Recycled Aggregate Concrete as Material for Reinforced Concrete Structures

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Processing crushing concrete into coarse aggregate for the manufacturing of new concrete is one common means for achieving more environmentally friendly concrete. The use of recycled aggregate from construction and demolition waste as replacement of natural aggregate has increased in recent years in order to reduce the high consumption of natural resources by civil engineering. In the research work an experimental investigation was carried out to analyze the influence of steel fiber reinforcement on the load-strain behavior of beams made of recycled aggregate concrete. In addition, the selected properties of recycled aggregate were assessed and the strength properties of concretes were also determined. The concretes tested contained natural fine aggregate and 100 % recycled coarse aggregate. The flexural behavior was tested on model reinforced concrete beams. Apart from reinforcing steel bars, the steel fibers with 6 mm length and aspect ratio of 37,5 were used in a volume fraction of 0,52 %. The results showed that the addition of steel fiber and recycled aggregate increased the mechanical strength and modified the flexural behavior and fracture process relative to that of recycled aggregate concrete.

Keywords: *recycled aggregate, reinforced concrete beam, steel fibre, waste management.*

1. Introduction

According to the concept of sustainable development, the environmental load of a building must be evaluated throughout its life cycle, from design to construction, maintenance or repair, demolition and rubble disposal (Van Loo 1998). Therefore, from a holistic point of view, sustainable construction means designing a reinforced concrete structure with appropriate durability during a specified service life. Among the possible solutions favoring greater environmental sustainability in the construction industry, material engineering is considering the use of recycled aggregates from building demolition to produce new concrete.

Decreasing natural resources of sand and gravel and increasing problems with waste management support the recycling of the accumulating waste materials. If the vision of a sustainable material flow is to be realized, the amount of recycled waste has to be increased. The building industry in particular is a major consumer of materials and, at the same time, a major producer of waste. One possibility is to recycle and reuse inorganic building waste as concrete aggregates (Marie and Quiasrawi, 2012; Chen *et al*., 2003). The use of waste from the demolition of concrete structures as aggregate in concrete has been widely studied and practiced for many years in developed countries (Corinaldesi and Moriconi, 2009). From the beginning, the main idea was the disposal of concrete waste in order to gain valuable raw material and thus the protection of natural aggregate sources according to sustainable development rules.

Over the last decades the significant number of experimental works has been carried out to investigate the material properties (Ajdukiewicz and Kliszczewicz, 2002; González-Fonteboa and Martínez-Abella, 2008; Cabral *et al*., 2010) and durability (Levy and Helene, 2004, Gokce *et al*., 2011; Lovato *et al*., 2012) of recycled aggregate concrete. Compared to natural aggregates, recycled aggregates usually have greater porosity and water absorption, lower density and lower strength than normal aggregate (Marinković *et al*., 2010, Hoffmann *et al*., 2012). As a result, RAC structural members invariably experience inferior physical and mechanical properties compared to normal aggregate concrete, such as low mechanical performance and poor durability behavior (Richardson *et al*., 2011, Kou and Poon 2012). For concrete made with 100 % recycled aggregate, the compressive strength reportedly decreased by 9–40 % (Tabsh and Abdelfatah, 2009). According to Casuccio *et al.* (2008) and Fathifazl *et al*. (2009) the lower elastic modulus of RAC is attributed to lower modulus of elasticity of recycled aggregate, and lower strength of RAC is mainly due to the weaker mortar as well as the weaker interfacial transition zone (ITZ) between the old mortar and new mortar.

Recycled aggregate concrete (RAC), which is used mainly for nonstructural purposes (aggregates in granular base or sub-base applications, for embankment construction and earth construction works), has the potential to be applied over a broad range of structural member types, based on the examples of structural behavior (behavior under flexural conditions, shear, bond, compression, etc.) presented by Xiao and Falkner (2007), Carneiro *et al*. (2014), Letelier Gonzalez and Moriconi (2014), Wang *et al*. (2013). However, still very few investigations have been performed in the field of structural behavior of RC members.

Available experimental data concerning the concrete made with recycled aggregate are highly variable since the quality of RAC mostly depends on the quality of original demolished concrete used for recycling (Ajdukiewicz and Kliszczewicz, 2002; Etxeberria *et al*., 2007). In addition to the fluctuation in the composition of recycled aggregates, the lack of knowledge concerning the structural behavior of members with RC is another factor limiting their use in construction. Although the use of construction and demolition waste as recycled aggregate in substitution of natural aggregate has been proved to be a good solution to minimize consumption of natural resources (Eguchi *et al.*, 2007; Breccolotti and Materazzi, 2010), the structural behavior of the recycled aggregate concrete is not yet fully understood and its use in structural applications is limited by European (DIN 4226-100, 2000) and Japanese (BCSJ 1977) standards.

Over the past several decades, steel fiber reinforced concrete has been used in many applications such as concrete pavements, overlays, patching repair of hydraulic structures, thin shells and precast products (Bentur and Mindess 1990). Nowadays, it is well established notion that the incorporation of steel fibers improves engineering performance of structural and nonstructural concrete, including better crack resistance, increase in ductility and toughness (Caneiro *et al*., 2014). There were the trials to combine the steel fibers with ordinary reinforcement in concrete members (Andriušis *et al*., 2013)

It is well known that the mechanical properties of steel fiber reinforced concrete depend on the aggregate type and matrix strength (Balendran *et al*., 2002). However, there is the lack of data regarding the mechanical behavior of steel fiber reinforced concrete with recycled aggregate.

The recent data in the literature (Eguchi *et al.*, 2007; Exteberria *et al.*, 2007; Xiao and Falkner, 2007) have shown that the use of relatively low amounts (up to 30 % of total amounts) of recycled aggregate does not substantially affect the concrete properties. Considering the effective utilization of waste materials for better environmental preservation, the searching of ways for the increase in recycled aggregate content in concrete is highly recommended.

The research programme concerned the concrete with the high content of recycled aggregate, it means that total volume of coarse aggregate was replaced by recycled aggregate. According to Chen *et al*. (2003) and Casuccio *et al*. (2008) the rough surface texture of recycled aggregate permits good mechanical interlocking between grains and cement matrix due to some penetration of cement paste into the open surface pores in the coarse aggregate particles.

The study discusses the experimental results for the behavior of concrete beams composed of recycled aggregate and steel fibre. The four-point bending test was conducted subsequently to investigate the flexural behavior of the model beams exposed to sustained load. The selected properties of recycled concrete and strength properties of concretes were also determined.

2. Methods

2.1. Materials

The commercial Portland cement CEM I 42.5 R according to EN-197-1 (2011) was used. Selected physical and chemical properties of cement are presented in table 1.

Tape water was used in all mixtures.

Fine quartz sand (0–2 mm) with density 2620 kg/m^3 was used as natural fine aggregate.

The construction and demolition waste, from reinforced concrete pre-caste elements, used in the experiment, were initially crushed using a jaw crusher. The pollutions and steel remains were removed. Then, the material was sieved to produce the recycled aggregates of two fractions: 2–4 mm and 4–8 mm, characterized by density 2410 kg/m^3 and 2475 kg/m^3, respectively. The aggregate used was processed in a laboratory.

The straight steel fibers (Dramix Hi Perform) in a volume fraction 0.52 % (40 kg/m^3) with 6 and 0.13 mm of length and diameter, respectively, were used.

In order to improve the steel fibers distribution in the concrete mix, the polycarboxylates based superplasticizer was used.

Table 1. *Physical and chemical properties of the Portland cement*

Property	**CEM I 42,5**	
Blaine surface (cm^2/g)	3800	
Initial set time (min)	160	
Final set time (min)	220	
Compressive strength (MPa)	2 days	28.0
	28 days	52.0
Chemical components (%)	SO_3	2.87
	Cl^-	0.08
Loss on ignition (%)	1.64	
Insoluble parts (%)	0.77	
Soundness (mm)	0.90	

2.2. Mix proportions and specimen preparation

The concretes tested contained 100 % natural fine aggregate (0–2 mm) and 100 % recycled coarse aggregate (2–8 mm). The maximum diameter of coarse aggregate was limited considering the sizes of model RC beams. Plain concrete (RAC) and steel fiber concrete (FRAC) were produced. The steel fibers were introduced into concrete mix replacing the part of coarse aggregate in volume (0.52 %). The content of steel fibers was determined considering the optimal content for reinforced concrete elements (Bentur and Mindess 1990). Both concretes were manufactured with the same water to cement ratio (*w/c*=0.50).

Table 2 presents the mix proportions and selected properties of fresh concrete. The density of fresh concrete was assessed according to EN 12350-6:2009 and the slump flow class was controlled according to EN 12350-5:2009.

Natural and recycled aggregates were used in surface-dried condition. For each type of aggregate, the total moisture content was determined immediately before the mixing procedure.

Table 2. *Mix proportions for concretes used and selected properties of fresh concretes*

Component/Property	RAC	FRAC
Cement (kg/m^3)	350	350
Water (kg/m^3)	175	175
Fine aggregate 0–2 mm (kg/m^3)	755	755
Coarse aggregate 2–4 mm (kg/m^3)	424	423
Coarse aggregate 4–8 mm (kg/m^3)	616	615
Steel fibers (kg/m^3)	–	40
Superplasticizer (kg/m^3)	2	6
Density (kg/m^3)	2280	2300
Flow class (-)	F3	F4

The concrete mixtures were produced using laboratory mechanical mixer. A two-stage mixing approach was used. The following sequence of mixing was applied: addition of the coarse aggregate, addition of 70 % water with superplasticizer, addition of cement and fine aggregate, addition of remaining water. When steel fibers were introduced, they were added with coarse aggregate. The mixing time of 10 min was used to guarantee the homogeneity of the concrete.

The cube specimens sized 150 × 150 × 150 mm for compressive strength, beam specimens sized 100 × 100 × 400 mm for flexural strength. Every series consisted of six replicates.

The model recycled concrete beams (80 × 120 × 1100 mm) were used to analyze the flexural behavior under sustained load. The beams had various reinforcement ratios equal 1 % (3 bars Ø6 mm), 1,5 % (2 bars Ø8 mm and 1 bar Ø6 mm) and 2 % (2 bars Ø8 mm and 1 bar Ø10 mm). The reinforcing bars of steel BSt 500s were used. Stirrups of 3 mm diameter were applied. All of the RC beam specimens were designed in accordance with EN 1992-1-1 (2004) and were ensured for flexural failure for testing. Three series of plain recycled aggregate concrete and three series of recycled aggregate concrete with steel fibers were tested. Every series consisted of three replicates.

All concrete specimens were cured in water at 20 ± 2 ^{o}C until the time of testing. One day before the proper test the specimens were air-cured in the laboratory environment.

2.3. Test methods

The experimental programme was divided into three phases: recycled aggregate testing, concrete properties testing and testing the flexural behavior of model concrete beams.

Aggregate properties tests included water absorption (EN 1097-6:2013), loose bulk density (EN 1097-3:2000) and aggregate particle shape (EN 12620:2013).

Concrete tests consisted of compressive strength $f_{c,cube}$ testing at 7, 14 and 28 days (EN 12390-3:2009 and EN 12390-4:2000) and flexural strength f_m determined in three point bend test at 7, 14 and 28 days (EN 12390-5:2009).

For flexural behavior analysis the simply supported specimens were investigated under four-point bend conditions using Universal Testing Machine. The net span length L (Fig. 1) was 1000 mm. The load was applied to the failure with displacement control at a rate of 0.05 mm/s. The automatic system for data acquisition was used to measure the deflection in the mid-span and the strain in the tensile reinforcement and compressive concrete.

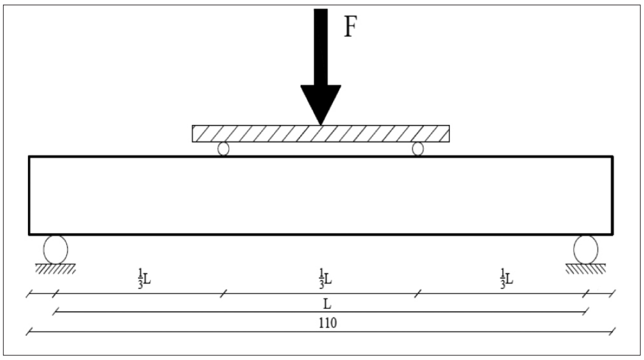

Fig. 1. *The way of load of RC specimen during test*

3. Results and discussion

3.1. Properties of recycled aggregate

The tests were performed on the coarse recycled aggregate.

The aggregate fraction 2–4 mm and 4–8 mm were characterized by loose bulk density 1280 kg/m^3 and 1340 kg/m^3, respectively. The loose bulk density of quartz sand was 1640 kg/m^3.

The water absorption of recycled aggregate (2–8 mm) after 2 hours was 9.27 % and after 24 hours – 11,05 %. The absorption of natural aggregate (0–2 mm) was 2.2 %. The texture of recycled aggregate is rougher due to the adhered mortar, thus it presents higher water absorption and lower density than natural aggregate.

The particle shape analysis showed relatively small part of irregular shape grains in coarse aggregate – 2 % of total mass. The recycled aggregate meets the standard requirements for aggregate used in concrete (EN 12620:2013). It is obvious that the recycled aggregate has similar particle shape as the crushed rocks used in normal concrete (Chen *et al*., 2003). The method of recycled aggregate production has a crucial influence on the proper particle shape.

3.2. Properties of hardened concrete

The strength properties development in time of recycled aggregate concrete with and without steel fibers were analyzed. Both concretes were classified to C35/45 strength class. The mean values of compressive strength

$f_{c,cube}$ as well as the standard deviation values δ_f are reported in Table 3.

Table 3. *Compressive strength development – mean values $f_{c,cube}$ and standard deviation δ_f*

Concrete type	**Compressive strength after n days (MPa)**					
	7 days		14 days		28 days	
	$f_{c,cube}$	δ_f	$f_{c,cube}$	δ_f	$f_{c,cube}$	δ_f
RAC	34.9	2.91	39,7	1.47	45.7	1.60
FRAC	35.8	1.53	41.8	1.82	47.6	2.81

The high surface roughness of recycled aggregate leads to a good bond between cement paste and aggregate and thus allows gaining the strength properties suitable for concrete structures. The addition of steel fibers slightly influenced the compressive strength. However, the presence of fibers had an effect on the failure mode of specimens made of concretes tested (Fig. 2). The concrete specimens with fibers kept their shape under destructive load.

Fig. 2. *Failure mode of specimens during compression: plain recycled aggregate concrete (left side), fiber reinforced recycled concrete (right side)*

The mean values of flexural strength f_m as well as the standard deviation values δ_f are reported in table 4. The flexural strength increased with increasing compressive strength. The significant difference in the relation between the compressive strength and flexural strength for RAC and FRAC was observed. The steel fibers improved the flexural strength of FRAC.

Table 4. *Flexural strength development – mean values f_m and standard deviation δ_f*

Concrete type	Flexural strength after *n* days (MPa)					
	7 days		14 days		28 days	
	f_m	δ_f	f_m	δ_f	f_m	δ_f
RAC	5.8	0.09	6.5	0.12	6.6	0.17
FRAC	5.5	0.08	6.3	0.08	7.4	0.14

Concerning the standard deviation values of strength properties, they were practically independent from the type of concrete, showing that the steel fibers had no influence on the homogeneity of concrete mixtures.

3.3. Flexural behavior of RC members made of recycled aggregate concrete

The model beams were tested in four-point bend test condition. Beam load, deflections, reinforcing bars strains and concrete strains were monitored. The mean values of deflection measured in the mid-span of the RAC and FRAC beams are presented in Fig. 3 and 4, respectively.

It is well known that the deflection depends on the longitudinal reinforcement ratio. However, the differences in load-deflection relationships, in considered range of reinforcement ratios, were greater for concrete with addition of steel fibers. The areas under the load-deflection curves for concrete members with fibers (FRAC) were significantly greater than for concrete members without fibers (RAC). Thus, the destruction of fiber reinforced beams required greater amount of energy. Similar results were obtained by Casuccio *et al*. (2008).

The model beams with steel fibers under maximum load did not destroy suddenly, but the process run smoothly. The destroyed members kept their shape. The quasi-plastic behavior was an effect of fibers interaction with cement matrix.

The fibers improved concrete members resistance to deformation. It was confirmed by the results of the maximum load measurement for particular beam series (table 5). Comparing the load bearing capacity of recycled aggregate concrete beams with and without steel fibers, it was found that the fibers had an effect on the dynamics of the capacity increase.

Table 5. *Maximum load values for concrete beams tested with different reinforcement ratio*

Concrete type	Maximum load (kN)		
	1 %	1,5 %	2 %
RAC	33.2 (100 %)	42.8 (129%)	53.0 (160%)
FRAC	33.1 (100 %)	44.9 (136 %)	57.2 (173 %)

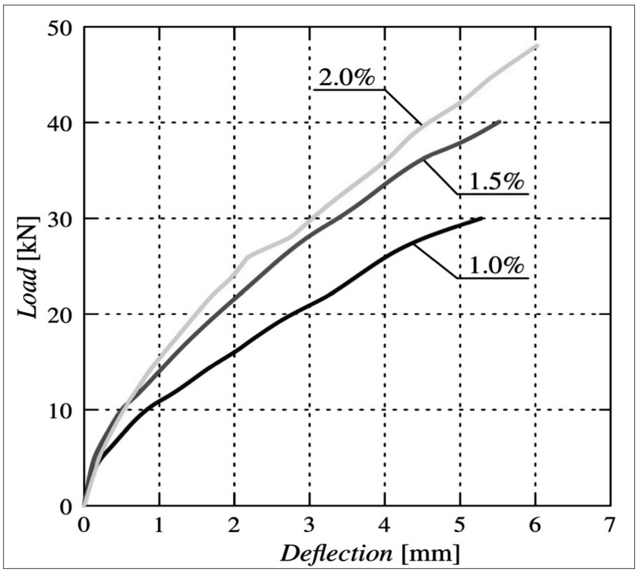

Fig. 3. *Load versus deflection in the mid-span for RAC model beams with various reinforcement ratios*

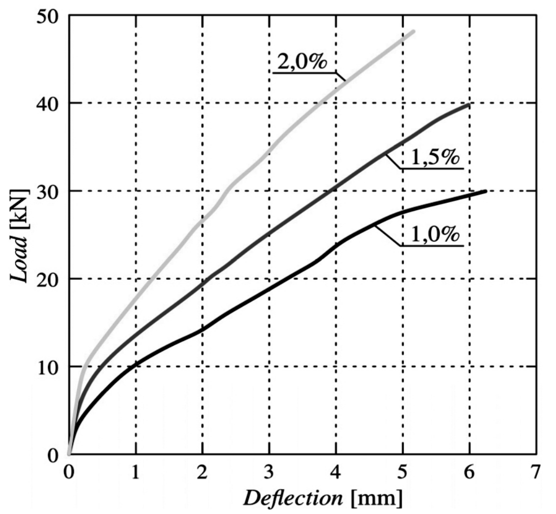

Fig. 4. Load versus deflection in the mid-span for FRAC model beams with various reinforcement ratios

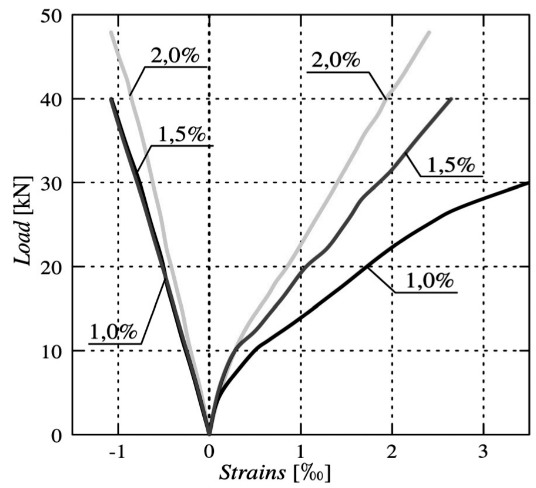

Fig. 6. Load-strain curves for FRAC model beams under flexural load

The load-strain curves obtained for RAC and FRAC members with various reinforcement ratios are presented in Fig. 5 and 6, respectively. Comparing the shape of the curves, it can be noted that although the constitutive relationships are not identical, they have a similar pattern at pre-peak zone.

The recycled aggregate may influence the failure mode of beam under flexure. In concrete with recycled aggregate the cracks can propagate both through the cement paste (interface zone) and through the aggregate due to the presence of grains with lower strength and stiffness. In these aggregates tensile stresses occurring at the tip of the grain and the high levels of tangential stresses that may occur in the matrix close to the interface and aggregate surface may affect the fracture process of the concrete. The strains in tensile zone decreased with the increase in reinforcement ratio.

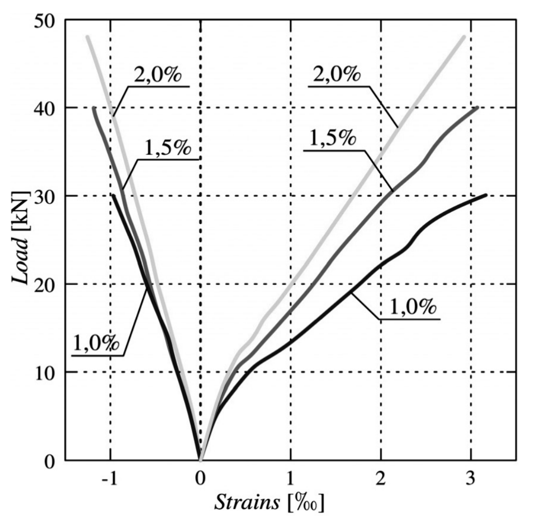

Fig. 5. Load-strain curves for RAC model beams under flexural load

The steel fibers had an effect on the limitation of deflection and the strains' values in both compressive and tensile zones of beams, making the concrete more ductile. The addition of steel fiber to recycled aggregate concrete improved its mechanical performance due to the greater resistance to sliding of pre-existing microcracks and by reduction of wing-cracks growth rate due to crack bridging. The presence of fiber had a positive effect to restore the level of crack initiation stress of concrete.

4. Conclusions

Both the mechanical properties of recycled concrete were studied and the physical properties of recycled coarse aggregate were studied. The flexural behavior was analyzed on model beams made of concrete containing recycled coarse aggregate.

The surface texture of the coarse recycled aggregate was more porous and rough when compared to natural aggregate. The density and specific gravity were lower and the water absorbability was higher in case of recycled aggregate due to low density and high absorption capacity of old mortar adhered to those. However, the rough surface of aggregate had beneficial effect on mechanical characteristics of concrete due to modification of fracture process.

The method used for recycled aggregate production, preparing of aggregate in wet conditions and proper way of recycled aggregate concrete curing lead to gaining the strength properties of concrete required for structural applications. The results showed that the medium strength structural concrete can be produced using 100 % recycled aggregate. RAC and FRAC showed similar trends in compressive as well as flexural strength development during 28 days of curing.

The addition of steel fibre (0.52 % by volume) increased the flexural strength of recycled aggregate concrete and had a beneficial effect on fracture process and flexural behaviour of model beams. No significant changes was observed in the compressive strength. The concrete members with fibres were characterized by greater resistance to deflection and strains in comparison to members of plain concrete. The fibre addition was particularly useful to control the post-crack regime of the load-strain curve of the recycled aggregate concrete.

The load bearing capacity of recycled aggregate concrete beams was related to reinforcement ratio, but the increase in the capacity was greater for concrete with steel fibers.

The test results reported in the paper are important and useful to understand the flexural behavior of recycled concrete beams. The research programme will be continued using different sizes of RC members and various load conditions, including long-term behavior of structural concrete as well as cyclic loading. The analysis of experimental results is essential in order to check the applicability of current design provision for recycled concrete beams.

Recycled aggregate is suitable for a wide range of concrete applications. However, its special properties have to be taken into consideration by the design of structures, concrete production, casting and curing in order to optimize performance. Recycled aggregate should be considered more extensively in standards in order to exploit its potential. This is an important prerequisite toward a sustainable material flow.

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