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Analysis of Possibilities for Using Recycled Concrete Aggregate in Concrete Pavement

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***Abstract*—**The present article describes the limits of using recycled concrete aggregate (denoted as RCA) in the top layer of concrete roads. The main aim of this work is to investigate the possibility of reuse of recycled aggregates obtained by crushing the old concrete roads as a building material in the new top layers of concrete pavements. The paper is based on gathering the current knowledge about how to use recycled concrete aggregate, suitability, and modification of the properties and its standards. Regulations are detailed and described especially for European Union and for Czech Republic.

***Keywords*—**Concrete, Czech Republic, pavements, recycled concrete aggregate, RCA, standards.

I. Introduction

RECYCLING construction waste in the form of aggregate in the new concrete mixtures is a field that is still developing even though it is not currently available in Czech Republic. Reasons are pretty obvious, and the major one is a small network of freeways compared to other countries with large transport infrastructure, such as the USA (over 1500000 km), Belgium (about 25000 km), and Germany (over 3000 km). Also, there is much higher demand, better environment for testing new technologies, and material innovations related to the recycling of the original structures in these countries [1].

This research is focused on narrow direction in a form of recycled aggregates concrete obtained by crushing old concrete roads (hereinafter marked RCA), i.e. the material which is relatively homogeneous in composition without a high content of other heterogeneities. The current practice of of using RCA is based more or less on the method of proven experiences. Therefore, a part of this article is also devoted to the current regulations and standards for RCA and concrete mixture with RCA.

II. Norms and Regulations

Concrete recycling is not a new topic, but there is still no comprehensive system of regulations and recommendations for its use in concrete construction and its components especially for highway construction. Currently, it is not even clear whether it should be considered as a recycling category. Various regulations and standards describe and classify recycled concrete aggregates according to many criteria: e.g., characteristics, materials, composition, application, and so on. The most important documents related to the Czech Republic are the following.

Appendix L of Czech national standards ČSN EN 206-1/Z3 complements this standard on information and some specifications regarding the use of recycled concrete mixtures. The most important criterion is the allowable content of recycled materials, which divides the recycling categories into the following four groups. The crushed material produced only by crushing concrete is Type 1, building rubble is Type 2, masonry is Type 3, and mixture of construction waste is Type 4. Only Type 1 conforms as recycled concrete aggregate for the top layers of concrete roads.

Standard EN 12620+A1 recycled aggregates are further categorized according to the grain size. "Recycled" here is classified according to the components of a typical coarse recycled aggregate having a grain size greater than 4 mm. The ratio of material components in coarse aggregates should be determined according to prEN 933-11.

TABLE I
Permissible Content of Recycled Materials in RCA

Recycled material	Type 1	Type 2	Type 3	Type 4
Concrete and aggregates	≥ 90	≥ 70	≤ 20	
Sintered ceramic (not porous brick)	≤ 10	≤ 30	≥ 80	≥ 80
Chalky sandstone			≤ 5	
Other mineral materials [a)]	≤ 2	≤ 3	≤ 5	≤ 20
Asphalt	≤ 1	≤ 1	≤ 1	
Other ingredients [b)]	≤ 0,2	≤ 0,5	≤ 0,5	≤ 1

[a]Other mineral such as: porous brick, lightweight and porous concrete, stucco, mortar, porous slag, cinders or pumice
[b]Other ingredients such as: glass, ceramics, slag from non-ferrous metal, gypsum, rubber, plastics, metals, wood, crop residues, paper.

Distribution that comes directly from the Czech regulation of technical conditions TP 210 or regulations OTP ARSM 01/2001 can be considered as an important source for the classification of conditions in the Czech Republic. Documents about recycling for the road construction are published by the Association for the development of recycled building materials in the Czech Republic (ARMS). Both of these regulations, however, compromise the components under the layer of concrete pavements only, but not the layers of concrete road itself. In a Change 3 of standard EN 206-1, NA 8, Article 5.1.3, the status of using recycled aggregates in top layers of concrete road following paragraph is clearly stated: "Recycled aggregates cannot be used for concrete resistant with environmental influences XF2, XF4, XD1 and XD3. It cannot also be used for pre-stressed structures or for structures with high requirements the impermeability of concrete and

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architectural concrete. Some limits of recycled aggregate solve tables L1 to L3." Therefore, concrete road layer belongs to the category which is classified as XF, and the use of RCA in concrete layer is expressly prohibited.

The information obtained from the document analysis can generally be stated: the permitted use of RCA after the necessary tests is specified in EN 12620+A1. The maximum natural coarse aggregate replacement to coarse RCA is limited and is usually in the range of 20-35% by weight. Using RCA in aggressive or otherwise extreme load environment must be very careful due to the chemical processes and the potential risks of corrosion and degradation. The use of RCA in prestressed concrete is banned in most standards [2].

III. Properties of RCA

RCA must generally meet the same requirements as virgin aggregate for the new concrete mixture, but the properties of natural and recycled aggregates vary significantly, and therefore, they are more complicated for RCA. Especially, achieving of required boundaries of water absorption after 24 hours is usually impossible. RCA have the absorptivity of 5 to 10% and in fine fractions even up to 10%, while the water absorption value of natural aggregates ranges up to 2% [3].

It is necessary to distinguish the properties of coarse and fine RCA, which differ greatly. The coarse aggregate has a high proportion of small particles, increased water absorption, reduced durability and frost resistance. Small aggregates are characterized by a high proportion of big particles, higher levels of floating particles, increased porosity and lower abrasion resistance and lower strength [4]. The content of the mortar in the RCA is generally 30% for coarse and up to 60% for fine aggregate. Higher binder content also increases the possibility of the presence of unreacted cement grains or foreign substances. This has a significant impact on concrete settings, and therefore it requires to carefully watching the processing times [5].

RCA may contain foreign materials as well as chemical impurities that change the properties of fresh and hardened concrete. Fine aggregate is generally more sensitive to pollution than the coarse fraction [6]. Typical examples of impurities influence the properties of hardened concrete, which are the dimensional instability and extract of fine particles. RCA made from old roads concrete may have higher chloride content, which is in the structure due to icing pavement in the winter season. Using fine RCA is riskier than using coarse RCA. Therefore, in most specifications and regulations, it is not allowed to use the RCA as fine aggregate [7]. One of the most important conditions of RCA use is the percent share of the replaced natural aggregate (no more than 30%). RCA are recommended to be used within structures that are not exposed to aggressive substances.

The requirements for aggregates in concrete pavements layers are, in some respects, more stringent than those for normal concrete [8]. There are almost no requirements in the standards for RCA, and thus the fulfillment of RCA limits on natural stone is quite difficult. Table II gives an overview of the requirements for concrete road and any specifications for the recycled aggregates.

TABLE II
Requirements for Aggregates Using to the Concrete top Layer of Pavements

Property	Virgin aggregate	RCA
Shape index (coarse)	max. SI 40 (top layer SI 20)	-
The content of fine particles (coarse)	$f_{1,5}$	-
L.A. Abrasion test	Mined max. LA 50 Crushed (D≤11) max. LA 35 Crushed (D>11) max. LA 30	-
Polished stone value (coarse)	PSV_{50}	-
Volume stability	shrinkage of not more than 0.075 %	no suitable test method
Water absorption (coarse)	$WA_{24} \leq 1.5$ %	Type 1: 10 wt.% Type 2: 15 wt.% Type 3: 20 wt.%
Resistance to freezing and thawing	percent weight loss ≤1 ≤2	-
Resistance to alkali-silica reaction	according to ČSN EN 206-1:2001 and TP 137	
The chloride content	unreinforcement concrete Max. 0.1 % reinforcement concrete Max. 0.02 %	Type1-3 max 0.04 wt.% Type4 max 0.15 wt.%
The content of sulphate sulfur	≤ 0.2 wt.%	-
The contents of total sulfur	Max. 1 wt.%	-
The content of light pollution (coarse)	Max. 0.05 %	Max. 0.2 %
Content humus substances	lighter than etalon	-

IV. Standards of RCA Tests

RCA properties are affected by the characteristics of original material from which they were obtained, and by the ways of its processing. The used method of crushing affects rounding, roughness, shape, and quantity of the mortar around the main grain of aggregate [7]. As it is apparent from the various national documents, RCA can replace only a certain amount of natural aggregates to maintain physical properties of upper layer of roads. The existing limits of replacement RCA were determined by a series of tests and research in the last decade around the world, and they are reported only in non-standard national guidelines and documents, and are taken mostly as a recommendation.

The amount of RCA may vary according to the properties of original aggregates. Therefore, it is very important to specify the data about the input material in the documentation, such as type, source and place of the origin, suppliers and carriers, and dump if necessary [9]. RCA is very divergent material and must be tested for each source from which is RCA manufactured. Summary of the characteristics and the standards which are necessary to test for using RCA as follows:

- Granularity EN 933-1
- The shape of the coarse aggregate EN 933-3,4
- The content and quality of fine particles EN 933-1
- Resistance to crushing of coarse aggregate EN 1097-2

- Abrasion of coarse aggregate EN 1097-1
- Determination of the polished stone value EN 1097-8
- Determination of particle density and water absorption EN 1097-6
- Methods for the determination of resistance to fragmentation EN 1097-2
- Determination of resistance to freezing and thawing EN 1367-1, EN 1367-2
- Determination of drying shrinkage (EN1367-4 annex A)
- Alkali-silica reaction
  - Chemical test, which is determined by ratio of dissolved SiO_2 and loss of alkalinity ČSN 72 1179 a)
  - The bar exam using Portland cement CEM I 42.5 with the addition of alkalis in the mixing water to 1.25 Na_2O_{eq} ČSN 72 1179 b)
  - Accelerated dilatometric beam exam is performed on specimens with dimensions 25x25x285 mm in an alkaline solution at 80 ºC ASTM C 1260-94
  - Dilatometric the bar exam when the test prisms with dimensions 75x75x250 mm placed in a humid environment at 40 ºC. Test can take up to one year. RILEM TC 106-3
  - Concrete test, when the test prisms with dimensions 75x75x280 mm kept afloat in a humid environment at 60 °C. The test duration is 140 days. RILEM TC 106-4
  - Alkali – Richtlinie test with addition of alkali to 1,3 % Na_2O_{eq} in the cement. The test specimen, a cube with 300 mm is left in a humid environment at 40 ºC.
  - Alkali – Richtlinie accelerated test, when the body 40x40x160mm (two days after manufacture) deposited on 13 days to 1 molar NaOH solution at 80 °C.
  - Alkali – Richtlinie informative test using stone mortar beam in 40x40x160 mm (at 70 °C - Alternative procedure). The test lasts 28 days. According to method B
- Organic matter content EN 1744-1 (determination humus substances)
- The contents of total sulfur EN 1744-1
- The content of water-soluble sulphates and The sulphate content of acid soluble EN 1744-1
- The content of substances affecting the setting and hardening of concrete EN 1744-6
  - Organic matter content EN 1744-1 (determination humus substances)
  - The content of light pollution EN 1744-1
  - The content of water-soluble pollutants EN 1744-6
- CO_2 content in fine aggregate for the surface layer of concrete roads EN 196-2:2005
- Petrographic analysis ČSN 72 1153

Global research shows that long-term water absorption according to the standard (EN 1097-6) significantly underestimated the time needed to reach the steady state and the time to reach the relevant data for the absorbability of lightweight and alternative aggregates [10].

V. Advantages and Risks of Concrete with RCA

Potential advantages and disadvantages of the use of recycled aggregate in new concrete have been extensively studied and will be investigated in future. While it is entirely possible to produce relatively good recycled concrete, the use of RCA in practice as a substitute for natural aggregates is not so easy [11].

One of the most serious problems in concrete with the RCA is alkali-silica reactions (shortened as ASR) which act as an expansion, and cracking is caused by the reaction of alkali in cement with the aggregates containing reactive silica. This SiO_2 reacts with alkali to form a silica gel which absorbs the water and consequently swells, i.e. its volume is greater than the amount entering into the reaction components. Due to swelling, expansion tension which consequently acts on structure of concrete appears. The most obvious act of the ASR is the formation of cracks on the concrete due to internal expansion [12].

Fig. 1 Damage of top layer of the concrete road with RCA due to ASR

Due to the complexity and methods of implementation, it is necessary to mention that the individual measurement may lead to different results depending on which test of ASR was chosen [13]. ASR incidence can be often highly variable both in the external manifestations and intensity. The most important factors which influence the ASR are high pH, temperature, humidity, and the presence of reactive SiO_2. Due to the higher share of cement in mixture and higher water absorption, it is necessary to reduce the influence of other factors as much as possible. Taking into account the high absorbability of ASR and relatively unprotected road construction environment against natural conditions, the risk of ASR thus increases several times.

Another big barrier restricting the use of RCA in new concrete mixtures is the diversity of quality RCA. It is necessary to take into account the changes in certain construction elements in a project of the road, when RCA is used in a concrete [14], [15]. One of the most common and most effective fact is the increased thickness of the concrete layer and reduced distance expansion joints [16].

Some chemical properties that mainly affect the composition of RCA may be dangerous. Recycled aggregate probably contains larger quantities of certain harmful or adverse substances such as chlorides, sulfates, organic materials, glass, plaster, plastic, wood, or paper. Recycled aggregates containing material from roadways may be contaminated and contain chloride ions from deicing salts used during winter season [17]. This adversely affects the influence of the steel reinforcement with increased risk probability of corrosion in concrete. It is higher by up to 65%.

VI. Sustainability

Recycling of construction materials is an important instrument for sustainable development and bridging the contradiction between economic growth and environmental protection. The concept of sustainable development includes rational use of natural resources [18]. Use RCA as alternatives to natural material leads unequivocally to reduction of the burden on the environment. And both in terms of exploitation of natural resources and in terms of reducing the amount of waste deposited. Sustainability is not a simple concept and exceeds the recycling itself. In the recycling process there are many aspects that need to be considered: e.g. power consumption caused by crushing or transport of RCA from the sampling point to the building site [19].

It is the question, under what circumstances the use of RCA in top concrete layer of road can be still considered as economically advantageous [20]. Used recycled material may not reach the price of natural aggregates (calculation including transportation and administration). Most of the recommendations, guidelines and standards restrict the use of RCA only approximately to 30% substitution of natural aggregates, primarily only the coarse fraction; therefore have to include the effect of technologies that are not fully utilized [21], [22]. The concept of sustainable development should include reasonable use of natural resources.

VII. Conclusion

Using RCA for concrete in general is possible. There are sub-national and international regulations and practical applications. In most countries, it prevails the recycling on site. For example, EN 206-1 in the change Z3 directly notes that RCA cannot be used in concrete for the environment XF2 and XF4, i.e. environment of concrete pavements in the Czech Republic.

Usually, the use of RCA is permitted in the form of coarse aggregate fraction and the recommended limit quantities between 20 and 30% according to specific countries. Then, the concrete can be regarded as a material whose properties are affected slightly/ineffectually by the addition of RCA. Furthermore, the RCA must meet the tests for common stone as well as the specified requirements for the recycled products (especially absorption and durability). Concrete and aggregates must be tested in more details by using different test methods when more than the recommended amount is used. Higher amounts of RCA can lead to the deterioration of a number of properties in both fresh concrete (workability) and hardened concrete (greater shrinkage, greater thermal expansion, lower compressive strength and flexural strength, modulus of elasticity, durability, and so forth.). In general, the RCA could be a quality aggregate in concrete. Differences that exist between RCA and natural aggregates are determined predominantly by the increased binder content due to crushing the original concrete.

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