Lukasz Skotnicki

Dr inż.

Politechnika Wrocławska, Zakład Dróg i Lotnisk

lukasz.skotnicki@pwr.edu.pl

Jarosław Kuzniewski

Dr inż.

Politechnika Wrocławska, Zakład Dróg i Lotnisk

jaroslaw.kuzniewski@pwr.edu.pl

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Application of recycled concrete aggregate in mineral-cement-emulsion mixtures

Abstract: The article presents selected problems connected with the accomplishment of the research grant ‘Application of reclaimed materials’ as part of the joint project Development of Road Innovations (RID) co-financed by the National Centre of Research and Development as well as the General Directorate for National Roads and Motorways. The main aim of the project was to analyse possibilities of application of reclaimed concrete obtained from the demolition waste from the existing roads to produce new layers of road pavements. The article presents selected test results which show the influence of the reclaimed concrete content on the strength parameters of the MCE mixtures. Significant variation of the tested MCE mixtures properties depending on the percentage of the reclaimed material has been indicated. It has been suggested that new tests should be implemented in the process of MCE mixtures design process. An optimal content of reclaimed concrete has been determined in order to obtain required values of the analysed parameters. The application of reclaimed concrete in conventional MCE mixtures made it possible to achieve positive economical and environmental effects.

Keywords: Recycling; MCE mixture; Reclaimed concrete.

Introduction

As part of the implementation of the research grant, Department of Roads and Airports of the Wrocław University of Technology in the years 2016-2017 participated in the project: "The use of recycled materials". The scope of the research topic included the recycling of concrete materials and the re-use of concrete aggregate in road pavement layers.

The main goal of the research topic was to study the properties of recycled materials and to analyze the possibility of using concrete aggregate for road pavement layers. Procedures for testing and assessing the properties of concrete reclamation as well as guidelines defining the conditions for the re-use of material originating from the recycling of concrete pavements, in layers of road pavement construction, improved soil and road embankments have been developed. One of the materials used to make road foundation layers are mineral-cement-emulsion mixtures. An innovative approach in the research topic consisted of the use of concrete mixtures in the composition of these mixtures in combination with an emulsion of asphalt and cement. The basis of the analysis was to determine the influence of the percentage of concrete reclaimed on the strength parameters of mineral-cement-emulsion mixtures (MCE). The scope of the research included: the strength of MCE blends for intermediate stretching, ITS, stiffness module IT-CY, content of free spaces V_m . In addition, for the MCE mixtures containing concrete debris, a complex stiffness modulus determined using the 4PB-PR 4-point beam method was determined. This feature is not

currently covered in the design process and in the requirements for foundation layers of MCE blends according to [4].

Recycled concrete aggregate

Most of the waste that can be re-used to make new elements come from demolition work. These wastes are referred to as construction and demolition waste materials (CDW).

The basic method of obtaining recycled concrete aggregate (RCA) is crushing of worn-out concrete elements in stationary crushers. The process of obtaining recycled concrete aggregate from CDW materials consists of: demolition of existing structural elements, storage of these materials, crushing in jaw crushers, spreading into individual fractions, crushing in drum crushers, separation of the finest fraction of aggregate, recovery of undesirable elements (e.g. reinforcement) in magnetic separators [3, 17]. As a result of this process, clean concrete aggregate with a given grain size is obtained.

Another example of stationary crushers is single-stage impact crushers or two-stage crushers (impact crushers in combination with hammer mills) [5] - Fig. 1.

1. Stationary crushers a) single-stage, b) dual-stage [5]

Depending on the crushing method used, concrete aggregate with different grain size and usable properties is obtained. Research conducted in Portugal, however, indicates that the strength and deformation parameters of materials made of concrete aggregate (e.g. cement concrete) have the greater impact on the properties of materials coming from demolition than the method of crushing this material [5]. In less developed countries, manual crushing methods are used [16]. This model of obtaining concrete aggregate is characterized by high heterogeneity in the graining of this material and high time-consuming process.

Testing of precast concrete elements made on the basis of recycled concrete aggregate has shown that they have lower strength compared to elements produced on the basis of natural aggregate. This may result in greater absorption of recycled aggregates compared to natural aggregates. However, the obtained parameters of prefabricated elements based on recycled concrete aggregate allow their use in new building constructions [16].

Currently, the use of the so-called on-site recycling for worn-out concrete elements. In the case of road surfaces, the innovative method is pulse discharge method, used by researchers from Japan. It was used in laboratory conditions for crushing mineral-asphalt mixtures [15]. Using the discharge electrodes in a water environment, the conglomerate of the aggregate and the bitumen binder crumble into the determined fractions. As a result of the process, recycled aggregate and asphalt binder fractions are obtained - Fig. 2. This method could be implemented in the future in field conditions for crushing asphalt surfaces as well as concrete pavements.

2. Crushing method with pulse discharge [15]

Another innovative method of crushing is the electro-dynamic method. The principle of crushing consists in generating electric discharges, causing cracking of the recovered material. Depending on the level of energy used, it is possible to obtain different crushing fractions. This method was used by scientists from Belgium and Switzerland in the innovative crushing of electronic components. Researchers found that there is a possibility of obtaining the grain size of recycled material, similar to the grain size obtained in hammer mills [14]. After appropriate modifications, the method could be introduced to crumble existing concrete structures.

Mobile crushers for on-site applications are popular in crushing degraded concrete structures. Mobile crushers allow obtaining the fragmentation of the material, which is later screened on the set of sieves to the required fractions - Fig. 3 [2].

3. The Hartle PC-160 mobile crushing machine [2]

In a study of Egyptian scholars, it was shown that recycled concrete aggregate could be successfully re-used to produce even cement concretes. It was shown that the content of recycled aggregates at the level of 25% does not significantly affect the properties of cement concrete. Concrete with a content of 25% - 50% recycled aggregate was characterized by lower strength parameters in comparison with conventional concrete, however, their features allowed the use of the final product in the constructions. The tests showed high absorbability and high abrasiveness of recycled concrete aggregate [2].

It was shown that mixtures made of high quality recycled concrete aggregate had very similar strength to samples made entirely of natural aggregate. This applies both to mixtures of rolled concrete and concrete mixtures reinforced with steel fiber [1].

The research presented in [18] showed the possibility of using a recycled concrete aggregate to create new concrete mixes. The analyzes concerned three basic mechanical properties (compressive strength, flexural strength, and modulus of elasticity) and two parameters of constancy of volume (contractions resulting from obscuring and limited

shrinkage cracks). It has been shown that the addition of polymeric aluminum sulfate improves the microstructure of the blend. This contributes to the improvement of mechanical properties, reduction of shrinkage due to drying and delay of limited shrinkage cracks.

Selection of ingredients of MCE mixtures

The mutual proportions between the individual components (concrete debris, doping material, hydraulic binder, asphalt binder) determine the strength and deformation properties of MCE blends. For research purposes, a number of analyzes were carried out regarding the effect of the grain size of the mineral mixture and the composition of MCE blends on selected properties of these materials. The composition of the mineral-cement-emulsion mixture will affect the properties of the future construction layer of the road surface.

The research involved the analysis of the percentage influence of the concrete reclaimed content on the basic strength characteristics of the MCE blends. For this purpose, different percentage proportions of concrete reclamation in the mix have been proposed. These mixtures were marked with the symbols MCE 1, MCE 2, MCE 3 and MCE 4. The proportions of the reclaimed concrete were assumed at 25%, 45%, 0%, and 70% respectively in relation to the entire mineral mixture. The rest was always a granulating material - granite.

The C60B10 R cationic emulsion was used for the analyzed MCE blends in accordance with the requirements [12]. In addition, according to [4], it is recommended that the emulsion also meet the following conditions: type of asphalt: 50/70 or 70/100 according to [6], no solvents and fluxes. In addition, the emulsion should have good binder tolerance. In the designed MCE blends CEM II class 32.5 Portland cement satisfying the requirements [13] was used. These relate to the composition of the cement and compatibility criteria for commonly used cement. The current study focuses on MCE mixes for road pavement layers laden with KR3 - KR7 traffic. The next step was to assume the percentage of binding agents. Using binders (emulsion, cement) their content was assumed: asphalt emulsion 5% by weight and cement: 3% by weight.

Samples for testing MCE blends were compacted at the optimum water content. This parameter consists of water coming from the emulsion and water contained in the materials and water added to the mixture. The optimal fluid content was determined based on the Proctor method according to the norm [11].

Granulation of batch materials is given in tab. 1. Mixtures of mixtures are provided in Tab. 2-5, while the granulation curves together with the limit curves in Fig. 2.

Tab. 1. Percentage of individual fractions for batch materials

Sieve	Rubble I (P2)	Granite
[mm]	[%]	[%]
31,5	18,2	4,0
16,0	24,6	22,2
8,0	17,9	14,0
4,0	18,0	13,4
2,0	9,5	9,1
1,0	6,7	9,7
0,5	3,0	7,2
0,125	1,5	10,1
0,063	0,4	3,5
<0,063	0,1	7,1
Total	100,0	100,0

Tab. 2. The composition of the MCE 1 mixture (25% rubble, 75% granite)

MCE 1	Components	Working composition MM	The composition of MCE	The content of C+E+W
	[-]	[%]	[%]	[%]
	Rubble I (P2)	25,0	21,4	14,6
	Granite	75,0	64,1	
	CEMENT	-	3,0	
	Emulsion 60/40	-	5,0	
	Water		6,6	
	Total	100,0	100,0	

Tab. 3. The composition of the MCE 2 mixture (45% rubble 55% granite)

MCE 2	Components	Working composition MM	The composition of MCE	The content of C+E+W
	[-]	[%]	[%]	[%]
	Rubble I (P2)	45,0	38,4	14,6
	Granite	55,0	47,0	
	CEMENT	-	3,0	
	Emulsion 60/40	-	5,0	
	Water		6,6	
	Total	100,0	100,0	

Tab. 4. The composition of the MCE 3 mixture (0% rubble, 100% granite)

MCE 3	Components	Working composition MM	The composition of MCE	The content of C+E+W
	[-]	[%]	[%]	[%]
	Rubble I (P2)	0,0	0,0	14,6
	Granite	100,0	85,4	
	CEMENT	-	3,0	
	Emulsion 60/40	-	5,0	
	Water		6,6	
	Total	100,0	100,0	

Tab. 5. The composition of the MCE 4 mixture (70% rubble, 30% granite)

MCE 4	Components	Working composition MM	The composition of MCE	The content of C+E+W
	[-]	[%]	[%]	[%]
	Rubble I (P2)	70,0	59,8	14,6
	Granite	30,0	25,6	
	CEMENT	-	3,0	
	Emulsion 60/40	-	5,0	
	Water		6,6	
	Total	100,0	100,0

4. Granulation of MCE mixtures

Research program

According to the guidelines [4], the designed MCE mix should meet the requirements given in Tab. 6. The following characteristics were taken into account in the analysis of the impact of grain size:

- ITS intermediate tensile strength (maturation of 7 days in air, 28 days in air, 28 days in water),
- IT-CY stiffness modulus (maturation of 7 days in the air, 28 days in the air, 28 days in water),
- Vm content (maturation of 28 days in the air),

and in addition to the scope of testing of MCE mixtures containing concrete debris, analyzes were included:

- A complex stiffness module using the 4-point 4PB-PR beam method (maturation of 28 days in the air).

Tab. 6. Requirements for samples from the MCE mixture [4]

Cecha:	Wymagane wartości:	
	Ruch KR1+KR2	Ruch KR3+KR4
Zawartość wolnych przestrzeni [%]	od 8 do 18 maksymalnie 14 ¹⁾	od 8 do 15 maksymalnie 12 ¹⁾
Wytrzymałość na pośrednie rozciąganie, T = +5°C, po 7 dniach, [MPa]	od 0,40 do 0,80	od 0,50 do 1,00
Wytrzymałość na pośrednie rozciąganie, T = +5°C po 28 dniach, [MPa]	od 0,60 do 1,40	od 0,70 do 1,60
Moduł sztywności IT-CY, T = +5°C po 28 dniach, [MPa]	od 1500 do 5000	od 2000 do 7000
Odporność na działanie wody (pozostała wytrzymałość na pośrednie rozciąganie po przechowywaniu próbek w wodzie), T = +5°C po 28 dniach, [%]	nie mniej niż 70	nie mniej niż 80

¹⁾ - Materiały rozbiórkowe zawierające smołę.

The IT-CY stiffness modulus was determined in the NAT (Nottingham Asphalt Tester) apparatus in [8] at a temperature of + 5 °C - Fig. 5.

The starting point for calculations is to measure the force and strain of the sample under the influence of the applied load. The stiffness modulus was determined by indirect stretching (1) :

$$S_m = \frac{F \cdot (\nu + 0,27)}{(z \cdot h)}, \quad (1)$$

where: S_m – intermediate stiffness modulus [MPa], F - maximum vertical force [N], ν - Poisson's coefficient of material [-], z - amplitude of the obtained deformation [mm], h - average thickness of the sample.

5. Stiffness modulation test using the IT-CY method

The results of stiffness module analyzes using the IT-CY method are shown in Fig. 6.

6. Stiffness modul IT-CY - influence of percentage content recycled concrete aggregate

With the increase of the amount of concrete reclamation in the MCE mix, the stiffness of the MCE blends increased. These dependencies were described by the polynomial function. Good results were obtained, the correlation coefficient of R^2 was more than 0.98. The IT-CY modules fulfilled the requirements after 28 days (2000 MPa - 7000 MPa). After this maturation of the samples, satisfactory average values were obtained at the content of the reclamation of about 45%. Above this content, the increase in the stiffness modulus of the mixes was negligible.

ITS intermediate tensile strength was determined in the Marshall Universal Press acc. [7], at + 5°C - Fig. 7. The results of intermediate tensile strength tests are shown in Figure 8.

The dependence was used to calculate the tensile strength of ITS (2):

$$ITS = \frac{2 \cdot P}{\pi \cdot D \cdot h}, \quad (2)$$

where: *ITS* – tensile strength for splitting [MPa], *P* - value of applied force [N], *D* - sample diameter [mm], *h* - sample height [mm].

7. Strength test using the ITS method

8. ITS durability - the impact of the percentage of recycled concrete aggregate

With the increase of the amount of reclaimed concrete in the MCE mix, ITS strength increased. These dependencies are described by polynomial functions presented in the figure. Good results were obtained, the correlation coefficient of R^2 was more than 0.95. The intermediate tensile strength was too low in relation to the requirement of a minimum of 0.7 MPa according to [4], while with the content of the destroyed within 40-70%, the strength values were maximal.

The content of free spaces V_m was determined using the hydrostatic method (bulk density) and methods in the pycnometer (density) according to [10] - Fig. 9. The results of free space analysis in MCE blends are given in Fig. 10.

Gęstość mieszanki obliczono wg zależności (3) [9]:

$$\rho_m = \frac{m_1 - m}{V - \frac{m_2 - m_1}{\rho_w}}, \quad (3)$$

where: ρ_m – density of the MCE mixture [g/cm³], m – mass of the pycnometer [g], m_1 – mass of the pycnometer with the sample [g], m_2 – mass of the pycnometer with the sample and water [g], V – volume of the pycnometer to the measurement mark on the cap [cm³], ρ_w – density of water at the test temperature [g/cm³].

9. Density test in pycnometer

The free space in the sample from the MCE mixture densified in the laboratory or in a sample taken from the compacted layer should be determined according to the (4) [10]:

$$Vm = \frac{\rho_m - \rho_b}{\rho_m} \cdot 100 \quad [\%], \quad (4)$$

where: Vm – free space content [%], ρ_m – density of the MCE mixture [g/cm³], ρ_b – bulk density of the thickened MCE mixture [g/cm³].

10. Free space content Vm - influence of percentage content

recycled concrete aggregate

The free space content ranged from 13.5-15.2%. With the increase in the amount of concrete reclamation in the MCE mix, the content of free space increased. This dependence was described by the polynomial function shown in Fig. 10. Good results were obtained, the correlation coefficient of R^2 was more than 0.98. The requirement for maximum free space is 15%. Guided by this requirement, the content of the reclaimed mixture can be up to 60%.

The complex stiffness modulus was determined in the bending test of a 4-point beam (4PB) according to [8], at +10°C - Fig.11. The samples were subjected to a sinusoidal load in the form of a given deformation. The charging frequency was 10 Hz. The combined stiffness modulus was analyzed at a given deformation: $\varepsilon = 50 \cdot 10^{-6}$ m / m. The results of the complex stiffness module analysis using the 4-point beam bending method are shown in Fig. 12.

During the loading call, using the force and displacement values, the dynamic composite stiffness modulus E^* of the material to be tested is determined according to the dependence (5), (6), (7) [47].

$$E^* = \sqrt{E_1^2 + E_2^2} . \quad (5)$$

The constituent sizes E_1 and E_2 are determined directly from the following relationships (6) i (7).

$$E_1 = \gamma \cdot \left(\frac{F}{z} \cdot \cos(\phi) + \frac{\mu}{10^6} \cdot \omega^2 \right) \quad (6), \quad E_2 = \gamma \cdot \left(\frac{F}{z} \cdot \sin(\phi) \right) , \quad (7)$$

where: E^* - combined stiffness module [MPa], F – force that causes sample deflection [N], z – deflection in the middle of the sample spread [mm], ϕ – phase shift angle [°], ω – loading frequency [rad/s], μ – mass ratio, γ – shape factor.

11. Endurance machine with insert for testing 4-point beam 4PB

12. Complex stiffness modulus 4PB-PR - the effect of the percentage of concrete aggregate from recycling

The complex modulus of the stiffness of MCE blends increased with the increase of the content of the reclaimed concrete in the blends to the value of about 45-50%. Above this content, there was a decrease in the stiffness of the analyzed material. This dependence is described by the polynomial function shown in the figure. Good results were obtained, the correlation coefficient of R^2 was more than 0.98. The complex stiffness modulus of 4PB assumed maximum values for the content of the reclamation at the level of 45%. Currently, the complex stiffness module analysis is not required in the MCE mix design procedure.

Summary

The conducted research and analysis confirmed the possibility of using recycled material, in the form of recycled concrete aggregate, to create MCE blends. The mixes meet the design requirements for use in the construction layers of new road surfaces. Concrete debris is suitable for making layers of MCE blends after application of appropriate biodegradation. MCE blends containing concrete aggregate can be used for the construction of road foundation layers with traffic load to the category of traffic KR7. The content of recycled concrete aggregate in MCE mixtures at the level of 45% allows obtaining the optimal graining of the mineral mix and the maximum strength properties of the MCE mixture. The content of recycled concrete aggregate in the MCE blend below 20% is economically unjustified, whereas increasing the content of recycled concrete aggregate above 60% may cause deterioration of the strength properties of blends.

Due to the use of recycled concrete aggregate in MCE mixtures, the existing procedures and design criteria for these mixtures should be modified and supplemented accordingly. The applicable design criteria for MCE mixtures do not apply to blends containing recycled concrete aggregates. At the same time, these criteria do not take into account the current research capabilities and the actual work of the layer made of the MCE mixture in pavement construction. For this reason, it should be extended to include the requirements for the 4PB-PR stiffness module and fatigue life.

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