CARACTERISTICI MECANICE ALE BETOANELOR AUTO – COMPACTANTE PREPARATE CU AGREGATE GROSIERE OBȚINUTE PRIN RECICLAREA ELEMENTELOR DE BETON PREFABRICAT

MECHANICAL CHARACTERISTICS OF SELF-COMPACTING CONCRETE MADE WITH COARSE AGGREGATE OBTAINED FROM CONCRETE PREFABRICATED ELEMENTS RECYCLING

BOJAN MILOŠEVIĆ[1], ŽARKO PETROVIĆ[2*], MARINA MIJALKOVIĆ[2], SLOBODAN RANKOVIĆ[2]

[1]*University of Belgrade, College of Applied Studies in Civil Engineering and Geodesy, 11000 Belgrade, H. Stankova 2, Serbia*

[2]*University Of Niš, Niš, Faculty of Civil Engineering and Architecture, 18000 Niš, A. Medvedeva 14, Serbia*

Self-compacting concrete (SCC) is intensively used in civil engineering due to its excellent characteristics both in fresh and in hardened state. In the several recent years, there is a growing need for testing of recycled aggregate use for making of concrete, which protects the environment and solves the problem of construction rubble disposal sites. The goal of this paper is to test the potential of usage of coarse recycled aggregate, obtained by crushing of concrete elements mechanically damaged in the production process of prefabrication elements, for making of SCC. Three concrete mixes were prepared for the experiment: the mixture made with the river aggregate as a reference mixture, the mixture where the coarsest fraction of the river aggregate was replaced by the recycled aggregate and the mixture in which both coarse fractions of the river aggregate were replaced by the recycled aggregate. In making of these concrete mixes, the principle of equal consistency of mixtures was followed. The mechanical characteristics determined for all the mixtures were: compressive strength, splitting tensile strength and modulus of elasticity. The obtained results indicate that the properties of these concretes exhibit minimal differences, and the application of the recycled aggregate obtained by crushing of prefabricated elements mechanically damaged in production process is justifiable for making of SCC.

Keywords: *Self compacting concrete, recycling aggregate, compressive strength, tensile splitting strength, tangent and secant elasticity modulus*

1. Introduction

In the last three decades since the self-compacting concrete (SCC) was invented (Japan 1980), a steady increase in its application is observable, with the development and research being particularly intensified in the recent years [1-3]. The term SCC refers to a high-performance concrete, which does not require additional vibrating in the placement process. It is capable of filling in the entire formwork under its own weight and attains high level of compaction, even in the presence of densely arranged reinforcement, at the same time retaining its consistency without any segregation and bleeding [4-7].

A lot of research related to SCC was based on its fresh-state properties [8-13]. The key properties of fresh SCC are: the flow capacity and viscosity, that is, capacity of fresh concrete mass to freely pass among the densely arranged reinforcement bars, as well as resistance to segregation. These characteristics are achieved by adding of superplasticizer usually with an admixture for additional modification of viscosity and/or certain amount of a mineral powder additions. The correct choice of the aggregate has a significant impact on SCC characteristics, both in fresh and hardened state, which is the topic of numerous researches [14-16]. Hardened SCC is dense, homogenous and almost has all the mechanical properties as a traditionally vibrated concrete [17-21].

In the last years, due to the environmental protection and sustainable development requirements becoming stricter and broader, a large number of researches worldwide have been conducted to investigate the potential for application of recycled construction rubble as the aggregate for concrete making [22-26]. The need to use the recycled construction rubble as aggregate is a consequence of the growth of disposal costs on one hand, and the lack of natural aggregate (especially river one), on the other hand, including the growing of the concerns about the natural environment. The qualities and potential of recycled aggregate application are defined and determined

* Autor corespondent/*Corresponding author*,Žarko Petrović
E-mail: zarko@gaf.ni.ac.rs

by the type and quality of construction rubble from which it was obtained. In this sense, by recycling the concrete from prefabricated elements, which were manufactured under the rigorous (controlled) conditions, should provide a higher quality raw material (aggregate), of uniform quality for production of concrete. Prior to using of the aggregate obtained in this way, it is necessary to test its quality and determine some of its characteristics, which will be a part of the research presented in this paper.

The potential of the recycled aggregate application was firstly tested for conventionally vibrated concretes [22-24] and in the recent years for SCC. The use of coarse recycled aggregate for making of SCC is presented in [25]; the research refers to the characteristics of this concrete in fresh state. Potential for application of both coarse and fine recycled aggregate for SCC is presented in the paper [26]. In all of these researches, the concrete obtained by demolishing of old structures was used for making of recycled aggregate.

The goal of the research presented here is the research concerning the potential for application of coarse recycled aggregate obtained by crushing construction rubble created from concrete prefabricated elements. On the occasion of designing the concrete mixture, one of the goals is that the viscosity characteristics of concrete made with the recycled aggregate correspond to those of the concretes made with the natural (river) aggregate. The mechanical characteristics of SCC in the hardened state were in this research tested for: compressive strength, tensile strength and modulus of elasticity. The obtained values of mechanical characteristics in the hardened state of concrete were compared to those defined by the regulations EC2 and ACI [27, 28], and to the recommendations based on the researches conducted so far [17, 29-31].

2. Experimental research

2.1. Applied materials

All the concrete mixtures tested within the experimental research were made using CEM I 42.5 R cement, manufactured by HOLCIM, whose characteristics are presented in Table 1.

Table 1

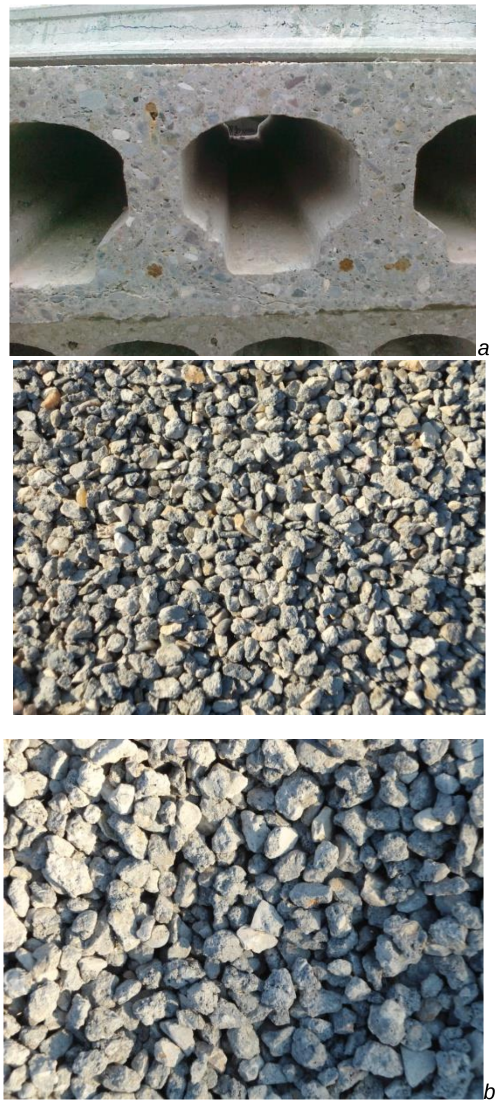
Physical-mechanical characteristics of cement

Setting time, min	Start 176, end 226
Density	3.13 g/cm^3
Bulk density in loose state	930 kg/m^3
Bulk density in compacted state	1515 kg/m^3
Tensile strength at 2 days	6.98 N/mm^2
Tensile strength at 28 days	9.30 N/mm^2
Compressive strength at 2 days	31.33 N/mm^2
Compressive strength at 28 days	55.15 N/mm^2

Table 2

Particle size composition of recycled aggregate

Percentage passing {%}	4-8 mm (recycled aggregate)	8-16 mm (recycled aggregate)
Bottom	0	0
0.125	0.24	0.20
0.25	0.29	0.26
0.5	0.32	0.29
1	0.36	0.32
2	0.44	0.35
4	1.63	0.74
8	99.77	39.45
11.2	100	88.86
16	100	100
22.4	100	100
31.5	100	100



a

b

Fig 1 - Appearance of prefabricated slab (a) and of the recycled aggregate, fractions 4-8 and 8-16 (b).

The rock flour which was used in the experiment as fine aggregate, was obtained by grounding of the limestone having specific mass 2,692 g/cm^3 and the standard deviation of cavity share according to Rigden of 25.4% (suppliers data).

The used recycled aggregate was obtained by crushing of mechanically damaged slabs prefabricated by extruding of the pre-stressed concrete - Figure 1 (a). The floor slabs are constructed from semi-dry concretes of the C50/60 class, having the following composition: total aggregate - 1740 kg/m^3 consisting of river aggregate 0-4 mm(46%), 4-8 mm(32%), crushed stone aggregate 8-16 (22%), cement - 450 kg/m^3 and water cement ratio 0,39.

For making of the concrete mixtures, the following fractions of the river aggregate were used 0-4, 4-8 and 8-16 mm, as well as the fractions 4-8 and 8-16 mm of recycled aggregate. The data of particle size composition of the recycled aggregate are presented in Table 2.

For good quality mix design with the recycled aggregate, it is necessary to know the amount of water absorbed by the recycled aggregate, since it is always higher in comparison with the same fraction of the river aggregate. The higher water absorption is a consequence of the presence of residual cement stone on the grains of recycled aggregate. The characteristics of the used recycled aggregate, such as: bulk density in loose and compacted state as well as water absorption are presented in Table 3.

Table 3

Characteristics of recycled aggregate

Aggregate fraction [mm]	Bulk density in loose state [kg/m^3]	Bulk density in compacted state [kg/m^3]	Water absorption [%]
4-8	1196	1306	4.13
8-16	1215	1300	4.08

The additive MC Power Flow 1102 was used in the experiment. This is a supper-plasticizer in accordance with EN 934-2 and in chemical terms,a modified polycarboxylate. Additive dosage was 0.5 % in relation to the mass of powdery components (cement and rock flour).

2.2 Mix designing

Three concrete mixes were prepared for the experiment:

1. the reference mixture was made with the river aggregate and it is marked as NAC (normal aggregate concrete);
2. the mixture where the coarsest fraction (8-16 mm) of the river aggregate was replaced by the recycled aggregate and it is marked as RAC 50 (recycled aggregate concrete in which 50% of the coarse fractions of the river aggregate were replaced by the recycled aggregate);
3. the mixture in which both coarse fractions (4-8 mm and 8-16 mm) of the river aggregate were replaced by the recycled aggregate and it is marked as RAC 100 (recycled aggregate concrete in which all of the coarse fractions of the river aggregate (100%) were replaced by the recycled aggregate).

In making of these concrete mixes, the principle of equal consistency of mixtures was followed.

For making of concrete mixtures, particle size distribution was performed based on SRPS U. M1.057:1984, which defines standard particle size distribution curves, A, B, C and D. These particle size distribution curves are recommended by the European Committee for Concrete. Particle size distribution of the aggregate used for making the reference NAC, RAC 50 and RAC 100 concretes, is presented in Figure 2. The quantity of other components of concrete was in all mixes unchanged, with the exception of small variations in the water quantity for the purpose of achieving an equal consistency and because of somewhat higher water absorption by the recycled aggregate. The composition of designed mixes is presented in Table 4.

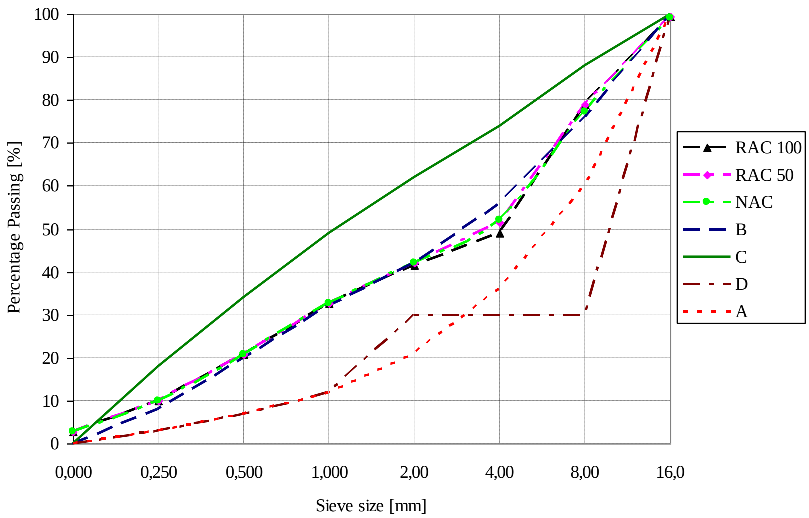


Fig. 2- Particle size distribution of aggregates.

Table 4

Concretes composition

Component (kg/m^3)	NAC concrete	RAC 50 concrete	RAC 100 concrete
limestone filler	100	100	100
cement	430.0	430.0	430.0
NA fraction 0-4 mm	807.5	807.5	807.5
NA fr. 4-8 mm	380	380	/
RA fr. 4-8 mm	/	/	380
NA fr. 8-16 mm	553.0	/	/
RA fr. 8-16 mm	/	553.0	553.0
Water	210	215	219.3
MC Power Flow 1102 additive	2.2	2.2	2.2

2.3 Testing methods

Experimental determination of SCC characteristics was conducted in two stages: (1) testing of fresh concretes characteristics and (2) testing of mechanical characteristics of hardened SCC.

One of the primary methods used for testing of SCC in fresh state is *Slump-flow test*, EN 206-9:2010 [7] which includes the determination of fresh concrete consistency and checking of the first of three key properties of SCC - workability. After lifting of loaded and previously moistened metal cone, the time required for the concrete to form a circle having diameter of 500 mm (time t_{500}), was measured, as well as the diameter of spreading of fresh concrete mass. The recommendations EFNARC [5] and regulations EN 206-9:2010 [7] require a diameter of 550 mm for spreading of fresh SCC concrete mass and the largest permissible diameter is 850 mm. Lower time t_{500} indicates a better flow capacity. In the engineering practice recommended time is 3 to 7 seconds.

The hardened concrete was tested for compressive strength as well as for tensile splitting strength and the tangent and secant modulus of elasticity were also determined.

Compressive strength tests for all the concrete mixtures were conducted on the 150x150 mm cubes. After casting, the samples were cured in water at 20°C, and the reading was performed after 2, 7, 14 and 28 days, in agreement with EN 206-1. Tensile splitting strength was tested on the cylinders with Φ=150 mm and h=300mm, after 28 days of hardening, in agreement with EN 12390-6. Tangent and secant modulus of elasticity were conducted in agreement with the standard EN 1992-1-1:2004 [26].

3. Results and discussions

3.1. Fresh concrete testing results

The results obtained by fresh concrete testing are presented in Table 5:

Table 5

The test results obtained on fresh concrete

Concrete type	Density, [kg/m^3]	Slump-flow test, D[cm]	t_{500}, [s]	ω_c (water cement) ratio
NAC	2305	60.5	4.8	0.49
RAC 50	2293	60.0	5.0	0.50
RAC 100	2268	60.2	5.0	0.51

By comparing the densities of the reference sample (NAC) and that of the samples with recycled aggregate (RAC 50 and RAC 100) (Fig.3) it can be observed that density diminishes for RAC 50 and RAC 100 samples in comparison with the reference NAC sample - with 15 kg/m^3 and 37 kg/m^3 respectively, i.e. 0.5 % and 1.6 %.

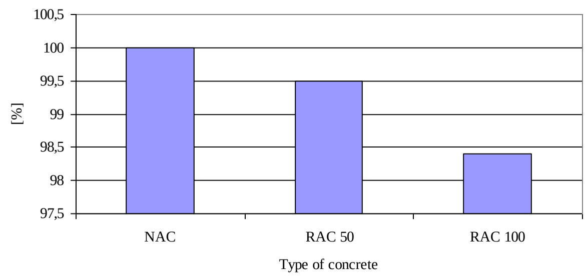


Fig. 3 - Density reduction of RAC 50 and RAC 100 in respect to NAC sample – fresh concretes

For testing of fresh concrete workability, *Slump-flow test* EN 12350-8 [7] was used. The test results showed that the diameter of spreading of the mixture RAC 50 and RAC 100 is lower than the reference mixture (NAC) with 0.5 cm and 0.3 cm, respectively. Based on the recommendations defined in EFNARC [5] and EN 206-9:2010 [7] the designed mixtures are classified as SF1.

As it is known, during the *Slump-flow test* by visual observation and/or measuring time (t_{500}) necessary for the concrete mass to achieve the diameter of 500 mm, the mixture viscosity is checked, and information of its resistance to segregation is obtained (Fig. 4). Based on the time of NAC mix spreading, and those of RAC 50 and RAC 100 samples, it is concluded that these concretes belong to the class VS2. No water separation was observed during the experiment.

-a-

- b -

Fig. 4 - Slump-flow test of the reference concrete (NAC) – a and of RAC 100 – b.

3.2. Hardened concrete testing results

The results obtained by testing of the compressive strength on cubes after 2, 7, 14 and 28 days are presented in Figure 5 and the results obtained by testing of the compressive strength on cylinder after 28 days are presented in Table 6.

Density reduction of RAC 50 and RAC 100 in respect to NAC sample are presented in Figure 6. Density of the hardened reference NAC sample is higher in comparison to the density of the RAC 50 sample with 92 kg/m^3 and higher in comparison to the density of the RAC 100 sample with 49 kg/m^3 (Table 6). For all three compositions the onset of early strength is prominent, as in the first 7 days they reach more than 60 % in respect to the strength achieved at 28 days.

The differences in strength values for the same age of concrete (28 days) vary depending of the mixture. The mixture RAC 50 has a strength of

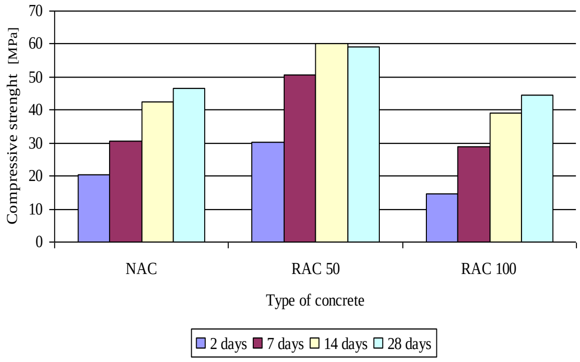


Fig. 5 - Graphic representation of the compressive strengths of the concretes determined on cubes.

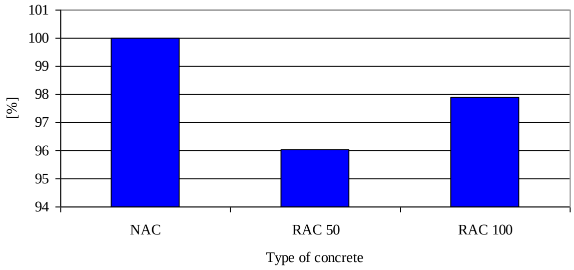


Fig. 6 - Density reduction of RAC 50 and RAC 100 in respect to NAC sample.

12.50 MPa, higher with 26.85% than the reference mixture, while the mixture RAC 100 has a lower strength - 2.05 MPa, with 4.40 % lower than the reference. The explanation for such variation of concretes strength made with the recycled aggregate (especially for RAC 50) can be found in the microstructure of the concretes made with this aggregate.

The recycled aggregate, as opposed to the natural aggregate, has two components in its composition: natural aggregate and the cement stone bound to it, which, to a lesser or bigger extent reduces quality. The presence of old cement stone in the recycled aggregate reduces density and increases water absorption capacity in comparison to the natural aggregate. The data from the available literature show that the share of the cement stone in 4-8 mm recycled aggregate fraction is from 33 % to 55 % while that in 8-16 fraction is lower, from 23 % to 44 %. The share of the cement stone is the highest in fine fractions, so their application is limited.

Table 6

The results of compressive strength tests after 28 days

Concrete type	Density (kg/m^3)	$f_{p,28}$ (N/mm^2)	SD (N/mm^2)	$f_{p,cil28}$ (N/mm^2)	SD (N/mm^2)
NAC	2325	46.55	0.919	48.60	1.622
RAC 50	2233	59.05	0.521	62.50	0.974
RAC 100	2276	44.50	0.480	46.50	1.651

The results of tensile splitting strength testing are presented in Figure 7. The standard deviation was 0.098, 0.05 and 0.10 MPa for NAC, RAC 50 and RAC 100 respectively.

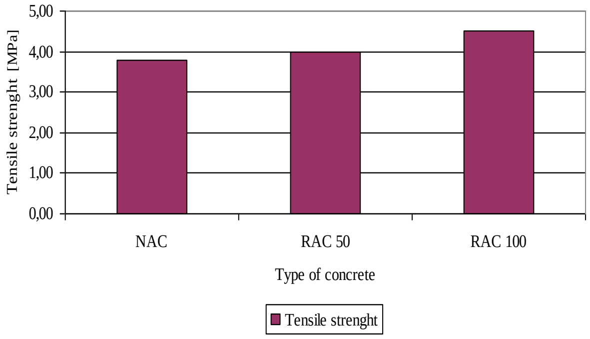


Fig. 7 - Graphic representation of the tensile splitting strength testing results.

The tensile splitting strength testing results after 28 days of hardening show that in respect to the reference NAC sample, the strengths of the RAC 50 and RAC 100 sample are with 0.2 MPa and 0.7 MPa respectively higher.

The modulus of elasticity as well as the compressive strength was determined after 28 days on the test core cylinders with Φ=150 mm and h=300mm. The tests were performed using three cylinders of each concrete type, and the tangent and secant modulus of elasticity were determined. The experiments yielded relatively low values of the modulus of elasticity E_{cm} both for the reference concrete (NAC) and for the concrete with recycled aggregate (RAC 50 and RAC 100). The mean values of tangent and secant modulus of elasticity are presented in Figure 8.

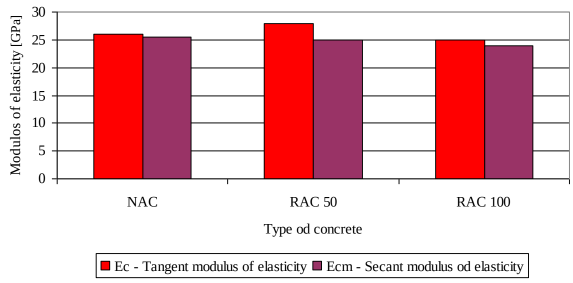


Fig. 8 - The testing results of tangent and secant elasticity modulus

The comparison of the experimental results was performed using the values defined on the basis of the regulations [27, 28] as well as using the recommendations based on the researches [17, 29-31] regarding the tensile strength of concrete and secant modulus of elasticity. For the comparison, the well known analytical relations of these mechanical characteristics and compressive strength of concrete presented in Table 7 were used and the results are presented in Figures 9 and 10.

Table 7

Analytical relations of tensile strength and modulus of elasticity to compressive strength

	Tensile strength	Modulus of elasticity
EC 2 [27]	$f_{ct}=0.3(f_{ck})^{(2/3)}$	$E_{cm}=22[(f_{ck}+8)/10]^{0,3}$
ACI 318 [28]	$f_{ct}=0.56(f_c)^{0,5}$	$E_{cm}=4730(f_c)^{0,5}$
Felekoglu et al [29]	$f_{ct}=0.43(f_c)^{0,6}$	$E_{cm}=1570(f_c)^{0,8}$
Dinakar et al [30]	$f_{ct}=0.82(f_c)^{0,5}$	$E_{cm}=4180(f_c)^{0,5}$
Kim [31]	$f_{ct}=0.52(f_c)^{0,5}$	/
Person [17]	/	$E_{cm}=3750(f_c)^{0,5}$

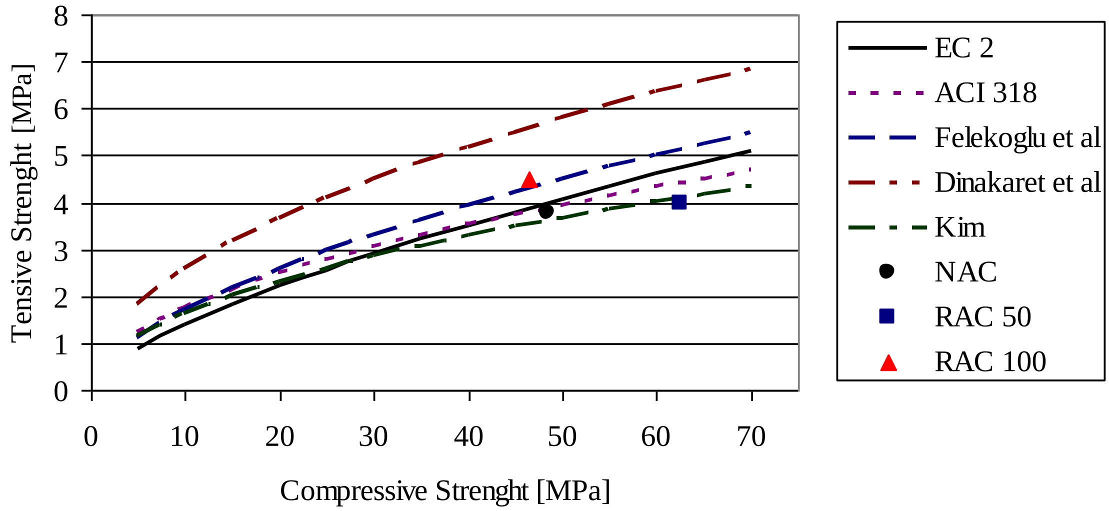


Fig. 9 - Tensile strength in relation with compressive strength.

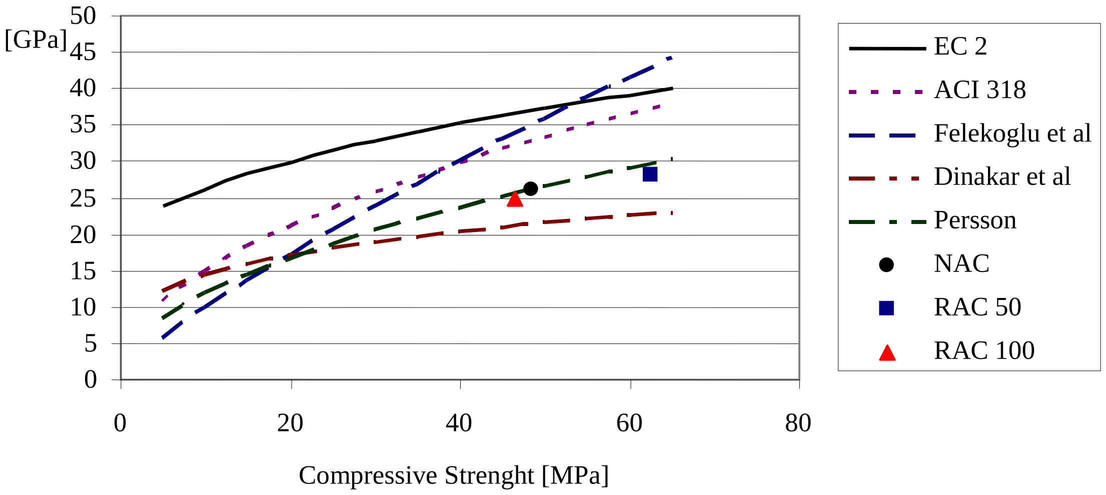


Fig. 10- Modulus of elasticity in comparison with compressive strength.

In Figure 9 it can be seen that the tensile strength values obtained in the experiment correspond to the area which is defined by the analytical expression based on the recommendations by Felekoglu et al. [29] and Kim [31]. The best match of the values of the secant modulus of elasticity obtained in the experiment of all the samples is the analytical curve proposed by Person [17] - Figure 10.

4. Conclusions

- When designing the concrete mixtures with recycled aggregate, the knowledge of their origin is of great importance. The higher quality of the original concrete, the better characteristics the newly made concrete will have. In this sense, is desirable to know the density of recycled aggregate in loose and compacted state, and the water absorption coefficient. The knowledge of the recycled material is desirable for the purpose of defining the mechanical characteristics of the recycled aggregate.
- In order to provide the approximately same concrete characteristics, it is necessary to add more water (w/c ratio) since the recycled aggregate absorbs more water than the river aggregate. In this research, the required amount of water for obtaining the same consistency of concrete was determined by measuring the water absorption of the recycled aggregate.
- By applying of a good quality recycled aggregate of the known composition, it is possible to obtain the compressive strength which differs minimally from the reference concrete. For RAC 100 sample the decrease of strength was 4.40 % which is negligible, while for RAC 50 sample, the strength increased with 26.85 % in comparison to the reference NAC sample, which should be accepted with reserve and has to be examined in future.
- Application of the recycled aggregate did not have noticeable effects on the tensile splitting strength. For RAC 50 and RAC 100, the increase of the tensile splitting strengths was 5.26 %, and 18.42 % in comparison to the reference NAC sample. The increase of tensile splitting strengths can be explained by the presence of crushed stone aggregate in hollow prefabricated slab from which the used recycled aggregate was obtained, as well as by the higher quantity of crushed cement stone.
- Low values of the modulus of elasticity, both tangent and secant, are characteristic for SCC, which is the consequence of higher volume of hardened cement paste in comparison with the aggregate. The tangent modulus of elasticity was with 11.2 % higher in RAC 50 sample, and with 3.85 % lower in RAC 100 sample in comparison to the reference NAC, while the secant modulus of elasticity decreased with 1.96 % and 5.88 % for RAC 50 and RAC 100 samples respectively, in comparison to the reference NAC sample.

The application of the aggregate obtained by crushing of prefabricated elements mechanically damaged in the process of their production is feasible and justifiable. The characteristics of both fresh and hardened concrete obtained using the recycled aggregate are satisfactory and the recycling process of the prefabricated elements damaged during production has a strong environmental protection importance.

Acknowledgments

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