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## Polymer powder-modified mineral-cement mixture with bitumen emulsion

**Abstract:** The article presents the impact of a polymer modifier (P) on the properties of mineral-cement-emulsion (MCE) mixes. The theoretical part of the article discusses the ways of producing mixes using deep cold recycling. The “in-place – on site” and “in-plant – delivered” production methods are described. The paper also presents a description of a redispersible polymer powder (RPP) used as the polymer modifier. The part dedicated to the conducted research presents the experiment design and discusses the research methodology used to evaluate the effect of the polymer modifier on the properties of the MCE mix. The project involved the production of MCE mixes varying in terms of the type and amount of polymer powder, cement and bitumen emulsion. Mixes were designed with a variable share of cement range from 0.5% to 3.5%, a share of bitumen emulsion ranging from 0% to 5% and a fraction of redispersible polymer powder from 0.5% to 3.5%. A total of 15 mixes were made as part of the experiment, designed according to the Box-Behnken experiment design. The following physical and mechanical properties were assessed in the plan of the research: air void content  $V_m$ , water absorption  $n_w$ , indirect tensile strength  $ITS$ , water damage resistance  $TSR$ ,  $IT-CY$  stiffness modulus and  $SCB$  fracture toughness. The test results were analysed to assess the impact of the redispersible polymer powder on the properties of the recycled MCE mix. Following the analyses, the composition of mix was optimised regarding the requirements set out in the Polish design guidelines.

**Keywords:** bitumen emulsion, reclaimed asphalt pavement, recycled cold mix, recycling, redispersible polymer powder.

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## 1. INTRODUCTION

The continuous increase in the number of road users directly translates into an increase in the loads transferred to road pavements. This causes degradation of the traffic sections in use, which consequently require increased maintenance. When the fatigue life of a structure expires [1], which occurs most often in the base courses, an expensive reconstruction of the damaged road section is required. Starting a reconstruction or renovation project usually involves the use of new materials. An alternative to this is the use of the recycling technology, which enables the reuse of materials from a damaged pavement. This technology allows interventions in the degraded base course, allowing the use of deteriorated asphalt layers, cement layers and mineral aggregate created in the process of demolishing the degraded road pavement. The most common solution is the use of reclaimed asphalt pavement (RAP) and recycled aggregate (RA) present in the old base course. If it is necessary to improve the grain size of the demolished aggregate or if there is not enough material left from the demolition, it is possible to add mineral virgin aggregate directly from the mine.

In the deep cold recycling technology, there are two types of mixes. Mineral-cement-emulsion mixes (MCE) [2] and mineral-cement mixes with foamed bitumen (MCAS) [1]. The two mixes differ only in the bituminous binder. MCE uses bitumen emulsions, while MCAS uses foamed bitumen. The mixes are also produced using mineral binders or bituminous binders. The continuous development of the technology results in the search for modifying agents [3]. Also, the recycling technology can also be a way to dispose of materials while harnessing their technological potential. Examples of this is rubber [4]. The use of the MCE or MCAS technology allows for the reuse of layers containing tar ingredients, which are only permitted when using “cold” methods, i.e., methods that do not involve heating [5].

The process of constructing cold recycle base courses consists of [6] a preliminary analysis and identification of the condition of the road section. The next step is to draw up a laboratory mix design and select the production method, i.e.: “on site – in-place” or “delivered – in-plant”. The next step is to perform the granulation and scarification of the road pavement (milling). Fig. 1 shows a diagram of the machinery line used to produce the MCE/MCAS mix.

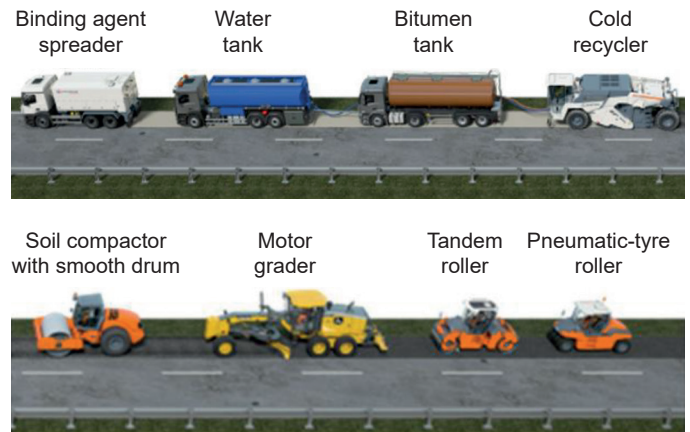


Fig. 1. Process of making the mix using the “in-place” deep recycling method [7]

The “in-place” method is implemented using a specialised device referred to as the recycler. This machine allows the individual ingredients of the mix to be thoroughly mixed. The machine has a mixing chamber containing a granulating and mixing drum and a spraying system that allows for the precise dosing of water and bitumen emulsion using the MCE technology or foamed bitumen using the MCAS technology. Fig. 2 shows the mixing chamber. In the central area, there is a drum with cutters for cutting and breaking the material. There are two rows of nozzles at the top of the chamber shell, one of which is designed to inject foamed bitumen into the mixing chamber.



Fig. 2. Mixing drum of the Wirtgen WR 200i recycler; photo: M. Krasowski

After the initial profiling of the material left from the demolition and the spreading of virgin aggregate (if any), the spreading of the hydraulic binder begins. This process is usually carried out using self-propelled seeders, dosing the binder in the amount set out in the mix design. This is followed by the homogenisation of the ingredients performed by a set of interconnected equipment consisting of a water tanker, a binder tanker and a recycler. Depending on the type of mix selected, the tanker transports either

slow-breaking emulsion or paving-grade bitumen. When making an MCE mix, the emulsion is injected directly into the mixing chamber and evenly introduced throughout the mix. If the MCAS method is used, the binder is foamed bitumen, which is formed by adding water at ambient temperature to the hot asphalt. Water evaporates rapidly upon contact with the hot asphalt, producing foamed bitumen [8]. It surrounds the aggregate grains and the particles of the previously spread hydraulic binder. After the pass of the recycler, profiling and compaction begins [9]. The material is initially evened out by a heavy steel roller and then profiled by a motor grader. The final compaction is carried out using a steel-rubber or rubber-pneumatic tandem roller [10-11]. Fig. 3 shows the recycler in operation.



Fig. 3. Wirtgen WR 200i recycler in operation; photo: J. Krasowski

An alternative way of producing mixes using deep cold recycling is the “in-plant” method. Making the delivered mix requires a special stationary mixing plant. This method involves taking the material left from the demolition to a laydown area located relatively close to the section to be built. The choice of this method enables an inspection of the subsoil condition and improvement of bearing capacity where necessary. The production method is based on a special plant that mixes the material left from the demolition, the virgin aggregate (if any), hydraulic binder and bituminous binder. The advantage of this method is the high accuracy of ingredient dosing. Once produced, the mix is loaded onto dump trucks and then placed using a motor grader or paver. The paver enables the perfect placement of the layer. It ensures the homogeneity of the mix, fast work progress and maintenance of the designed geometric parameters. The next step is to compact the

layer in the same way as for the previously described “in-place” method [12-13]. Fig. 4 shows the mobile mixing plant in operation.



Fig. 4. Wirtgen KMA 220 mobile mixing plant in operation; photo: M. Krasowski

There are many binders available on the market, including hydraulic binders, special road binders and bituminous binders. In addition, there is ongoing research into new binders, additives [4] or modifiers [10]. Each of them has the same function, i.e., to improve the performance of the material, enhance strength and increase the resistance to weather factors.

Depending on the selected work technology, appropriate binders are selected. Important considerations include the availability, price and method of placement. Advances in technology can lead to the development of new, better and cheaper binders. However, there is a real opportunity to improve performance using modifications [10]. There is also ongoing work regarding the incorporation of rubber dust [5], [13] or dust from the process of removing fines from aggregate [12]. Further research could lead to the invention of a method for using other industrial waste that currently pollutes the environment. Examples of innovative solutions are also observed in the sectors of hydraulic binders [13-14], bituminous binders [15], asphalt mixtures [16], cement concrete mixes [17-18] or mixes bound with a hydraulic binder [10], [19-20].

Polymer modification has been successfully used in cement concrete mixes. Popular products include redispersible polymer powders. When cement and powder are mixed, a new type of binder is obtained – the polymer-cement binder. Binding in a concrete mix produced with such a binder is perfectly illustrated in Fig. 5. Binding consists of four stages. At the first stage, the fine particles of the modifier are dispersed in the liquid phase of

the cement grout (Fig. 5a). Then, as the setting process begins, they accumulate on the surface of the unbound cement particles and mineral grains (Fig. 5b). Next, the free polymer powder grains are enclosed in the air voids of the mix (Fig. 5c). Finally, during the drying process, the polymer particles are densely packed and coalescence occurs, resulting in the formation of a continuous polymer film (Fig. 5d).

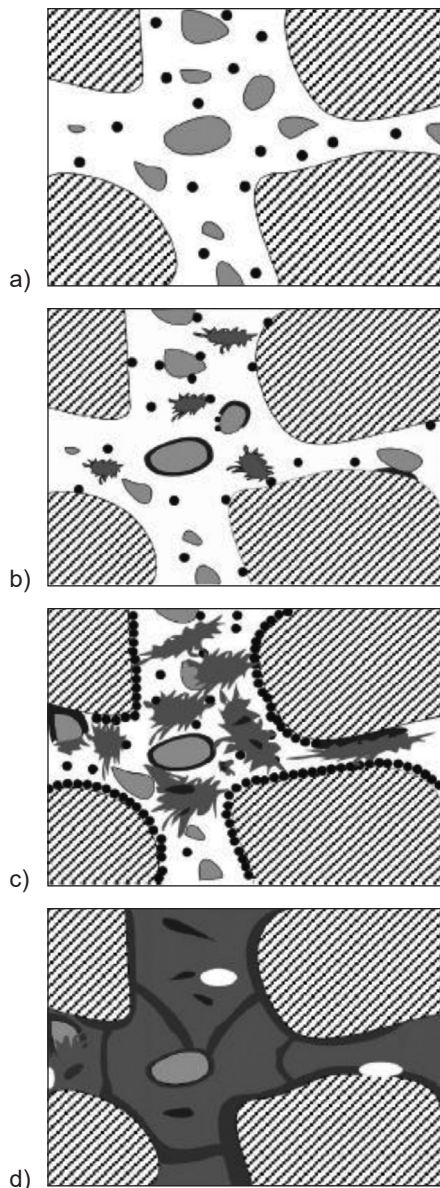


Fig. 5. Model of the effects of redispersible polymer powder in a mix [21]: a) dispersion in the liquid phase of the cement grout, b) accumulation on the surface of the unbound cement particles and mineral grains, c) enclosing of free polymer powder grains in the air voids of the mix, d) formation of a continuous polymer film

Polymer-modified cement concrete has better resistance to water penetration and improved workability. Aggregate adhesion is improved, and the mix is more flexible, which increases bending strength. The adhesion of the concrete mix to the substrate is also improved [21].

The use of polymer modification also has a beneficial effect on the performance of mineral mixes bound with hydraulic binders (CBGM). The research published in the paper [10] has produced positive results: improved workability, reduced air void content and lower stiffness without reducing the compressive strength of the mix. The presented analysis uses a redispersible polymer powder based on the ethylene-vinyl acetate (EVA) copolymer. Bound mixes carry the risk of cracking transferring to the surface layers of the road pavement. Repairing this type of damage is time-consuming and expensive. The modification technology may reduce the risk of cracking. An increase in fracture toughness was observed. Thanks to polymer modification, the CBGM mix showed greater flexibility. Tests of the *IT-CY* stiffness modulus [22] showed that the stiffness modulus values of the modified mixes were maintained despite a change in the testing temperature. There was also no identified impact on axial compressive strength [23], which is the main parameter analysed in this type of mixes. The indirect tensile strength is also unchanged. In addition, the visual analysis of specimens of cement-bound and polymer powder-bound mixes after a conditioning period revealed the bridging of the spaces between aggregate grains, confirming the formation of a continuous polymer phase and modification of the mix structure. Fig. 6 shows the visible polymer structure.



Fig. 6. Visible polymer network structure on CBGM mix specimens; photo: M. Krasowski

Positive results of polymer modification were also obtained in the case of tests of mineral-cement mixes with foamed bitumen (MCAS) [3]. The use of redispersible polymer powders (RPP) was found to have a beneficial effect on the compaction process, as it reduced the amount

of energy required to compact the mix. A comparison of physical and mechanical properties, as well as water and frost sensitivity, confirmed that the “RPP” modifier increased the resistance to water penetration. The use of the modifier also had a positive effect on the mechanical properties of the mix. The modification contributed to an increase in cohesion and flexibility without stiffening the base course, i.e., no increase in the elastic modulus was observed. The use of the modification extends the viscoelastic range of the MCAS mix. The results suggest a positive impact of polymer modification in the case of deep cold recycling mixes and may indicate the formation of a mineral-cement-polymer composite microstructure [24]. Such an effect can have a positive effect on other parameters of the mixes.

Given the positive experience of the authors of the study on the effect of polymer modification on CBGM mixes [10] and MCAS mixes [3], it seems necessary to carry out a study on MCE mixes using polymer powder. The use of polymer modification in MCE mixes can lead to improved workability, which could reduce the air void content of the mix, directly contributing to weather resistance. The use of polymer powders also leads to an increase in deformability and fracture toughness, which is often a weakness of conventional recycled mixes.

## 2. SUBJECT OF RESEARCH. EXPERIMENT DESIGN

The subject of the research is a recycled mineral-cement-emulsion (MCE) mix. The scope of the research included an analysis of the effect of the redispersible polymer powder on the properties of the mix. Thus, MCE mixes were designed using conventional binders such as cement and bitumen emulsion. The mineral skeleton was based on mineral aggregate and reclaimed asphalt pavement. The variables in the mix were the amount of binders and polymer modifier. An analysis of the impact of binders on the physico-mechanical properties of the MCE mix was performed using a fractional 3-level Box-Behnken design. The hydraulic binder and redispersible polymer powder were dosed in 1.5% increments: 0.5%, 2.0% and 3.5%. The bituminous binder, i.e., bitumen emulsion, was dosed at a rate in 2.5% increments: 0.0%, 2.5% and 5.0%. Marshall specimens were prepared under laboratory conditions, followed by tests of physical and mechanical properties. The impact of climatic factors

was examined as well. The testing process was based on known methods that are commonly used in the laboratory testing of mineral-cement-emulsion mixes. Table 1 shows the plan of laboratory tests.

Table 1. Plan of laboratory tests

Property	Test
Air voids content $V_m$	PN-EN 12697-8 [25]
Water absorption $n_w$	PN-S 04001 [26]
Intermediate tensile strength $ITS_{DRY}$	PN-EN 12697-23 [27]
Water resistance $TSR$	Wirtgen [28]
The modulus of stiffness $S_m$ at temp. +5°C	PN-EN 12697-26 [22]
Fracture toughness $K_{Ic}$	PN-EN 12697-44 [29]

In laboratory studies, the measurement was replicated to obtain reliable results. Six replications of the measurement were therefore performed, for each test of the properties of the MCE mix. The results obtained were evaluated within a confidence interval with an assumed probability ( $P = 95\%$ ). This made it possible to identify measurements with an error and eliminate them from further consideration. The confidence interval was calculated according to formula (1):

$$\bar{x} \pm 1.96 \left( \frac{\sigma}{\sqrt{n}} \right), \quad (1)$$

where:

$\bar{x}$  – expected value,

1.96 – statistic for significance level  $\alpha = 0.05$ ,

$\sigma$  – standard deviation,

$n$  – sample size.

Planning an experiment is an extremely complex task. The common method of testing “one variable at a time” requires a significant amount of time and financial resources [30-31]. The overriding aim of planning an experiment is to obtain an answer to the question posed in an efficient manner, which means that the selection of an appropriate experiment design becomes a crucial task. Choosing the correct plan at the very beginning saves plenty of time and also money.

An analysis of the impact of individual binders on the physico-mechanical properties of the MCE mix was performed using a fractional 3-level Box-Behnken design. The plan adopted belongs to the group of experiment designs where independent variables have three possible

levels:  $-1.0$ ,  $0.0$ ,  $+1.0$  [32]. This means that binders were dosed to the MCE mix at three levels: minimum ( $-1.0$ ), maximum ( $+1.0$ ) and average ( $0.0$ ). The experiment design provided for controlling the input quantities, shown in Table 2 and schematically in Fig. 7.

Table 2. Experimental domain for the evaluation of the impact of redispersible polymer powder on the properties of the MCE mix

Component	Min [%]	Max [%]	Average [%]
Portland cement (CEM)	0.5	3.5	2.0
Redispersible polymer powder (P)	0.5	3.5	2.0
Bitumen emulsion (EMU)	0.0	5.0	2.5

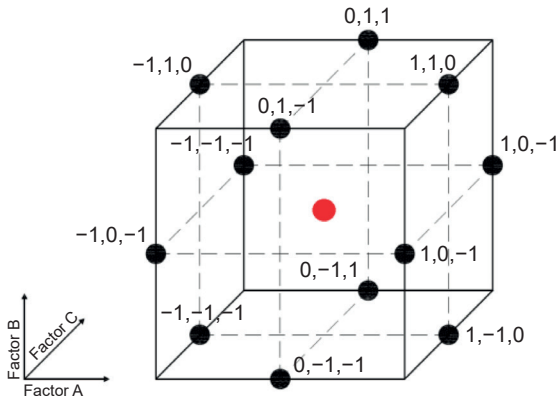


Fig. 7. Schematic diagram of the Box-Behnken trivalent fractional plan [33]

The values presented in Table 2 were adopted after taking into account the guidelines for the design of MCE mixes [6], which include the recommended content of binders in the MCE mix. The adopted experimental domain allowed the results to be described using a polynomial of degree two. The polynomial of degree two used in the experiment design is described by formula (2):

$$y = b_0 + \sum_{i=1}^k b_i \cdot x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} \cdot x_i \cdot x_j + \sum_{i=1}^k b_{ij} \cdot x_i^2, \quad (2)$$

where:

$k$  – number of independent variables,

$b_{ij}$  – experimental factors,

$y$  – dependent variable (measured variable),

$x$  – input variable (e.g. CEM).

The Box-Behnken design enables reducing the number of variables in relation to the 33 full factorial design without losing any of the interaction terms. Thus, there is an opportunity to reduce the full factorial design from 27 combinations to only the necessary 15 combinations. For ease of description and analysis, the individual MCE mixes are described using a code represented by formula (3):

$$0.5C - 2P - 0E, \quad (3)$$

where:

$0.5C$  – Portland cement content of 0.5% (m/m) in the MCE mix,

$2P$  – polymer modifier content of 2.0% (m/m) in the MCE mix,

$0E$  – bitumen emulsion content of 0.0% (m/m) in the MCE mix.

The above formula should be read as follows: the number preceding the capital letter of the alphabet indicates the percentage, while the capital letter  $C$ ,  $P$  or  $E$  is the Portland cement, polymer powder or bitumen emulsion, respectively.

### 3. MCE MIX DESIGN

The design work on the mineral-cement-emulsion mix analysed in the project was carried out on the basis of the guidelines for MCE design in Poland [6]. The mineral mix used was made using 50% (m/m) of asphalt reclaimed asphalt pavement (RAP), 30% (m/m) of recycled aggregate (RA) with a grain size of 0/31.5 mm and 20% (m/m) of virgin aggregate (VA) with a grain size of 0/4 mm. Fig. 8 shows the grain size curves of the minerals used.

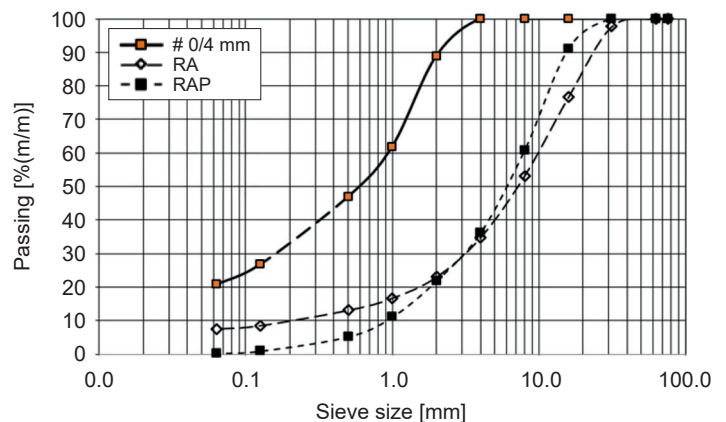


Fig. 8. Grain size of mineral mix ingredients

The design of the mineral mix was prepared in such a way as to meet the requirement to keep the designed mineral mix grain size curve within the good grain size range, i.e., between the limit curves. The essential premise of deep cold recycling is to maximise the use of reclaimed asphalt pavement (RAP). In the project, the RAP share was 50% (m/m) of the mineral mix. The proportion of recycled aggregate with a grain size of 0/31.5 mm was then designed as 30% (m/m) of the mineral mix. A virgin aggregate (VA) with a continuous grain size of 0/4 mm at a rate of 20% (m/m) was used to complement the mix composition to 100%. The percentages of mineral mix ingredients are shown in Table 3.

Table 3. Percentage of mineral mix ingredients

Component	Origin	Density [g/cm <sup>3</sup> ]	MM [% (m/m)]
Reclaimed asphalt pavement (RAP)	–	2.50	50
Recycled aggregate (RA) 0/31.5 mm	Limestone	2.71	30
Virgin aggregate (VA) 0/4 mm	Dolomite	2.69	20

The designed mineral mix grain size curve is shown in Fig. 9.

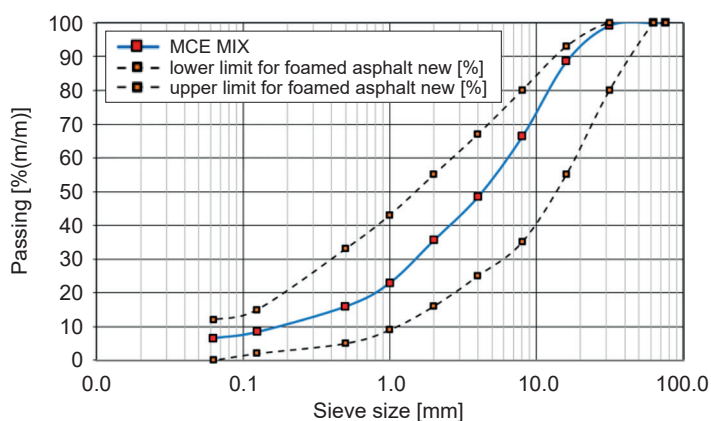


Fig. 9. MCE mix grain size

The composition of the MCE mix is complemented by binders. Portland cement CEM I 42.5R (CEM), bitumen emulsion C60B10 ZM/R produced using 70/100 (EMU) asphalt and redispersible polymer powder (RPP) were used in the research activities. All the ingredients used in the design are summarised in Table 4.

Table 4. Percentage of MCE mix ingredients

Component	Origin	Density [g/cm <sup>3</sup> ]	MM [% (m/m)]
Reclaimed asphalt pavement (RAP)	–	2.50	45,8-48,8
Recycled aggregate (RA) 0/31.5 mm	Limestone	2.71	27,5-29,3
Virgin aggregate (VA) 0/4 mm	Dolomite	2.69	18,3-19,5
CEM I 42.5R Cement	–	2.99	0.5-3.5
Bitumen emulsion	–	1.00	0.0-5.0
Powdered EVA polymer	–	0.50	0.5-3.5

The number of mixes that were tested regarding the analysed question was in line with the experiment design and amounted to 15. An important element of the analyses was the construction of mathematical models consistent with formula (1), which describe the dependence of the amount of binders on the properties of the MCE mix.

The binder analysed in this paper was a redispersible polymer powder. The polymer used is a thermoplastic EVA (polyethylene-co-vinyl acetate) copolymer. This substance comes in the form of a white powder formed by evaporating water from the polymer dispersion. It is obtained in the spray-drying process. The chemical composition of the redispersible polymer powder is given in Table 5.

Table 5. Chemical composition of redispersible polymer powder

Component	Participation [%]
C	67.67
O	29.13
Mg	0.52
Si	1.65
Ca	0.75
Al	0.29

According to an analysis of the studies [3] and [21], the use of the above-mentioned polymer modifier in the recycled mixes can improve their mechanical properties. This is caused by the occurrence of cross-links between the polymer particles and the cement matrix, which produce a continuous polymer phase [21].

The next stage of the MCE mix design process involved designing the amount of binders, i.e., Portland cement CEM I (CEM), bitumen emulsion (EMU) and redispersible polymer powder (RPP). The percentage of binders in the mix composition was determined by the domain of the Box-Behnken experiment design, the ranges of which are presented in Table 2. As a result of the assumptions, the final composition of the MCE mix was as shown in Table 4. To obtain a homogeneous mix, the ingredients were mixed in the laboratory using the WLM30 mixer shown in Fig. 10.



Fig. 10. Wirtgen WLM 30 laboratory mixer; photo: J. Krasowski

The total material input into the mixer was 30 kg. Due to the nature of the mix, which requires the optimum moisture content, the study determined the optimum moisture content using the Proctor's method [23]. The optimum moisture content of the MCE mixes is summarised in Table 9. It was necessary to adjust the optimum moisture content due to the use of bitumen emulsion in the mix. The final amount of water defined in Table 6 as " $W_{add}$ " resulted from the optimum moisture content  $W_{opt}$  minus the percentage of water from the precipitated bitumen emulsion.

The batches were used to form the specimens used for further tests. The specimens to be tested were divided into two groups, depending on compaction methods. The breakdown is shown in Table 7.

The specimens were conditioned as follows: on the first day, the specimens were stored at 20°C. Subsequently, from day 2 to day 7, they were stored in dry conditions at 40% to 70% humidity, also at 20°C ± 2°C. Then, the specimens were kept under dry conditions. The tests were performed after 28 days of conditioning.

Table 6. Optimum moisture content of MCE mixes with the polymer modifier

Type of mix MCE	$W_{opt}$ [%]	$W_{add}$ [%]
0.5C-2P-0E	4	3.7
3.5C-2P-0E	4	3.7
0.5C-2P-5E	4	0.2
3.5C-2P-5E	4	0.2
0.5C-0.5P-2.5E	4	2.0
3.5C-0.5P-2.5E	4	2.0
0.5C-3.5P-2.5E	4	2.0
3.5C-3.5P-2.5E	4	2.0
2.0C-0.5P-0E	4	3.7
2.0C-0.5P-5E	4	0.2
2.0C-3.5P-0E	4	3.7
2.0C-3.5P-5E	4	0.2
2.0C-2P-5E	4	3.7
2.0C-2P-0E	4	0.2
2.0C-2P-2.5E	4	2.0

Table 7. Breakdown of tests depending on the compaction method

Property	Research standard	Procedure for preparing samples
Air voids content $V_m$	PN-EN 12697-8 [25]	Marshall (2 lots of 75 strokes) in accordance with EN 12697-30 [34]
Water absorption $n_w$	PN-S 04001-12 [26]	
Intermediate tensile strength $ITS_{DRY}$	PN-EN 12697-23 [27]	
Water resistance $TSR$	Wirtgen [28]	
The modulus of stiffness $S_m$ at temp. +5°C	PN-EN 12697-26 [22]	Gyratory compactor in accordance with PN-EN 12697-31 [35]
Fracture toughness $K_{Ic}$	PN-EN 12697-44 [29]	

## 4. RESULTS OF THE STUDY

### 4.1. AIR VOID CONTENT

The first of the physical properties assessed for MCE mixes is the air void content  $V_m$ , which, according to PN-EN 12697-8 [25], is defined as the volume of air voids in the specimen, expressed as a percentage of the total volume of the specimen described with (4):

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

where:

$V_m$  – air void content [0.1%],

$\rho_m$  – density of the mineral-asphalt mix [ $\text{Mg}/\text{m}^3$ ],

$\rho_b$  – bulk density of the mineral-asphalt mix [ $\text{Mg}/\text{m}^3$ ].

The air void content  $V_m$  obtained for the MCE mixes that were the subject of the experiment was ranked in order from lowest to highest. The results are summarised in Fig. 11. Polish guidelines for MCE mixes [6] allow for an air void content in the MCE mix ranging from 8.0% to 15.0%. Blue indicates mixes with a minimum cement content of 0.5%, green – 2.0% cement and orange – mixes with a cement content of 3.5%.

The results obtained are within the ranged indicated by the guidelines [6]. It should be noted that an air void content of less than 10% in the MCE mix was recorded for mixes that contain 2% of the redispersible polymer powder (RPP) modifier in their composition and no bitumen emulsion. The 3.5C-2P-5EMU MCE mix with a high content of bitumen emulsion and polymer modifier has the highest air void content – 13.9%. The lowest value was recorded for the mix with the symbol 3.5C-2P-0EMU – 8.8%. The significance of impact of the analysed ingredients on the air void content of the MCE mix regarding binders is shown in Table 8.

Table 8. Impact of factors on the property: air void content  $V_m$

	$V_m$ [%], $R^2 = 0.67$ , Pure error $MS = 0.22$		
	$t$	Factor	$p \leq 0.05$
Average / Constant	25.94	11.55	0.000
(1) CEM [%] (L)	5.25	1.43	0.000
CEM [%] (Q)	-10.04	-0.59	0.000
(2) EMU [%] (L)	0.93	0.13	0.358
EMU [%] (Q)	-1.54	-0.03	0.129
(3) RPP [%] (L)	-4.85	-1.32	0.000
RPP [%] (Q)	6.66	0.39	0.000
1L refer 2L	7.85	0.25	0.000
1L refer 3L	2.02	0.11	0.049
2L refer 3L	-1.96	-0.06	0.057

Factors with a significant impact on the feature under consideration are marked in red

The values obtained are subject to an MS estimation error of  $\sqrt{0.22}$ . The average air void content for the MCE mix regardless of the amount of cement, bitumen emulsion and polymer powder is equal to 11.55%. In contrast, the coefficient of determination  $R^2$  is equal to 0.67. Using a mathematical model in the form of a polynomial of degree two, response surfaces were developed to represent the impact of the analysed ingredients on the air void content  $V_m$ . The results are summarised in Fig. 12.

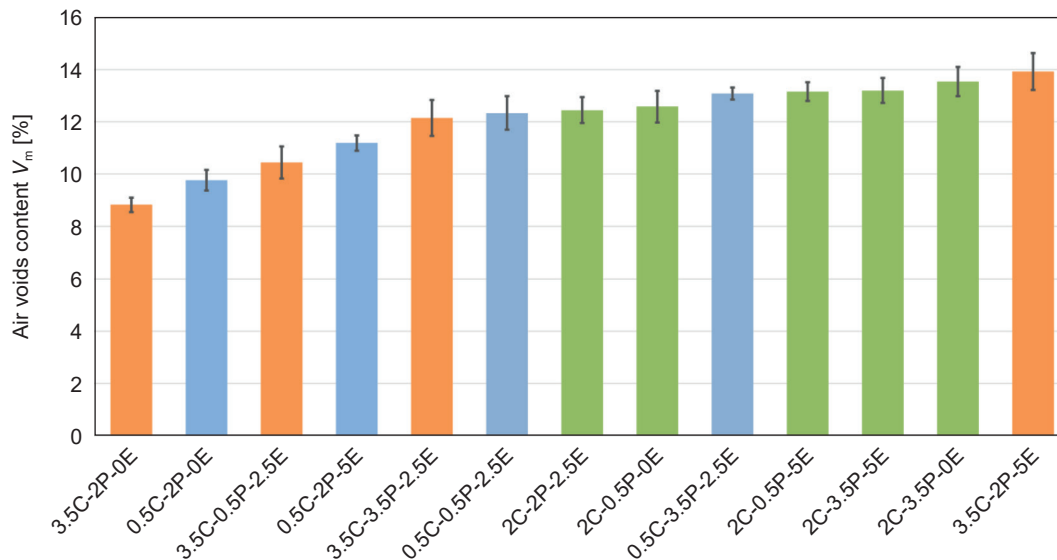


Fig. 11. Air voids content  $V_m$  for MCE mixes (the error bar represents the 95% confidence interval)

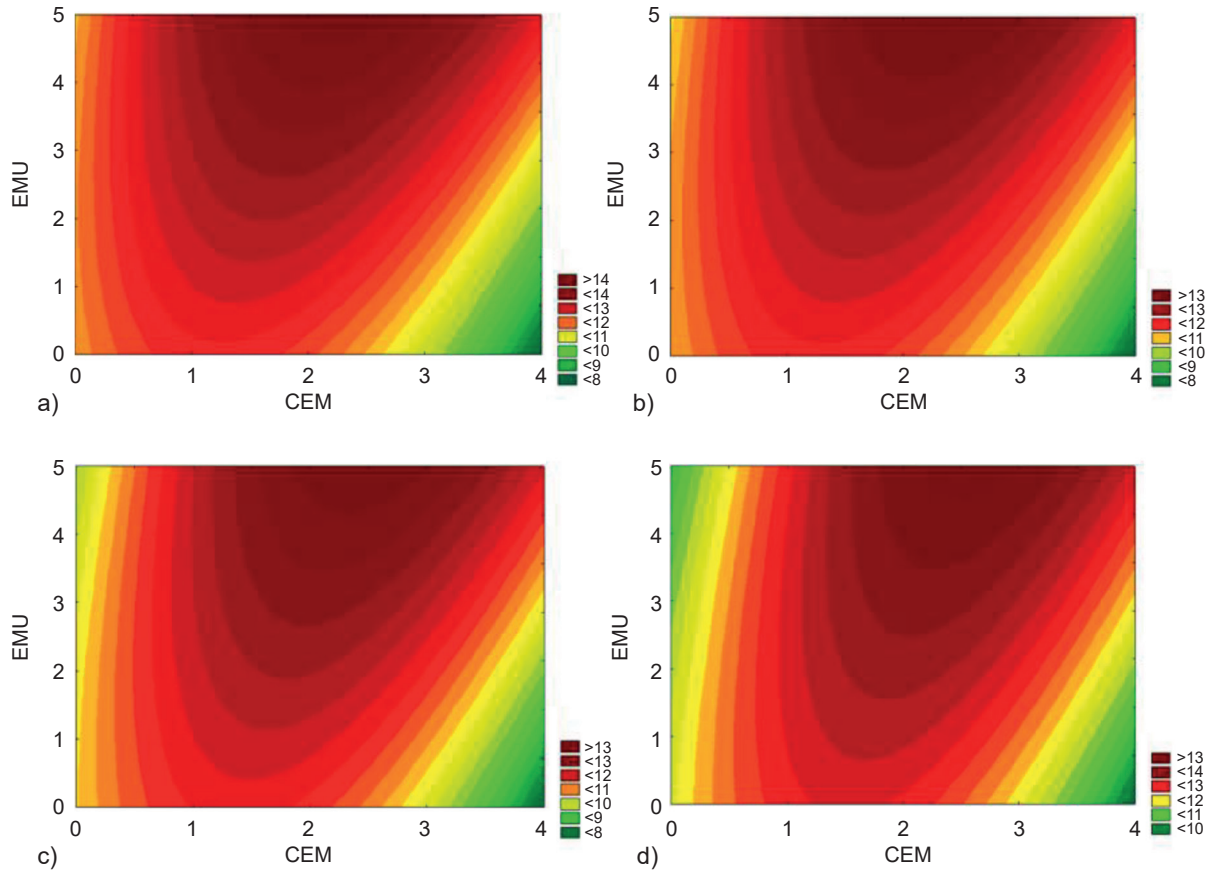


Fig. 12. Parameter response surface for free space content  $V_m$  in relation to Portland cement and asphalt emulsion content at: a) 0.0% RPP, b) 0.5% RPP, c) 2.0% RPP, d) 3.5% RPP

The addition of the polymer modifier RPP to the MCE mix at a rate of 0.5% does not change the air void content. The results obtained are very similar to the results without the RPP modifier, which are shown in Fig. 12. For MCE mixes without the modifier, the air void content is mainly determined by the amount of cement in their composition. The lowest  $V_m$  values are recorded for high cement contents, above 3.0%. Highest  $V_m$  content is visible with minimal cement share. An increase in the polymer powder content of the MCE mix results in sealing for two ingredient combinations: a mix with a minimum cement content of 0.5% and a maximum bitumen emulsion content, i.e., above 4.0%, or for an MCE mix with no bitumen emulsion and cement content above 3.0%. A dosage of 2.0% of redispersible polymer powder is sufficient to achieve an acceptable air void content. The decrease in air void content progresses as the amount of polymer increases successively up to 3.5%. A lower air void content leads to the sealing of the MCE mix, which is essential due to the

nature of the pavement layer it is used for, i.e., the base course, which may be damaged by water from the environment. The addition of a polymer modifier in the form of a redispersible polymer powder has a beneficial effect on the air void content. An increase in the content of the RPP modifier in the MCE mix results in a decrease in air void content and the sealing of the MCE mix.

## 4.2. WATER ABSORPTION

Another parameter assessed for the analysed MCE mixes is their water absorption. Water absorption  $n_w$  is the mass and volume of water absorbed by a specimen immersed in water for 24 hours at  $25 \pm 5^\circ\text{C}$  and then dried to constant weight. Water absorption  $n_w$  is calculated as a percentage (m/m) with an accuracy of 0.1% with formula (5) [26]:

$$n_w = \frac{m_1 - m}{m} \cdot 100\%, \quad (5)$$

where:

$n_w$  – water absorption by weight [%],

$m_1$  – weight of the specimen saturated with water [g],

$m$  – weight of the dry specimen [g].

The water absorption  $n_w$  obtained for the MCE mixes that were analysed according to the experiment design was ranked from lowest to highest. The results are presented in Fig. 13. The water absorption values obtained for the MCE mix range from 1.3% to 3.9%.

Table 9. Impact of factors on the property: water absorption  $n_w$

	$n_w$ [%], $R^2 = 0.88$ , Pure error $MS = 0.06$		
	$t$	Factor	$p \leq 0.05$
Average / Constant	15.87	3.77	0.000
(1) CEM [%] (L)	5.26	0.77	0.000
CEM [%] (Q)	-8.72	-0.27	0.000
(2) EMU [%] (L)	-6.30	-0.47	0.000
EMU [%] (Q)	3.67	0.04	0.001
(3) RPP [%] (L)	-3.85	-0.56	0.000
RPP [%] (Q)	3.64	0.11	0.001
1L refer 2L	-1.43	-0.02	0.160
1L refer 3L	0.25	0.01	0.804
2L refer 3L	3.45	0.06	0.001

Factors with a significant impact on the feature under consideration are marked in red

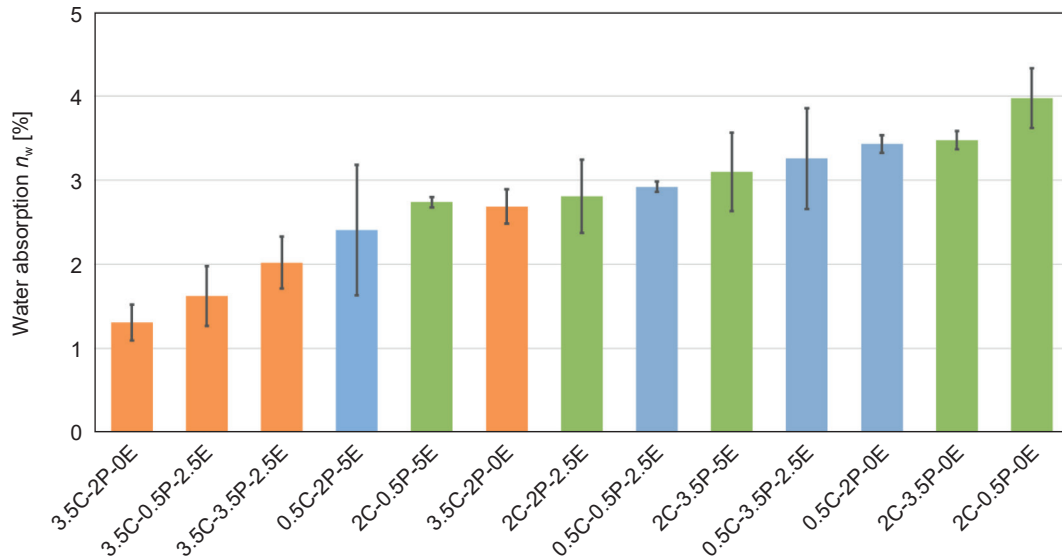


Fig. 13. Water absorption  $n_w$  of analysed MCE mixes (the error bar represents the 95% confidence interval)

The lowest water absorption value was achieved by MCE mixes with a high cement content in the composition, i.e., 3.5% CEM, whose water absorption value does not exceed 2.0%. The tests showed that the bitumen emulsion in the MCE mix, similarly to cement, reduces the analysed property  $n_w$ , sealing the mix. In effect, this limits its ability to absorb water. The reduction in polymer content resulted in an increase in the water absorption of the mix by approximately 0.5%, i.e., from 3.5% to 4.0%. The impact of the analysed ingredients on the considered property of the MCE mix is shown in Table 9.

The analysis shows that the values obtained are subject to an MS estimation error of  $\sqrt{0.06}$ . The coefficient of determination  $R^2$  for the results obtained is equal to 0.88. maximum value of 4.0% was obtained for the 2C-0.5P-0E mix, while the minimum value, which amounts to 1.3% and is three times lower, was recorded for the 3.5C-2P-5E MCE mix. The presence of polymer powder in the MCE mix reduces water absorption. The factor that most strongly impacts the water absorption value of an MCE mix is the Portland cement content. As the cement content increases, the water absorption of the MCE mix decreases. Similarly, an increase in emulsion content reduces water absorption. It is important to point out the significant relationship of

the decrease in water absorption of the MCE mix with an increase in the amount of cement. With 3% cement in the mix and 2% bitumen emulsion, the water absorption of MCE mixes drops below 2%. The lowest absorption can be achieved with the maximum bitumen emulsion content in the MCE mix. The bitumen emulsion seals the mix, which does not allow water to be absorbed from the environment. This is an important property because the mix is to be used in the base course. Absorption of water by the base course causes it to degrade due to excessive water content and loss of durability. The presence of RPP in the MCE mix reduces the water absorption. The most favourable results – and thus the lowest values of air void content – were recorded with the amount of RPP in the MCE mix equal to 3.5%.

### 4.3. INDIRECT TENSILE STRENGTH

#### $ITS_{DRY}$

The test of indirect tensile strength  $ITS_{DRY}$  of the MCE mix was carried out on Marshall specimens with a diameter of  $101.6 \pm 0.3$  mm and a height of  $62.5 \pm 2.5$  mm. Specimens of the MCE mix were made according to the methodology shown in Table 7. The test was performed at  $25 \pm 2^\circ\text{C}$ . The test is carried out by placing the specimens between two plates and subjecting them to compression with a constant displacement rate of  $50 \pm 2$  mm/min. The indirect tensile strength  $ITS_{DRY}$  is calculated according to (6). The test is schematically illustrated in Fig. 14 and Fig. 15 shows the obtained results:

$$ITS_{DRY} = \frac{2 \cdot P}{\pi \cdot h \cdot D}, \quad (6)$$

where:

$P$  – maximum failure load of the specimen [N],

$h$  – height of the specimen [mm],

$D$  – diameter of the specimen [mm].

The results of the tests are presented in a specific order, from the lowest to the highest. Mixes containing 3.5% of cement in their composition are marked in orange in the diagram. They are characterised by an indirect tensile strength of more than 1100 kPa. MCE mixes containing 0.5% of Portland cement in the composition have the lowest  $ITS_{DRY}$  values, with indirect tensile strengths below 700 kPa. An increase in the bitumen emulsion content of the mixes reduces the indirect tensile strength. As an example, in mixes where the bitumen emulsion content was increased from 0% to 5%, with equal content of CEM and RPP, a 40% decrease in  $ITS_{DRY}$  was recorded. The test results indicate an interesting impact of RPP on MCE mixes. Favourable values of the  $ITS_{DRY}$  parameter for the base course are obtained when the RPP is contained in an amount of up to 2% in the composition of the MCE mix. An example would be a mix with 2% CEM and 2% RPP. The indirect tensile strength in this case is approximately 720 kPa, whereas with 3.5% RPP, the strength amounts to 600 kPa. The impact of the analysed ingredients on the considered property  $ITS_{DRY}$  of the MCE mix is shown in Table 10.

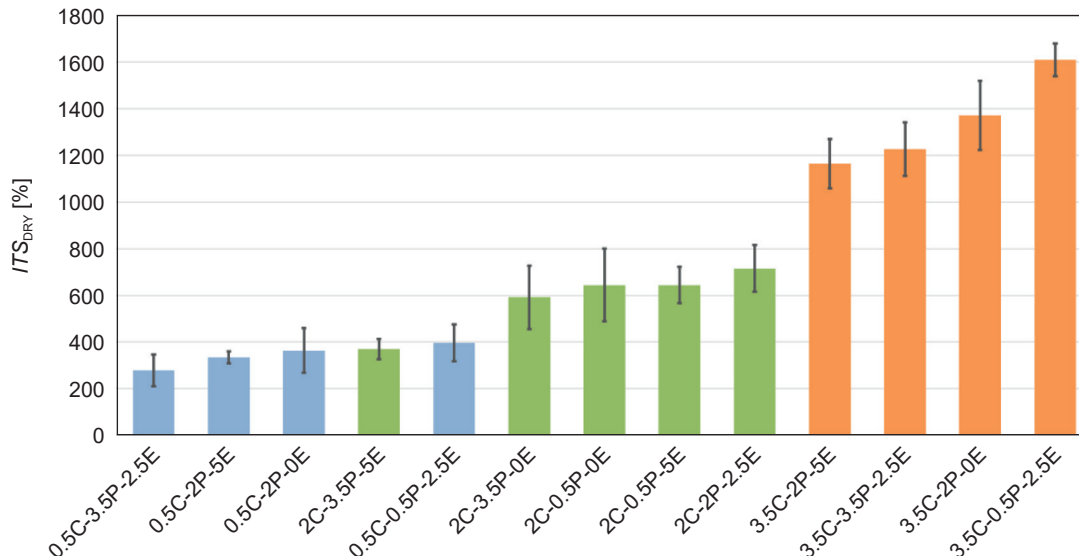


Fig. 14. Results of the  $ITS_{DRY}$  indirect tensile test (the error bar represents the 95% confidence interval)



Fig. 15. Indirect tensile strength test used for calculate  $ITS_{DRY}$ ; photo M. Krasowski

The  $ITS_{DRY}$  parameter values obtained during the tests have an MS estimation error of  $\sqrt{1185}$ . The coefficient of determination  $R^2$  is equal to 0.99. The ingredient of the MCE mix that significantly affects the indirect tensile strength is the cement (CEM). The addition of cement to the MCE mix increases the  $ITS_{DRY}$  parameter. Another ingredient with a high impact is the redispersible polymer powder (RPP). An increase in the percentage of the RPP modifier in the composition of the MCE mix reduces indirect tensile strength. This relationship is confirmed by the findings presented in the publications [36-37]. The bitumen emulsion in the MCE mix, similarly to the RPP, causes an increase in the flexibility of MCE mixes. The bitumen emulsion content of the MCE mix leads to a decrease in the value of the  $ITS_{DRY}$  parameter. It is possible to use RPP in the MCE mix as long as the amount of EMU in the composition is minimised. This is also indicated by the proportion of cement and polymer, which are significant in relation to each other. The results obtained made it possible to determine the relationship between the binders in the MCE mix. Response surfaces showing the changes

Table 10. Impact of factors on the characteristic: indirect tensile strength  $ITS_{DRY}$

	$ITS_{DRY}$ [%], $R^2 = 0.88$ , Pure error $MS = 0.06$		
	$t$	Factor	$p \leq 0.05$
Average / Constant	5.28	172.23	0.000
(1) CEM [%] (L)	2.92	58.56	0.005
CEM [%] (Q)	21.19	90.63	0.000
(2) EMU [%] (L)	11.49	118.98	0.000
EMU [%] (Q)	-11.54	-17.77	0.000
(3) RPP [%] (L)	4.99	99.86	0.000
RPP [%] (Q)	-4.28	-18.29	0.000
1L refer 2L	-5.13	-11.77	0.000
1L refer 3L	-7.67	-29.34	0.000
2L refer 3L	-6.43	-14.75	0.000

Factors with a significant impact on the feature under consideration are marked in red

in indirect tensile strength as a function of the amount of each ingredient in the MCE mix. The charts are shown in Fig. 16.

On the basis of the test results presented in Fig. 16, it should be pointed out that an increase in the amount of cement in the recycled mix has the most significant effect on indirect tensile strength. With a cement content of more than 2.5% in the MCE mix, the indirect tensile strength  $ITS_{DRY}$  reaches values over 1000 kPa. An indirect tensile strength of more than 800 kPa can already be achieved with a cement content of approximately 1.5%. Interestingly, a minimal increase in RPP content, from 0.0% to 0.5%, enables more favourable results to be obtained with a minimal amount of cement and bitumen emulsion. A further gradual increase in the amount of RPP, to values of 2.0% and 3.5% in the mix, reduces  $ITS_{DRY}$ . For an RPP content of 2.0% and a CEM content of more than 3.5%, the indirect tensile strength is approximately 1600 kPa; for the polymer content of 3.5%, the strength is already 1400 kPa.

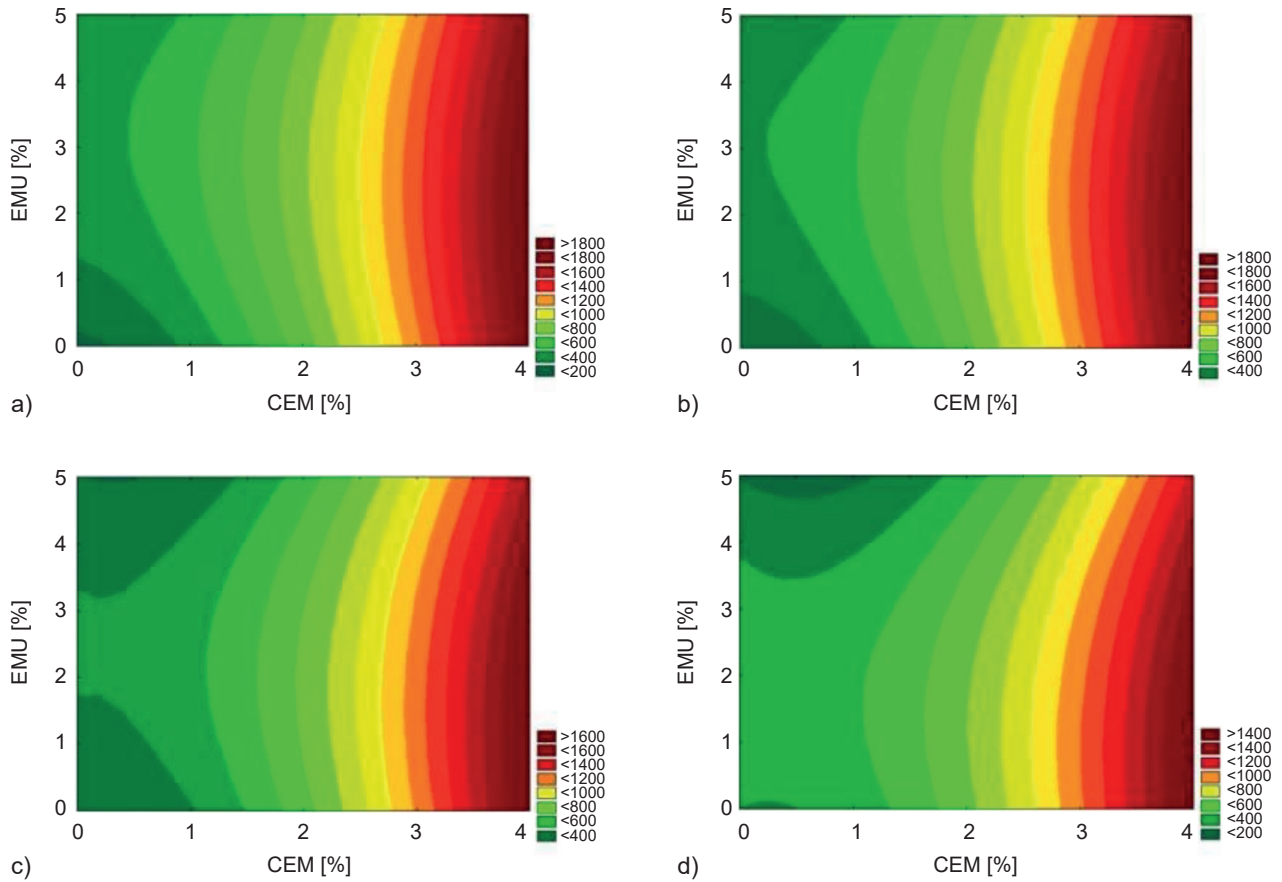


Fig. 16. Response surfaces for the parameter: indirect tensile strength  $ITS_{DRY}$  in the context of Portland cement and bitumen emulsion contents for different amount of RPP in MCE mix: a) 0.0%, b) 0.5%, c) 2.0%, d) 3.5%

#### 4.4. WATER RESISTANCE RATIO

The water resistance ratio  $TSR$  was determined by assessing the decrease in indirect tensile strength of specimens subjected to 24-hour conditioning in water at  $25 \pm 2^\circ\text{C}$  compared to specimens stored in air-dry conditions at  $25^\circ\text{C}$ . The test specimens were compacted in a Marshall compactor at a frequency of  $2 \times 75$  strokes according to PN-EN 12697-30 [6]. The index was determined 28 days after compaction, the strength tests were performed at  $25 \pm 2^\circ\text{C}$ , the result was calculated according to formula (7). The resistance to climatic conditions characterises MCE mixes in terms of water impact. The average water resistance values  $TSR$  are presented in Fig. 17:

$$TSR = \frac{ITS_{WET}}{ITS_{DRY}}, \quad (7)$$

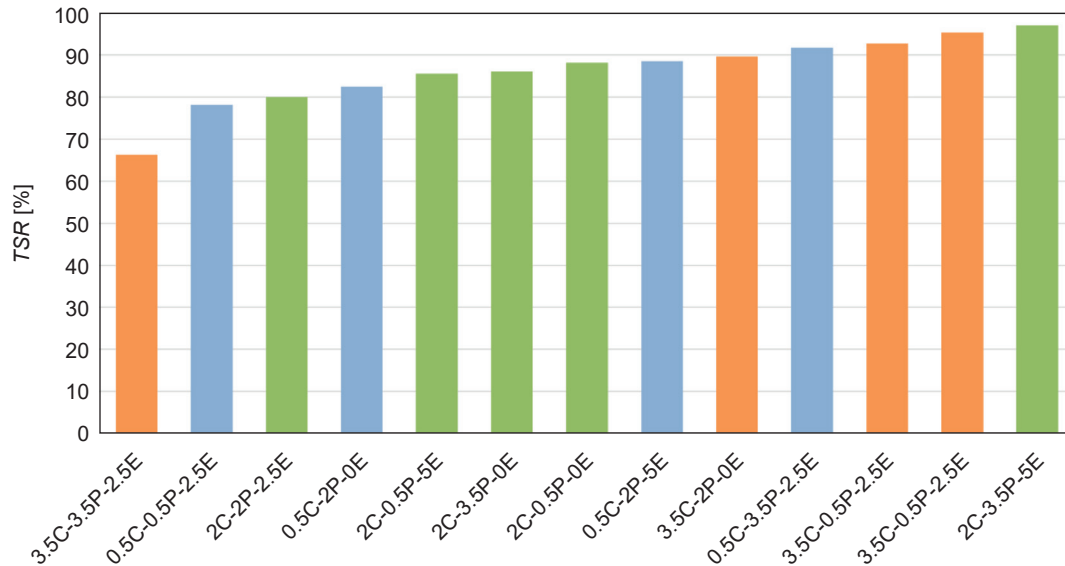
where:

$TSR$  – water resistance [%],

$ITS_{WET}$  – indirect tensile strength of the conditioned specimens at  $25^\circ\text{C}$  [kPa],

$ITS_{DRY}$  – indirect tensile strength at  $25^\circ\text{C}$  of unconditioned specimens [kPa].

The required value, i.e.,  $TSR \geq 80\%$  as defined by the Polish guidelines for MCE mixes [6], was not obtained only for two mixes. Most of the analysed MCE mixes met the water resistance  $TSR$  criterion. Only mixes with codes 3.5C-3.5P-2.5E and 0.5C-0.5P-2.5E failed to achieve the required water resistance above 80%. The impact of the individual mix ingredients on the analysed property is shown in Table 11.

Fig. 17. Test results of the *TSR* parameter for MCE mixesTable 11. Impact of factors on the property: water resistance *TSR*

	<i>TSR</i> : $R^2 = 0.85$ , Pure error $MS = 41.92$		
	<i>t</i>	Factor	$p \leq 0.05$
Average / Constant	5.53	75.24	0.011
(1) CEM [%] (L)	0.99	8.46	0.395
CEM [%] (Q)	0.24	0.44	0.829
(2) EMU [%] (L)	-1.48	-6.39	0.234
EMU [%] (Q)	1.70	1.17	0.187
(3) RPP [%] (L)	0.41	3.47	0.712
RPP [%] (Q)	0.43	0.82	0.700
1L refer 2L	-0.23	-0.20	0.836
1L refer 3L	-3.31	-4.75	0.045
2L refer 3L	1.05	0.90	0.372

Factors with a significant impact on the feature under consideration are marked in red

According to the data shown in Table 11, the factor that significantly affects the *TSR* parameter is the interaction of the amount of cement and polymer powder. Changing their share in the composition of the MCE mix alters the value of the discussed *TSR* parameter. The interaction of the cement with the polymer modifier reduces *TSR* water resistance. Charts have been prepared to show how changing the amount of each ingredient in the MCE mix affects the *TSR* parameter. The data is summarised in Fig. 18.

Analysis of the test results presented in Fig. 18 regarding water resistance *TSR* supports the conclusion that changing the amount of the RPP modifier in the MCE mix strongly affects the durability of the MCE mix. The use of the RPP modifier at a rate of 0.0% to 0.5% with a simultaneous use of cement at a rate of 1.5% guarantees *TSR* above 80%. The presence of bitumen emulsion in the MCE mix has no significant effect on the change in water resistance *TSR*. Interesting results are shown in Fig. 16c, which includes 2% polymer powder in the mix. It shows that with 2% content of the modifier in the MCE mix, regardless of the content of cement and bitumen emulsion, a *TSR* result > 80% can be achieved. This makes it possible to meet the requirements set out in the guidelines [6] for roads of categories KR 1 to KR 4. Changing the amount of polymer in the mix to 3.5% leads to a complete change in the shape of the chart, which indicates a significant change in the analysed water resistance *TSR*. For 3.5% RPP in the MCE mix, *TSR* values greater than 80% are obtained for mixes containing up to 2% of cement in their composition. The results obtained and their analysis indicate that the most favourable option is to dose up to 2% of the polymer modifier in the MCE mix for optimal *TSR* water resistance.

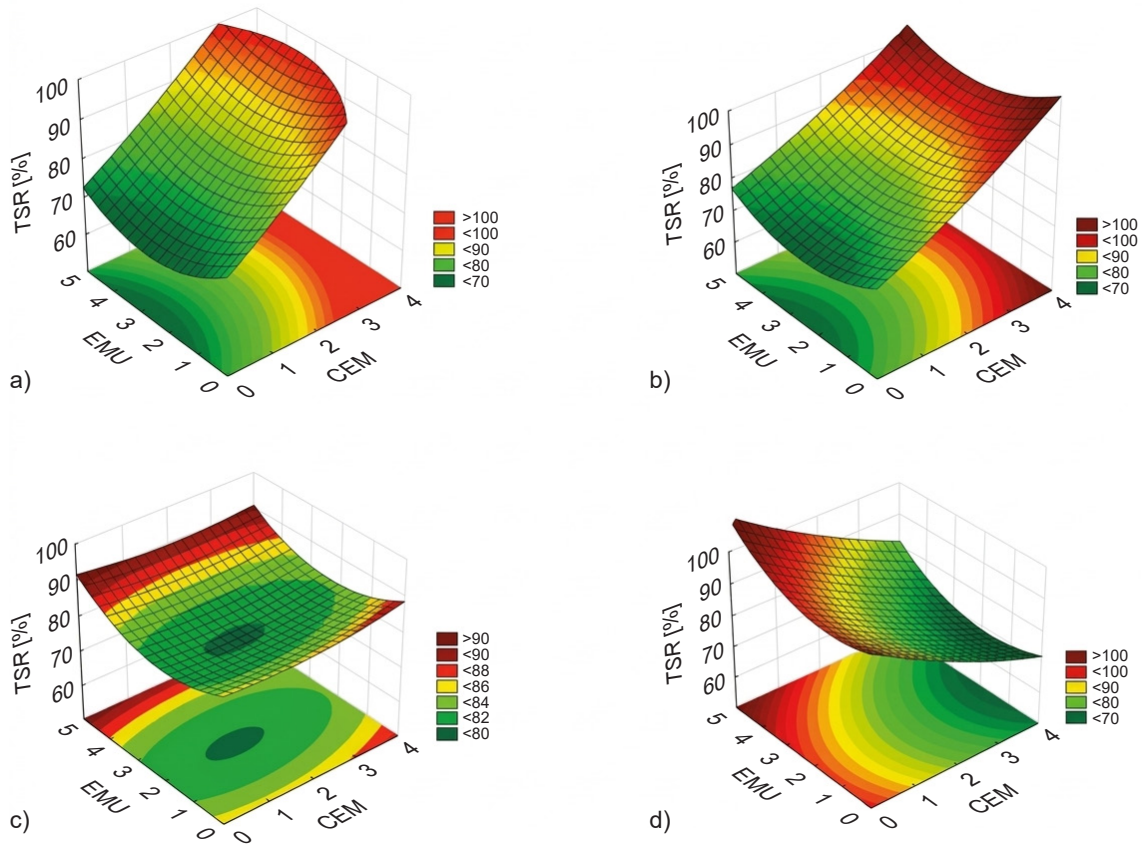


Fig. 18. Response surfaces for the parameter: water resistance  $TSR$  in the context of Portland cement and bitumen emulsion content for different amount of RPP in MCE mix: a) 0.0%, b) 0.5%, c) 2.0%, d) 3.5%

#### 4.5. *IT-CY* STIFFNESS MODULUS

Another important parameter that describes the materials used in road pavements is the stiffness modulus  $S_m$ . To determine the stiffness modulus of the MCE mixes, a test was performed in the *IT-CY* indirect tensile scheme. The stiffness modulus was determined in accordance with the requirements of PN-EN 12697-26 [22], Annex C. The horizontal displacement was  $5 \pm 2 \mu\text{m}$ , the loading time was  $124 \pm 4 \text{ ms}$ . The stiffness modulus is determined from (8), and the Poisson's ratio from (9):

$$S_m = \frac{F \cdot (v + 0.27)}{z \cdot h}, \quad (8)$$

$$v = 3.59 \cdot \frac{z}{\Delta V} - 0.27, \quad (9)$$

where:

- $S_m$  – stiffness modulus of the specimen [MPa],
- $F$  – maximum force applied to the specimen [N],
- $v$  – temperature-dependent Poisson's ratio,
- $z$  – amplitude of horizontal displacement of the specimen under load [mm],
- $h$  – thickness of the specimen [mm],
- $\Delta V$  – the maximum vertical displacement of the specimen (corresponding to the maximum horizontal displacement) [mm].

Analysis of formula (10) indicates that an increase in the transverse strain and thickness of the specimen reduces the internal stresses and thus the stiffness modulus  $S_m$ . Fig. 19 shows the stiffness modulus test. According to the applicable Polish guidelines [6], the *IT-CY* stiffness modulus is to be checked at  $+5^\circ\text{C}$ . Fig. 20 illustrates a summary of the average measurements.

The MCE mixes with the highest values of the  $S_m$  stiffness modulus contain 3.5% of cement in their composition. Both the addition of bitumen emulsion and RPP reduce the stiffness modulus. To prevent excessive pavement stiffness, it seems reasonable to look for solutions that

reduce the stiffness of the mix without adversely affecting other properties. The impact of the individual ingredients used in the composition of the MCE mix on the analysed characteristic is shown in Table 12.



Fig. 19. Test RIG for *IT-CY* stiffness modulus tests; photo M. Krasowski

Table 12. Impact of factors on the property: *IT-CY* stiffness modulus at 5°C

	<i>IT-CY</i> 5°C, $R^2 = 0.97$	
	Factor	$p \leq 0.05$
Average / Constant	2986.8	0.012
(1) CEM [%] (L)	6487.4	0.000
CEM [%] (Q)	801.6	0.000
(2) EMU [%] (L)	-1140.8	0.003
EMU [%] (Q)	111.8	0.044
(3) RPP [%] (L)	2305.1	0.002
RPP [%] (Q)	-239.3	0.117
1L refer 2L	-652.0	0.000
1L refer 3L	-1770.7	0.000
2L refer 3L	272.3	0.001

Factors with a significant impact on the feature under consideration are marked in red

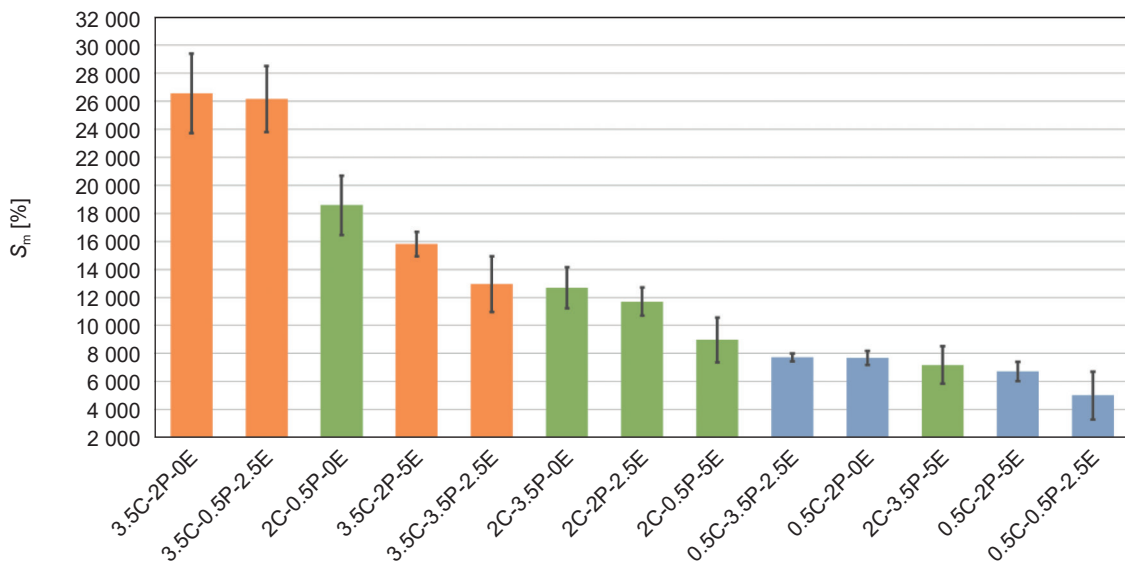


Fig. 20. Stiffness modulus  $S_m$  values at 5°C (the error bar represents a confidence interval of 95%)

The coefficient of determination that was obtained for the test results at 5°C is equal to  $R^2 = 0.97$ . This means that the mathematical model accurately describes the results obtained. The obtained values of the stiffness modulus at 5°C are subject to an estimation error of  $\sqrt{1204.4}$ . Cement is a factor that strongly contributes to an increase in the stiffness modulus. This is also reflected in publications [38-39]. An important ingredient in the MCE mix is the RPP. The effect of the polymer modifier reduces the stiffness modulus, but the magnitude of the effect is three times lower than the dominant cement bond. It is worth noting the importance of the cement content, the polymer content and the interaction of the two binders. It is an important phenomenon that, on the one hand, shows that the bitumen emulsion in the MCE mix can be replaced by a smaller amount of redispersible polymer powder

with the same end result, i.e., a reduction in the stiffness modulus of the mix. The results of the tests enabled the preparation of charts showing the variation of the stiffness modulus of the mix depending on the amount of ingredients in the MCE mix. They are summarised in Fig. 21.

#### 4.6. EVALUATION OF FRACTURE TOUGHNESS

To ensure the correct behaviour of the pavement, it is necessary for the mix used in the layer to have an adequate fracture toughness  $K_{Ic}$ . In view of current experience, mixes bound with a hydraulic binder are more at risk of cracks, which propagate all the way to the wearing course. An important element of the ongoing research is the evaluation of the effect of the polymer modifier on the fracture toughness  $K_{Ic}$  of MCE mixes.

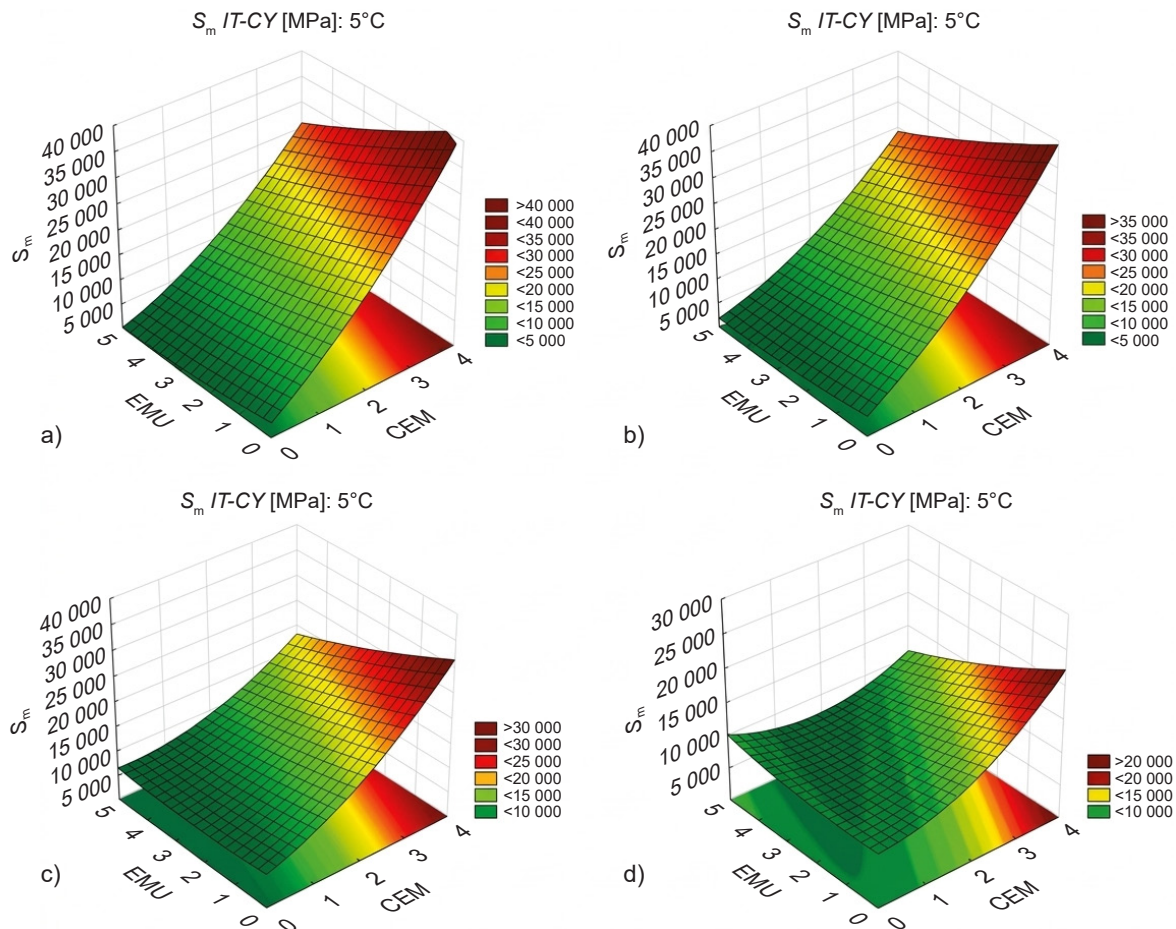


Fig. 21. Response surface for the parameter: IT-CY stiffness modulus at 5°C in the context of Portland cement and bitumen emulsion content for different amount of RPP in MCE mix: a) 0.0%, b) 0.5%, c) 2.0%, d) 3.5%

The study used the classic SCB (Semi Circular Beam) test method, which is used to assess the fracture toughness of mineral-asphalt mixes. The test was carried out on half-cylinder specimens with a notch with a depth of 10 mm and a width of 1 mm. The specimens were compacted in a gyratory compactor in accordance with the requirements of PN-EN 12697-31 [35] to a density guaranteeing a compaction ratio of 98%-100%. Notch parameters were used as proposed by the authors [2]. The specimen was subjected to a three-point bending test in such a way that the central part of the test specimen base was subjected to tensile stress. During the test, the strain increases at a constant rate of 5 mm/min. The corresponding pressure increases to the maximum value  $F_{\max}$ , which is directly related to the fracture toughness of the specimen. Fig. 22 shows a diagram of the testing frame.

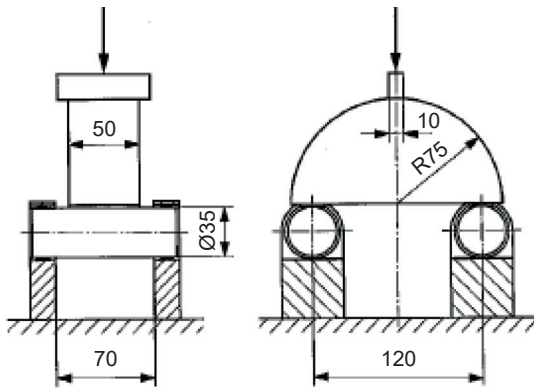


Fig. 22. SCB test frame – standard scheme [29]

A crack (notch)  $N$  with a nominal width of  $1.0 \pm 0.10$  mm and a depth of  $10.0 \pm 1.0$  mm was cut out in the middle of the specimen. Specimens were tested at  $0^\circ\text{C}$  and  $20^\circ\text{C}$ . Prior to testing, the specimens were placed in a climate chamber at the test temperature for at least 4 h. The study included the determination of quantities calculated based on PN-EN 12697-44 [29] and an analysis of the relevant studies [40]. The notched specimen is shown in Fig. 23.

The fracture toughness  $K_{Ic}$  of specimen  $i$  ( $i = 1, 2, 3, 4$ ) was calculated based on (10):

$$K_{Ic,i} = \sigma_{\max,i} \cdot Y \cdot \sqrt{\pi \cdot a_i} \left[ \frac{\text{N}}{\text{mm}^{\frac{3}{2}}} \right], \quad (10)$$

where:

- $a_i$  – is the specimen crack depth [mm],
- $\sigma_{\max,i}$  – the specimen failure load [ $\text{N}/\text{mm}^{3/2}$ ],
- $Y$  – the normalised stress ratio according to (11):

$$Y = 4.782 - 1.219 \cdot \left( \frac{a_i}{r_i} \right) + 0.063 \exp \left( 7.045 \cdot \left( \frac{a_i}{r_i} \right) \right). \quad (11)$$

It should be emphasised that the assessment of the fracture toughness of mineral-cement mixes with bitumen emulsion is important from the point of view of the durability of road pavements. MCE mixes are prone to cracking resulting from rebound cracking damage, which can carry over to the upper layers of mineral-asphalt mixes. Therefore, it would be desirable to look for solutions that will increase the fracture toughness of MCE mixes. Fig. 24 shows the moment the specimen was tested.

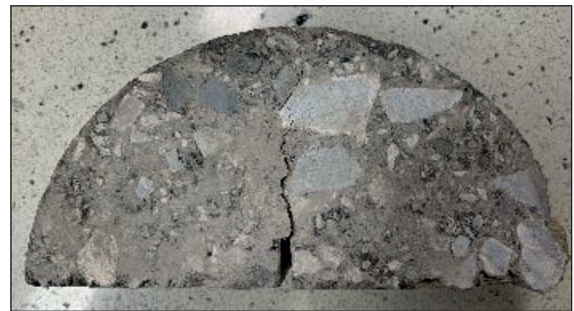


Fig. 23. Semi-circular notched specimen; photo: J. Krasowski



Fig. 24. SCB (Semi-Circular Beam) test; photo: J. Krasowski

The parameter that describes the fracture toughness of the MCE mix is the  $K_{Ic}$  ratio. The assessment of fracture toughness was carried out for the MCE mixes subjected to the experiment at two temperatures:  $0^\circ\text{C}$  and  $20^\circ\text{C}$ . The coefficient of determination obtained for the mathematical model in the form of a polynomial of degree two describing the test results obtained at  $0^\circ\text{C}$  is  $R^2 = 0.67$ , while for  $20^\circ\text{C}$ ,  $R^2 = 0.55$ . The data are presented in Table 13, which shows the impact of the individual ingredients of the MCE mix with the RPP polymer modifier on the analysed parameter.

Table 13. Impact of factors on the property: fracture toughness  $K_{Ic}$ 

	$K_{Ic}$ 0°C, $R^2 = 0.67$ , Pure error MS = 1.17		$K_{Ic}$ 20°C, $R^2 = 0.55$ , Pure error MS = 1.02	
	Factor	$p \leq 0.05$	Factor	$p \leq 0.05$
Average / Constant	-0.64	0.483	-0.95	0.232
(1) CEM [%] (L)	2.59	0.000	3.05	0.000
CEM [%] (Q)	-0.08	0.494	-0.43	0.000
(2) EMU [%] (L)	1.14	0.000	1.34	0.000
EMU [%] (Q)	-0.17	0.000	-0.28	0.000
(3) RPP [%] (L)	3.22	0.000	0.55	0.261
RPP [%] (Q)	-0.63	0.000	0.23	0.028
1L refer 2L	0.01	0.795	0.29	0.000
1L refer 3L	-0.26	0.016	-0.31	0.001
2L refer 3L	-0.01	0.838	-0.23	0.000

Factors with a significant impact on the feature under consideration are marked in red

Tests at 0°C showed the impact of the binders and modifier on fracture toughness  $K_{Ic}$ . The increase in cement content, to a large extent, leads to higher fracture toughness. The cohesive force of the ingredients caused by the hydraulic bonds coming from the binder is a significant factor. This is confirmed by the findings presented in the paper [2]. The factors affecting fracture toughness also include the interaction of cement and bitumen emulsion as well as the interaction of bitumen emulsion and polymer powder. The presence of a modifier in the MCE mix increases fracture toughness. It is important to choose the right amount of binders in the MCE mix and optimise its composition. The results obtained in the course of the research were presented in the form of charts showing the changes in fracture toughness as a function of the amount of individual binders in the mix. For measurements at 0°C, they are shown in Fig. 25.

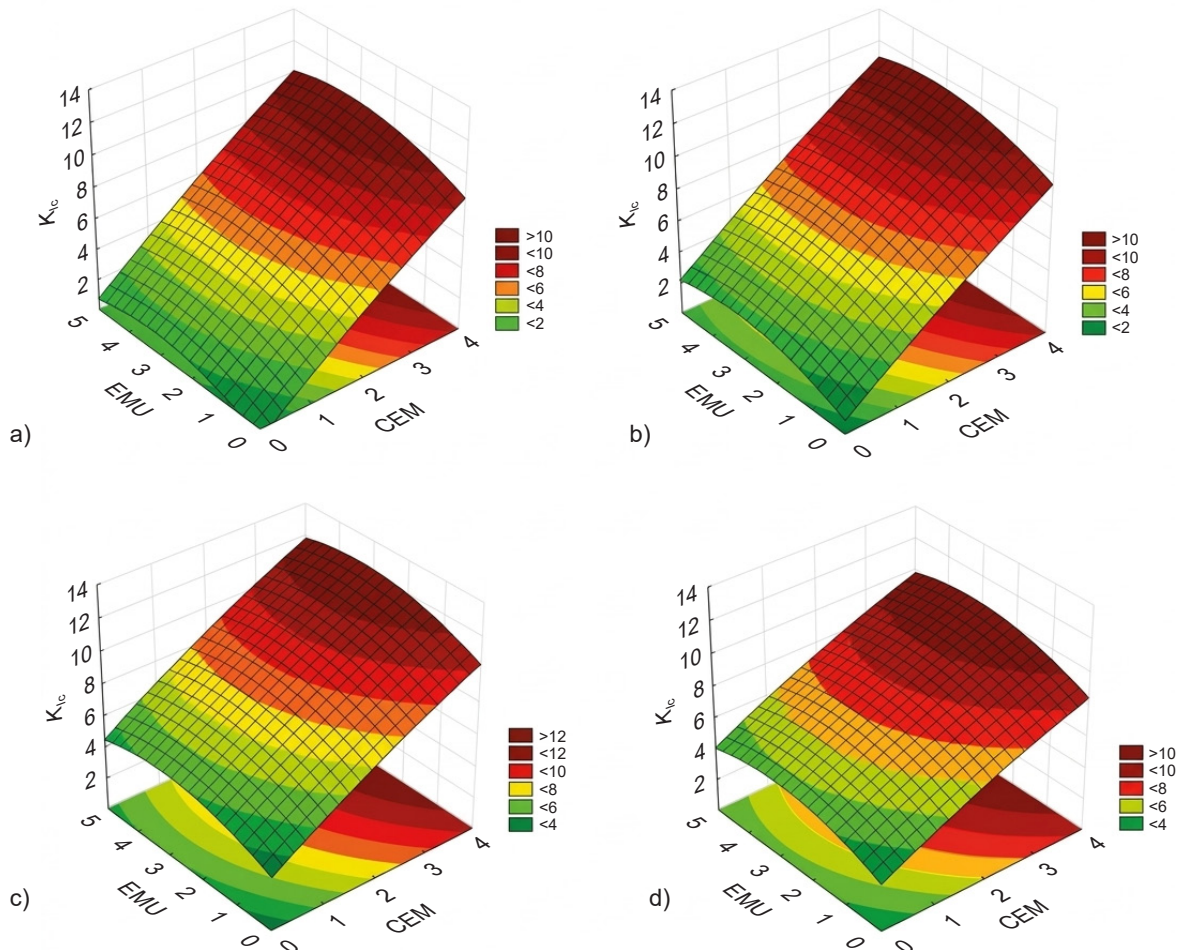


Fig. 25. Response surface of the parameter fracture toughness  $K_{Ic}$  at 0°C as a function of Portland cement and bitumen emulsion contents for different amount of RPP in MCE mix: a) 0.0%, b) 0.5%, c) 2.0%, d) 3.5%

The highest fracture toughness values are recorded for high cement content. This is also confirmed by the findings presented in the publications [41-42]. An improvement in the parameter can be achieved using the polymer modifier. Tests conducted at 0°C showed that an MCE mix containing 2.0% of cement, 2.0% of polymer powder and 2.5% of bitumen emulsion achieved higher  $K_{Ic}$  fracture toughness than a mix with 2.0% of cement, 3.5% of polymer powder and 5.0% of bitumen emulsion. The results obtained were 8.89 N/mm<sup>3/2</sup> for the 2C-2P-2.5E mix and 7.86 N/mm<sup>3/2</sup> for the 2C-3.5P-5E mix, respectively. For a fixed cement quantity of 2.0%, a mix having 3.5% RPP and 0.0% EMU has the same fracture toughness as a mix with 0.5% RPP and 5.0% EMU. Of all those analysed mixes, the highest result was obtained with a mix of 3.5% of cement, 0.5% of polymer and 2.5% of bitumen emulsion. With no polymer content or minimal polymer

content in the mix, the highest fracture toughness of the base course are obtained by MCE mixes with more than 3.0% of cement. Increasing the content of the RPP modifier to 2.0% enables a reduction in the amount of cement in the MCE mix while maintaining high fracture toughness. For this amount of the modifier, the most favourable  $K_{Ic}$  fracture toughness results are obtained above 12 N/mm<sup>3/2</sup>. It should be noted that the fracture toughness has improved in MCE mixes with a minimal amount of cement and bitumen emulsion. The addition of 3.5% of polymer enables a reduction of the content of Portland cement to 2.0% and the bitumen emulsion content to 1.0%, making it possible to achieve a high fracture toughness of the MCE mix – amounting to approximately 10 N/mm<sup>3/2</sup>. Corresponding response surface charts derived from the results obtained during measurements at 20°C are shown in Fig. 26.

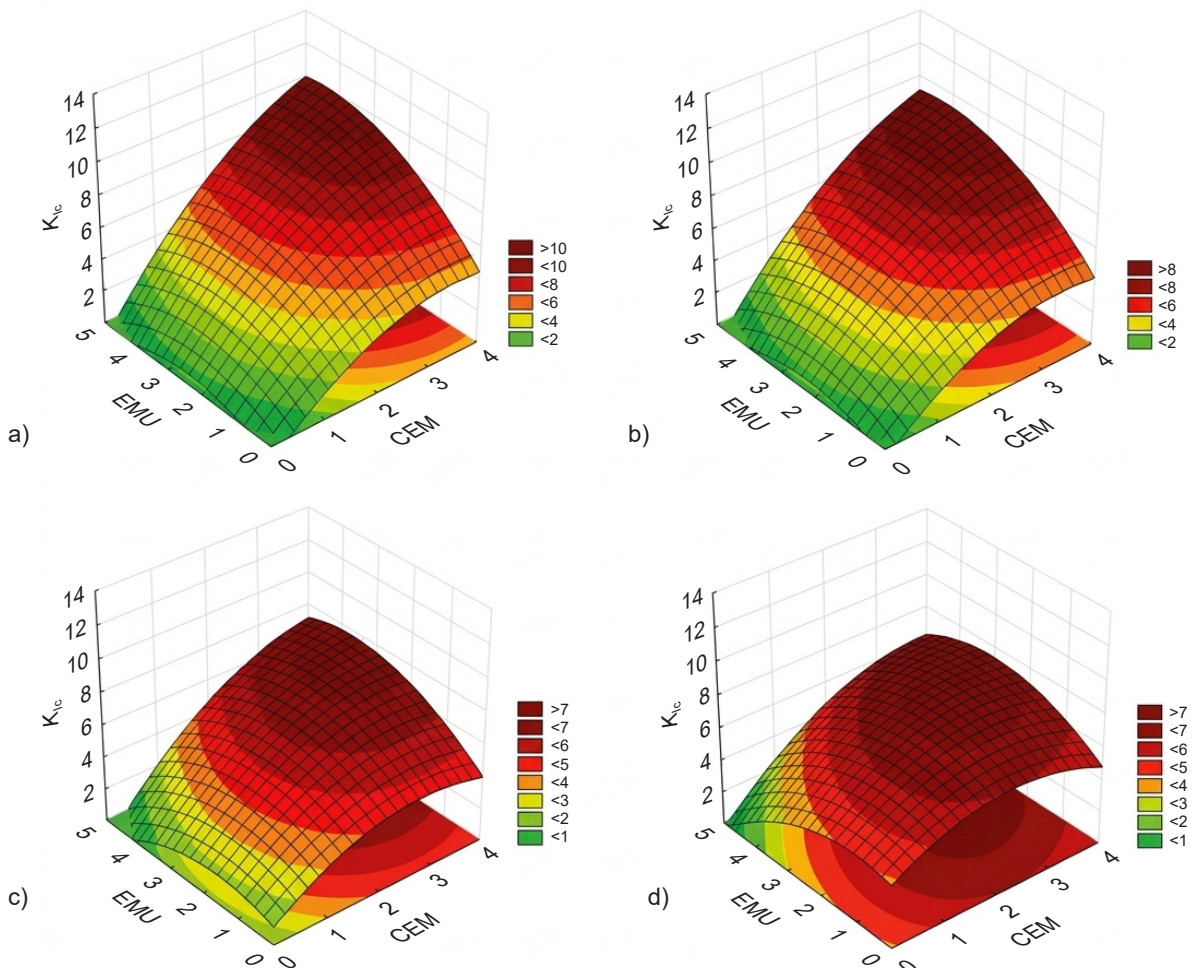


Fig. 26. Response surface of the parameter fracture toughness  $K_{Ic}$  at 20°C as a function of Portland cement and bitumen emulsion contents for different amount of RPP in MCE mix: a) 0.0%, b) 0.5%, c) 2.0%, d) 3.5%

Changing the test temperature to 20°C indicates an increase in the significance of the presence of polymer powder in the MCE mix. The impact of the polymer manifests at higher ambient temperatures, as confirmed by the assessment of the significance of the impact presented in Table 13. The highest fracture toughness was obtained with a mix of 3.5% of cement, 0.5% of polymer and 2.5% of bitumen emulsion. A high fracture toughness of 8.6 N/mm<sup>3/2</sup> was obtained in a mix without bitumen emulsion that contained 2.0% of cement and 3.5% of polymer modifier. The two MCE mixes have a similar fracture toughness index of 7.4 N/mm<sup>3/2</sup> – 7.7 N/mm<sup>3/2</sup>. The former contains 3.5% of cement, 2.0% of polymer and 5.0% of bitumen emulsion. The latter, with a marginally higher result, is a mix also containing 3.5% of cement, but with an emulsion content reduced to 2.5% and a higher modifier content of 3.5%. The right amount of polymer modifier increases fracture toughness and reduces the need to use bitumen emulsion in the MCE mix. An example is a mix of MCE with 2.0% of the modifier and 2.0% of cement. Increasing the amount of the polymer modifier in the mix to 3.5% allows for an even greater reduction in the content of the other binders in the MCE mix. Almost the maximum fracture toughness results are obtained for the MCE mix for just 1.0% of cement and 1.0% of bitumen emulsion.

## 5. OPTIMISATION OF THE COMPOSITION OF THE MCE MIX TO MEET THE REQUIREMENTS OF THE POLISH GUIDELINES

The results obtained revealed the significance of the impact of the contribution of the individual binders and the polymer modifier on the parameters of the MCE mix. It seems natural to look for an optimum solution that will ensure the favourable properties of the MCE mix and, thus, of the road base course made from this type of mix. The optimisation process takes into account predetermined criteria. Changing the optimisation criteria leads to significant changes in material properties. Thus, for a comprehensive evaluation of the issue under consideration with regard to the MCE mixes, it is beneficial to use multi-criteria optimisation. It uses a general utility function [43]. In the indicated optimisation method, the value of the criteria under consideration is expressed on a dimensionless scale. To construct this type of scale, it is necessary to define a range of satisfactory values for each criterion. The individual

criteria are assigned non-negative factors reflecting their significance. Their sum must be equal to 1. Determining the appropriate weights for the individual features requires knowledge of the technical requirements. Using the indicated methodology, the optimum quantities of MCE mix ingredients, i.e., cement, bitumen emulsion and polymer modifier, were determined. The general utility function  $U_i^{III}$  contains numbers from the range (0;1). The quality intervals of the functions are shown in Table 14 [43].

Table 14. Assessment of the qualitative utility function [43]

Qualitative range	Interpretation
1.00	Excellent value
1.00-0.83	A very good value representing the achievement of material quality with extraordinary optimisation properties
0.8-0.63	This range represents good, above-average quality
0.63-0.37	Satisfactory (sufficient) value, acceptable under certain conditions
0.37-0.2	Unacceptable value that may increase the unreliability of the optimised product

The utilities  $d_i$  attributed to the individual features  $y^{(i)}$  are determined by two algorithms, and their profiles are shown in Fig. 27.

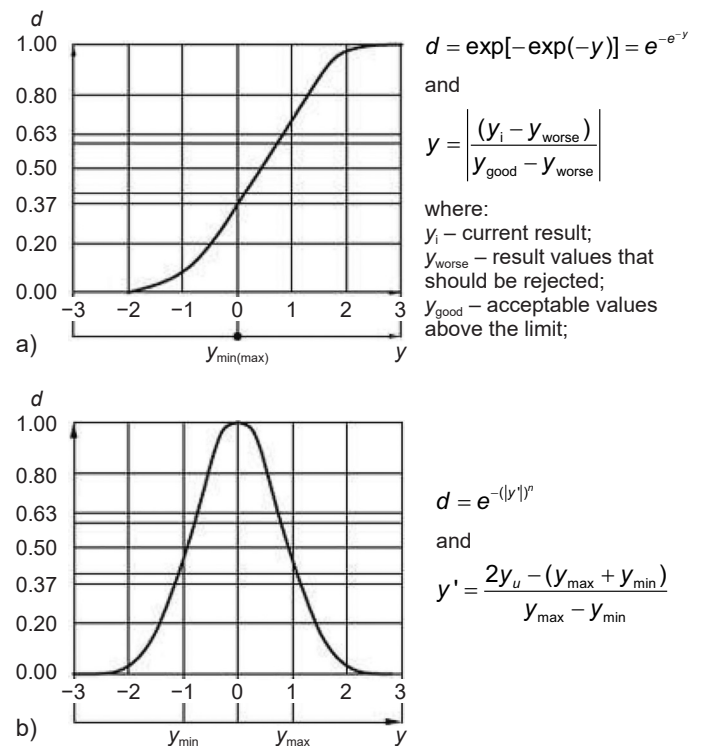


Fig. 27. Utility function profiles for: a) one-sided (asymmetric) profile function, b) two-sided (symmetric) profile function

The general utility  $U^{III}$  or denoted as  $D$  is taken as the weighted geometric mean of the individual  $d_i$  (12) [43]:

$$D = \left[ \prod_{u=1}^n d_u \right]^{1/n}, \quad (12)$$

where:  $n$  – number of variables.

The indicated utility function profiles represent two possible cases that can be encountered in the optimisation process. The first is when the limit value of a specific property is represented by a single value (one-sided function – Fig. 27a), and the second case concerns a situation where the optimal value is within a certain range (two-sided function – Fig. 27b). Therefore, the optimisation task is to search for a solution or solution area where the utility function takes a value of at least 0.37. The optimal solution is the result of an optimisation process that takes into account predetermined criteria. Changing a criterion significantly affects the result of the estimation of the desired outcome in terms of material properties. The parameters adopted to optimise the MCE mix in terms of percentage of Portland cement, bitumen emulsion and polymer powder are shown below:

- air void content  $V_m$ ,
- indirect tensile strength  $ITS_{DRY}$ ,
- stiffness modulus  $S_m$  at  $5^\circ C$ ,
- water resistance  $TSR$ .

The optimisation was conducted using the models presented in Table 15.

Table 15. Mathematical models describing the impact of the polymer modifier on the properties of the MCE mix

Mathematical models describing	$R^2$
$V_m = 11.55 + 1.43 \cdot CEM - 0.59 \cdot CEM^2 + 0.13 \cdot EMU + -0.03 \cdot EMU^2 - 1.32 \cdot RPP + 0.39 \cdot RPP^2 + 0.25 \cdot CEM \cdot EMU + 0.11 \cdot CEM \cdot RPP - 0.06 \cdot EMU \cdot RPP$	0.67
$ITS_{DRY} = 172.23 + 58.56 \cdot CEM + 90.63 \cdot CEM^2 + + 118.98 \cdot EMU - 17.77 \cdot EMU^2 + 99.86 \cdot RPP - 18.29 \cdot RPP^2 - 11.77 \cdot CEM \cdot EMU - 29.34 \cdot CEM \cdot RPP + - 14.75 \cdot EMU \cdot RPP$	0.99
$S_m(5^\circ C) = 2986.8 + 6487.4 \cdot CEM + 801.6 \cdot CEM^2 + - 1140.8 \cdot EMU + 111.8 \cdot EMU^2 + 2305.1 \cdot RPP - 239.3 \cdot RPP^2 - 652.0 \cdot CEM \cdot EMU - 1770.7 \cdot CEM \cdot RPP + + 272.3 \cdot EMU \cdot RPP$	0.97
$TSR = 75.24 + 8.46 \cdot CEM - 0.44 \cdot CEM^2 - 6.39 \cdot EMU + + 1.17 \cdot EMU^2 + 3.47 \cdot RPP + 0.82 \cdot RPP^2 - 0.20 \cdot CEM \cdot EMU - 4.75 \cdot CEM \cdot RPP + 0.90 \cdot EMU \cdot RPP$	0.85

The choice of the parameters listed was affected by the guidelines for the design of MCE mixes in Poland [6]. Thanks to the estimated regression models of the functions of the object under test, it was possible to obtain optimisation effects. The optimisation results were determined with a step of 0.5%, representing the amount of a given ingredient in the MCE mix. Optimisation was performed on results approximated from mathematical models. This was done in such a way that changes in the properties of the MCE mix could be indicated, highlighting the effect of the polymer powder.

The aim of the optimisation to meet the requirements of Polish guidelines was to find an MCE mix that met Polish guidelines for the design and incorporation of MCE mixes [6]. Thus, the mix has an adequate stiffness modulus  $S_m$  at  $5^\circ C$ . The road base course made of the MCE mix should also have adequate air void content  $V_m$ , up to 15%. It also involves the indirect tensile strength  $ITS_{DRY}$  and water resistance  $TSR$ . The parameters of the adopted criterion are summarised in Table 16.

Table 16. Optimisation criterion – MCE meeting the requirements of the Polish guidelines

	Air void content $V_m$ [%]	Indirect tensile strength $ITS_{DRY}$ [kPa]	Stiffness modulus $S_m$ $IT-CY$ $5^\circ C$ [MPa]	Water resistance $TSR$ [%]
Better	8	550	7000	81
Worse	15	400	2000	80

The results of the optimisation are shown in Fig. 28 with a response function representing the values of the  $U^{III}$  utility function. The criterion includes the air void content of  $V_m$  between 8% and 15%, indirect tensile strength values between 400 kPa and 550 kPa, stiffness modulus  $S_m$  at  $5^\circ C$  with values between 2000 MPa and 7000 MPa and water resistance  $TSR$  of more than 80%.

To achieve the effect assumed in the optimisation criterion (Table 16), it is necessary to use between 2.0% and 3.0% of Portland cement. Lower content leads to low indirect tensile strength ( $ITS_{DRY}$ ). Higher cement content leads to stiffening of the mixture. The amount of bitumen emulsion does not significantly affect the objectives set out in criterion I, what is shown in the Table 17. The presence of a polymer modifier improves the performance of

the MCE mix. With 2.0% of RPP in the MCE mix, the optimisation criterion is fully achieved for MCE mixes containing a minimum of 1.0% of cement and 0.5% of bitumen emulsion. Thus, the presence of the RPP modifier improves the parameters of the MCE mix required in the standards and enables a reduction in the content of other binders. Increasing the amount of the RPP modifier to 3.0% causes a deterioration in the performance of the MCE mix. It is due to higher susceptibility to water. Optimal is to use 2.0% of RPP in the MCE mix. For MCE mixes containing from 2.5% to 3.0% cement, from 1.5% to 2.0% of polymer and bitumen emulsion at 1.0% to 2.0%, the  $U_i^{III}$  utility function is between 0.89 and 0.98. An example is MCE mix with the code 2.5C-1.5P-1E.

The described process of optimizing the MCE mix composition, including Portland cement, asphalt emulsion, and polymer modifier, allowed for the selection of two MCE mixes. This was achieved by considering all optimization criteria. The first mix contained 2.5% Portland cement, 2.0% asphalt emulsion, and 0% polymer modifier. Its properties were compared with an MCE mix containing 2.5% Portland cement, 2.0% polymer modifier, and 0% asphalt emulsion. These two combinations of ingredients were selected because the mixes demonstrated very similar and simultaneously favourable properties for the given optimization criteria. Table 17 summarizes  $U_i^{III}$  utility functions for each of the considered optimization criteria.

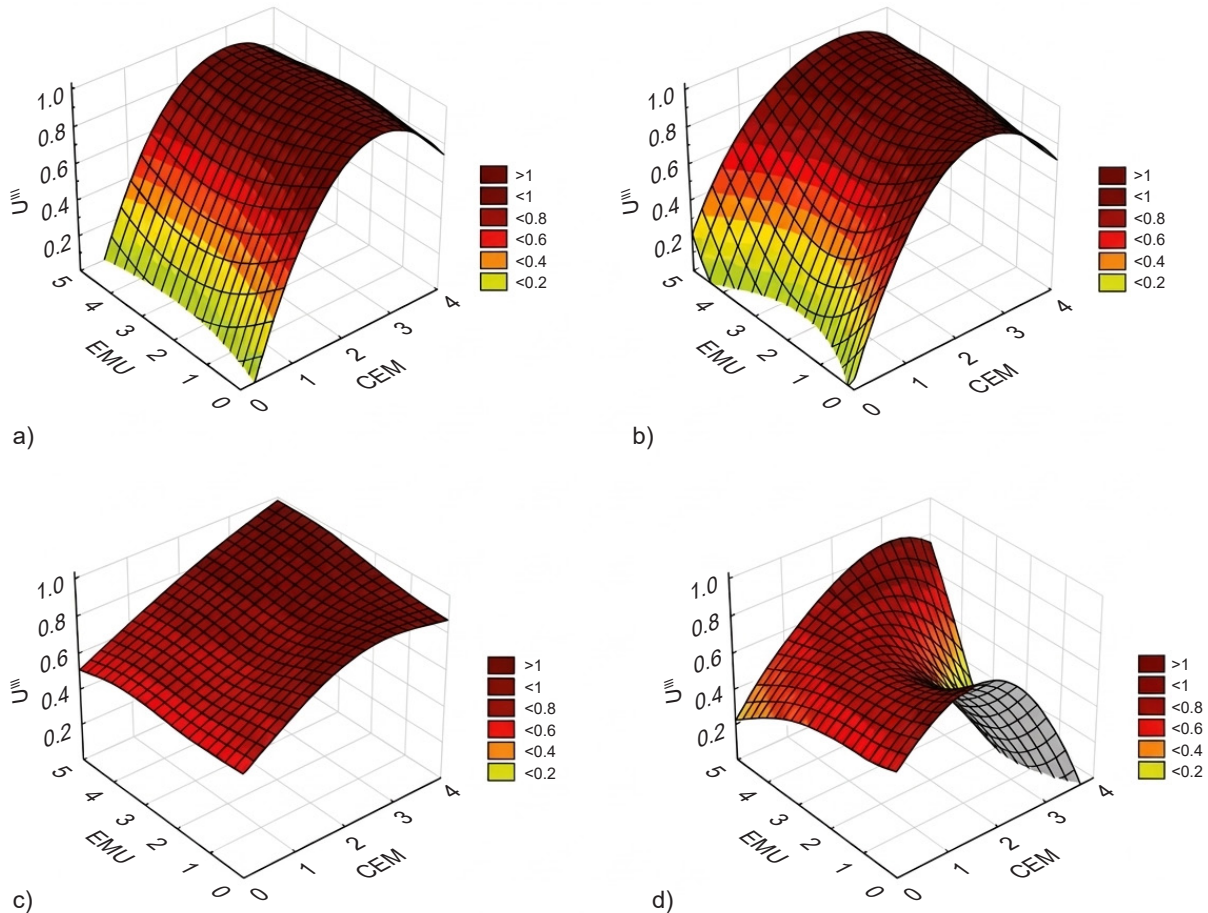


Fig. 28. Variation of the utility function depending on the percentage of ingredients for the properties of the MCE mix required by the standards with different amount of RPP: a) 0.0%, b) 1.0%, c) 2.0%, d) 3.0%

Table 17. Utility functions  $U_i^{\text{III}}$  for MCE mixtures after optimization

Type of mix MCE	Utility functions $U_i^{\text{III}}$			
	Criteria I	Criteria II	Criteria III	Criteria IV
2.5C-0P-2E	0.90	0.78	0.83	0.65
2.5C-2P-0E	0.94	0.84	0.85	0.66

## 6. CONCLUSIONS

The test results and analyses of the impact of the redispersible polymer powder on the properties of the MCE mixture support the following conclusions:

1. It is possible to use 80% (m/m) of waste materials in the composition of the cold-recycle mixture. Optimisation of the formulation confirmed that an MCE mix with a combination of the binders 2.5C-0P-2E and 2.5C-2P-0E meets all the criteria for optimisation.
2. The use of redispersible polymer powder (RPP) in the composition of the MCE mix as an alternative to bitumen emulsion enables the mix to be made at ambient

temperature, without the need to heat the ingredients, thus causing the MCE technology (2.5C-2P-0E mineral-cement-polymer mix) to be classified as a “100% cold” technology.

3. The use of the RPP polymer modifier in the form of a redispersible polymer powder (EVA) improves the properties of the mineral-cement mix with bitumen emulsion.
4. The addition of the RPP modifier to the MCE recycled cold mix causes results in the sealing of the mixture. This reduces the air void content  $V_m$ .
5. The use of the polymer modifier RPP in the MCE mix at 2% enables the achievement of water resistance  $TSR > 80\%$  regardless of the bitumen emulsion and cement content of the MCE mix.
6. The right amount of polymer modifier increases fracture toughness  $K_{Ic}$  and reduces the need to use bitumen emulsion in the MCE mix.

## REFERENCES

- [1] Iwański M., Chomicz-Kowalska A., Buczyński P., Mazurek G., Cholewińska M., Iwański M.M., Ramiączek P., Maciejewski K.: Procedury projektowania oraz wytyczne stosowania materiałów odpadowych i z recyklingu do technologii wytwarzania mieszanek metodą na zimno z asfaltem spienionym (MCAS). Wytyczne do Raportu RID-I/6, NCBiR, GDDKiA, 2018 (available in Polish from the authors)
- [2] Szydłowski C., Dołżycki B.: Ocena odporności na pęknięcie podbudów drogowych z mieszanek mineralno-cementowo-emulsyjnych (MCE). Materiały Budowlane, **1**, 10, 2017, 83-87, DOI: 10.15199/33.2017.10.28 (in Polish)
- [3] Buczyński P., Iwański M.: The influence of a polymer powder on the properties of a cold-recycled mixture with foamed bitumen. Materials, **12**, 24, 2019, DOI:10.3390/ma12244244
- [4] Kukielka J., Bańkowski W.: The experimental study of mineral-cement-emulsion mixtures with rubber powder addition. Construction and Building Materials, **226**, 2019, 759-766, DOI: 10.1016/j.conbuildmat.2019.07.276
- [5] Pilat J., Radziszewski P.: Nawierzchnie asfaltowe. Wydawnictwa Komunikacji i Łączności, Warszawa, 2004 (in Polish)
- [6] Dołżycki B.: Instrukcja projektowania i wbudowania mieszanek mineralno-cementowo-emulsyjnych (MCE). GDDKiA, Warszawa, 2019 (in Polish)
- [7] <https://www.wirtgen-group.com/en-pl/applications/road-construction/road-rehabilitation/cold-in-situ-recycling/> (available: 16.09.2024)
- [8] Recykling na zimno. Wirtgen Group Company, Windhagen, 2004, [https://www.wirtgen-group.com/binary/full/o254548v95\\_Cold\\_recycling\\_Highlight\\_flyer\\_plPL.pdf](https://www.wirtgen-group.com/binary/full/o254548v95_Cold_recycling_Highlight_flyer_plPL.pdf) (available in Polish: 16.09.2024)
- [9] Bitumen stabilised materials. A guideline for the design and construction of bitumen emulsion and foamed bitumen stabilised materials. Asphalt Academy, Technical Guideline 2 (TG2). Second Edition, Pretoria, 2009
- [10] Buczyński P., Iwański M., Mazurek G., Krasowski J., Krasowski M.: Effects of Portland cement and polymer powder on the properties of cement-bound road base mixtures. Materials, **13**, 19, 2020, Article ID: 4253, DOI: 10.3390/ma13194253
- [11] Pilat J., Radziszewski P., Kalabińska M.: The analysis of visco-elastic properties of mineral-asphalt mixes with lime and rubber powder. Proceedings of the 2nd Eurasphalt and Eurobitume Congress, Book 1-Session 1, Barcelona, 2000, 648-654
- [12] Iwański M., Buczyński P., Mazurek G.: The use of gabbro dust in the cold recycling of asphalt paving mixes with foamed bitumen. Bulletin of the Polish Academy of Sciences, Technical Sciences, **64**, 4, 2016, 763-773, DOI: 10.1515/bpasts-2016-0085

- [13] *Badagliacco D., Megna B., Valenza A.*: Induced modification of flexural toughness of natural hydraulic lime based mortars by addition of giant reed fibers. *Construction Materials*, **13**, 2020, Article ID: e00425, DOI: 10.1016/j.cscm.2020.e00425
- [14] *Zapała-Sławeta J., Mazurek G., Woś J.*: Analysis of the influence of PET and glass packaging waste materials on the physical and mechanical properties of cementitious composites. *Applied Sciences*, **13**, 22, 2023, Article ID: 12409, DOI: 10.3390/app132212409
- [15] *Radziszewski P., Liphardt A., Sarnowski M., Kowalski K., Pokorski P., Konieczna K., Król J., Iwański M., Chomicz-Kowalska A., Maciejewski K., Iwański M.M., Michalec M.*: Ageing Evaluation of foamed polymer modified bitumen with bio-flux additive. *Materials*, **16**, 6, 2023, Article ID: 2167, DOI: 10.3390/ma16062167
- [16] *Eslandarsefat S., Venturini L., Ciarlitti A., Sogno E., Ottonelli L.*: Asphalt concrete modification with plastomers: A case study conducted 7 years after construction. *Infrastructures*, **7**, 3, 2022, Article ID: 29, DOI: 10.3390/infrastructures7030029
- [17] *He L., Ma Y., Liu Q., Mu Y.*: Surface modification of crumb rubber and its influence on the mechanical properties of rubber-cement concrete. *Construction and Building Materials*, **120**, 2016, 403-407, DOI: 10.1016/j.conbuildmat.2016.05.025
- [18] *Stepien A.*: Recycling in building materials: Analysis of the possibilities and results of using recycled glass sand in autoclaved materials. *Energies*, **16**, 8, 2023, Article ID: 3529, DOI: 10.3390/en16083529
- [19] *Crucho J., Picado-Santos L., Neves J.*: Mechanical performance of cement bound granular mixtures using recycled aggregate and coconut fiber. *Applied Sciences*, **12**, 4, 2022, Article ID: 1936, DOI: 10.3390/app12041936
- [20] *Buczyński P., Iwański M., Krasowski J.*: Assessment of the impact of hydraulic binder on the properties of the cold recycled mixture with foamed bitumen and bitumen emulsion: Field tests. *Buildings*, **10**, 12, 2020, Article ID: 223, DOI: 10.3390/buildings10120223
- [21] *Łukowski P.*: Modyfikacja materiałowa betonu. Stowarzyszenie Producentów Cementu, Kraków, 2016
- [22] PN-EN 12697-26:2018 Bituminous mixtures – Test methods – Part 26: Stiffness
- [23] PN-EN 13286-41:2021 Unbound and hydraulically bound mixtures – Part 41: Test method for determination of the compressive strength of hydraulically bound mixtures
- [24] *Buczyński P., Iwanski M.*: Rheological properties of mineral-cement mix with foamed bitumen with the addition of redispersible polymer powder. *IOP Conference Series: Materials Science and Engineering*, **471**, 3, 2019, Article ID: 032013, DOI: 10.1088/1757-899X/471/3/032013
- [25] PN-EN 12697-8:2005 Bituminous mixtures – Test methods for hot mix asphalt – Part 8: Determination of void characteristics of bituminous specimens
- [26] PN-S-04001-12:1967 Drogi samochodowe i lotniskowe. Mieszanki mineralno-bitumiczne. Badania. Oznaczenie nasiąkliwości (in Polish)
- [27] PN-EN 12697-23:2004 Bituminous mixtures – Test methods for hot mix asphalt – Part 23: Determination of the indirect tensile strength of bituminous specimens
- [28] Cold recycling: Wirtgen cold recycling technology. Wirtgen Group, Windhagen, 2012, [https://www.researchgate.net/profile/Kim-Jenkins-4/publication/327738860\\_Recommendation\\_of\\_RILEM\\_TC237-SIB\\_on\\_cohesion\\_test\\_of\\_recycled\\_asphalt/links/5bab48b445851574f7e65b40/Recommendation-of-RILEM-TC237-SIB-on-cohesion-test-of-recycled-asphalt.pdf](https://www.researchgate.net/profile/Kim-Jenkins-4/publication/327738860_Recommendation_of_RILEM_TC237-SIB_on_cohesion_test_of_recycled_asphalt/links/5bab48b445851574f7e65b40/Recommendation-of-RILEM-TC237-SIB-on-cohesion-test-of-recycled-asphalt.pdf) (available: 16.09.2024)
- [29] PN-EN 12697-44:2019 Bituminous mixtures – Test methods – Part 44: Crack propagation by semi-circular bending test
- [30] *Piasta Z., Lenarcik A.*: Applications of statistical multi-criteria optimisation in design of concretes. In: Optimization methods for material design of cement-based composites. E & FN Spon, London, New York, 1998, 45-59
- [31] *Kukielka L.*: Podstawy badań inżynierskich. Wydawnictwo Naukowe PWN, Warszawa, 2002
- [32] *Gadomska-Gajadur A., Jańczewski D., Różycki C., Synoradzki L.*: Projektowanie procesów technologicznych: matematyczne metody planowania eksperymentów. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, 2020
- [33] <https://develve.net/Box-Behnken%20design.html> (available: 10.03.2015)
- [34] PN-EN 12697-30:2018 Bituminous mixtures. Test methods. Specimen preparation by impact compactor
- [35] PN-EN 12697-31:2007 Bituminous mixtures. Test methods for hot mix asphalt. Specimen preparation by gyratory compactor
- [36] *Raschia S., Chauhan T., Panwar S., Carter A., Graziani A., Perraton D.*: Effect of water and cement content on the mechanical properties of cold recycled mixtures (CRM) with bitumen emulsion. *Proceedings of the 5th International Symposium on Asphalt Pavements & Environment (APE)*, Springer, Cham, 2019, Lecture Notes in Civil Engineering, **48**, 2019, 274-282, DOI: 10.1007/978-3-030-29779-4\_27
- [37] *Graziani A., Iafelice C., Raschia S., Perraton D., Carter A.*: A procedure for characterizing the curing process of cold recycled bitumen emulsion mixtures. *Construction and Building Materials*, **173**, 2018, 754-762, DOI: 10.1016/j.conbuildmat.2018.04.091
- [38] *Dolżycki B., Jaczewski M., Szydłowski C.*: The Impact of long-time chemical bonds in mineral-cement-emulsion mixtures on stiffness modulus. *The Baltic Journal of Road and Bridge Engineering*, **13**, 2, 2018, 121-126, DOI: 10.7250/bjrbe.2018-13.406

- [39] *Dołżycki B., Szydłowski C., Jaczewski M.*: The influence of combination of binding agents on fatigue properties of deep cold in-place recycled mixtures in Indirect Tensile Fatigue Test (ITFT). *Construction and Building Materials*, **239**, 2020, Article ID: 117825, DOI: 10.1016/j.conbuildmat.2019.117825
- [40] *Khalid H.A., Monney O.K.*: Moisture damage potential of cold asphalt. *International Journal of Pavement Engineering*, **10**, 5, 2009, 311-318, DOI: 10.1080/10298430802169838
- [41] *Xia Y., Lin J., Chen Z., Cai J., Hong J., Zhu X.*: Fatigue cracking evolution and model of cold recycled asphalt mixtures during different curing times. *Materials*, **15**, 13, 2022, Article ID: 4476, DOI: 10.3390/ma15134476
- [42] *Dołżycki B., Jaczewski M., Szydłowski C.*: Cold recycled mixtures for binder courses – laboratory evaluation of mechanical properties. *Proceedings of the 7<sup>th</sup> International Conference on Road and Rail Infrastructure*, Pula, Croatia, 2022, 355-361, DOI: 10.5592/CO/CETRA.2022.1388
- [43] *Lazić Ž.R.*: Design of experiments in chemical engineering: A practical guide. Wiley-VCH, Weinheim, 2004

### Mieszanka mineralno-cementowa z emulsją asfaltową modyfikowana proszkiem polimerowym

**Streszczenie:** W artykule zaprezentowano wpływ modyfikatora polimerowego (P) na właściwości mieszanki mineralno-cementowo-emulsyjnych (MCE). W części teoretycznej artykułu omówiono sposoby produkcji mieszanek w technologii recyklingu głębokiego „na zimno”. Opisano metodę produkcji „in place – na miejscu” oraz „in plant – z dowozu”. Przedstawiono również opis redyspersyjnego proszku polimerowego (RPP) pełniącego rolę modyfikatora polimerowego. W części badawczej przedstawiono plan eksperymentu oraz omówiono metodykę badawczą wykorzystaną w ocenie wpływu modyfikatora polimerowego na właściwości mieszanki MCE. Projekt zakładał wykonanie mieszanek MCE, zróżnicowanych pod względem rodzaju oraz ilości proszku polimerowego, cementu oraz emulsji asfaltowej. Zaprojektowano mieszanki mineralno-cementowo-emulsyjne z modyfikatorem polimerowym o zmiennym udziale cementu od 0,5% do 3,5%, emulsji asfaltowej od 0% do 5% oraz redyspersyjnego proszku polimerowego z przedziału od 0,5% do 3,5%. W ramach eksperymentu wykonano łącznie 15 mieszanek, zaprojektowanych zgodnie z planem eksperymentu Boxa-Behnkena. W planie badań dokonano oceny następujących właściwości fizycznych i mechanicznych: zawartość wolnych przestrzeni  $V_m$ , nasiąkliwość  $n_w$ , wytrzymałość na rozciąganie pośrednie ITS, odporność na szkodliwe działanie wody TSR, moduł sztywności wg metody IT-CY oraz odporności na pękanie w układzie SCB. Na podstawie wykonanych badań dokonano analizy uzyskanych wyników badań i oceniono wpływ redyspersyjnego proszku polimerowego na właściwości recyklowanej mieszanki MCE. Po wykonaniu analiz, przeprowadzono proces optymalizacji składu mieszanki w zakresie wymagań określonych w polskich wytycznych do projektowania.

**Słowa kluczowe:** destrukcja asfaltowa, emulsja asfaltowa, recykling, recyklowana mieszanka na zimno, redyspersyjny proszek polimerowy.