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# ODRŽIVOST I ENERGETSKA EFIKASNOST U KONTEKSTU PRIMENE RECIKLIRANOG AGREGATA U PROIZVODNJI ASFALTNIH MEŠAVINA

## SUSTAINBILITY AND ENERGY EFFICIENCY IN THE CONTEXT OF APPLICATION OF RECYCLED CONCRETE AGGREGATE IN THE ASPHALT MIXTURES PRODUCTION

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*Građevinska industrija predstavlja jednog od najvećih zagađivača životne sredine, uz korišćenje velikih količina prirodnih materijala. Iz tog razloga, u načnim krugovima, se već duži niz godina vrše analize i ispitivanja mogućnosti primene principa održivog razvoja prilikom proizvodnje građevinskih materijala. Posebna pažnja posvećuje se primeni agregata od recikliranog betona, s obzirom da se njegovom ponovnom primenom umanjuje i količina otpada koja se isporučuje na deponije.*

*U radu se analizira mogućnost zamene 30% i 45% sitnog i krupnog prirodnog agregata, agregatom od recikliranog betona iste krupnoće u proizvodnji asfaltnih mešavina za noseće slojeve kolovozne konstrukcije. Prvo su prikazani rezultati standardnih ispitivanja asfaltnih mešavina, a zatim je izvršena procena uštede energije tokom proizvodnje ovih mešavina.*

***Ključne reči:*** *energetske uštede; reciklaža; transport; trajna deformacija; otpornost na dejstvo vode*

*Building industry presents one of the biggest pollutant producers, with simultaneous use of large quantities of natural materials. For this reason, in scientific cycles, in the last years analysis and testing of the possibilities of applying sustainable development principles during the production of building materials, have been performed. Special attention has been paid to the application of recycled concrete aggregate, having in mind that its consumption reduces the quantities laid on the waste fields.*

*Within this paper possibilities of replacing 30% and 45% of natural stone aggregate with recycled concrete aggregate of the same fineness, in the production of asphalt mixtures for the base course has been analyzed. First, results of the standard test of asphalt mixtures were shown, and than the assessment of the energy savings during the mixture production has been presented.*

***Key words:*** *energy efficiency; recycling; transportation; permanent deformation; water resistance*

## 1 Introduction

Green design and sustainable development have emerged as the bridge between our advancing civilization and a weakened environment [1]. The building sector is often being underlined as one of industries with the highest use of natural resources as well as with the highest waste production. By the end of the 20th and in the first quarter of the 21st centuries one of the main research interests of the scientists dealing with building materials is the reduction of the use of natural resources, waste production, greenhouse gas (GHG) emission and energy consumption.

One of the ways to reduce waste in construction industry, is the use of recycled materials in the production of new materials. In this light, many studies have been performed on the use of the recycled concrete aggregate (RCA) as a partial replacement of natural aggregates in both concrete and asphalt concrete mixtures [2,3].

In this way all of the mentioned areas can be beneficially affected. Nevertheless, since the addition of RCA usually lead to reduction of some of the physical and mechanical properties of the asphalt concrete, the percent of the replacement has to be carefully chosen.

Different studies have been performed in order to estimate the energy consumption and carbon footprint in the production and maintenance of commonly used construction materials. In the case of asphalt concrete mixtures, total cycle of their production can be divided in the following phases:

1. Raw material extraction and initial transformation,
2. Manufacturing,
3. Placement,
4. Use and maintenance,
5. Removal, recycling and disposal [1].

Partial replacement of the natural aggregate with recycled concrete aggregate can affect only the first stage of the process, while the manufacturing, placement, use and maintenance should remain similar or unchanged.

The efficiency of aggregate quarry operations depends on the geological variability, homogeneity of gravels, grain size, scale of production, climatic conditions, equipment technology and maintenance, site organization and geography [4].

When efficiency of the use of demolished concrete is concerned, one of the most cost effective and energy efficient option was the use of portable crusher, to recycle the concrete and use the recycled concrete aggregate at the project site. Hameed et al. [5] showed that it was more effective than when the crushed concrete was landfilled and new virgin aggregate bought. It was also shown that the transportation distance influences the use of one or other aggregate type. If the distance between the job site and the recycling plant were increased for increments of 5 km, there was a point at which virgin aggregate became a more favorable option than using a RCA from recycling plant [5].

Also, several authors have reported the advantages of using recycled materials in the reduction of GHG emission. For example, in Taiwan, in production of pavements, recycled materials replaced 67% of crushed stone, 50% of sand, 70% of asphalt binder. Reduction of GHG's was in this case 16% to 23% [6]. In the USA, Asutosh and Nawari [7] reported that the use of recycled materials in pavement construction reduces GHG emission about 12% [8]. It should be stated that this reduction is mostly achieved through reuse of the binder, while influence of the aggregates is much smaller. When coarse recycled concrete aggregate has been compared with natural aggregate, the difference in the emission was around 3% [8].

Another case study showed that the construction of the HMA mix layer generated a carbon footprint of 65.8 kg of $CO_2$ per lane-km. Of this amount 2% was contributed by the construction of the roadway while the remaining amount was contributed by the required to obtain the materials needed for the roadway. Aggregate production contributed approximately 6% of total GHGs which was similar to the transport contribution [9]. The study was performed for a specific case of road construction in Costa Rica, where almost all electrical energy comes from renewable sources, which should be taken into account when compared with other similar studies.

## 2 Materials and methods

In this study, one asphalt mixture designed for the base course AC 22 BASE, was used as a reference mix, in order to investigation of the possibilities for partial replacement of natural aggregate with RCA. This solution was chosen because of the potentially higher consumption of RCA compared with wearing courses, and because it is more appropriate to use RCA it in the base courses, where they are not directly exposed to traffic loading and environmental conditions, and therefore the less strict technical requirements can be applied.

The total of five asphalt mixtures was made: one control, two mixtures with partial replacement of coarse natural aggregate (4/22.4 mm) with RCA in amount of 30% and 45% by mass, and two mixtures with partial replacement of fine natural aggregate (0/4 mm) with RCA in the same amounts of 30% and 45%. These asphalt mixtures were labelled as E, C-30, C-45, S-30 and S-45, indicating the type and the replacement percentage of the natural aggregate by RCA. In all mixtures, the aggregate gradation was kept constant. The targeted volume of air voids was set to 5.2%. The Marshal method was adopted for the mixture design. Finally, water resistance, stiffness and permanent deformation resistance were determined. At the end, analysis of energy consumption and GHG emission when using mixtures with RCA was performed.

### *2.1 Materials*

The RCA used in this study originated from the sub-structure of the tramway tracks consisting of cementitious concrete slabs. Although more than 30 years old, this concrete was never exposed to open ambient conditions, since it was protected by an asphalt layer. During the tramway reconstruction, the concrete core samples were taken from the structure and concrete class C35/45 was established, according to EN 206. After the crushing, the obtained RCA consisted of 98% of old concrete, 1.2% of asphalt, and 0.8% of brick material. The maximum aggregate size of 22.4 mm was adopted for all asphalt mixtures. Crushed limestone was used as the natural aggregate. Grading curves of natural and recycled aggregates are presented in Figure 1. The mineral mixture contained 5% of filler, 41% of 0/4 mm particles, 15% of 4/8 mm particles, 24% of 8/16 mm particles, and 15% of 16/22.4 mm particles. The main aggregate properties are shown in Table 1. In all mixtures, limestone filler and bitumen B 50/70 were used. The lower density of RCA is a consequence of the presence of adhered cementitious mortar. Also, RCA is characterized by increased water absorption as a result of the higher porosity of this mortar. Decreased resistance to crushing, expressed by a lower value of the Los Angeles (LA) coefficient, points to weaker mechanical properties of RCA. However, the equivalent value of LA for the mineral mixture, even with a high RCA content, is still lower than 30, which satisfies the technical requirements for bituminous base layers for medium traffic load [10].

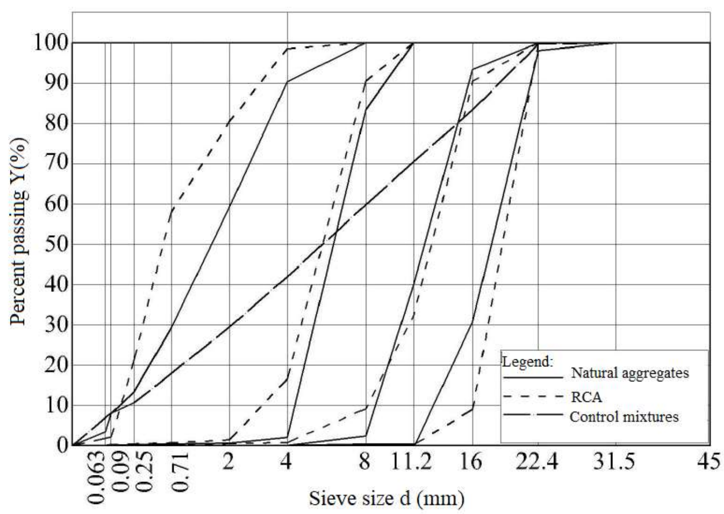


*Figure 1: Sieve analysis of aggregates [11]*

*Table 1: Physical-mechanical properties of aggregates [11]*

| Test | *Standard* | *Coarse aggregate* | | *Fine aggregate* | |
|---|---|---|---|---|---|
| | | *RCA* | *Natural* | *RCA* | *Natural* |
| $\rho_a$ (kg/m$^3$) | EN 1097-6 | 2667 | 2743 | 2645 | 2717 |
| $\rho_{SSD}$ (kg/m$^3$) | | 2532 | 2731 | 2512 | 2650 |
| $\rho_{rd}$ (kg/m$^3$) | | 2450 | 2724 | 2430 | 2580 |
| WA (%) | | 3.2 | 0.2 | 3.4 | 0.4 |
| LA (%) | EN 1097-2 | 31.5 | 26.1 | - | - |

Following marks were used in table 1:

$\rho_a$ - apparent specific gravity,

$\rho_{ssd}$ - bulk specific gravity SSD,

$\rho_{rd}$ - bulk specific gravity of samples dried in the oven,
WA - water absorption,
LA - Los Angeles abrasion.

Basic physical and mechanical properties of the component materials were performed in order to design the mixtures and to determine potential influence that each of the materials used (natural aggregate, recycled aggregate, bitumen and filler), could have on the properties of asphalt mixtures. Presented research was conducted in Laboratory of pavement and Laboratory of materials at the Faculty of Civil Engineering, University of Belgrade.

Limestone filler produced by "Rujevac" – Ljig and asphalt binderB50/70 produced in Oil refinery in Pancevo were used in all the mixtures. The gradation of the filler is shown in Table 2.

*Table 2. Filler gradation [12]*

| *d (mm)* | 0.063 | 0.09 | 0.25 | 0.71 |
|---|---|---|---|---|
| *Y (%)* | 75.9 | 84 | 97.2 | 100 |

Basic bitumen properties were determined through standard tests: penetration, apparent specific gravity and softening point. Results from these tests are presented in Table 3.

*Table 3. Properties of asphalt binder [12]*

| *Test* | *Units* | *Standard* | *Value* |
|---|---|---|---|
| Penetration | (25°C, 0.1 mm) | EN 1426 | 53.4 |
| Specific gravity | (kg/m$^3$) | EN 15326 | 1004 |
| Softening point | (°C) | EN 1427 | 50.5 |
| Penetration index | (-) | EN 12591 | -0.9 |

### *2.2 Asphalt mixtures*

Preparation of the mixtures was performed using the Marshal procedure at a temperature of 150°C, with compacting energy of two times 50 blows. In order to provide comparison between the results gained with different mixtures, optimal bitumen content (OBC) in all mixtures was adopted for a target air voids (AV) volume of 5.2%. Table 4 presents values of OBC, AV, voids in mineral aggregate (VMA), percentage of voids filled with bitumen (VFB), density (G), maximum density (G_max), as well as Marshall stability and flow for each mixture.

*Table 4 Volumetric properties of asphalt mixtures*

| Mix | *OBC* | *AV* | *VMA* | *VFB* | *G* | *G_max* |
|---|---|---|---|---|---|---|
| | *(%)* | *(%)* | *(%)* | *(%)* | *(kg/m$^3$)* | *(kg/m$^3$)* |
| Control (E) | 3.4 | 5.2 | 13.5 | 61.0 | 2419 | 2553 |
| C-30 | 3.5 | 5.6 | 14.0 | 59.6 | 2388 | 2531 |
| C-45 | 3.5 | 5.4 | 13.8 | 60.6 | 2388 | 2525 |
| S-30 | 3.5 | 4.6 | 13.0 | 64.9 | 2410 | 2525 |
| S-45 | 3.6 | 5.4 | 14.0 | 61.1 | 2379 | 2516 |
| Specification | | 5-9 | NR | 55–74 | NR | NR |

Influence of RCA on the properties of asphalt mixtures was determined on the samples prepared in a way that realistically simulates the behavior of asphalt concrete in the road structure.

### *2.3 Methods*

Water resistance of asphalt mixtures was tested by measuring indirect tensile strength (ITS) of dry and wet samples, in accordance to EN 12697-12, method A. Six Marshal cylindrical samples were prepared for each mixture and separated into two groups. Each group contained three samples with similar densities. The first group was kept in dry conditions, at the room temperature of 20°C. The second group was placed into water at the pressure of 6.7 kPa for 30 min, and afterwards conditioned in water at a temperature of 40°C during next 72 hours. Before testing, the samples were kept at 25°C for 2 h. ITS testing was conducted on the universal compression machine UTM-25, according to EN 12697-23.

Testing of the resistance to permanent deformation was performed using the small wheel tracking device in air, at a temperature of 60°C, after 10000 cycles (20000 passes), all in accordance with EN 12697-22, Annex B, small appliance. Wheel load of 700 N is transferred over contact surface of 1900 mm^2 with frequency of 0.88 Hz. According to this method, resistance of asphalt mixtures to permanent deformation is determined by measuring of the depth of the track that is formed after each wheel loading cycle. Figure 3 presents the laboratory WTT (Wheel tracking test) machine produced by INFRATEST 20-4000, that was used for this test.

## 3 Experimental results

### *3.1 Water resistance test*

The indirect tensile strength (ITS) was calculated using the following expression:

$$ITS = \frac{2 \cdot P}{\pi \cdot h \cdot d_s} \quad (1)$$

where: P is the maximum force (kN), h - sample height (mm), $d_s$ - sample diameter (mm).

Indirect tensile strength ratio (ITSR) that represents the measure of water resistance of asphalt mixtures is defined as a ratio between the measured indirect tensile strengths of samples conditioned in wet and dry environment. The average values of all indirect tensile strengths of dry ($ITS_{dry}$) and wet ($ITS_{wet}$) samples for each of the tested mixtures, together with their ratio (ITSR), are presented in Table 5. Water resistance of asphalt mixtures (ITSR) is defined as ratio between measured indirect tensile strengths of samples conditioned in wet and dry environment:

$$ITSR = \frac{ITS_{wet}}{ITS_{dry}} \cdot 100$$

*Table 5: Average values of ITS and ITSR*

| Mix | $ITS_{dry}$ (kPa) | $ITS_{wet}$ (kPa) | ITSR (%) |
|---|---|---|---|
| E | 937.2 | 692.9 | 73.9 |
| C-30 | 981.1 | 679.1 | 69.2 |
| C-45 | 879.9 | 676.3 | 76.9 |
| S-30 | 921.7 | 696.6 | 75.6 |
| S-45 | 963.3 | 719.5 | 74.7 |

Measured values of ITS, for asphalt mixtures made with RCA, increased with higher RCA content, independently of the way of conditioning (dry or wet). These results are consequence of the better interaction and higher friction between the RCA particles, due to their rough surface and sharper edges.

Indirect tensile strength ratio (ITSR), that presents measure of water resistance of asphalt mixtures, was higher for three out of four mixtures with RCA when compared to control mixture.

### 3.2 Resistance to permanent deformation

According to the test results presented in Figure 2, partial replacement of natural with RCA did not lead to greater changes in the measured track depth. Best results in both type of mixtures were achieved with the aggregate replacement of 30%. In the case of replacement level reaching 45%, mixture with coarse RCA reached similar deformation as referent mix, while mixture with fine RCA reached higher level of deformation than the reference mixture. Still, it has not exceeded 7% which is the upper limit for proportional track depth according to the national Technical requirements [10].

The improvement of the resistance to permanent deformation for mixtures S-30 and C-30, can be explained by the structure and the texture of RCA. Its surfaces are rough, when compared to natural aggregate, with sharp edges, which increases the specific surface area and the friction between aggregate particles. For this reason, particle grains are well compacted, and do not move during traffic loading.

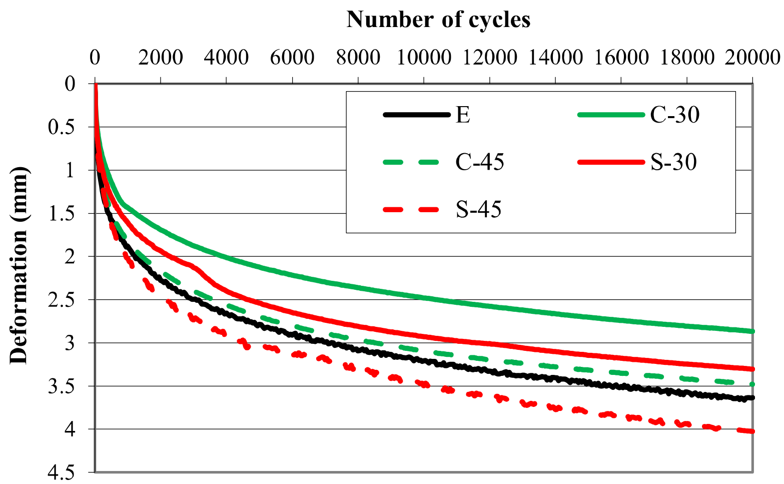


*Figure 2. Permanent deformation of mixtures made with RCA*

## 4 Energy efficiency estimation

Since the asphalt mixtures tested in this paper were prepared for the determination of the influence of recycled concrete aggregate on some of the key properties of asphalt mixtures, it is not possible to determine the exact energy use for the production, transportation and use of these mixtures in real conditions. For this reason, study performed by Han et al. [13] concerning monitoring and evaluation of energy consumption in the whole process of asphalt pavement construction was used for determination of the relative share of two above noted stages in asphalt pavement production in the whole process. In this paper, the whole process of the asphalt pavement construction for the highway project was taken into account. It is also stated that in asphalt pavement production different types of energy are used. The unification of all of these energy sources is usually performed (according to China's General Principles of Comprehensive Energy Consumption Calculation) through calculation of the average low calorific value for each of the energies and its conversion factor of standard coal. It is also stated that natural aggregate production process usually includes stone mining, stone crushing and stone sieving. Similarly, for the recycled aggregates the main energy consumption in the processing is the power consumption of the secondary screening equipment and the fuel consumption of loaders and transportation vehicles. The main phases in the production of this kind of aggregates are transporting back to the mixing plant, crushing and screening. If the calculated energy consumption of the aggregates are compared, the coarse and fine limestone aggregate with 0.86 kgce and 0.96 kgce, respectively, are using more energy than recycled concrete aggregate whose production is using 0.56 for coarse and 0.58 kgce for fine grains. According to the same authors, for the production and placing of ordinary asphalt AC-25 total energy consumption is 21.86 kgce (640.75 MJ/t). The proportion of energy consumption of asphalt mixture mixing is the largest, accounting for about 45% of the total energy consumption. Aggregate production makes around 4.75% of the total energy, while total raw material transportation estimated on 150 km, uses 18.6% of the total energy [13]. When 45% of coarse natural aggregate is replaced with RCA the total energy consumption reduces for 0.135 kgce, while in the case of fine aggregate replacement this reduction would be 0.180 kgce. This represents 15.7% of energy reduction in production of coarse aggregate and 18.7% in production of fine aggregate. Compared to the total energy consumption for production and placing of asphalt mixture, these reductions would present 0.62% and 0.82% respectively.

Although these reductions are not significant when compared to the whole process, they are a step towards more rational energy consumption. Here some other factors should also be included, first, by replacing the natural aggregate, a natural resource that cannot be reproduced is being preserved, secondly, waste material such as crushed concrete would be placed on a landfill, with small possibility to be reused again.

Apart from energy consumption, water is one of the most important factors when quarrying and mining is concerned, since it is used in many of the processes: cooling, crushing, grinding, milling, slurry transportation and tailings storage. Employing water efficiency practices reduces water loss and saves money, protecting surface and groundwater supplies [4].

When natural aggregate is replaced with recycled aggregate, water savings are achieved, through elimination of the cooling step.

Third important issue when production of building materials is concerned is the possible reduction of the GHG emission. Biswas showed in his study the carbon footprint of a road construction using virgin materials and recycled materials (cases 1 and 2) [14]. In this case 180 tons of $CO_2e$ and 170 tons of CO2e were observed, respectively. Maintenance operations over a lifetime of 100 years represented 79% of the total life cycle of GHG emissions because they included the transport of materials, excavation activities, leveling and paving [9].

## 5 Conclusions

As building industry is one of the major consumers of natural resources and different types of energy, while at the same time one of the greatest waste producers, many studies have been performed in order to reduce negative impact of the construction on the environment. One of the main courses of this aim has been use of recycled materials in the production of new building materials. In this light, RCA has been proposed as a replacement for natural aggregate both in concrete and asphalt concrete mixtures.

In this paper possibilities of partial replacement of fine and coarse RCA in base asphalt mixtures was discussed, with focus on splitting resistance and permanent deformation resistance of the tested samples. In both tests mixtures containing RCA showed good results. Only one mixture with RCA (with 30% replacement of coarse aggregate) showed lower ITSR percent than the reference mixture. Similarly, only mixture containing 45% of fine aggregate replacement showed higher permanent deformation than the reference mixture, but still lower than the value given in national technical requirements.

The analysis of the energy savings, and the reduction in GHG emission could only be partially performed, since the mixtures were only prepared in the laboratory conditions, and have not yet been applied on site. It was concluded that the reductions could only be achieved in the first phase of the asphalt concrete production, which is raw material extraction and initial transformation. When the values connected to the different aggregates production are included in the existing calculations, it was concluded that when 45% of coarse natural aggregate is replaced with RCA the total energy consumption reduces for 0.135 kgce, while in the case of fine aggregate replacement this reduction would be 0.180 kgce.

These values seem very low, when compared to the total energy consumption in one cycle of asphalt pavement production, but having in mind other benefits of the RCA application, the reduction in the natural aggregates consumption, and reduction of the waste placed on the landfields, it seems beneficial to continue investigating the possibilities of RCA application in asphalt concrete mixtures.

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