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ACHIEVING SUSTAINABILITY OF CONCRETE BY RECYCLING OF SOLID WASTE MATERIALS

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ABSTRACT

The concept of a sustainable development in the field of engineering offers several possibilities for utilization of the recycled solid waste materials. This paper deals with the properties of cementituous composites (concrete and mortar) based on recycled materials and the specific problems for their production technology and application. The main goal of the performed research was to achieve a more sustainable concrete using different recycled aggregate types, such as: "demolished" concrete, crushed bricks, recycled rubber and recycled "Ytong" blocks. Also, part of the investigation included the possible application of supplementary mineral materials – cement substitutes such as metakaolin, slag, fly ash etc. The acquired experience in this field and a possible practical application of such composites are presented in the paper.

Keywords: recycling, sustainability, concrete, aggregate, solid waste materials, recycled concrete, crushed brick, recycled rubber, concrete mix design

1. INTRODUCTION

It is commonly known that the generation of solid construction waste represents one of the most significant problems of our civilization. The increase of population, the urbanization and the industrialization directly affect the increase in consumption of all kinds of materials and energy sources and, therefore, the increase of the amount of solid waste. The possible solution of this problem is presented by the philosophy of sustainable development. To recall, the so called "sustainable development" implies such a developing path, which will ensure the use of natural resources and will create assets in a manner to ensure meeting the needs of the present generations, without compromising the future generations. Sustainable development is one of the few ever present issues, which is, from day to day, more topical - primarily because it is of great importance for a modern society. The application area of sustainable development is practically inexhaustible, considering that the present concept is applicable to all forms of human activity. Thus, in the construction sector, sustainable development is applicable on many levels, one of which is the production and the use of the recycled materials, especially concrete (as a percentage of the most commonly used construction material). The term "recycling", in general, is defined as a single use or multiple usages of waste materials as an effective substitute for a commercial product or as raw material in further industrial process.

According to the available data regarding the construction materials, the bricks have the highest percentage of recycling (35%), followed by concrete (20%) and wood (12%) etc. (see Fig. 1) [1].

Generally, construction is an activity, harmful to the environment. Its adverse effects include damage to the biosphere and the biodiversity, the exploitation and the transformation of the terrain, the depletion of natural resources (energy, minerals, water, fertile soil), chemical, physical and visual pollution (for land, air and water), the waste generation and the climate change.

When we talk about concrete as a potential environmental or "green" material, first we should point out its basic flaws. Namely, the production of its component materials (cement, aggregates, chemical and mineral supplements) and, finally, the production of the concrete itself, require a large amount of energy and generally represent a significant source of environmental pollution. It is a known fact that the production of one ton of cement, releases into the atmosphere about the same amount of carbon dioxide (CO_2). Globally, about 5% of all CO_2 emissions come from the cement production. It is therefore of special importance to implement the well-known principle of "3R" (Reduce, Reuse, Recycle) in this area. The goal is to reduce energy consumption and the pollution levels (Reduce), re-use the old concrete as the aggregate in order to produce new (Reuse), recycle the concrete (Recycle). Also, within this concept, the cement used for making concrete can be successfully replaced by different mineral materials (for example, fly ash or slag) or binders, whose production requires less energy consumption (for example, highly reactive metakaolin) [1, 28].

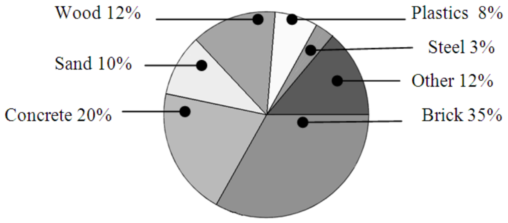

Fig. 1. Recycling percentages of different building materials [1]

Recycling of Construction and Demolition Waste (C&D Waste) is a socio-economic priority, since it represents a non-negligible percentage of the total quantity of waste generated as a product of various human activities. Of course, the amount of C&D Waste, lies in direct proportion to the level of the construction activity and differs from country to country [2], but it represents a significant problem, practically everywhere.

From the economic point of view, recycling of C&D waste is generally an expensive process. Investors and contractors reach compensation in this process, only if the state finds interest to help them in such effort - through various forms of positive (reduction of fiscal obligations, direct cash grants, soft loans, etc.) or negative stimulus (eco-tax, for example). In order to achieve cost savings (in money or energy consumption), to conserve the non-renewable resources, in terms of environmental protection and similar,), or simply to make 1 m3 of concrete cheaper, it is necessary to establish a cooperation among the various entities in the community. These include: cement factories, aggregate separations, manufacturers of chemical and mineral supplements, concrete factories, state and local governments, manufacturers of building materials, investors and contractors, the financial sector, chambers of commerce and chambers of engineers, scientific and research organizations (universities and institutes) etc. Of course, it is not easy to establish such a complex relationship and to ensure that all subjects in such a project find a common interest. The state, as a promoter of higher "government" and "global" goals, must play a key role in the process.

The most common case of obtaining recycled aggregates, which can be used to make new concrete, is related to the application of fractured clay bricks remains and old (so-called "demolished") concrete. This is because the reconstruction of the individual buildings, or even the entire neighborhoods, is often performed in modern cities, usually in order to modernize the city's central zone. In doing so, the most ruined buildings are being partially or totally destroyed and the waste building material is removed from these sites. Also, due to degradation over time and the limited life cycle, many objects need to be replaced with new, technically and economically favorable solutions. In addition, especially lately, we are witnessing numerous devastating natural disasters (earthquakes, floods, typhoons, tsunamis, fires) and man-made disasters (wars, terrorist attacks and nuclear accidents). These events are inevitably followed by processes of clearing the debris and removing the waste building materials. Hence, the disposal of such materials is becoming an increasing problem, particularly in densely populated urban areas. Solving this problem is quite challenging in technical, technological, economic, as well as in ecological terms.

It should be noted that, during the recycling process of solid construction waste, particular attention must be paid to removing unwanted and/or harmful impurities, such as lime, gypsum, clay, glass, metals, humus and alike. If we take into account that, for instance in Serbia, over 80% of buildings are partially or completely made of brick, it is obvious that the future in this field lies in the recycling of old degraded brick.

Construction is an activity in which, as noted above, large amounts of natural resources are being used. For example, the annual production of concrete in the world uses about 9 billion tons of aggregate and over 2 billion tons of cement. According to the postulate of sustainability, the main goal is to find alternative sources of raw materials for these products, which can be achieved by recycling.

As a good example of recycling, we can mention used (waste) tires which are a very valuable raw material because they can be completely recycled and used as a partial replacement of aggregate for concrete. Specifically, the primary product of this recycling process of waste tires consists of rubber granules; a mass of granules represents 55-65% of the tire weight. A secondary product of this process is the steel wire (25-30% of the mass) and a tertiary product is the textile fibers that make up about 10% of the tire weight. As it is already known, a wide application of rubber in the past 100 years and its use in the automotive industry resulted in the vast amounts of used tires to be disposed of. The European norms in this area are clear: according to the EU Directive 199/31 EC, the disposal of whole waste tires into the environment is not permitted since 2003 and even the disposal of cut waste tires is not permitted since 2006.

What is the situation in this field, in Serbia? Although there are no precise data, it is estimated that, in Serbia, about 28,000 tons of waste tires are ”generated” annually, of which 7000 tons are used by cement factories as fuel. The main problem of the disposal of used old tires is the tire size, i.e. about 75% of space that holds the tire is empty. Used tires in landfills threaten human health, and they are an excellent basis for the development of pests (insects and rodents); also, they represent a great threat for the occurrence of fire. However, as a "shining" example in Serbia, one can cite the fact that recently "Tigar" corporation from Pirot began the production of various products made of recycled tires [21, 26].

As for the recycling of bricks in Serbia, this area is still not fully regulated, which means that this type of aggregates can be obtained only from the waste material generated during the production of construction ceramics. However, the amount of such waste is not large (in the case of applying a modern technology, it amounts to only 3-5% of the total production). It naturally raises the question of economic feasibility of using fractured bricks as aggregate for the production of the concrete. The producers of construction ceramics often use this waste as a raw material in their further manufacture, as a more profitable solution, or even grind it and then sell it as powder (used, for example, as a surface of tennis courts).

The situation is similar with other recycled materials that can be used, more or less successfully, as aggregates or fillers for the asphalt or the classic concrete. These materials are: waste glass, recycled Ytong (Siporex) blocks, fly ash etc.

2. BASIC PROPERTIES OF RECYCLED AGGREGATE

The use of recycled aggregate as a component for producting new concrete requires a thorough database regarding the properties of such aggregates. Above all, properties such as: the absorption of water by volume, the gravity, the amount of fines and contaminants (for instance, organic matter and potentially harmful particles), the crushing resistance, the wear and freeze-thaw resistance are the most important ones that must be recognized.


Fig. 2. Appearance of recycled concrete aggregate

In fact, the investigations have shown that the recycled aggregate, in comparison to natural one, shows following properties: a higher water absorption, a lower density, a greater amount of contaminant particles, a higher content of organic and other potentially harmful substances, a lower crush resistance, a lower resistance to abrasion and a lower freeze-thaw resistance.

The appearance of the recycled crushed aggregate, based on "demolished" concrete (various fractions) is shown in Fig. 2 [1, 20].

Naturally, the quality and characteristics of the concrete made with the recycled aggregate will directly depend on the properties of the used recycled aggregate.

It is known that the recycled concrete aggregate consists of the used - original aggregate and a layer of mortar remaining after crushing. The water absorption of the recycled concrete aggregate tends to be significantly greater than of natural aggregate, which is certainly related to: the type of the original aggregate, the initial strength of concrete and the largest aggregate grain in the original concrete [8].

The water absorption of recycled concrete aggregate tends to be even larger, if the quantity of mortar surrounding the original grains increases. Investigations showed that the water absorption of recycled aggregates increases with decreasing the size of grain used in the original concrete. This is due to larger specific surface area of smaller grains, to which a larger amount of mortar can be attached.

The recycled aggregate’s capacity of water absorption, which certainly depends on the quality and the thickness of mortar layers wrapped around the aggregate, should be determined as one of the fundamental properties - before incorporating recycled aggregates in the new concrete. Also, the recycled aggregate generally has a lower density than the natural one because of the presence of the porous layer of mortar, as discussed earlier.

As many researchers reported, the impact and the wear resistance of the recycled aggregate is lower in comparison to the natural aggregate; this is also due to the existence of a porous mortar layer around the grain of the recycled aggregates, which spalls and crushes more easily [8].

All above mentioned features directly imply certain details in the technology of making concrete with recycled aggregate, which will be discussed later.

Some authors [16] proposed the division of the recycled concrete aggregates in classes based on the water absorption and the freeze-thaw resistance, determined using sodium sulfate (Na_2SO_4) method. Thus, three classes have been proposed for the coarse recycled aggregates, with a maximum water absorption ≤7%, and two classes for the fine recycled aggregates, with a maximum water absorption ≤10% (Table 1). Closely related to this, the authors recommended possible applications (for reinforced and unreinforced concrete, tampons, pads for leveling and so on) in construction (Table 2).

Table. Recycled concrete aggregate classes

Aggregate type	Coarse recycled aggregate				Fine recycled aggregate	
Aggregate class	C1	C2		C3	F1	F2
Absorption (%)	≤ 3	≤ 3	≤ 5	≤ 7	≤ 5	≤ 10
Freeze-thaw resistance – method based on immersion in Na_2SO_4 sollution (%)	≤ 12	≤ 40	≤ 12	-	≤ 10	-

Table 2. Recycled concrete aggregate classes and possible application in construction industry

Application class	Coarse aggregate	Fine aggregate	Compressive strength (MPa)	Proposed application in construction industry
Engineering structures				
CI	C1	Natural	18 – 24	Reinforced and unreinforced concrete: substructure of bridges, tunnel lining, retaining walls
CII	C2	Natural or F1	16 – 18	Unreinforced concrete: building blocks, road bases, docks, retaining walls, etc..
CIII	C3	F2	< 16	Tampons, leveling layers
Buildings				
BI	C1	Natural	≥ 18	Building structure elements
BII	C2	Natural	≥ 18	Foundations, piles
BIII	C2	F1	≥ 18	Foundation plates, on-ground plates, leveling layers
BIV	C3	F2	≥ 18	Bases, leveling layers

3. THE STRUCTURE OF CONCRETE WITH RECYCLED AGGREGATES

The structure of concrete, as it is known, represents a three-phase system as follows:

- the macrostructure - the structure of two-component system composed of mortar and a coarse aggregate,
- the microstructure, i.e. structure of hardened cement paste and
- the interfacial transition zone ("interface") between the aggregate and the cement stone.

The interfacial transition zone (ITZ) between the cement paste and the aggregate in the concrete is always a critical place and many properties of the concrete as a composite (especially durability) depend on the properties of this zone (e.g. its quality, its thickness)

[12]. The structure of the concrete with recycled aggregate is, therefore, even more complex. In fact, the concrete made of a recycled aggregate (Recycled Aggregate Concrete - RAC) has two ITZ zones, one between the recycled aggregate and the cement paste (new ITZ) and another between the recycled aggregates and the "old" mortar (old ITZ). This is shown in Fig. 3 [2].

The residual cement mortar in the ITZ is significantly porous and contains cracks that affect the final properties of such a concrete (RAC), especially on bearing the compressive strength. Studies have shown that the ITZ appears between 20-40% of the total volume of the cement matrix [4].

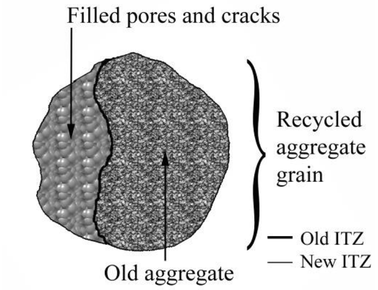

Fig. 3. The interfacial transition zones (ITZ) in concrete with recycled concrete aggregate

As noted above, these pores and cracks increase the need for water, i.e. increased water absorption of the recycled aggregate is taking place. This water is being drained from the fresh cement paste. Therefore, the problem of the water lack needed for the complete hydration of cement in the concrete, is possible. The quality of the ITZ primarily depends on the surface properties of the aggregates, the degree of water separation ("bleeding"), the type of the chemical bonds, the curing methods and others. Scientists agree that the strength of the concrete increases with the strength of the matrix-aggregate bond [2].

In order to make recycled aggregate suitable for higher performance concretes, it is necessary to control the problems of high porosity, surface cracks, high content of sulfate and chloride, high level of the impurities and the residual cement mortar attached on the grains of the recycled aggregates.

4. SPECIFICS OF THE RECYCLED AGGREGATE CONCRETE MIX DESIGN

Different proposals in the technology of making concrete with recycled aggregates will be presented here. These proposals are based on literature data, depending on the manner and order of dosage of components in the mixer, and the duration of mixing. In all these cases, the recycled aggregate or a mixture of natural and recycled coarse aggregates were used as a coarse aggregate in a new mixture, while the fine aggregate (sand) in a new mixture was strictly natural, a river aggregate.

According to the usual (traditional) process of the concrete production, all the solid components of concrete are mixed first, then water is added and then it starts the mixing of the fresh concrete. More precisely, once the amounts of the component materials are measured (the coarse and fine aggregate, cement and water), the mixer is first filled with half of the coarse aggregate, then with the fine aggregate and the cement and, eventually, we add the rest of the coarse aggregate. After this, the entire amount of water is added and the mixing process starts, lasting approximately two minutes. The described procedure can be named as a normal mixing process (Normal Mixing Approach - NMA). It is also shown schematically in Fig. 4a. The explanation of the symbols is given as a legend below Fig. 4.

There is a second approach to define a mixing procedure, according to Tam et al. [2], based on the principle of separating the total amount of water in two. Therefore, this approach is usually named Two Stage Mixing Approach (TSMA). The process of making concrete on the basis of this approach (Fig. 4b) consists of the following activities: first the aggregate (sand and coarse aggregates) is added and the mixture is homogenized by mixing dry mixing (without water) for approximately 60 s. Then about half of the total amount of water is added and then further mixing is carried out for ≈60 s. After that, the entire quantity of the cement is added and mixed for about 30 s. Then the rest of the water is added and the mixing is prolonged within a period of approximately two minutes.

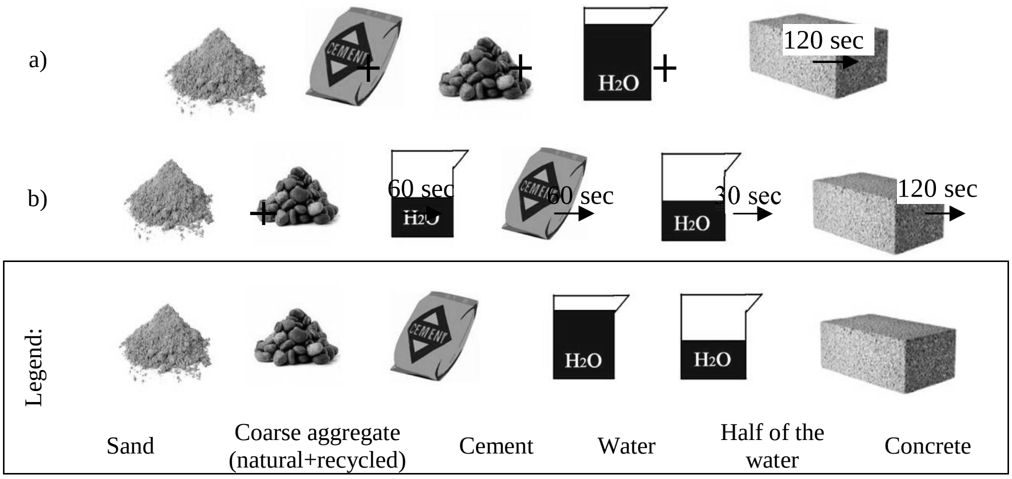

Fig. 4. (a) NMA method, (b) TSMA method

The TSMA method is proposed in the case of applying the recycled aggregates in the concrete, as an improvement of the NMA. In TSMA method, during the first stage of mixing, the cement and half of the amount of water form a thin layer of cement paste on the surface of the recycled aggregates. This paste can penetrate the porous old cement mortar, filling "old" cracks and voids (a reinforcement effect). In the second stage of mixing, the remaining water is sufficient for the hydration of the new cement. Through scanning electronic microscopy (SEM), it was observed that the interfacial transition zone becomes more compact when using TSMA method and that the cracks in the recycled aggregate grains are filled with more paste than the cracks in RAC prepared using NMA method [4] (Fig. 5).

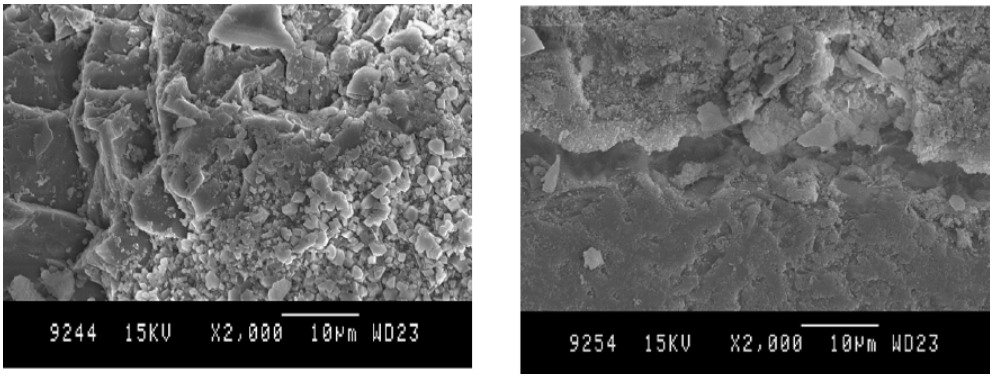

Fig. 5. Interfacial zone for TSMA (left) and NMA (right) methods

On the other hand, more gaps and cracks were discovered in the newly formed interfacial transitional zone in the RAC concrete which was prepared in the usual way (NMA), given that full hydration of the mortar in this zone was prevented by lack of water (absorbed by the grain of the recycled aggregate). A schematic representation of the recycled aggregates according to the method of mixing the two phases, is shown in Fig. 6.

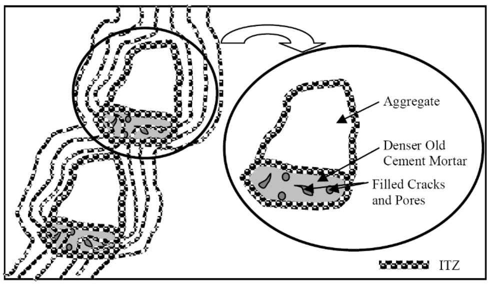

Fig. 6. Improvement of structure of recycled aggregate by TSMA method

Having in mind previous discussion, one can easily realize that improving the quality of new concrete is conditioned by improving the mechanical properties of ITZ. This improvement can be carried out by the use of a very fine pozzolanic materials (e.g. silica fume), which fills the cavities and cracks in the grains of the recycled aggregates, i.e. inside the mortar matrix attached to the old aggregate.

The addition of silica fume (e.g. ~2%) in the RAC generally leads to an improved performance of the concrete, as well as in the ordinary concrete. The concrete with addition of silica fume achieves greater strength through a longer period of time. The basic mechanical properties of concrete made in two phases (TSMA) as compared to normal (NMA) mixing process, i.e. compressive, tensile or flexural strength, splitting tensile strength and static modulus of elasticity, can be improved from 10% to 30% in the RAC composites, depending on the content of recycled aggregate in new concrete [2, 14].

5. INVESTIGATION OF THE CONCRETE MADE OF RECYCLED SOLID WASTE MATERIALS

For more then ten years continuously, experimental studies on several types of concrete made of recycled aggregates have been performed in the Laboratory for Materials, Faculty of Civil Engineering, University of Belgrade. This research includes applicability of crushed aggregate on the basis of "demolished" concrete, recycled rubber and fractured brick. The properties of the insulating lightweight concrete, based on the crushed "Ytong" blocks as aggregate, cement and polypropylene fibers, were also tested. Recent research has shown that the concrete based on recycled ”demolished” concrete can be successfully applied in various structural elements made of reinforced concrete.

5.1. The recycled aggregate concrete

A mix design of RAC is usually done on the basis of empirical methods, e.g. Scramtaev or Bolomey [26]. To carry out this procedure, it is essential to determine the density of each fraction of the recycled aggregate and the absorption of water. The problem of higher water absorption of the recycled aggregate can be solved in three ways according to [18] and [26], i.e. similar to light-aggregate concrete. The first way is to saturate recycled aggregate grains with water before the mixing process. The second way is to increase the water content, on the basis of water absorption after 30 minutes. The third way is to add water on site, to achieve the required consistency and this way should certainly be avoided.

Authors Malešev and Radonjanin [18] conducted an extensive experimental study of RAC at the Faculty of Technical Sciences in Novi Sad and recommended determination of water absorbed by the recycled aggregate after 30 minutes, as the additional amount of water for concrete. Also, these authors suggested checking the consistency of the fresh concrete after 30 minutes.

The relation between the coarse and fine aggregate in RAC (i.e. the optimal grain size distribution curve) is assumed to be the same as in the concrete with natural aggregates. The experiences show that, when using coarse recycled aggregate with natural fine aggregate, it can be assumed that the required w/c (water/cement) ratio for the targeted compressive strength will be the same as for concrete made entirely with natural aggregate.

According to the recommendations in many countries, the use of the coarse recycled aggregate with grains over 16-20 mm is restricted. Of course, the reason for this is the problem of durability of RAC.

Experiments have shown that the need for free water in RAC made of recycled coarse aggregate increased by 10 l/m^3 as compared to the conventional concrete. Due to the growing need for free water in the mixtures with recycled aggregates, the calculated quantity of cement should be slightly higher, in order to preserve the same w/c ratio. As for the type of cement for making concrete of the recycled aggregates, studies showed that all types of cement (CEM I - CEM V) may be used.

The mix design becomes more complex when it comes to production of SCC (Self Compacting Concrete) based on the recycled concrete aggregates. Namely, it is a known fact that SCC mixtures are very sensitive to changes in the water content. Therefore, they tend to lose their consistency very easily or the segregation of fresh concrete can occur. There is undergoing research of SCC with the addition of aggregates of "demolished" concrete, at the Civil Engineering and Architecture Faculty in Niš. The studies on the possibility of using the waste glass as aggregate for the mortar and the concrete are being conducted within the same institution.

5.2. Lightweight concrete based on crushed "Ytong" blocks

Three variant solutions of lightweight thermal insulation concrete mix composition were made of the cement class 42.5N, crushed „Ytong“ block grains, water and monofilament polypropilene fibers. Lightweight thermal insulation concrete marked as "1" contained only middle fraction (0.8-2.2 mm) of crushed „Ytong“ block grains. Two fractions (0.8-2.2 mm and 2.2-4.0 mm) were used for the preparation of concrete marked as "2", while a fine aggregate fraction (0.0-0.8 mm) was added in the concrete mixture marked as "3", besides two already mentioned fractions. The compositions of these three mixtures are shown in Table 3, together with water/cement (w/c) ratio and the composite density in fresh and hardened state [33].

Table 3. Lightweight thermal insulation concrete composition

Concrete mixture	"1"	"2"	"3"
Crushed „Ytong“ block grains size (mm)	- 0.8-2.2 -	- 0.8-2.2 2.2-4.0	0.0-0.8 0.8-2.2 2.2-4.0
w/c ratio	0.47	0.42	0.43
Density in fresh state (kg/m^3)	1420	1296	1426
Density in hardened state (kg/m^3)	909	865	967

According to the investigation programme, the following physical, mechanical and rheological properties were studied: the concrete density in fresh and hardened states, the flexural strength and the compressive strength after 7 days and 28 days, the adhesion to the concrete substrate after 28 days and the drying shrinkage deformation.

The compressive and flexural strength test results (according to SRPS ENV 197-1) after 7 and 28 days, are shown in Table 4. The adhesion to the concrete substrate, investigated after 28 days with "Controls" Pull-off testing device (Fig. 7), are also presented in Table 4. In all of these investigations, the fracture took place within the lightweight aggregate concrete.

Fig. 7. Adhesion measurement using Pull off device

The rheological behavior of these mixtures was also monitored. Namely, the drying shrinkage deformation of the lightweight concrete was measured on a cprism shaped 4 cm x 4 cm x 16 cm specimens, with built-in invar inserts. The measurements were made on an Amsler type apparatus (Fig. 8).

Table 4. Mechanical properties of lightweight concrete

Concrete mixture	"1"		"2"		"3"	
Age (days)	7	28	7	28	7	28
Compressive strength (MPa)	0.61	1.08	0.81	1.28	0.80	2.41
Flexural strength (MPa)	0.23	0.37	0.28	0.69	0.40	0.81
Adhesion (MPa)	-	0.12	-	0.15	-	0.74

Fig. 8. Drying shrinkage measurement on a specimen with built in invar inserts

The drying shrinkage deformations measured on the lightweight concrete *"1", "2" and "3"* amounted to 0.810 mm/m, 0.670 mm/m and 0.860 mm/m, respectively, at the age of 28 days.

The results showed that density of the hardened lightweight concrete based on crushed "Ytong" blocks varied within the limits of 865-967 kg/m^3. This concrete was designed as non-structural, thus achieving a high compressive strength was not of essential importance. However, this property varied between 1.08 MPa and 2.41 MPa, at the age of 28 days. The adhesion to the concrete surface varied between 0.12 MPa and 0.74 MPa, while the shrinkage strain after 28 days amounted to 0.670-0.860 mm/m. The thermal conductivity of this composite obtained a value of about 0.4 W/m°C, which means that this lightweight concrete has five times better the thermal protection in comparison to the conventional concrete [33].

According to this investigation and the analysis of the obtained results, such a lightweight thermal insulation concrete tends to represent a quite appropriate material for using it as a cement screed or as a basis for the final layers of practically all flooring materials types, executed over ground or all concrete plates. In such cases, this concrete acts not only as common cement screed, but also as a thermal insulation layer. It is important to stress that such a function can not be achieved using any ordinary kind of cement screed.

5.3. Crushed brick aggregate

The experimental tests [35, 36] conducted on composites based on recycled ceramic material (crushed brick) included the preparation and the testing of six different mortar mixtures (marked with capital letters A, B, C, D, E and F). All mixtures were made using 400 kg/m^3 of Portland cement blended with 15% of pozzolana:

- Mixture A – mortar based on crushed-brick aggregate fractions 0/2 mm, 0/4 mm and 4/8 mm.
- Mixture B – mortar based on crushed-brick aggregate fractions 0/2 mm, 0/4 mm and 4/8 mm with addition of 900 g/m^3 monofilament polypropylene fibers - type ″Fibrin″(Adfil, Great Britain).
- Mixture C – mortar based on crushed-brick aggregate fractions 0/2, 0/4 and 4/8 mm and river sand with grain diameter between 0/4 mm.
- Mixture D – mortar based on crushed-brick aggregate fractions 0/2 mm, 0/4 mm and 4/8 mm and river sand with grain diameter between 0/4 mm with addition of 900 g/m^3 monofilament polypropylene fibers - type ″Fibrin″ (Producer: Adfil, Great Britain).
- Mixture E – mortar based on crushed-brick aggregate fractions 0/2 mm, 0/4 mm and 4/8 mm with addition of 2% of ″Iriplast″ superplasticizer (Producer: Iris, Skoplje, R. of Macedonia),
- Mixture F – mortar based on crushed-brick aggregate fractions 0/2, 0/4 and 4/8 mm with addition of fibers (same as mixture B) and superplasticizer (same as mixture E).

The adopted mix designs for all six tested mortars are presented in Table 5. The quantities of water shown in the table represent the total doses meaning that one part of the used water was absorbed by the aggregate and another part provided the desired consistency of the fresh mixture.

Table 5. Mortar mix design

Mortar type		A	B	C	D	E	F
Cement (kg/m^3)		400	400	400	400	400	400
Aggregate (kg/m^3)	(I) 0/2 mm	574	574	328	328	574	574
	(II) 0/4 mm	492	492	410	410	492	492
	(III) 4/8 mm	574	574	574	574	574	574
	(IV) 0/4 mm	-	-	328	328	-	-
	Total	1640	1640	1640	1640	1640	1640
Water (kg/m^3)		490	490	416	416	430	430
Polypropylene fibers (kg/m^3)		-	0.9	-	0.9	-	0.9
Superplasticizer (kg/m^3)		-	-	-	-	8	8

The marks (I), (II) and (III) presented in the Table 5 stand for certain fractions of the crushed-brick aggregate, whereas mark (IV) stands for river sand. The measured densities of these aggregates in compacted state were as following: 1177 kg/m^3 (fraction I), 930 kg/m^3 (fraction II), 965 kg/m^3 (fraction III) and 1862 kg/m^3 (fraction IV).

The testing of mechanical properties of hardened composites based on recycled ceramic material (crushed brick) consisted of compressive and flexural strength tests. These properties were monitored over an extended period of time. Each test was carried out on three specimens (4 cm x 4 cm x 16 cm) from each of the six series, at the ages of 7, 28 and 180 days. Table 6 contains the compressive and flexural strength testing results of the mortar specimens from the series A, B, C, D, E and F.

Table 6. Compressive (f_p) and flexural (f_{fl}) strength values (MPa) of composites based on recycled ceramic material (crushed brick) of different ages

Type of mortar	Age of specimens (days)					
	7		28		180	
	f_p	f_{fl}	f_p	f_{fl}	f_p	f_{fl}
A	20.10	4.04	30.50	5.82	31.80	6.00
B	20.97	4.29	32.08	6.14	32.85	6.20
C	20.02	4.02	31.69	4.83	32.60	5.10
D	21.30	4.28	36.82	6.04	37.23	6.30
E	22.60	4.42	32.40	5.96	33.80	6.10
F	22.60	4.75	34.65	6.20	35.68	6.42

As concerning the rheological properties of the mortar, the experiment consisted of shrinkage measurements, which were performed on the prismatic specimens with dimensions 4 cm x 4 cm x 16 cm. This part of the test was especially important because of the fact that the shrinkage values for crushed-brick mortar and concrete are usually 20-60% higher than the same values for the normal composites. Because of the limited space, only the most interesting results will be highlighted here. Thus, for instance, at the age of 28 days the specimens of series B had 8% smaller average shrinkage than the specimens of series A, whereas the mortar marked as series D showed a 17% decrement in shrinkage deformation in relation to the mortar C. These relative rheological improvements in mortar quality can be contributed mostly to the presence of the monofilament polypropylene fibers at the series B and D.

The testing results of mechanical properties of fiber reinforced recycled brick composites showed that the addition of polypropylene fibers generally leads to improvement of these properties. For example, the increment of the compressive strength varies between 5% and 16% and the increment of the flexural strength, between 4% and 25%, in comparison to the non-reinforced mortar with the same consistency in the fresh state. These improvements can also vary with the change of the applied type of aggregate, i.e. depending on the adopted solution: to make the mortar using only the recycled bricks or to combine the recycled bricks with the regular river sand. As concerning the time-dependant shrinkage deformations, they usually tend to have higher values if the composite is based on the recycled brick aggregates, but such negative effects can be diminished to some extent with the addition of the fiber reinforcement. This hypothesis was confirmed during the laboratory testing, which showed a maximal decrement of shrinkage in amount of approximately 17%.

5.4. Waste tire rubber aggregate

Based on the results of several experimental studies [21, 22, 26, 36, 37] it can be concluded that the rubber granules can also be successfully used as an aggregate for the mortar and concrete. The percentage of the replacement of the total amount of aggregate in concrete with recycled rubber aggregate, affects the properties of the concrete, both in fresh and in the hardened state. The impact on the properties of fresh concrete includes change in density, percentage of entrained air, order of components dosage, as well as the possible presence of superplasticizer, in order to achieve a certain consistency.

The mix composition of the concrete made of 0%, 10% and 20% replacement of total quantity of aggregate with rubber aggregate (concrete mixtures designated as "1", "2" and "3") is shown in Table 7 [30]. The appearance of the cut specimens including rubber aggregate is shown on Fig. 9.

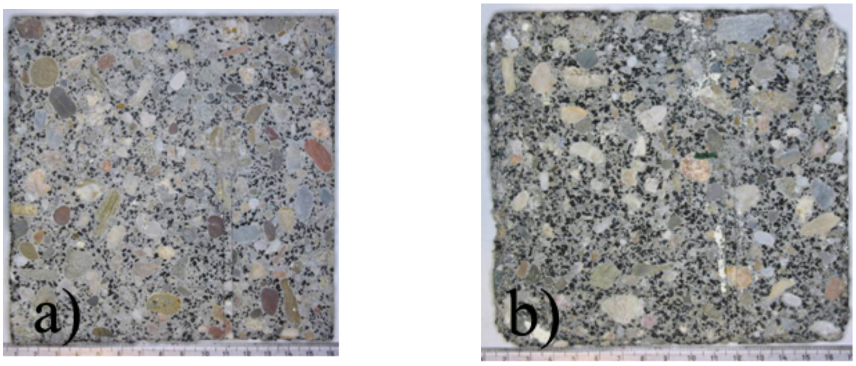

Fig. 9. Surface of the observed plates made of a) concrete with 10% and b) 20% of rubber aggregate

Table 7. Mix compositions for concretes with the addition of rubber aggregate

Concrete	ω	m_c (kg/m^3)	m_{ad} (kg/m^3)	m_w (kg/m^3)	m_a (kg/m^3)	m_I (kg/m^3)	m_{II} (kg/m^3)	m_{III} (kg/m^3)	m_{rr} (kg/m^3)
"1"	0.5	350	-	175	1804	769	393	642	-
"2"	0.5	350	1.75	175	1464	624	319	521	146
"3"	0.5	350	1.75	175	1232	525	269	439	246

Symbols used in the table: ω – water/cement ratio, m_c – mass of cement, m_{ad} – mass of superplasticizer, m_w – mass of water, m_a – mass of aggregate, m_I – mass of the first fraction of aggregate, m_{II} – mass of the second fraction of aggregate, m_{III} – mass of the third fraction of aggregate, m_{rr} – mass of recycled rubber.

The influence of the rubber aggregates addition on the properties of hardened concrete is reflected in the reduction of mechanical strength; the compressive strength and the tensile strength decrease with the increase of the applied recycled aggregate. This statement was confirmed by other researchers in previous studies. Results of the investigations made on hardened composites with 0%, 10% and 20% (vol) of rubber granulate (concrete mixtures designated as "1", "2" and "3") are shown in Table 8.

Table 8. Properties of hardened concrete

Concrete	Density (kg/m^3)	$f_{c,7}$ [MPa]	$f_{c,28}$ [MPa]	$f_{t,28}$ [MPa]	$f_{st,28}$ [MPa]	E_s (GPa)	E_D (GPa)	v (m/s)
"1"	2370	39.8	41.8	2.82	2.98	30.9	38.8	4211
"2"	1931	10.9	13.5	1.27	1.68	17.1	18.4	3123
"3"	1702	6.2	6.6	0.63	0.62	6.3	9.1	2415

While the compressive strength (f_c) was measured at the age of 7 days and 28 days, respectively, the tensile strength (f_t), the spliting tensile strength (f_{st}), the static (E_s) and dinamic (E_D) moduli of elasticity and the ultrasonic sound velocity (v) results are obtained at the age of 28 days.

The investigation results showed that the addition of the recycled rubber has a considerable influence on the hardened concrete properties, leading to reduced mechanical strengths. Both compressive and tensile strengths declined with the increased content of the applied rubber aggregate. According to the results, the incorporation of 10% and 20% of the rubber aggregate in the concrete leads to the reduction of the compressive strength with 67.7% and 84.2%, at the age of 28 days, respectively. The reduction is 55.0% and 77.7%, respectively, for the tensile strength at 28 days; a reduction of 18.5% and 28.2% in the density of hardened concrete. Observing the deformation characteristics through resonant frequency, ultrasonic pulse velocity and modulus of elasticity, it is obvious that the rubberized composite materials have shown a decrease of these values.

The recycled aggregate concrete based on waste tire rubber aggregate falls in the category of lightweight concretes ($\gamma<2000$ kg/m^3) and can find a wide application in construction - especially as noise and vibration protection materials.

Due to its properties such as: elasticity, durability and freeze-thaw resistance, the rubber as aggregate is already widely used in civil engineering. In fact, for many years now, recycled rubber has been added to asphalt mixtures in road construction industry. This field of application is based on the advantages of this material such as: noise reduction, braking distance reduction, increased service life of road construction, increased cracking resistance. The composites based on recycled rubber are also suitable for road construction industry elements: parking poles, signaling devices, rail crossings, traffic barriers etc. Due to the above-mentioned properties, the rubber granules have also found a great application in the manufacture of elements for railways, such as: rubber panels, railway sleepers etc.

6. POSSIBILITY OF REPLACING CEMENT WITH RECYCLED MINERAL SUPPLEMENTS AND/OR OTHER BINDERS

Recycling of various by-products of heavy industry and energy sector is also more studied recently. Application of these by-products allows partial substitution of the cement. For example, in the last 20-30 years, materials like: fly ash, blast furnace slag, granulated slag and silica fume have mainly been used as the partial replacement of clinker in cement. Natural limestone and natural pozzolanic materials are often used as well, as components of cement. Figure 10 shows the estimate of the application of clinker mineral supplements in the period 1973-2007 [39].

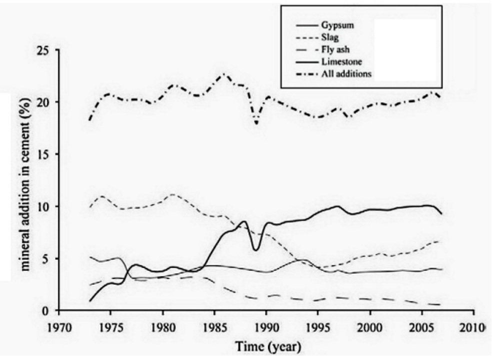

Fig. 10. The estimated clinker replacement percent with different mineral admixtures, in the period 1973-2007

Using these so called conventional admixtures has limitations. Therefore, extensive researches of the possibilities of using new materials are being conducted all over the world. Their application could lead to achieving certain improvements in characteristics of cement, mortar and concrete, while reducing the energy consumption and the emissions and, if possible, the price reduction of the final product, at the same time. One of the mineral supplements of the new generation, which meets the requirements of a sustainable development and contributes to the improvement of the properties of the mortar and the concrete, is the metakaolin.

In addition, regarding the quality of the mineral admixture, the metakaolin is a consistent product, because it is produced under controlled conditions concerning: the chemical composition, the size distribution of particles, the pozzolanic activity and the color.

In Serbia, the annual production of Portland cement with artificial pozzolans amounts to approximately 2.5 million tons (blast furnace slag, silica fume, fly ashes, natural pozzolans), labeled as CEM II. The share of the additives in the cement ranges from 5% to 35% (mass weight) and mainly depends on the market demand for certain types of cement. In Serbia, the cement is produced in three cement factories ("Lafarge" - Beočin, "Titan" - Kosjerić and "Holcim" - New Popovac); none of the above mentioned cement factories use the metakaolin as a constituent in cements because this material is not produced in our country [32].

Since the mid-1990s, a highly reactive metakaolin (HRM) is produced in several factories around the world: AGS Mineraux-France, Cluz as-Czech Republic, BASF-USA, Advanced Cement Technologies, LLC-USA, Whitmund-Canada etc. HRM is conventionally produced by thermal activation/calcinations of previously purified clay with a high content of kaolin and its application in the standard concrete is limited due to relatively high production cost (500 $/t). The production costs of the metakaolin could be significantly reduced, if the process of the thermal activation of the kaolin clay with a low content of kaolinite is applied, but without a purification stage. This change in the production process is justified, even for the production of the standard mortar and concrete [28, 39].

Having all of the foregoing in mind, the Institute for Testing Materials IMS developed the technology for obtaining an artificial pozzolana – the metakaolin out of kaolin clay Vrbica. The verification of the pozzolanic behavior of the produced metakaolin was done by determining the properties of Portland cement with the addition of 5%-20% metakaolin and comparing to the properties of the ordinary Portland cement. The comparative analysis of the characteristics of the pure Portland cement (CEM I) and the cement with the addition of the metakaolin (CEM II) showed that the addition of the metakaolin shortens the setting time (beginning and end) and leads to lower values of the compressive strength after 2 days. Regardless of the percent of the metakaolin, the compressive strength after 7 days and 28 days, respectively, was greater than the strength of Portland cement. It was found that the addition of 10%-15% of metakaolin to the cement (which represents the optimal amount) increases the compressive strength of the composite with approximately 15%.

6. CONCLUSIONS

Fully understanding the properties of recycled aggregate (crushed bricks, concrete, rubber or other materials), their producing procedures, i.e. crushing and selection by categories and classes depending on their primary properties (density, water absorption, frost resistance, strength of original concrete etc.) will certainly contribute to a smaller dissipation of results in the future research. Also, a proper dosage of the components and a carefull mix design with respect to the general guidelines, will provide the production of a higher-performance concrete, i.e. the structural concrete based on the recycled aggregates. The cooperation among researchers from different fields (civil engineers, technologists, chemists, mineralogists) is welcome in order to verify the microstructural properties of the newly made concrete. Thus, the recycled aggregate will no longer be a heterogeneous component, i.e. an uncertainty in the technology of making concrete, but a solid construction waste, which experts skillfully manage.

The research of many scientists in this field shows that there is a great variation in the test results, so a general conclusions can not be done, for example, neither about the optimum percentage of the replacement of the natural coarse aggregate with the recycled aggregate, nor the utilization of the recycled fine aggregates. If we also add the possibility of using different additives like fly ash, admixtures and the use of the super plasticizers and the application of various types of fiber reinforcement, then, surely, there is scope for further experimental research in this area, within the limits of an economic profitability. The existence of some relatively contradictory test results in this field can slow down the journey towards a more intensive use of the recycled aggregates in the concrete. However, there should be hope that the synergy among the recycling facilities, the standards and the information networks will increase the use of the recycled aggregate as a concrete component. Considering this, a special attention should be given to the trial batch tests (especially regarding the optimum percentage of the recycled aggregates in the mix) and the specifics of the technology of making concrete based on the recycled aggregates.

At the end of these considerations, we must raise the question of how to move forward in the environmental policy to influence the increase in the percentage of recycling the construction materials and the industrial waste, how to build cheaper and, yet, of good quality and environmentally friendly? This can be achieved only by education, easily accessible information, better planning of projects, understanding the problems of recycling in the broadest sense, as well as selection and certification of recycled materials. Numerous examples in the world clearly show that it is necessary to make a political decision and implement the principle of "polluter pays", no matter how clearly the need for recycling is showed. In general, the construction industry is relatively conservative, and changes in the established procedures require considerable time and long-term policy and strategy. The introduction of the economic and legal instruments that encourage the recycling of the solid waste materials and the use of the recycled aggregate, can overcome the traditional barriers. As an example, it should be mentioned that some countries have introduced special taxes and cash benefits in favor of recycling. For example, the Danish government introduced a tax on the waste that is not recycled but disposed of in landfills, since 1986. Today, this tax is around 50 euros per ton of the disposed waste. Unfortunately, such fees in Serbia do not exist yet, but one should expect, however, that the path we are taking towards the European Union will partly be made of the recycled materials.

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