Original scientific papers UDK 666.97/.98:691.32
doi: 10.7251/COMEN1402239M

PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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Abstract: Following an example of the world's great powers that developed the recycling industry after natural disasters and wars, the paper points to the possibility of using large quantities of construction and demolition waste, generated as a result of the recent floods in the B&H and Serbia. Based on the years of extensive experimental research, and the research conducted by eminent experts, an overview is provided of the most basic properties and application of recycled aggregate concrete. It has been shown that the application of coarse recycled concrete aggregate, as the component materials in the concrete mixtures, it is possible to produce structural concrete that can be satisfactory and even with high quality, which primarily depends on the characteristics of crushed demolished concrete.

Keywords: recycled aggregate concrete, construction and demolition waste, concrete properties, research.

1. INTRODUCTION

Recent floods, that struck our our country and the region, have caused widespread damage, among which damage to building structures is dominant. Society is not only faced with the problems of finding solutions for the construction, reconstruction and repair of buildings, but also with huge issues concerning disposal of the construction and demolition waste, which, during the still ongoing cleaning of the recently flooded areas, is being indiscriminately disposed of at municipal waste landfills or often at the so-called illegal dumps. In particular, in the Republic of Srpska, something that aggravates the problem is the fact that in the existing regional sanitary landfills: „Ramići" in Banja Luka and „Brijesnica" in Bijeljina, and regional sanitary landfills, whose construction is in progress: „Crni Vrh" in Zvornik and „Stara pruga - Kurevo" in Prijedor, there are not even specific sections of landfills that would be used for disposal of inert waste, such as construction waste.

As a sustainable solution to the problems at hand, modeled after the experience of the world's biggest economies, which strategically approached the concept of reconstructing buildings destroyed during the war and/or natural disasters, this paper suggests, to scientific and professional community, a possibility of recycling wasted construction material, primarily concrete, which is mostly used.

The recycling of construction waste was first done at a large scale after the Second World War in Russia and Germany - as it was needed to remove the war-torn buildings and build new ones - construction waste was used as an important resource. Since then, and especially after the world summit in Rio de Janeiro, held in 1992 and the promotion of Agenda 21, with a tendency to appreciate the principles of sustainable development, protection of environment and treating waste as one of the most important environmental problems, numerous studies were undertaken throughout the world, which were to show that the recycled construction waste, mainly concrete and asphalt made of concrete and brick, could have a wide range of use in the construction industry.

Figure 1 shows a complex of residential buildings „Waldspirale" in Darmstadt, Germany, described as attractive in terms of architectural form, built in 1998, for which all of the internal structure elements, as well as the base plate were made of concrete with a recycled coarse aggregate, whilst, fly ash - a byproduct of thermal power plants was used as mineral addition.

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Figure 1. Complex of residential buildings „Waldspirale", Darmstadt, Germany [1]

2. PROPERTIES OF RECYCLED AGGREGATE

The use of recycled aggregate obtained from the waste concrete, as a component of the new concrete mixture, implies a thorough understanding of its basic properties, considering that some of them may significantly differ from the properties of aggregates obtained from natural resources. In addition, their differences primarily depend on the quantity and quality of cement mortar, which is attached to the grains of recycled aggregate (Figure 2), then, on the quality of the original concrete from which the aggregate is made by recycling and also on recycling methods. Nonetheless, in cases where the recycled aggregate comes from many different sources, the uneven quality, i.e. variations in the properties of recycled aggregate are much more pronounced than as is the case with natural aggregates.

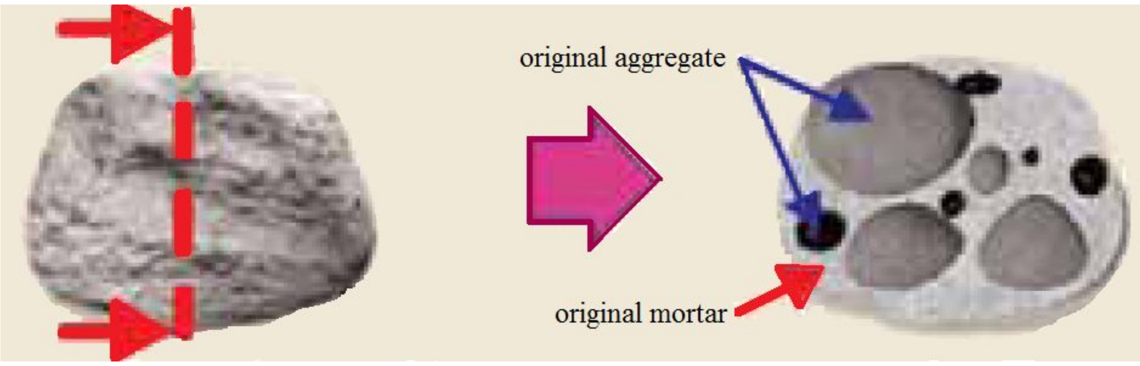

Figure 2. Appearance of the recycled aggregate grains [2]

2.1. Aggregate grading

Grading of recycled coarse aggregate normally satisfies the standards for natural aggregate, while in the case of recycled fine aggregate, composition corrections are often necessary, because, according to many practical experiences, it was found that there was often a certain amount of grains larger than what is required by standards for natural aggregate [2,3].

It has been shown that the presence of recycled fine aggregate has a negative impact on the physical-mechanical properties of concrete, therefore, even though through a careful mix design and application of appropriate production technology these effects can be reduced to an acceptable level, in practical application, a fine fraction of recycled aggregate is usually left out, in a way that it is completely replaced by the river sand [4,5]. Figure 3 shows different fractions of recycled aggregate, produced by a classical procedure.

Figure 3. Shape and surface texture of different fractions of recycled aggregate

2.2. Shape and surface texture of aggregate particles

In terms of morphological characteristics, recycled aggregate is less favorable than natural aggregate. The grains are irregular, mostly with angular shape, rough and with cracked surface and porous. These grain characteristics grains significantly affect the workability of fresh concrete, as well as the permeability of liquids and gases in the hardened state; they also significantly depend on the properties of concrete used in recycling for production of aggregate, especially its strength, porosity, exploitation conditions to which it was subjected, but also on the ways and levels of recycling – the type of applied crusher and possible additional processing procedures.

2.3. Water absorption

Water absorption of recycled aggregate is a characteristic by which this aggregate differs most from the aggregate obtained from natural resources. According to all available research in this area, it has been shown that recycled concrete aggregate has a significantly higher absorption level compared to natural aggregates. The reason for that is that the original cement mortar, which is an integral part of the recycled aggregate, has a significantly more porous structure in comparison to natural aggregate, whereby its porosity primarily depends on the water-cement ratio of the original (old) concrete. Thus, the absorption of water of recycled aggregate is even bigger, as the quantity of mortar, which is attached grains of the original recycled aggregate, increases.It has been shown in practice that the stated amount of cement mortar in recycled aggregate ranges from 25% to 65% (in volume percentage), and that it differs in certain fractions – the smaller the fraction, the greater the amount of cement mortar, as well as the level of water absorption [2]. Also, the analyses undertaken in extensive research around the world indicate that the stated amount of old cement mortar depends on the crushing method in the recycling process, thereby, according to some researchers, the maximum amount of mortar layer in recycled aggregate is recommended to less than 44% for constructional concrete. Additionally, the researchers from the University of Hong Kong recommend that the amount of recycled aggregate in structural concrete should range from 20% to 30%, in order to ensure that the maximum water absorption of aggregate used is less than 5% [6].

It is known that the aggregates from domestic natural resources have negligible absorption, up to 1% as maximum, while the value of the classically recycled coarse aggregate typically ranges within the interval from 3.5% to 10%, and for the fine aggregate, within the interval from 5.5% to 13% [2,7]. According to the Japanese standard for the use of recycled aggregate as a component of concrete, there is a limit so that a coarse fraction of recycled aggregate whose absorption is not higher than 7%, and fine fractions whose absorption goes up to 13% [8], i.e. 10% can be used for the production of concrete.

Accordingly, the absorption capacity of recycled aggregates should be treated as one of the basic properties, which is to be taken into account while designing the mixture of new concrete on the basis of this aggregate. Through the influence on the water-cement ratio porosity and consistency, an increased water absorption of recycled aggregate also influences a range of physical-mechanical properties of fresh, as well as hardened new concrete.

2.4. Bulk density of aggregate

The bulk density of the recycled aggregate, due to a higher porosity of mortar layer, has a lower value than the bulk density of natural aggregates and their mutual difference decreases if recycling is conducted by an advanced technology, which can remove a significant portion of the old cement mortar. Also, the smaller the fraction, the greater the amount of cement mortar in the total mass of aggregates, so the bulk density is accordingly lower. According to practical experience, it was shown that the bulk density of recycled aggregate was on the average by 10% lower compared to the bulk density of natural aggregates [6,9,10].

2.5. Crushing and abrasion resistance

Mechanical properties of recycled aggregate are primarily dependent on the quality of the original cement mortar present in the aggregate, and also, as in the case with natural aggregates, depend on a number of other factors - the type of the original aggregate, structure, shape and size of grains, aggregate grading and so on.

The resistance to crushing and abrasion of recycled aggregate is less than the respective resistance of natural aggregate, which is a consequence of easier separation and crushing of the mortar layer around the recycled aggregate grains. In addition, recycled aggregate, in most cases, meets standard requirements in terms of the resistance to crushing and abrasion, which are prescribed for aggregates from natural resources. Their differences may widely range - from 0% up to 70%, which, as already pointed out, primarily depends on the quality, original concrete compressive strength, as well as the methods of crushing of recycled aggregate [2,9].

2.6. Presence of harmful substances

Harmful substances, which may be present in recycled aggregate, are a consequence of harmful substances present in the original concrete, furthermore, of exposure of the original concrete to aggressive effects of various chemicals during the original exploitation, of inadequate levels of treatment during the recycling process, of possible mixing of different waste materials etc. These substances can be found in the following forms: lumps of clay, humus, gypsum, various organic substances (bitumen, wood, paper, cardboard, plastic, coal, plant materials, and various colors), steel and other metals, glass, lightweight concrete, brick, etc.

The presence of the stated components negatively affects the characteristics of the new concrete, and the studies show that they can cause a reduction in compressive strength by up to 15%.

According to the Japanese standard for use of recycled aggregate in concrete, the amount of harmful materials of density less than 1200 kg/m^3 is limited to 2 kg/m^3, and plastic, clay, humus and other harmful substances of density less than 1950 kg/m^3 to 10 kg/m^3.

In the event of contamination of recycled aggregate by gypsum, Rilem recommendations refer to the use of sulphate resisting cement, while the total content of sulphates should not be higher than 1% of the dry aggregate mass [8].

3. PROPERTIES OF FRESH RECYCLED AGGREGATE CONCRETE

3.1. Entrapped air content

The application of recycled coarse aggregate has no effect on the amount of entrapped air in fresh concrete, furthermore, the information about increase of the amount of entrapped air of up to 1% was found in some research - which can be considered as negligible.

3.2. Bulk density

An increase in a share of recycled aggregate in total mass of the component aggregate reduces the bulk density of fresh concrete, where it was shown that the bulk density of the recycled aggregate concrete was 5% to 10% lower than in the comparable natural aggregate concrete, while concretes made with the recycled coarse aggregate and natural fine aggregates had densities of 1% up to 5% lower than in the comparable natural aggregate concrete. In general, the values of bulk densities of the fresh concrete based on recycled aggregates range from 2280 kg/m^3 to 2360 kg m^3 [11−14].

3.3. Consistency

The use of recycled aggregate affects the consistency, in the sense that due to a usually higher absorption of recycled aggregate grains, as well as the less favorable grain shape and texture, the flowability of the concrete mixture is reduced, while the specified property is also significantly affected by the method of preparation of recycled aggregate in the concrete mixing process. By using saturated, surface dry recycled aggregate, the consistency of the comparable concretes does not differ that much from the recycled and natural aggregates, while in the case of the use of dry recycled aggregate and extra amount of water, the same consistency can be achieved after the required time period [5 and 9].

4. PROPERTIES OF HARDENED CONCRETE

4.1. Rheological properties

Shrinkage of concrete increases as the share of recycled aggregate increases in the total weight of the component aggregate, considering that the recycled aggregate, due to the presence of the old mortar in its composition, has a lower elasticity modulus value, and therefore provides a lower resistance to shrinkage. According to available research it is shown that, in comparison to natural aggregate concrete, shrinkage values are 4% up to 70% higher when using recycled aggregate. In addition, in relation to the coarse fraction of the recycled aggregate, fine fraction influences more an increase in shrinkage. Also, the stated feature, as well as in the case of natural aggregate concrete, significantly depends on: air temperature and humidity, the quantity and type of applied cement, quantities of water and water-cement ratio, aggregate grading, the size of the samples to be tested, etc.

The content of recycled aggregate significantly affects the creep deformations of concrete, in the sense that they increase alongside with an increase in the share of recycled aggregates - given that the creep deformation is proportional to the amount of cement mortar in concrete, which is more present in recycled aggregate concrete than in the comparable natural aggregate concrete. Based on a significant number of personally conducted experimental tests, it was shown that the creep of concrete, designed with a 100% content of the recycled aggregate in coarse fraction is by 25% to 60% larger than the creep of the comparable natural aggregate concrete and in the case of concrete in which the total quantity of aggregate is - recycled aggregate, the value of creep can be several times higher than in the case of comparable natural aggregates concrete. Therefore, in accordance with the creep characteristics, for the production of structural recycled aggregate concrete it is recommended that the recycled fine aggregate be replaced by natural sand, that is, that recycled coarse aggregate in the corresponding ratio be used, depending on its quality, structural requirements and environmental conditions.

4.2. Hydro-physical properties

Recycled aggregate concrete typically has higher absorption than comparable natural aggregate concrete, in the sense that an increase in share of recycled aggregate in total mass of the component aggregate proportionally increases the concrete absorption.

Water permeability of recycled aggregate concrete depends on the capillary porosity of the cement matrix of new concrete and capillary porosity of the cement matrix of recycled aggregate concrete. If the recycled aggregate is obtained by crushing small porosity concrete, permeability level of new concrete will primarily depend on the choice of aggregate grading and achieved structure of the new cement matrix, consequently, it is possible to produce waterproof concrete by using recycled aggregate.

4.3. Physical-mechanical properties

Compressive strength of recycled aggregate concrete primarily depends on the quality of applied aggregates, so that it is possible to obtain higher, identical or lower strength compared to the natural aggregate concrete. In fact, a considerable amount of research confirms that in the case of application of recycled aggregate produced by concrete crushing, whose compressive strength was higher than the targeted compressive strength of new concrete, recycled aggregate concrete of equal or greater strength in relation to comparable natural aggregate concrete are obtained. Moreover, in case that the compressive strength values of the original concrete, of which recycled aggregate is manufactured, and targeted compressive strength value of new aggregate, were approximately equal, it was found that the strength values of recycled aggregate concrete was 5% to 10% lower than those of the comparable natural aggregate concrete. In case of designing such recycled aggregate concrete the targeted strength value is greater than the one of the original concrete (which is usually the case in practical application), lower strength class of recycled aggregate concrete is inevitably obtained than in the comparable natural aggregate concrete, while a decrease of strength depends on the level of application of such recycled aggregate. Furthermore, it was observed that during the application of both - fine and coarse recycled aggregate, the above mentioned decline in the strength of recycled aggregate concrete of 15% to 50%, compared to the comparable concrete made entirely with natural aggregate, occurs. The application of solely recycled coarse aggregate and natural sand leads to the maximum decrease of strength of such concrete in relation to the comparable one, in range of 5% to 10%, while in the case of application of recycled aggregate in the amount up to 30% of coarse fractions (or up to 50% - differences in research) obtained concretes in which the decline of strength is generally negligible, if the strength of original concrete is not drastically lower than the target value of new concrete. Compressive strength values of concretes with a mixture of aggregates made of natural coarse aggregate and recycled fine aggregate is up to 50% lower in relation to the comparable natural aggregate concrete - which implies the exclusion of this combination in practical application. In addition to the above, the variations of compressive strength of recycled aggregate concrete depend on uniformity of quality of recycled aggregate, so potential problems in the practical application could occur if concretes without proper classification, i.e. with significant differences in compressive strength, is delivered to recycling plants.

An increase in the compressive strength during the period up to 28 days of age is usually higher in natural aggregate concrete in relation to concrete made entirely from the recycled aggregate, in ages higher than 28 days the situation is reversed, which is explained by the reaction of cement from previously unhydrated cement paste, attached from grains of recycled aggregates.

Tensile strength, usually determined by splitting tensile test through the line pressure, and more rarely by flexural tensile test, does not significantly depend on the type and amount of applied recycled aggregate (especially if only recycled coarse aggregate is used in the mixture), but, its primary function is the ratio of aggregates and cement amounts – an increase in this ratio reduces tensile strength. In fact, studies have shown that the presence of only coarse fraction of recycled aggregates causes a decrease in tensile strength up to the maximum 10%, whereby the level of participation of coarse fractions of recycled aggregate of 20% to 50% usually results in about 2% lower tensile strength in comparison to the concretes made entirely with natural aggregate. Differences in tensile strength in relation to natural aggregate concrete are to be expected in the range of 10% to 20% only in cases when concrete is prepared entirely with recycled aggregate. Thus, in relation to the coarse fraction, fine fraction of recycled aggregate has a slightly higher impact on this feature.

The tensile and compressive strength ratio in recycled aggregate concrete is lower than the ratio defined for natural aggregate concrete according to Eurocode 2 - which can be concluded by analysis of the diagram shown in Figure 4, where the test results of several researchers are summed up. In this regard, it is noted that the values in the diagram refer to different percentages of replacement of both - coarse and fine natural aggregate with the recycled one.

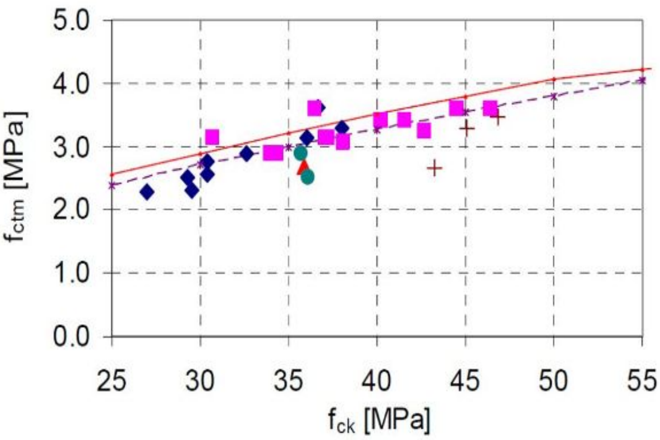

Figure 4. Diagram of relationship between tensile strength and compressive strength of recycled aggregate concrete [4]

The full line in the diagram shown in Figure 4 represents the connection between tensile and compressive strength according to Eurocode 2, i.e. according to equations 1 and 2 for the class up to C50/60, that is for the class higher than C50/60, respectively:

$$f_{ctm} = 0{,}30 \cdot f_{ck}^{\ 2/3} \ [\text{MPa}] \quad (1)$$

$$f_{ctm} = 2{,}12 \cdot \ln(1 + \frac{f_{cm}}{10}) \ [\text{MPa}] \quad (2)$$

Where:

f_{ctm} [MPa] – the mean value of axial tensile strength of concrete cylinder,

f_{ck} [MPa] − characteristic compressive cylinder strength of concrete at 28 days and

f_{cm} [MPa] – the mean value of concrete cylinder compressive strength.

The dashed line in the diagram in Figure 4 represents a good approximation of the connection between tensile and compressive strengths, as already noted, by various experimental researches, which is derived by the modification of the above-stated expressions in the form:

$$f_{ctm} = 0{,}28 \cdot f_{ck}^{\;2/3} \quad [\text{MPa}] \qquad (3)$$

Based on the above, it can be seen that tensile and compressive strength ratio of recycled aggregate concrete is averagely by 7% lower than the ratio defined for natural aggregate concrete according to Eurocode 2, regardless of the share of recycled aggregate in the total mass of applied aggregate.

The elasticity modulus of recycled aggregate concrete is lower than the one of comparable natural aggregate concrete, which is a consequence of significant amount of old cement mortar (in grains of recycled aggregates), which has relatively low elasticity modulus. Research suggests that the level of decrease of modulus significantly depends on the type of fine fraction in the aggregate mass. In fact, in concrete with 100% content of recycled coarse aggregate and natural fine aggregate, a decline of elasticity modulus in relation to concrete made entirely with natural aggregate goes up to 20%, while in the case of concrete produced entirely of recycled aggregates, decline of elasticity modulus ranges from 15% to 45% in relation to natural aggregate concrete. Also, it is interesting to note that several studies have noted that the difference level in elasticity modulus between recycled aggregate concrete and natural aggregate concrete depends also on the compressive strengths of observed concretes, in the sense that for concretes with middle values of strength of up to 30 MPa the difference in the modulus values is almost negligible, while on the other hand, with the increase in strength above the stated value, the difference between the subjected modules increases.

4.4. Abrasion resistance

The use of recycled aggregate concrete influences abrasion resistance, in a way that an increase in the quantity of this aggregate reduces resistance to abrasion, due to higher amount of cement matrix, which is more easily abraded than the grains of natural aggregates.

Adhesion between concrete and reinforcement does not significantly depend on the presence of recycled aggregate in the mixture, since the adhesion is achieved through the new cement matrix.

4.5. Exploitation properties in sense of durability

General conclusions about the characteristics essential for the durability of concrete with recycled aggregate cannot be made due to contradictory conclusions in the existing literature. However, the facts related to the existence of two interfacial transition zones and usually higher permeability of concrete based on recycled aggregate in relation to the comparable natural aggregate based concrete, indicate greater vulnerability to degrading mechanisms during exploitation. However, as permeability largely depends on the size, distribution and continuity of capillary pores in cement matrix and interfacial transition zones in concrete structure, by applying the above-described specificities related to the composition, design and preparation of these types of concrete, it is possible to produce satisfactory, even high-performance concretes, in terms of durability [4,9,15−25].

5. STRUCTURE OF CONCRETE

The recycled aggregate concrete generally has much more complex structure than natural aggregate concrete, primarily due to the existence of two different forms of interfacial transition zones within the composition of grains. Namely, while analyzing at micro level, the so-called „old" and „new" interfacial transition zone can be observed. Old interfacial transition zone is located between the original grain and original cement mortar that is completely or partially attached to it, while the new interfacial transition zone is located between the recycled aggregate grain and the new cement mortar. Furthermore, the complexity of the form is even more pronounced when the recycled aggregate concrete is produced with a certain share of recycled aggregates, as it is often the case in practice, for which stated concretes are made (especially structural concretes). Then there will be two forms of new transition zones, which differ in terms of structure (first - an interfacial transition zone between cement mortar and natural aggregate and second - between cement mortar and recycled aggregates).

According to all results, whether our own, or from the research of the cited authors, it is not possible to influence the characteristics of the „old" interfacial transition zone during the mix design of the new concrete, but the appropriate principles and methods of preparing can affect the properties of the „new" interfacial transition zone.

Researches conducted by S. C. Poon, H. Z. Shui and L. Lam, from the University of Hong Kong, [26] point out that the new interfacial transition zone, within the recycled aggregate grain, to a large extent has the properties of interfacial transition zone between the grains of the lightweight aggregates and the mortar - in the case of lightweight concretes, where due to the porosity of the grain, it begins below the grain surface and spreads to the cement mortar, whilst being dependent on various possible processes, such as:

− water absorption from cement paste, when the aggregate is dry,

− release of water in the interfacial transition zone when the aggregate is moist,

− penetration of the cement material into the pores and

− possible chemical reaction with the aggregate.

Researchers from the University of Science and Technology in Norway - M. H. Zhang and O. E. Gjorv [27], have found that the structure of the interfacial transition zone has a lower density if the aggregate grain has a higher density in the surface layer. In fact, this is because there are more calcium hydroxide ($Ca(OH)_2$) crystals in the interfacial transition zone, similar to the interfacial transition zone at the contact of natural nonporous aggregates, so that the water that accumulates in the vicinity of grains cannot be absorbed into the pore structure of aggregates, to the extent at which it would have been absorbed if the grain was more porous. The cited researchers also suggest that a thicker interfacial transition zone implies better adhesion between aggregate grain and cement matrix, and finally better physical-mechanical properties. The stated conclusions were confirmed several years later by researchers from the Technical University in Israel - R. Wasserman and A. Bentur [28], who examined the rapidity of water absorption in the aggregate grains. By heating aggregates at high temperatures, the properties of the surface layer of aggregate changed in a way that the porosity was reduced, density increased, and thus the rate of water absorption decreased, but also, the width of the interfacial transition zone increased. Thus they concluded that the absorption of water from the cement paste, into the aggregate pore system, prevents the accumulation of water in that zone, which is generally considered to be the main cause of the formation of its porous structure.

By applying „SEM" (scanning electron microscope, which achieves up to 300.000 times magnification) for interfacial transition zone recording, researcher M. Radeka from the University of Novi Sad, found that the interfacial transition zone in the concrete based on aggregates obtained by recycling old concrete could be seen as a zone that has properties somewhere in between the properties of the interfacial transition zone in the „ordinary" concrete (made from natural aggregates, assuming that the natural aggregate is non-porous) and the properties of the interfacial transition zone in lightweight aggregate concrete (lightweight aggregate is porous). Also, the mentioned researcher believes that the recycled concrete aggregates with high mechanical properties can be expected to have the characteristics of the interfacial transition zone which are closer to the „ordinary" concrete (natural aggregate concrete), and also that the situation is reversed in the case of aggregates obtained by recycled lower strength concretes [6, 29].

Based on the above, it is clear that the porosity of recycled aggregate grains can, to a certain extent, have a certain advantage over natural aggregate, because the present pores can absorb water from the cement paste, so that the interfacial transition zone of greater compactness is formed, but, on the other hand, at the same time its significant disadvantage is in the fact that the water absorption from the cement paste may cause a deficiency of water needed for the process of cement hydration, within the newly-made concrete. In this regard, the conclusion arises that for the modeling of the microstructure of recycled aggregates concrete it is necessary to know the precise value of the actual characteristics of recycled aggregates, primarily its capacity in terms of absorption.

In 2004 the Spanish researcher E. M. Larranga published his research [30] on recycled aggregate concrete, in which he, according to a comprehensive analysis of experimental tests of physical-mechanical properties and the structure of transit zones, using the SEM, found that the best characteristics of concrete were obtained when recycled aggregate from waste concretes was previously saturated with water, up to the value of 80% of the total water that it can absorb.

Chinese researchers L. Gengying, X. Huicai and X. Guangjing, in their work related to finding possibilities for modeling the microstructure of recycled aggregate concrete [31], have estimated the quality of the connection between the recycled aggregate and the new cement matrix on the basis of morphology, mineralogy and microstructure formed in the interfacial transition zone. They used „SEM", supplied with „EDS" analysis (energy dispersive spectrum), to compare concretes made from different cements, such as: pure portland cement, expansive cement, cement with the addition of polymers - epoxy resin, and pozzolanic cement. Based on the determination of strength during movement on the part of the transiting zone which represents the zone between the original mortar (which is an integral part of the recycled aggregate) and the new mortar, it was found that the best connection is established by use of pozzolanic cement, then expansive cement, while the worst connection was established in concretes made with cement with an addition of polymers. In their explanation, the authors point out at hydrophilic properties of concrete which are the reason for a significant flow of water from the new cement paste towards the surface of the original mortar. The flow of water leads to local increase of water-cement ratio. Due to chemical reaction of the amorphous silicon from the pozzolan with calcium hydroxide occurs the formation of a compound of CSH, and the pores get filled in. Pozzolan particles effectively fill in the pores in the interfacial transition zone, which results in an interfacial higher density transition zone. When expansive cement is used, ettringite dominantly forms, and when portland cement is used, both calcium hydroxide and ettringite form. In the case of cement modified with polymers, only a film based on polymers is observed in the transition area [32,33].

6. CONCLUSION

The quality and properties of recycled aggregate are most dependent on the quantity and quality of cement mortar, which is attached to the grains of recycled aggregate, that is, on the quality of the original concrete by whose recycling the aggregate is produced, whereby, a method of recycling also has a considerable influence. Generally, recycled aggregate, in comparison to the aggregate obtained from natural resources, is characterized by: higher water absorption, lower density, higher content of organic and possibly harmful substances, higher level of crushability, reduced abrasion resistance and reduced resistance to frost. In addition, in cases when the recycled aggregate originates from many different sources, that is, if produced from a number of different waste concretes, quality unevenness, in the sense of variations in properties, will be much more pronounced than in the case of natural aggregates, and therefore, it should be a common practice of concrete manufacturers to make a thorough analysis of the properties of recycled aggregates before using them.

Recycled aggregate concretes can have a satisfactory, even high level of performance, which primarily depends on the characteristics of the waste concrete, in terms of being a feedstock for the production of recycled aggregates, primarily on its compressive strength, but also recycling method, as well as the knowledge of all the specificities related to mix design and preparation of these types of concrete. In this regard, it is especially pointed out that fine fractions of recycled aggregate generally have a bigger impact on reduction of quality of concrete, therefore, in practical application they are usually replaced by fine fractions of aggregates which come from natural resources, mostly with river sand, while for the designing of structural recycled aggregate concrete, the use of recycled aggregate usually ranges from 20% to 45% of the total coarse fraction mass.

By using recycled aggregate made of original concrete with higher compressive strength than the target value of strength of the new concrete, in general, concretes that are made are of the same and often better performance compared to the same natural aggregate concrete. However, in practical application it often happens that available resources, in the sense of original concrete, have almost equal, frequently even lower strength values compared to the target value of new concrete, so that, in general, it has been shown that the presence of recycled aggregate reduces bulk density, compressive strength and elasticity modulus, affects the increase of shrinkage and creep deformations of concrete, the increase of abrasion resistance, permeability increase, etc.

Finally, according to a comprehensive analysis of research conducted by eminent professional and scientific public, as well as based on personal year-long experimental studies and practical application, it can be concluded that the recycled aggregate is suitable for the production of concrete of most frequently requested properties in practice. Due to the emergence of extremely large amounts of construction waste which resulted from recent floods, the governmental strategic planning in the sense of findings presented in this paper is highly recommended.

7. ACKNOWLEDGEMENTS

This paper presents a part of research that was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia within the technological project TR 36017 entitled: „Utilization of by-products and recycled waste materials in concrete composites in the scope of sustainable construction development in Serbia: investigation and environmental assessment of possible applications”.

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СВОЈСТВА БЕТОНА НА БАЗИ РЕЦИКЛИРАНОГ АГРЕГАТА

Сажетак: По узору на велике свјетске силе, које су након природних катастрофа и ратова развиле индустрију рециклаже, у раду се указује на могућност искоришћења велике количине грађевинског отпада, насталог као посљедица недавних поплава у Босни и Херцеговини и Србији. На основу дугогодишњих опсежних експерименталних истраживања, али и истраживања еминентне стручне јавности, даје се преглед најбитнијих карактеристика и могућности примјене бетона, пројектованог на бази рециклираног агрегата – производа отпадног бетона. Показује се да је примјеном крупног рециклираног агрегата од отпадног бетона, као компонентног материјала у бетонским мјешавинама, могуће произвести конструкцијске бетоне задовољавајућег, па чак и високог квалитета, што првенствено зависи од карактеристика бетона чијим дробљењем је добијен агрегат.

Кључне ријечи: бетон на бази рациклираног агрегата, грађевински отпад, својства бетона, истраживања.