of climate change.

1 INTRODUCTION

Current concrete technology contributes to the exploitation of non-renewable natural resources. Recycling concrete demolition waste promotes a circular economy strategy and reduces the environmental impact. The use of recycled aggregates represents a valid alternative to natural ones for concrete production helping natural resources preservation and reducing landfill disposal (Kovler and Roussel, 2011; Pepe et al. 2014).

Indeed, the recycling of concrete construction and demolition wastes to obtain coarse recycled aggregates contribute to reduce raw material exploitation and, at the same time allows to create opportunities from the decommissioning of existing structures at the end of their service life. In life cycle cost analysis approach, deterioration induced by environmental conditions strongly influences the decision about the most suitable intervention: refurbishment or demolition and reconstruction. An interesting example of refurbishment of an existing Reinforced Concrete R.C. building can be found in (Sassu et al. 2017). In this case the full structural and thermal refurbishment was cheaper with respect to demolition and reconstruction intervention and was considered strategic by public administration. As climate change significantly affects the deterioration rate, its effects need to be duly considered in the analysis.

From the other side, when recycled concrete is used, great attention has been devoted the optimization of the new mix design and production process, to obtain homogeneous and consistent product chain. Several study as: Puppio et al. 2017, Puppio el al 2019, Cardinali, Tanganelli t al 2022 highlight that existing concrete structure also shows consistent problems due to material irregularities particularly for seismic actions.

In the last years, at University of Cagliari (Italy) a set of experimental studies have been developed on mechanical and durability properties of concretes casted with recycled aggregates obtained from different construction and demolition wastes, while at University

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of Pisa effects of climate change on constructions have been extensively studied, stressing their influence on the most relevant deterioration processes, like carbonation of concrete and steel reinforcement corrosion.
Recent studies demonstrate that there is no technical or scientific limit to the use of recycled concrete aggregate for structural and non-structural concretes (González-Fonteboa & Martínez-Abella 2008; Pani et al. 2020, Pepe et al. 2014, Sassu et al. 2016). Moreover, experimental data concerning concrete made with Recycled Concrete Aggregate (RCA) show that recycled concrete with medium compressive strength can be produced, regardless of the parent concrete quality (Pacheco 2019, Francesconi 2016, Longarini et al. 2016, Stochino et al.; 2017; Tabsh and Abdelfatah, 2009, Pani et al. 2020).
Recently, RCA have been used for full scale reinforced concrete elements (see Stochino et al. 2017, Xu et al. 2017, Xu et al. 2018, Xu et al. 2019).
In addition to the clear environmental benefits the use of RCA can bring economic advantages also to the precast concrete industry where scraps of processing waste can be transformed in RCA, reducing land-filling and raw materials costs.
In this work, starting from the results of an experimental campaign, the effects of parent concretes on coarse recycled aggregates and on new structural concretes produced with different replacement percentages of recycled aggregates are discussed. Concrete plinths have been realized with recycled aggregates to demonstrate the actual feasibility of such kind of structural elements, inferring that the mechanical properties of the concrete realized with recycled aggregates seem scarcely affected by the quality of parent concrete, while, on the contrary, the mix design plays a key role. In the manuscript we present an overview of these results, highlighting pros and cons of using concrete with recycled aggregates for future developments of the concrete construction market, also stressing the influence of climate change.

2 EFFECTS OF PARENT CONCRETE

2.1 Parent concrete

In the present investigations the parent concrete comes from concrete structures of the old Cagliari football stadium (built between 1965 and 1970). Recycled Concrete Aggregates are obtained from beams and foundation blocks.
A set of 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. The C. Found parent concrete shows higher mechanical characteristics than C. Beam.

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. Average	*10*	*2314*	*27.90*	*25335*	*2.05*
C. Beam. Average	*32*	*2270*	*21.00*	*18042*	*1.49*

The experimental data show that the beams and foundations belong to two different concrete classes, characterized by differing mechanical properties and composition. Moreover, significant compositional differences between the two materials are confirmed by petrographic analyses on thin sections. Under the polarizing microscope, the conditions of the concrete in both structural elements 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 analyses 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 sharp-edged rock fragments, with quartz and feldspar free crystals. 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.
The two types of RAs were subjected to all the tests complying with UNI EN 12620: 2008 and UNI 8520-1: 2015. The obtained results are summarized in Table 2.
The analysis carried out demonstrates that RAs, even if obtained by crushing two different concretes, have very similar characteristics. In fact, it can be observed from Table 2 that only four parameters (Shape Index, Percentage of fines, Content of acid-soluble sulfate, Content of water-soluble sulfates) are slightly different.

Table 2. Recycled aggregate characteristics.

Identification	RA_Foundation	RA_Beam
Size designation	*4/16*	*4/16*
Cat. 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	ρ_b*=1.23Mg/m^3* *v%=45*	ρ_b*=1.14Mg/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; 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	*SS = 0.148%*	*SS = 0.068%*
Water absorption	*WA24 = 7.0*	*WA24 = 6.7*

Since the adhered cement mortar to the original natural aggregate particles in RA significantly influences physical properties, workability and mechanical performances of recycled concrete, the determination of the Residual Mortar Content (RMC) in RA is a key point in understanding and evaluating the properties of recycled concrete. Unfortunately, there is currently no standard method for RMC determination. In the study, it has been adopted the method proposed by Abbas et al. in 2007, consisting in submitting representative samples of RA to daily freezing and thawing cycles in a solution of sodium sulphate. As shown in Table 3, the RMC in RA_F and RA_B samples, divided into two fraction sizes (retained by 4 mm and 10 mm sieve), are significantly similar.

Table 3. Residual mortar content (%)

Identification	RA_Found.	RA_Beams
4 mm sieve retained	*55.81%*	*49.67%*
10 mm sieve retained	*45.82%*	*45.65%*

2.2 Recycled concrete

Cement CEM II/A-LL 42,5 R, natural aggregates (NAs) and coarse RAs were used in concrete mixes adopted to prepare recycled concrete samples. Beside the above-mentioned types of recycled aggregates (RA_F and RA_B), crushed natural granite was adopted as NA, while natural sand was used as the fine aggregate in all concrete mixes. A superplasticizer based on polycarboxylate was utilized in all the concrete mixtures, see Table 4 for details. Figure 1 presents the average slump test value for each mix.

Table 4. Mix proportions of concretes per m^3.

Label	**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)**	**Addi-tive (kg/m^3)**	**Dens. (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

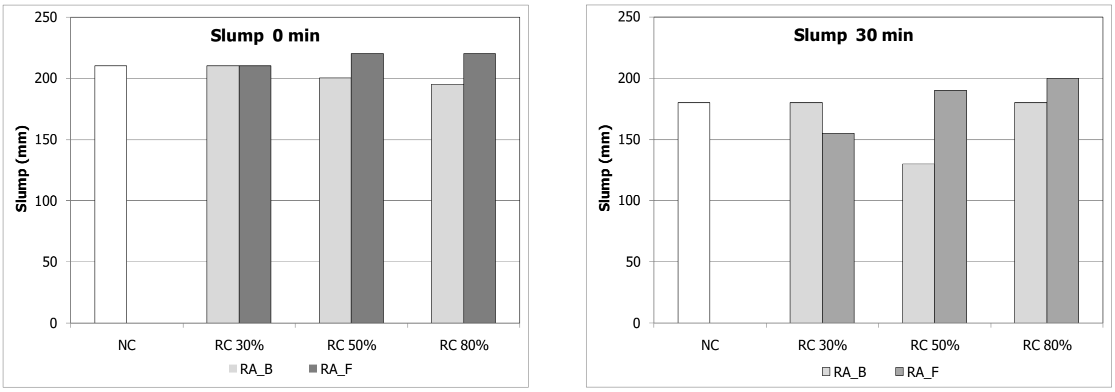

Figure 1. Slump test immediately (left) and 30 minutes (right) after casting.

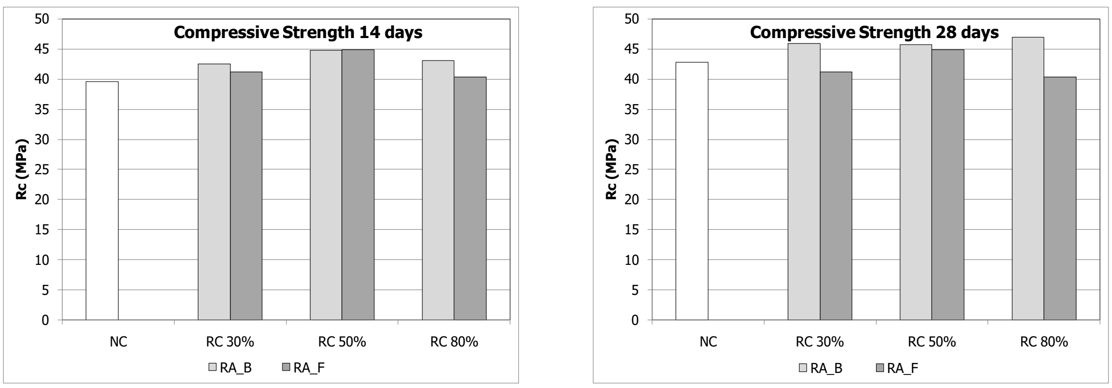

Figure 2. Average concrete compressive strength at 14 (left) and 28 days (right).

Compressive and splitting tensile strength and secant modulus of elasticity in compression tests were performed according to UNI EN 12390-3: 2019, UNI EN 12390-6: 2010 and UNI EN 12390-13: 2013, respectively. The compressive strength test for each mix was carried out at 14 and 28 days, while splitting tensile strength and modulus of elasticity were carried out at 28 days: results are summarized in Table 5. The values of compressive strength at 14 and 28 days (Figure 2) demonstrate that performances are satisfactory even when the percentage of coarse RA reaches 80%, the compressive strength of recycled concrete being scarcely influenced by the parent concrete quality.

Moreover, it can be remarked that, while in some cases recycled concretes exhibit higher compressive strengths than NC, as shown in Figure 3 (left), recycled concretes almost systematically display splitting tensile strengths not smaller than the corresponding NCs. This increase in concrete's tensile strength is not surprising and it can be explained by the greater roughness of RA.
The secant modulus of elasticity in compression (Figure 3 (right)) appears slightly lower, within a 10% difference, for recycled concrete compared to NC. This result was again largely expected, being mainly due to the adherent mortar (Salem & Burdette 1998).

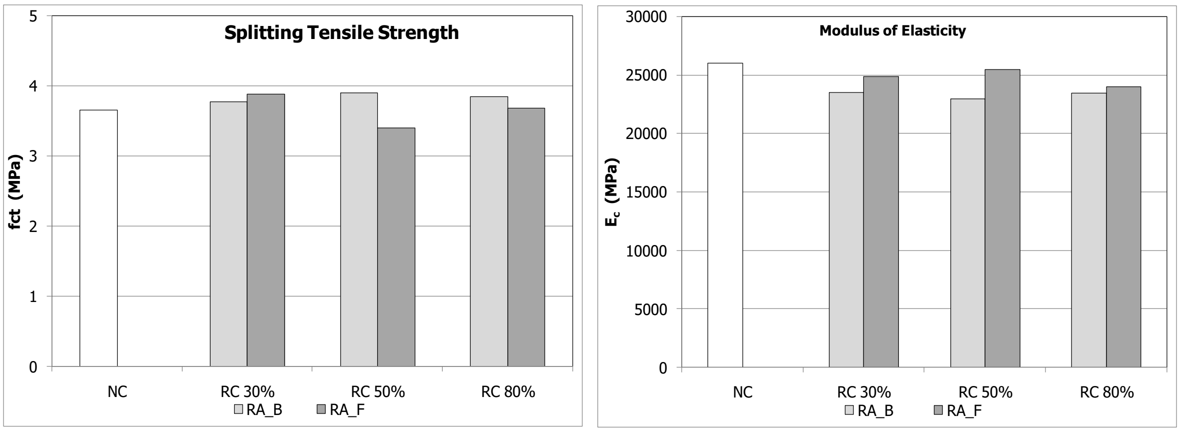

Figure 3. Concrete splitting tensile strength (left) and Elastic Modulus (right).

3 RECYCLED CONCRETE PLYNTHS

3.1 Materials and specimens

To study the application of recycled concrete in a real scale structural element the attention was focused on prefabricated recycled concrete plinths. Two recycled concrete mixes, characterized by 30% and 50% by weight of coarse recycled aggregates, respectively, were investigated. Results are compared to those obtained for a reference plinth cast with natural aggregates. The precast elements were manufactured by "Vibrocemento Srl", a precast concrete company, the geometrical details of the specimens and the reinforcement arrangements are illustrated in Figure 4; the specimen is shown in Figure 5.
The tests, aiming to evaluate the capacity and the collapse mechanism of the plinths, were carried out reproducing usual operational conditions. The load on the structure is applied on the top section of a precast reinforced concrete column connected to the plinth, according to the test setup.
The three different concrete mixes used for casting the plinths were labelled, depending on the percentage by weight of coarse natural aggregates, RC0%, RC30%, and RC50%, respectively: RC0% with 100% fine and coarse natural aggregates was the reference mix; RC30% with 100% fine natural aggregates, 70% natural and 30% recycled coarse aggregates; RC50% with 100% fine natural aggregates, 50% natural and 50% recycled coarse aggregates. Precast columns were made with a mix labelled RC0%. Table 5 presents the

characteristics of the aggregates, as well as the compressive strength ($R_{c,28d}$), the tensile strength (f_{ct},), and the elastic modulus E_c of the concretes.
B450C steel reinforcing bars (f_{yk}=450 MPa; f_{tk}=540 MPa) were adopted for all the tested elements.

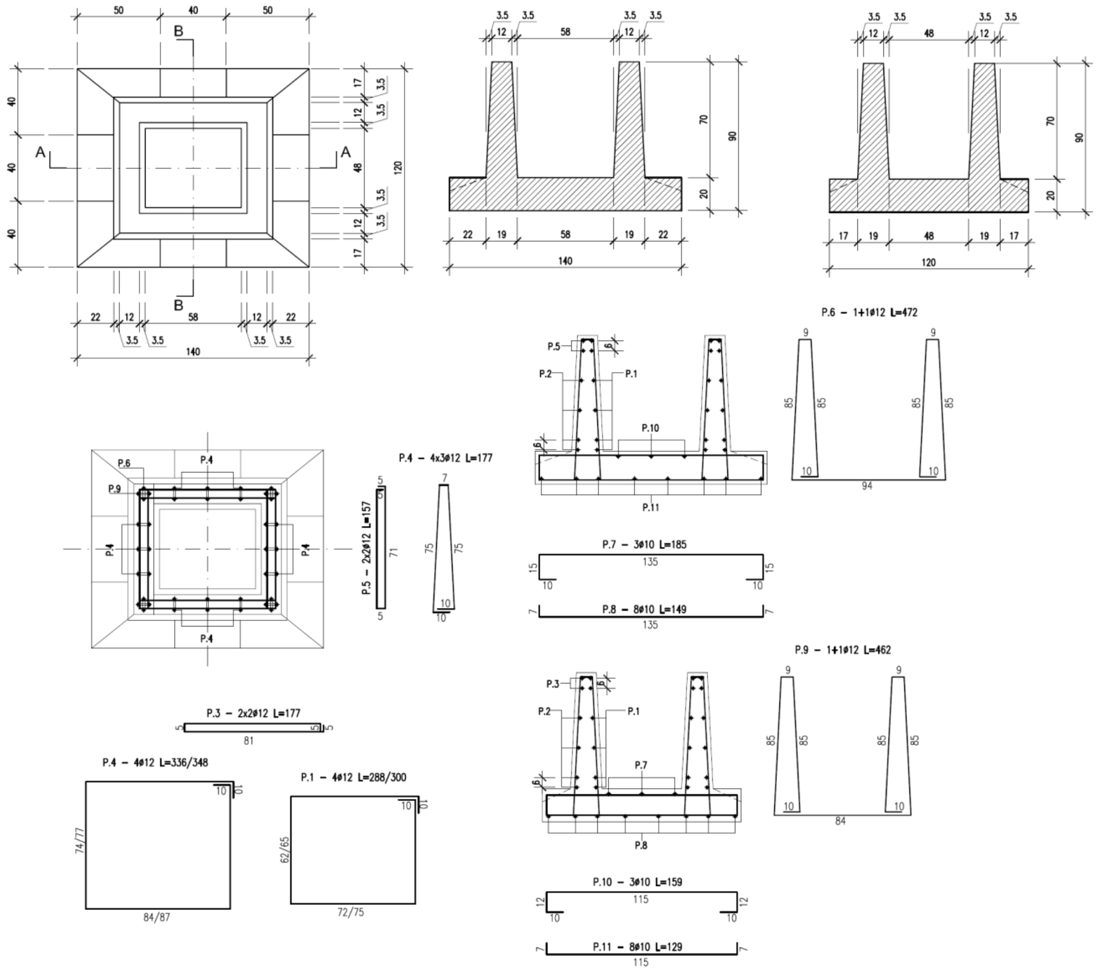

Figure 4. Plinth details and reinforcements distributions. Measures in cm.

Figure 5. Example of complete test specimen.

Table 5. Plinths' concrete mechanical characteristics

Concrete mix design	$R_{c,28d}$ (MPa)	$R_{c,28d\ average}$ (MPa)	f_{ct} (MPa)	$f_{ct,average}$ (MPa)	E_c (MPa)
RC0%	*37.5* *38.2* *37.9*	*37.87*	*3.55* *3.41* *3.35*	*3.44*	*28640*
RC30%	*37.1* *39.1* *38.1*	*38.10*	*3.53* *3.49* *3.43*	*3.48*	*28814*
RC50%	*37.8* *33.7* *33.4*	*34.97*	*3.30* *2.96* *3.13*	*3.13*	*24678*

3.2 Testing method

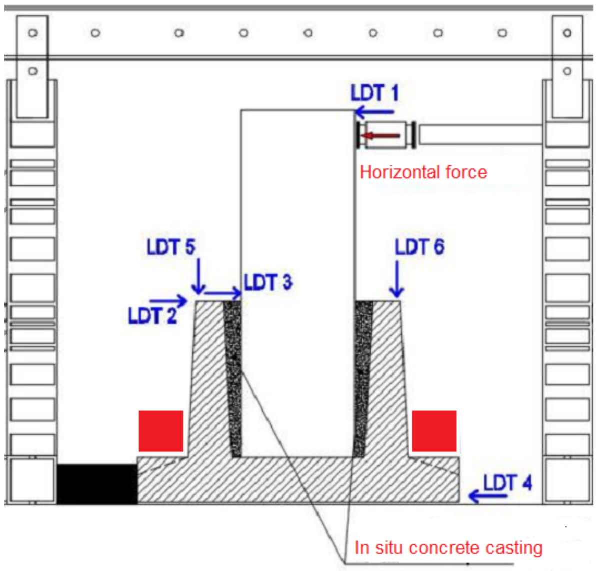

Figure 6. Test set up.

The experimental test arrangement is illustrated in Figure 6. A horizontal force, applied at the top of the RC column connected to the plinth, was suitably controlled, in order to achieve a constant displacement rate of 0.10 mm/sec, until the precast plinth-column system reached the collapse mechanism.
The loading system was able to apply a horizontal force up to 500 kN, with a maximum displacement at the top of the column equal to 200 mm.
To prevent the uplift of the plinth, a suitable constraint system was realized, consisting of two steel beams, indicated by the red squares in Figure 6. Displacements were measured by means of displacement transducers applied to the column and to the plinth, located in the positions pointed by the blue arrows in Figure 6.

3.3 Results

Referring to the horizontal displacement of the top column's section (displacement transducer LDT1 in Figure 6), the load – displacement diagrams for the three tested specimens have been obtained, as illustrated in Figure 7.
The highlighted dots in the load-displacement diagrams denote the first crack opening in the plinths. All tested specimens showed a similar behavior till the collapse, which is

characterized by the opening of a single crack at the base of the plinth (see Figure 8), so confirming that, as expected, this is the weak point of the tested elements. The collapse forces are summarized in Table 6.

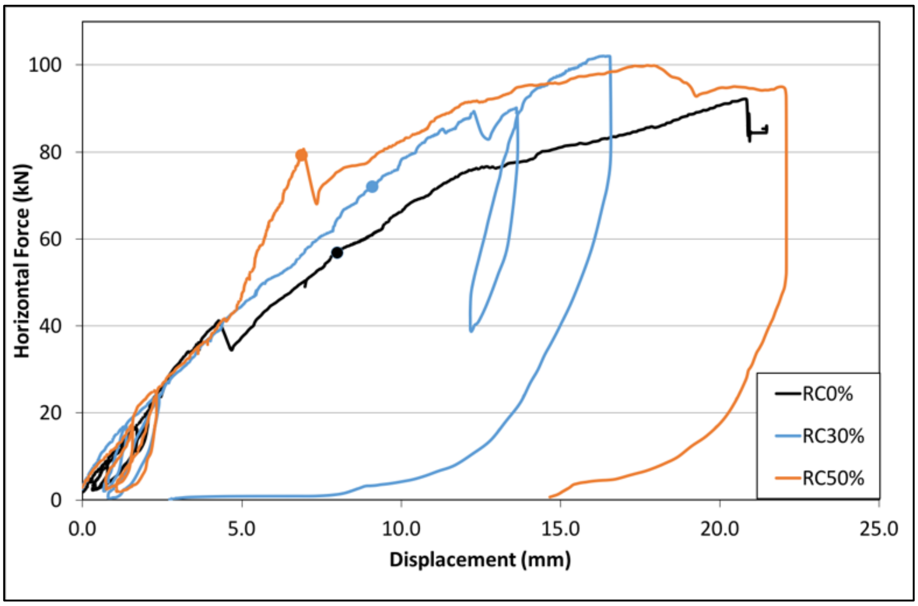

Figure 7. Load – Displacement curves.

Figure 8. Collapse mechanism for different mixes: left RC0%, center RC30%, right RC50%

Table 6. Capacity of each specimen

Specimen	Collapse Force (kN)
Plinth RC0%-Column RC0%	98
Plinth RC30%-Column RC0%	102
Plinth RC50%-Column RC0%	100

4 DISCUSSION AND CONCLUSIONS

In this paper, the mechanical properties of recycled concretes prepared with different parent concretes and the structural performances of precast recycled concrete plinths have been discussed, based on the results of ad-hoc experimental campaigns.
The experimental results show that the mechanical properties of recycled concrete are not affected by the mechanical characteristics of the parent concrete. In addition, it is possible to obtain satisfactory mechanical properties even when the percentage of replacement of

coarse RA in recycled concrete reaches 80%. Consequently, the presence of RA does not necessarily lead to a reduction in the performance, in comparison with reference concretes made with NAs. Of course, it cannot be disregarded that the concrete mix design plays a crucial role even in the presence of recycled aggregates.
Looking at the precast concrete plinths results shown in Section 3, it is clear that, despite the different concrete mixes (see Table 5), the structural performances of the tested specimens are very similar (Figure 7 and Table 6). Moreover, since the collapse load and the failure mechanism of different plinths are almost the same, even in case the plinth is cast with natural aggregates, it is possible to affirm that, in general, the use of recycled concrete is not detrimental for the mechanical behavior, and can even lead to higher performances in comparison with reference concrete cast with natural aggregates.
Actually, the use of this kind of concrete can also produce beneficial results for all the society reducing the building impact on the environment and creating new opportunities for the construction companies. For example, the processing scraps can be successfully used as recycled aggregates in the precasted production companies.
Finally, these materials can be very important also in case of the retrofitting of existing structures and infrastructures, see Stochino 2018a, b. In particular, when the environmental impact of the retrofitting intervention is taken into account (see Sassu 2017, Mistretta 2019) the use of recycled aggregates can reduce the equivalent CO_2 cost of that intervention. Further developments of this research are expected, also considering the durability properties of these materials.

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