POSSIBLE APPLICATION OF RECYCLED CONCRETE AGGREGATE FOR PRODUCTION OF STEEL FIBER REINFORCED CONCRETE

Dimitrije Zakić[1],
Iva Despotović[2],
Aleksandar Radević[3],
Dijana Vrcelj[4]

Summary: Lack of good-quality natural aggregates well as the problem of removal and disposal of large quantities of demolished concrete waste, represent significant challenges in contemporary civil engineering. The testing results of properties of recycled concrete aggregate are presented in the first part of the paper. The second part deals with experimental research on properties of fresh and hardened concrete made with 50% substitution of coarse river aggregate by recycled concrete. Four series of concrete specimens were tested, two of which were made with addition of steel fibers. The research included testing of the following properties: density, compressive strength, splitting tensile strength, adhesion by pull-off method, static modulus of elasticity, as well as the impact resistance. The obtained results indicate that recycled concrete aggregate can be successfully applied for production of steel fiber reinforced concrete.

Keywords: Recycled concrete aggregate, steel fibers, fiber reinforced concrete, physical and mechanical properties

1. INTRODUCTION

Nowadays, natural aggregate (NA) represents a major part of cement based concrete and asphalt. Consequently, the global demand for construction aggregate is huge, its production exceeding 26 billion tons per year [1]. This situation inevitably leads to many problems, such as the deficit of good-quality natural aggregate, increased distance between the sources of natural aggregate and construction sites, as well as the problem of disposal of large quantities of demolished concrete waste. A possible solution for the aforementioned problems could be recycling of construction and demolition (C&D) waste materials, primarily concrete.

---

[1] PhD, Assistant professor, University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, dimmy@imk.grf.bg.ac.rs
[2] PhD, professor, College of Applied Studies in Civil Engineering and Geodesy, Hajduk Stankova 2, Belgrade, ivickad@gmail.com
[3] MScCe, University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, aradevic@grf.bg.ac.rs
[4] MScCe, Velestroj montaz, vrceljdijana@gmail.com

Recycled concrete aggregate (RCA), obtained by crushing of original concrete, consists of natural aggregate grains and cement mortar matrix. Typically, RCA is used for production of cementitious concrete, road pavement construction and soil stabilization [2,3]. The presence of old adhered cement mortar usually leads to decreased quality of RCA in comparison to NA. This means higher porosity, lower strength, higher water absorption and lower density [4,5], as well as a higher Los Angeles (LA) coefficient and fine particles content [6].

The paper presents the results of research on the effect of coarse recycled aggregate, used as a partial substitute for natural aggregate, on the properties of hardened concrete, combined with the addition of steel fibers. Different authors have been investigating the influence of coarse RCA on physical and mechanical properties of steel fiber reinforced concrete (SFRC) and there is a general consensus that the optimum results can be reached by 30 to 50% substitution of NA with RCA [7,8,9]. As a rule, the addition of fiber reinforcement has less influence on the improvement of the mechanical properties of concrete (tensile strength, flexural strength, shear strength), but it more contributes to increasing ductility of the composite and its resistance to dynamic effects (cyclic fatigue and impact load) [10].

2. RECYCLED CONCRETE AGGREGATE

The RCA used in the experiment was obtained by crushing a relatively high-quality original concrete, which had a compressive strength class C35/45 (according to EN 206-1:2011). For more than three decades this concrete served as a base structure for tram tracks, where it was not subjected to any harmful environmental conditions. Hence, the RCA grains were exceptionally compact and homogeneous, consisting of original cementitious concrete (98%), asphalt (1.2%) and brick debris (0.8%).

After the crushing process, the RCA was classified into standard fractions: 0/4 mm, 4/8 mm, 8/16mm and 16/32 mm, according to EN 933-1:2012. Considering the fact that the majority of relevant studies do not recommend the application of fine RCA (0/4 mm) for concrete production, this component was not used in the research [1,11,12]. In comparison to the fine NA, the RCA has significantly larger specific surface, which requires an increased amount of water. The biggest fraction of RCA (16/32 mm) was also excluded from the research. Namely, it is estimated that more than 80% of contemporary concrete production in Serbia is based on a 16 mm maximum aggregate size. The main physical and mechanical properties of coarse RCA (fractions 4/8 mm and 8/16 mm) are presented in Table 1.

Table 1: Physical and mechanical properties of RCA

		RCA	
		4/8 mm	8/16 mm
ρ_a	(kg/m^3)	2618	2699
ρ_{ssd}	(kg/m^3)	2499	2530
ρ_{rd}	(kg/m^3)	2426	2431
WA	(%)	3.0	4.1
LA	(%)	31.5	

In Table 1, the following symbols are used:

ρ_a (kg/m^3)   –   apparent particle density,

ρ_{ssd} (kg/m^3)   –   saturated and surface-dried particle density,

ρ_{rd} (kg/m^3)   –   oven-dried particle density,

WA   (%)   –   water absorption,

LA   (%)   –   Los Angeles coefficient,

Particle size distribution of all fractions of NA and RCA used in the research are shown in Figure 1.
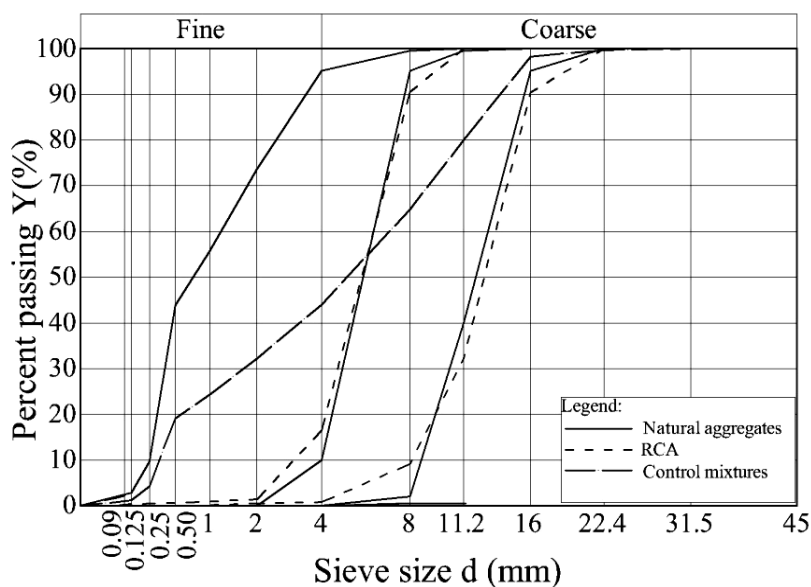

Figure 1. Particle size distribution of NA and RCA

3. EXPERIMENTAL

For the purposes of experimental research, four concrete mixtures were made.
Mixture A – control concrete with three-fraction (0/4mm, 4/8mm, and 8/16mm) natural-river aggregate
Mixture B – made with 50% substitution of NA of the II and III fraction by RCA.
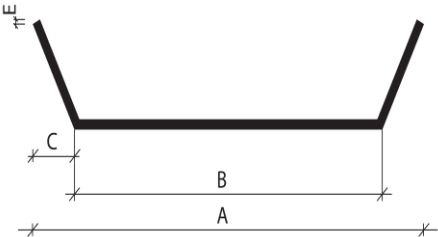Mixture C – with three-fraction NA in which steel fibers were added.
Mixture D – where NA was replaced by RCA with the addition of steel fibers, i.e. 50% of NA of the II and III fraction was replaced by RCA, with the addition of steel fibers in the same amount as in the case of mixture C.

Besides natural and recycled aggregate, concrete mixtures were made of cement type PC 20M(S-L) 42.5R (manufacturer "Lafarge", Beočin), 16 mm long hooked-end steel fibers

with the diameter of 0.4 mm and aspect ratio L/d=40 (manufacturer IRI, Ljubljana, Slovenia), superplasticizer Sika Viscocrete Techno 205 and water from the municipal water supply. The same amount of fibers was added to each mixture (C and D) – 30 kg/m^3 (~ 0.4 % of the fresh concrete total volume).

The appearance and properties of the used steel fibers are shown in Table 2.

Table 2: The appearance and properties of steel fibers

Parameters	Declared properties	
Type and appearance	Steel, hooked-end	
Cross section	Round	
Tensile strength	min. 1100 MPa	
Melting point	app. 1500˚C	
Bending angle	min. 45˚	
Total length (A)	16±2 mm	
Diameter (E)	0,4±0,1 mm	
Length of the straight section (B)	13±1 mm	
Length of the bent section (C)	1,5±0,5 mm	

The adopted composition of concrete mixtures is shown in Table 3.

Table 3: Composition of concrete mixtures

	A (kg/m^3)	B (kg/m^3)	C (kg/m^3)	D (kg/m^3)
Cement	380.0	380.0	380.0	380.0
NA 0/4mm	395.7	768.6	768.6	768.6
NA 4/8mm	595.7	197.8	395.7	197.8
NA 8/16mm	768.6	197.8	595.7	197.8
RCA 4/8mm	/	297.9	/	297.9
RCA 8/16mm	/	297.9	/	297.9
Water	195.3	195.3	195.3	195.3
Admixture	/	0.6	0.6	0.6
Steel fibers	/	/	30	30
Fresh concrete density	2310.2	2313.6	2340	2327.2

3.1. TEST RESULTS

Compressive strength testing

The shape and dimensions of the specimens, used for the determination of compressive strength, were checked in accordance with the provisions of the standard SRPS EN 12390-1:2008. Thereby, making and curing of specimens taken from the fresh concrete, were conducted in accordance with the standard SRPS EN 12390-2:2010. Immediately prior to the compressive strength tests (at 28 days of age), in order to determine the density of the hardened concrete, the dimensions and weight of specimens were measured, in accordance with the standard SRPS EN 12390-7:2010. Results of the test ranged within the limits of 2287 to 2321 kg/m^3 indicating that neither partial substitution of natural coarse aggregate by recycled aggregate, nor added steel fiber reinforcement, significantly affected the change of the concrete density. Compressive strength testing was performed after 3, 7 and 28 days, in accordance with the standard SRPS EN 12390-3:2010. The results of this testing are shown in Table 4.

Table 4: Compressive strength testing after 3, 7, and 28 days

Concrete mixture	Compressive strength of concrete after 3 days f_p (MPa)	Compressive strength of concrete after 7 days f_p (MPa)	Compressive strength of concrete after 28 days f_p (MPa)
A	28.2	40.1	47.1
B	29.9	41.6	49.3
C	29.3	41.5	51.4
D	29.2	41.1	51.1

Splitting tensile strength testing

Splitting tensile strength testing (or the so-called "Brazilian test"), was performed on the cylindrical specimens aged 28 days, in accordance with the standard SRPS EN 12390-6:2008. At Figure 2, the comparison between test results obtained by splitting the concrete specimens of various compositions (f_{zc}) is presented.
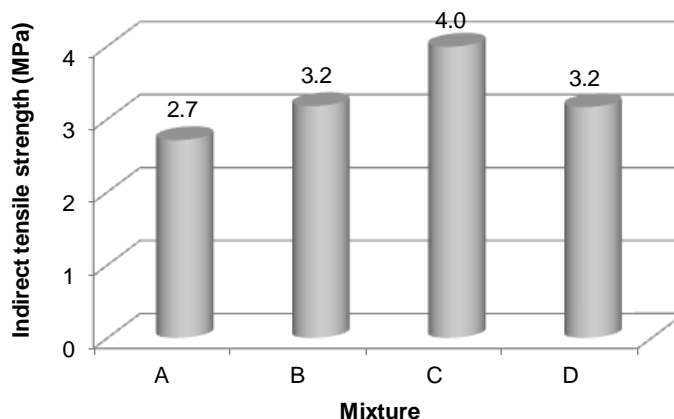

Figure 2. Splitting tensile strength after 28 days

Adhesion testing by *Pull - off* method

4. Pull-off test is the standard method (SRPS EN 1542:2010), intended primarily for testing in situ, but also for laboratory testing of concrete tensile strength, i.e. adhesion of various materials to the concrete base (e.g. cement screeds**,** repair mortars, carbon strips**,** epoxy and other protective systems, etc). In the research, this test was done in order to determine whether the adhesion between the cement paste and aggregate grains decreases if RCA is used instead of coarse natural river aggregate. Also, the impact of the addition of steel fibers on mechanical properties of concrete was analyzed. A set of concrete specimens, before and after the Pull-off test, is shown in Figure 3.

Figure 3. Specimens before and after the Pull-off test

Table 5: Results of the adhesion testing after 3 and 28 days

Concrete mixture	Adhesion after 3 days f_z (MPa)	Adhesion after 28 days f_z (MPa)	Type of failure
A	2.16	3.39	concrete failure
B	2.51	2.96	concrete failure
C	2.42	3.12	concrete failure
D	2.82	3.22	concrete failure

Static modulus of elasticity testing

Static modulus of elasticity is defined as the rate between stress ($\Delta\sigma$) and elastic deformation (ε). It was obtained by testing cylindrical specimens exposed to pressure, in accordance with the standard ASTM C469/C469M. The results of this test are shown in Table 6.

Table 6: Results of the static modulus of elasticity determination after 3 and 28 days

Concrete mixture	Static modulus of elasticity after 3 days E (GPa)	Static modulus of elasticity after 28 days E (GPa)
A	25.8	34.4
B	25.6	34.7
C	30.1	38.7
D	26.8	40.8

Impact resistance testing

In the research, the *Drop-weight* method was adopted for testing the impact resistance of concrete. In this specific case, it meant that the weight of 5kg was allowed to fall through the plastic graduated tube, from a height of 20cm, onto a concrete slab with dimensions 40x40x6 cm. Thereby, the total amount of energy used, was determined on the basis of the number of impact blows needed to form the first crack (E_1), i.e. the number of blows that caused the concrete failure (E_2).The results of this test are shown in Table 7, and the appearance of the specimen after testing in Figure 4.

Table 7: Results of impact resistance testing at the age of 28 days

Concrete mixture	Energy needed for forming the first crack E_1 (J)	Energy needed for the concrete failure E_2 (J)
A	49.1	68.7
B	49.1	68.7
C	58.9	88.3
D	68.7	88.3

Figure 4. Concrete slab specimen after impact resistance testing

4. CONCLUSIONS

The results shown in Table 4 show that there was no significant change in the value of compressive strength (at the age of 3 and 7 days) due to the partial substitution of the natural aggregate by recycled aggregate, or due to the addition of fibers. However, at the age of 28 days, SFRC had about 9% higher strength compared to the control mixture.

Based on the results of splitting tensile test (Figure 2), it can be concluded that the partial substitution of natural coarse aggregate by RCA, led to an increase in the splitting tensile strength, in the amount of 18%, while the addition of steel fiber reinforcement affected this increase to be 48%, compared to the control mixture.

The results presented in Table 5 show that there was no significant decrease in the value of adhesion (obtained by *Pull-off* method) on concrete specimens made with RCA, i.e. that the adhesion between the cement paste and RCA is approximately equal to the adhesion between the cement paste and NA.

The results presented in Table 6 show that, at 28 days, there was no significant change in the static modulus of elasticity, due to the partial replacement of coarse NA by RCA. On the other hand, in the case of mixtures made with the addition of steel fibers (C and D), there was an increase of the module of about 11% and 19%, respectively.

Based on the results shown in Table 7, it can be concluded that the addition of steel fibers affected the improvement of concrete impact resistance, in average of about 30% compared to the control mixture. At the same time, the partial replacement of coarse natural aggregate by recycled aggregate, did not lead to any change of this property.

In general, the research results indicate that recycled concrete aggregate can be successfully applied for production of steel fiber reinforced concrete.

REFERENCES

[1] Panduragan, K., Dayanithy, A., Om Prakash, S.: Influence of treatment methods on the bond strength of recycled aggregate concrete. *Construction and Building Materials,* **2016.**, vol.120, p.p. 212–221.

[2] Oikonomou, N.D.: Recycled concrete aggregates. *Cement and Concrete Composites,***2005.**, vol. 27(2), p.p. 315-318.

[3] Radević, A., Zakić, D., Mladenović, G., Đureković A.: Effects of recycled concrete aggregate on stiffness and rutting resistance of asphalt concrete. *Construction and Building Materials,* **2017.**, vol. 136, p.p. 386–393.

[4] Tam, V.W.,Tam, C.M., Le, K.N.: Removal of cement mortar remains from recycled aggregate concrete using pre-soaking approaches*. Resources, Conservation and Recycling,***2007.**, vol. 50 (1) p.p. 82–101.

[5] Lee, C.H., Du, J.C., Shen, D.H.: Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt. *Construction and Building Materials,* **2012.**, vol.28 (1), p.p. 66–71.

[6] McNeil, K., Kang, T.H.: Recycled concrete aggregates: A review. *International Journal of Concrete Structures and Materials,***2013.**, vol. 7(1), p.p. 61-69.

[7] Gao, D., Zhgang,L., Nokken, M.: Compressive behavior of steel fiber reinforced recycled coarse aggregate concrete designed with equivalent cubic compressive strength. *Construction and Building Materials,***2017.**, vol. 141, p.p.235-244.

[8] Moallemi, P., Alam, S.: Investigation of Compressive Bond Behavior of Steel Rebar Embedded in Concrete With Partial Recycled Aggregate Replacement. *Structures,***2016.**, vol. 7, p.p.153-164.

[9] Carneiro, J.A., Lima, P.R.L., Leite, M.B., Toledo Filho, R.D.: Compressive stress–strain behavior of **steel fiber** reinforced-**recycled aggregate concrete.** Cement and *Concrete* Composites, **2014.**, vol. 46, p.p. 65-72.

[10] Zakić, D.: Istraživanje parametara duktilnosti i udarne otpornosti sitnozrnih betona mikroarmiranih sintetičkim vlaknima, Doktorska disertacija, Građevinski fakultet Univerziteta u Beogradu, **2010**.

[11] Katz, A.: Treatments for the improvement of recycled aggregate. *Journal of Materials in Civil Engineering,* **2004.**, vol. 16(6),p.p. 597-603.

[12] Tam, V.W.V., Gao, X.F., Tam, C.M.: Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement and Concrete Research,***2005.**, vol. 35(6), p.p.1195-1203.

МОГУЋНОСТ ПРИМЕНЕ АГРЕГАТА ОД РЕЦИКЛИРАНОГ БЕТОНА КОД КОМПОЗИТА МИКРОАРМИРАНИХ ЧЕЛИЧНИМ ВЛАКНИМА

Резиме: Недостатак природног агрегата задовољавајућег квалитета, као и проблем одлагања све већих количина бетонског грађевинског отпада, представљају значајне изазове у савременом грађевинарству. У првом делу рада приказни су резултати испитивања карактеристика агрегата добијеног од рециклираног бетона. Други део рада посвећен је експерименталним испитивањима својстава свежег и очврслог бетона, код кога је 50% крупног речног агрегата замењено агрегатом од рециклираног бетона. Испитане су четири серије бетона, од којих су две биле справљене са додатком челичне микроарматуре. Предметна испитивања обухватила су одређивање: запреминске масе у очврслом стању, чврстоће при притиску, чврстоће при затезању цепањем, атхезије ("Pull-off" методом), статичког модула еластичности, као и отпорности на дејство удара. Добијени резултати показују да се агрегат од рециклираног бетона може успешно применити за справљање композита микроармираних челичним влакнима.

Кључне речи: Агрегат од рециклираног бетона, челична влакна, микроармирани бетон, физичко-механичка својства