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EFFECT OF MIXING APPROACH ON THE PROPERTIES OF CONCRETE WITH DIFFERENT AGGREGATE TYPES

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Abstract: The subject of the experimental tests presented in the paper is the influence of the mixing method on the physical and mechanical properties of fine-grained concrete with the nominally largest aggregate grain of 8 mm. Concretes with three different aggregate compositions (river, crushed and mixture with coarse recycled aggregate) were mixed using the usual approach, and then two-stage mixing approach (TSMA). Slump and flow, density and temperature were tested on fresh concrete. The compressive strength, flexural, splitting tensile strength, density, ultrasonic pulse velocity, and water absorption was recorded on hardened concrete. Concretes prepared using recycled aggregate, according to all the mentioned tests, can be used as an adequate replacement for concretes prepared using river or crushed aggregate, while the two-phase approach had the greatest effect on the increase of the splitting tensile strength.

Keywords: recycled aggregate, concrete, two-phase mixing, properties of concrete.

1. INTRODUCTION

The construction industry produces large amounts of construction and demolition waste. Concrete, with an annual production of about 10 billion tons globally [1] presents the most common construction material. Therefore, progress in the concrete production industry when it comes to the amount of waste and the impact on the environment leads to progress in the entire construction sector.

To preserve natural resources and the environment, along with an unsustainable amount of concrete waste and a shortage of space for construction waste disposal, there is a rising demand for recycling and reusing concrete waste. Recycling concrete waste into aggregate has proven to be economically viable and technically correct for handling non-structural elements [2], primarily by reducing the need for landfills for construction waste and transportation costs, while preserving the natural reserves of aggregates. The biggest problem with aggregates obtained by crushing deposited concrete is the residue of old cement paste and mortar, which makes these aggregates more porous and less resistant to mechanical influences. Furthermore, the higher level of various impurities as by-products in the process of recycling mixed construction waste [3] should not be neglected. In addition to the reduced strength of concrete with recycled aggregate, there is also a well-founded concern regarding the durability of concrete from recycled aggregate [4].

However, a number of concrete structures made with recycled aggregate have been built during the last two decades. The Netherlands, a country with a few sources of natural aggregate, started the construction of recycled concrete facilities at the earliest. In the period from 1988 to

1992, several facilities were built – three dams, two viaducts and a ship's lock. All these facilities were built with partial replacement of 20% of large river aggregate with recycled aggregate. In Germany, a business facility with a multi-story garage was built in 1998, for which concrete was used with 100% replacement of the natural coarse fraction by recycled coarse aggregate. Facilities were built in Japan in 2005 as part of the thermal power plant and in 2007 a residential complex was built using concrete in which 100% of the coarse fraction was replaced by recycled aggregate [5].

The presence of old cement mortar in the grain of the recycled aggregate is a factor that negatively affects the physical and mechanical properties of the recycled aggregate, and consequently, the concrete handled with this aggregate. The improvement of recycled aggregate quality is always based on the procedures for partial or complete removal of cement mortar from aggregate grains. Several different methods have been developed to remove cement mortar. The methods are based either on completely mechanical removal of cement mortar or mechanical removal after pre-treated aggregate by heating, wetting or chemical agents. It should be emphasized that all procedures for removing cement mortar from recycled aggregate are very expensive (high consumption of electricity, chemicals, etc.) and that their application is economically unjustified at present.

Research of recycled concrete aggregate applications usually is based on the design of concrete made with natural river aggregate, followed by certain corrections, i.e., the composition of concrete made with recycled aggregate has to be adjusted so that some properties are set to be the same for both concretes. Usually, the same effective water to cement ratio was retained in all analyzed concretes, with the same amounts of cement and free water. In addition to the same water to cement ratio, in a smaller number of studies, natural aggregate concrete and concretes made with recycled concrete-based aggregate had the same target consistency.

Intending to improve the quality of recycled aggregate concrete and expand its application, Tam (2005) et al. proposed new technology for making concrete with recycled aggregate, the so-called "Two-Stage Mixing Approach (TSMA)". Experimental research in their work has shown improvements in the strength of such concrete. The effect is explained by the fact that, due to the high porosity of the recycled aggregate grains, the "pre-mixing" process of the first stage helps fill pores and cracks, producing concrete with higher bulk density, improved interfacial transition zone around the recycled aggregate (ITZ), and thus greater strength compared to the traditional mixing approach [6]. Lee (2012) investigated the ITZ and the influence of the mixing method, concluding that a two-phase approach gives a denser and more homogeneous microstructure, and thus better mechanical properties of concrete with recycled aggregate [7]. Brand (2015) examined the impact of a two-phase mixing approach on high-quality recycled aggregate at different degrees of water saturation (completely dry, partially saturated, fully saturated) and the results showed that the two-phase approach contributed to the workability of the concrete mix, leading to an improvement in the strength of concrete when using partially saturated recycled aggregate [8].

The choice of fractions used and their ratio is a very important aspect when designing a concrete mix. Due to this, care must be taken to apply the optimal amount of cement paste, which at the same time implies the use of aggregates of appropriate aggregate mixture composition [9]. Concretes with only two aggregate fractions (0/4) (4/8) instead of the usual four have limited application in building construction due to the elimination of larger grain fractions, which are usually directly related to obtaining concrete with better physical and mechanical properties. In such application, great care must be taken because it has been shown that the compressive strength, the tensile strength and the flexural strength are directly related to the grain size of the aggregate, i.e., these strengths increase with the size of the used grain [10]. R. Kozul (1997) examined the effect of type (limestone or basalt) and aggregate size on the strength of hardened concrete. It has also been observed that with increasing grain size of the aggregate used, the fracture energy in high-strength concrete decreases, while in conventional-strength concrete, the fracture energy increases with increasing grain size of the aggregate used [11]. Brouwers et al. (2005) in their work conducted research increasing the share of finer fractions in concrete mixtures, where high strengths of concrete under pressure and bending were obtained using fine sand (0/1 mm fraction) [12].

The motivation behind the study presented in this paper was based on the fact that fine recycled aggregate is rarely used for the preparation of concrete mixtures, while the content of residual paste is higher than in coarse recycled aggregate. Three different mixtures were made with river aggregate, crushed aggregate and recycled aggregate, following the usual mixing procedure, and then made again using TSMA. A set of physical and mechanical properties of fresh (slump, flow, density and temperature) and hardened concrete (compressive strength, flexural, splitting tensile strength, density, ultrasonic pulse velocity and water absorption) were compared and analyzed.

2. MATERIALS

For the production of the concrete, two fractions of aggregate were used: I (0/4 mm) and II (4/8 mm). The natural river aggregate "Moravac" was used, and crushed aggregate "Kojić", Ljig. The recycled aggregate was used in fraction II (4/8 mm), obtained by crushing laboratory concrete cubes using RETSCH BB 300 MANGAN laboratory crusher and separating it into fractions. The fraction I (0/4 mm) of recycled aggregate was not used because it largely consists of cement paste which is very porous and can initiate major problems in determining the amount of water required to hydrate the cement, as well as for the desired consistency of the concrete. Instead, river aggregate was used.

Grain size analysis for all fractions and subfractions were obtained according to SRPS EN 933-1 (Determination of granulometric composition – sieving method) by sieve device MATEST and shown in Figure 1, together with the mixture. The share of individual fractions in the aggregate mixture was determined based on the reference sieve analysis curve for pumped concrete, for mixtures with a maximum aggregate grain D = 8 mm [9]. Fine particle content (SRPS B.B8.036) is presented together with the values of water absorption (SRPS ISO 7033) and aggregate density in a loose and compacted state (SRPS ISO 6782) in Table 1. Densities of the aggregate grains were also measured (SRPS ISO 7033) and amounted to approximately 2700 kg/m^3 for river and crushed aggregates, while for recycled concrete it approximated 2400 kg/m^3.

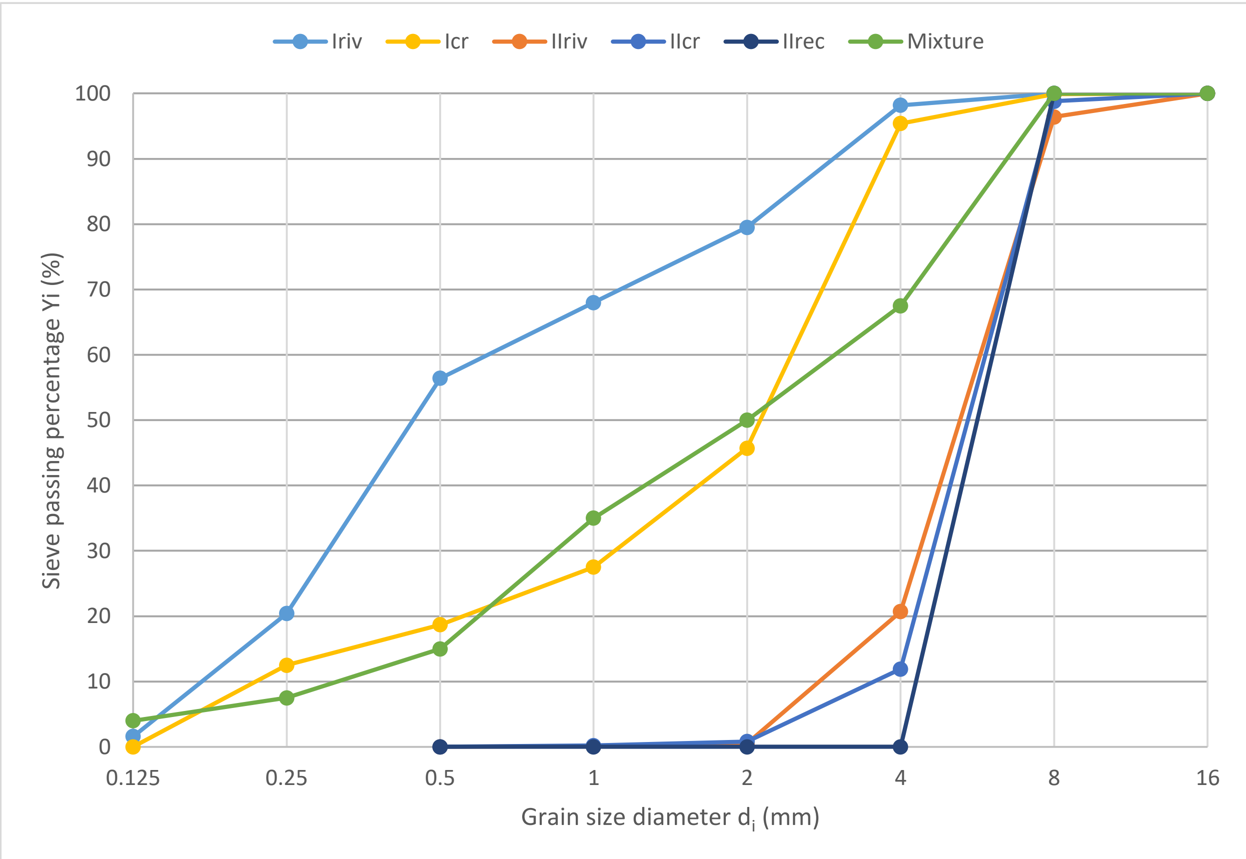

Figure 1. *Sieve analysis curves for all aggregates used in the study and the target mixture*

Table 1. *Physical properties of the used aggregates*

Aggregate type	River		Crushed		Recycled
Fraction	I (0/4)	II (4/8)	I (0/4)	II (4/8)	II (4/8)
Fine particle content (%)	0.87	0.49	0.24	0.45	1.43
Water absorption (%)	0.58	1.58	0.75	0.79	4.68
Loose density (kg/m^3)	1678	1603	1452	1467	1175
Compacted density (kg/m^3)	1774	1666	1599	1558	1317

Based on the producer's data sheets, natural limestone ("Granit Peščar", Ljig, Serbia), with a gravity of 2720 kg/m^3, specific surface of 3800 cm^2/g, and medium size of 250 μm was used as mineral filler to improve the structure of concrete by filling voids between aggregates, resulting with better structure and with the improvement of properties. Cement PC 20 M(S-L) 42.5 R, produced by "Lafarge", Beočin, was used in this study. The gravity of cement was 3010 kg/m^3, and the specific surface by the Blaine method was 4240 cm^2/g. Ordinary tap water from the city water supply was used.

3. DESIGN OF THE CONCRETE MIXTURES AND THE ADOPTED MIXING PROCEDURES

The parameters regarding concrete mixtures were set to obtain workable concrete (plastic consistency) and MB40 strength class. The procedure to calculate the composition of two mixtures of ordinary concrete with river or crushed aggregate was carried out in the following order, according to the usual algorithm [9]:

– establishing the amount of water depending on the required consistency of fresh concrete,

– adopting the water to cement ratio, and then cement content,

– establishing the aggregate content, based on the volume of components (without vacancies) in 1 m^3 of concrete,

– adopting aggregate mixture composition and calculation of the participation of individual fractions of aggregates.

The same goals in terms of consistency and strength were set for the mixture with recycled aggregate, preserving the effective water to cement ratio, and hence the design procedure consisted of the following steps:

– the same amount of cement was adopted as for concrete with river aggregate,

– the effective water-cement ratio was adopted to be equal to the water-cement ratio of concrete with river aggregate and the same amount of water for cement hydration,

– establishing the amount of recycled aggregate based on the volume of components (without vacancies) in 1 m^3 of concrete,

– adopting mixture grain size composition and calculation of the participation of individual fractions of aggregates,

– according to the maximum absorption of recycled aggregate using previous aggregate tests, the water to be absorbed by the recycled aggregate (additional water) was determined.

Following the stated procedures, quantities of component materials for each concrete mixture were established. Compositions of the mixtures are shown in Table 2. Since the same consistency was to be achieved for all of the concrete mixtures, the mixture M2 (made with crushed natural aggregate, which has a negative impact on consistency) contained a higher amount of water and cement, but the water to cement ratio was fixed. Since the grains of the used aggregate were smaller, the calculated quantities of cement for all of the mixtures were above 450 kg/m^3.

Table 2. *Compositions of the mixtures*

Mixture	M1	M2	M3
Cement (kg/m^3)	450	557	450
Water (kg/m^3)	238	294	238
Additional water (kg/m^3)	-	-	25
Fraction (0/4) (kg/m^3)	1084	920	1084
Fraction (4/8) (kg/m^3)	542	460	542
Filler (kg/m^3)	100	100	100

Two different mixing procedures were adopted for the production of concretes: normal (N), and the two-stage mixing approach (TSMA). Therefore, each concrete mixture was produced following first the usual procedure, and then again, the TSMA procedure. Thus, six different batches of concrete were made to evaluate differences in properties of these mixtures, based on mixing procedure and type of aggregate. The usual mixing procedure consisted of the following steps:

– the required quantities of components were weighed,

– components were put in the mixer in the following order: II fraction of aggregate, cement and filler, and then I fraction,

– dry mixing was performed for about 1 min, and then, without interrupting the mixing operation, the measured amount of water required for hydration of cement was added in the next 30 sec,

– mixing was continued for another 2 min, therefore total mixing time was 3.5 min,

– at the end of mixing, the temperature of the mixture and consistency were determined.

The mixing procedure for TSMA consisted of the following steps:

– the required quantities of components were weighed, and divided into two equal parts in separate vessels,

– the measured component quantities were put in the mixer in the following order: first the II fraction of the aggregate, then the previously measured half of the total amount of cement and filler, and then the I fraction,

– dry mixing was performed for about 1 min, and then, without interrupting the mixing operation, a measured half of the total amount of water was added in the next 30 sec, and mixing was continued for another 1 min,

– mixing was stopped and the remaining amount of cement and filler was added to the mixer, mixing was continued and in the next 30 seconds the remaining amount of water was added, at the end of mixing, the temperature of the mixture and consistency were determined.

4. EXPERIMENTAL CHARACTERIZATION AND DISCUSSION

Tests conducted on fresh concrete mixtures included the following properties: slump test (SRPS EN 12350-2), flow table test (SRPS EN 12350-5), density (SRPS EN 12350-6), and temperature (SRPS U.M1.032). The concrete temperature was close to the ambient temperature, ranging between 22.3°C and 24.9°C, and the results of the density and consistency tests (Figure 2) are shown in Table 3.

Figure 2. *Measurement of consistency and temperature of the fresh concrete mixtures*

Table 3. *Fresh concrete properties*

Mixture	Density γ (kg/m^3)	Slump Δh (cm)	Flow D (cm)
M1-N	2385	5	34.0
M1-TSMA	2373	3	31.5
M2-N	2349	16	50.0
M2-TSMA	2360	14	48.8
M3-N	2327	5	36.0
M3-TSMA	2356	5	38.5

The presented results of fresh concrete tests show there was no significant difference in the tested properties induced by different mixing approaches. Small differences in the slump flow, flow and even density of both approaches can be attributed to the reproducibility of the tests of the same mixtures. When discussing the differences between the mixtures, it can be concluded that the mixture M2 displayed substantially different behavior than the other two mixtures, regardless of the mixing approach. Such a behavior can be explained by the higher amount of paste used for this mixture because crushed aggregate was made. Although this paste content was a direct result of the design of concrete, which takes into account the type of fine and coarse aggregate, an observation was made that, in this case, the design procedure resulted in a higher fluidity of the concrete mixture.

Tests conducted on hardened concrete mixtures included the following properties: density (SRPS EN 12390-7) using hydrostatic scale KERN 0/24.100kg/0.1g, compressive strength (SRPS EN 12390-3), flexural strength (SRPS EN 12390-5) using AMSLER compression machine (6/0.1 kN for flexural, 1/200 kN for compressive strength), splitting tensile strength (SRPS EN 12390-6) using AMSLER compression machine (60/0.5 kN), ultrasonic pulse velocity (SRPS EN 12504-4) with an 82 kHz pulse PUNDIT tester, and water absorption (ASTM C1757) of samples after five days of full immersion in water, using the same previously mentioned scale. The recorded results correspond with the age of 28 days of samples and have been given as average from triplicates of measurements conducted on 4x4x16 prisms.

Results of the tests regarding physical properties (density, ultrasonic pulse velocity and water absorption) are presented in Table 4 concerning the normal (N) and two-stage mixing approach (TSMA). Corresponding results of the mechanical tests (compressive, flexural and splitting tensile strength) are shown in Figure 3.

Table 4. *Hardened concrete properties*

Mixture	Density (kg/m^3)	Ultrasonic pulse velocity (m/s)	Water absorption (%)
M1-N	2391	4516	8
M1-TSMA	2397	4503	7
M2-N	2342	4580	10
M2-TSMA	2355	4563	10
M3-N	2313	4404	10
M3-TSMA	2332	4404	10

Densities of the mixtures, at the age of 28 days, were between 2313 and 2397 kg/m^3. As expected, higher values were measured on mixtures with river and crushed aggregate, while the lowest one was measured on the recycled aggregate mixture, mixed by a normal approach. There was a certain increase in density with the change of the mixing approach, most probably because of the prolonged mixing induced by the two-stage mixing approach. Nevertheless, this increase in density was not followed by the increase in ultrasonic pulse velocity or water absorption. At the same age, ultrasonic pulse velocities were from 4404 m/s to 4580 m/s, with the lowest values corresponding to the use of recycled aggregate (mixture M3), and the highest corresponding to the use of crushed aggregate (mixture M2). The relatively high values of 7-10% for water absorption were probably the direct result of the samples used (prisms 4x4x16 cm), providing a more intense intake of water than the usually used samples of concrete. In terms of water absorption, there was no measurable effect of the mixing approach, except for the mixture with river aggregate under certain conditions.

The respective flexural and splitting tensile strength values ranged from 12.9 MPa to 16.1 MPa and from 3.2 MPa to 4.4 MPa. The highest values of both of these properties were recorded on the mixture made with the crushed aggregate. This effect can be attributed to the locking effect of the angular crushed aggregate grains. Although this locking effect is present in the recycled concrete grains as well, the quality of the grains is substantially lower and therefore the values of flexural and splitting tensile strength for mixture M3 resemble the ones of mixture M1. Two-stage mixing approach resulted in the best effect on the mixture with recycled concrete M3, with a percentual increase of 9.2% in flexural strength, and 14.3% in splitting tensile strength.

The reached values of compressive strength were between 52.4 MPa and 62.7 MPa. All of these values corresponded to the concrete strength class MB 40, after the conversion to a 20 cm cube. The lowest value was recorded on a mixture of recycled concrete aggregate, mixed using the normal approach. Based on the results of the tests, there was no significant increase in compressive strength for the mixtures with river and crushed natural aggregate, induced by a two-stage mixing approach. Nevertheless, the improvement was evident in the mixture M3, where the compressive strength of the mixture produced by the two-stage mixing approach was 13.7% higher than the compressive strength of the mixture produced by the normal mixing approach.

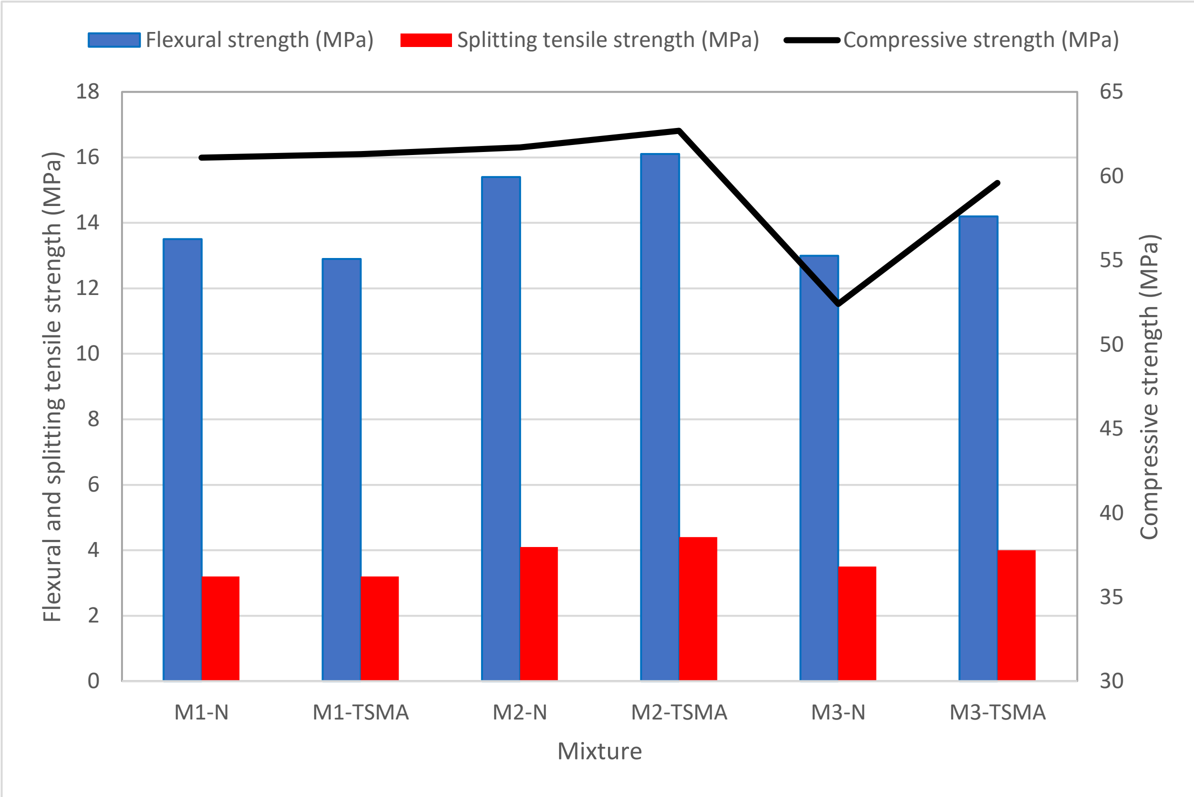

Figure 3. *Results of the mechanical properties tests*

Besides the fact that the difference in the type of aggregate used could be correlated to the compressive strength and ultrasonic pulse velocity values, which resulted in the grouping of the values, a proper correlation between these two properties could not be formed. Ultrasonic pulse velocity measurement is shown in Figure 4.

Figure 4. *Ultrasonic pulse velocity measurement on 4x4x16 cm prisms*

5. CONCLUSIONS

This paper presents an experimental study of the influence of mixing technology and the choice of aggregates on the physical and mechanical properties of concrete. The normal and two-stage mixing approaches were applied on fine-grained concretes made with the natural river, natural crushed and recycled concrete aggregates, with grains of a size below 8 mm.

Lower densities of fresh concrete with recycled aggregate were obtained because recycled aggregates have a lower density than natural aggregate.

The concrete mixtures made with crushed aggregate showed significantly higher slump and flow, i.e., more fluid consistencies, than the target. The higher consistency of the fresh concrete mixtures made with natural crushed aggregate did not have a negative effect on the compressive strength of the hardened concrete. Small differences in the slump, flow and even density of concrete mixtures produced by both approaches can be attributed to the reproducibility of the tests. Based on the obtained results, concrete preparation technology does not have a major impact on the consistency of fresh concrete mass.

Concretes with recycled aggregate displayed the lowest test results of ultrasonic pulse velocity, in the range of 2-3% lower than the concrete with natural aggregate. All types of concrete generally showed high water absorption, and the production technology alteration showed no measurable effect on this property of concrete.

Concrete preparation technology had different effects on flexural strength depending on the aggregate used. Although there was no positive effect on the flexural strength of concrete mixtures made with river aggregate, an increase in flexural strength of 4.5% in concrete with crushed, and 9.2% in concrete with recycled aggregate was recorded. As for the splitting tensile strength, the same conclusion can be drawn, however, with stronger effects: an increase in splitting tensile strength of 7.3% in concrete with crushed, and 14.3% in concrete with recycled aggregate was recorded.

There was no significant increase in compressive strength for the mixtures with river and crushed natural aggregate, induced by the two-stage mixing approach. Nevertheless, the improvement in compressive strength of the mixture produced by the two-stage mixing approach was 13.7% higher than the compressive strength of the mixture produced by the normal mixing approach.

Given the obtained results of concrete mixture design and tests, as well as the conclusions drawn, this type of concrete made with recycled aggregate can be applied in construction. With the use of coarse aggregate obtained from recycled concrete, new concretes can be made with the same strength level as those made with natural aggregate, and with the same effective water to cement ratio.

Generally, concrete preparation technology did not show a large impact on river aggregate concretes, while improvements in mechanical properties were recorded in concrete with crushed and recycled aggregate, especially when it comes to flexural and splitting tensile strength. Further research is needed to fully understand the impact of the recycled concrete aggregate production technology and apply the two-phase mixing approach.

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УТИЦАЈ МЕТОДЕ МЕШАЊА НА СВОЈСТВА БЕТОНА СА РАЗЛИЧИТИМ ВРСТАМА АГРЕГАТА

Сажетак: Рад приказује експериментална испитивања утицаја начина мешања свеже бетонске масе на физичко-механичка својства ситнозрних бетона номинално најкрупнијег зрна агрегата у износу од 8 mm. Бетони са три различита састава агрегата (са речним, дробљеним и мешавином са крупним рециклираним агрегатом) замешани су уобичајеним начином справљања, а затим и двофазном методом. Слегање и распростирање, запреминска маса и температура бетона испитани су на бетону у свежем стању. Чврстоћа при притиску, при затезању савијањем, при затезању цепањем, запреминска маса, брзина простирања импулса ултразвучних таласа и упијање воде испитане су на очврслом бетону. Бетони справљани коришћењем рециклираног агрегата се, према свим претходно наведеним испитивањима, могу користити као адекватна замена бетона справљаних применом речног или дробљеног агрегата, док је двофазни приступ имао утицај највише на повећање чврстоће при затезању савијањем.

Кључне ријечи: рециклирани агрегат, бетон, двофазни метод, својства бетона.

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