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INFLUENCE OF THE BINDER ON THE PROPERTIES OF COLD MIXTURES

WPŁYW ŚRODKA WIĄŻĄCEGO NA WŁAŚCIWOŚCI MIESZANEK NA ZIMNO

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Abstract

The paper aims to present the basic properties of cold mixes in terms of the type of binding agent. In the theoretical part of the article, a description of the technology for producing cold recycled mixtures and the types of road binders used in cold mixtures was presented. The research part presents the experimental design, and gives an overview of the research methodology used to assess the impact of the type of binding agent. Mixes differing in type and binder content were designed. During the laboratory work, mixtures were prepared with cement binder (CBGM), cement-modified polymer binder (CBGM+P), mineral-cement-emulsion modified with polymer binder (BE-RCM+P), and mineral-cement mixtures with foamed bitumen modified with polymer binder (FB-RCM+P). The project aimed to produce cold mixtures with variations in the type and amount of binder used. The mixtures were prepared using cold mix technology. The effect of the binder on the cold mix properties was studied. During the research, the following properties were examined: void content (V_m), indirect tensile strength (ITS), resistance to water damage (TSR), stiffness modulus using the IT-CY method and an axial compressive strength. On the basis of the research carried out, an analysis was made. Among other things, the polymer modification was found to have a positive effect on the void content of the mix. The research carried out in this way made it possible to show the influence of the binder on the properties of cold mixes.

Keywords: cold mixture, recycling, substructure, foamed asphalt, asphalt emulsion, hydraulic binder, modification

Streszczenie

Praca miała na celu przedstawienie podstawowych właściwości mieszanek na zimno w aspekcie rodzaju środka wiążącego. W części teoretycznej artykułu przedstawiono opis technologii wykonywania mieszanek metodą recyklingu głębokiego na zimno oraz rodzaje spoiw drogowych wykorzystywanych w mieszankach na zimno. W części badawczej przedstawiono plan eksperymentu oraz przybliżono metodykę badawczą wykorzystaną w ocenie wpływu rodzaju środka wiążącego. Zaprojektowano mieszanki związane cementem (CBGM), mieszanki związane cementem modyfikowane polimerem (CBGM+P), mieszanki mineralno-cementowo-emulsyjne modyfikowane polimerem (MCE+P) oraz mieszanki mineralno-cementowe z asfaltem spienionym modyfikowane polimerem (MCAS+P). Projekt zakładał wykonanie mieszanek w technologii na zimno, zróżnicowanych pod względem rodzaju oraz ilości zastosowanego spoiw. W ramach badań sprawdzono zawartość wolnych przestrzeni V_m, wytrzymałość na rozciąganie pośrednie ITS, odporność na szkodliwe działanie wody TSR, moduł sztywności według metody IT-CY oraz przeprowadzono badanie wytrzymałości na ściskanie osiowe po 28 dniach pielęgnacji. Na podstawie wykonanych badań dokonano analizy. Tak przeprowadzone badania pozwoliły na ukazanie wpływu spoiwa na właściwości mieszanek na zimno.

Słowa kluczowe: mieszanka na zimno, recykling, podbudowa, asfalt spieniony, emulsja asfaltowa, spoiwo hydrauliczne, modyfikacja

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1. INTRODUCTION

Continued growth in the number of road users directly translates into increased loads transferred to road surface structures [1]. This causes degradation of the traffic sections in use, which consequently require increased maintenance. When the fatigue life of a structure is lost [2], which occurs most often in the substructure layers, costly reconstruction of the damaged road section is necessary. The start of a remodelling or refurbishment project usually involves the use of new materials. This translates into increased lead times, increased costs and increased environmental degradation. The use of recycling technology enables the reuse of materials from the deteriorated structure, allowing for intervention in the degraded subbase layer and improving the parameters of the subsoil. One of the most common technologies used for road reconstruction is cold recycling technology. Cold mixtures also use binders in the form of asphalt bonding agents [3] and hydraulic binders. The continuous development of technology is leading to a search for modifying agents [4-7]. Recycling technology can also become a place for the disposal of materials, while exploiting their technological potential [8, 9].

The concept of "cold" deep recycling encompasses two types of mixtures. Mineral-cement-emulsion (BE-RCM) and mineral-cement mixtures with foamed bitumen (FB-RCM). Both technologies involve reusing material from the demolition of damaged structures. In addition, a hydraulic binder, bonding agent, water and possible graded aggregate are added during the manufacturing process [10]. The use of BE-RCM or FB-RCM technology allows for the re-building of layers containing tar components, which are only possible using the "cold" methods, i.e. without heating, at ambient temperature [11]. This fact makes BE-RCM and FB-RCM extremely economical and environmentally friendly technologies.

A wide variety of binding agents are used in the cold-mix technology around the world, and their main purpose is to improve the properties of the materials to be incorporated. In many places there is a lack of availability of high-quality raw materials. The method of using binding agents can be used for the construction of new roads but also for the renovations of old sections. The local material is enriched by various binding agents and is then built in again, so that no new material has to be supplied, resulting in high financial, time and environmental savings [14]. There are many binding agents available on the market. Hydraulic binders, special road binders and asphalt bonding agents are used. In addition, there is ongoing research into new binders [15] additives [8] or modifiers [16]. Each of the measures has the same task, to improve the performance of the material, increasing strength and resistance. Depending on the chosen technology, appropriate binding agents are selected. Important considerations are availability, price and method of building in.

One of the characteristic features of material recycled with the use of asphalt bonding agents is the characteristic distribution of the bonding agent between the fine particles of the mineral skeleton. In the case of foamed asphalt, it is combined with a fine fraction. When asphalt emulsion is used, the coarser fractions (above 2 mm) play a more important role in the mix. When the layer is compacted, we obtain a mixture with a void content of less than 12%. This value was obtained, among others, in publications by Buczyński [15] and Dołżycki [17]. The produced recycled mix therefore behaves partly like an unbound mix, using friction between the grains to transfer loads. In addition, it works as a visco-elastic material that transmits tensile stresses without causing damage. The produced component is therefore treated as a hybrid layer combining the properties of unbound mixes and partly the properties of susceptible mixes [10].

Mineral binders are among the most widely used binding agents in the world. These include cement, lime, and their mixtures with the addition of fly ash, blast furnace slag [18]. The main function of these binders is to increase load-bearing capacity. In the case of lime binders, a reduction in soil plasticity is observed [12]. The strength achieved with mineral binders will depend mainly on the amount of agent used and the type of material being processed. However, this does not mean that applying a large amount of binder will have a positive effect. As demonstrated by Buczyński and Iwański [19], improperly designed cold recycled mixes can become excessively stiff, leading to shrinkage cracks in the substructure. In contrast, as Jaworska has shown [20], an insufficient amount of cement can reduce the indirect tensile strength and thus shorten fatigue life.

Today's technologies make it possible to improve the properties of traditional materials. This process involves the introduction of a new ingredient that improves the properties of the starting material. This method is called modification and the most commonly used substances in this technology are polymers, used in various forms [20]. Polymer modification has been used successfully in cement concrete mixtures. When cement and a polymer modifier are mixed together, a new type of bonding agent called a polymer-cement binder is obtained. Bonding in a concrete mix produced with such a bonding material is as follows:

- fine particles of the modifier are dispersed in the liquid phase of the cement slurry. As the setting process begins, unbound cement particles and mineral grains accumulate on the surface;
- free grains of polymer powder are encapsulated in the air voids of the mixture. During the drying process, the polymer particles are densely packed and coalescence occurs, resulting in the formation of a continuous polymer film.

Polymer-modified cement concretes have better watertightness and workability. Aggregate adhesion is improved and the mix is more susceptible, thus increasing bending strength. In addition, the adhesion of the concrete mix to the substrate is improved, as described by Łukowski [22]. The use of polymer modification also has a beneficial effect on the performance of mineral mixtures bound with hydraulic binders (CBGM). Research carried out by Buczyński, Iwański, Mazurek, Krasowski J., Krasowski M. [16] give positive results on fracture resistance. Bound mixtures carry the risk of cracking, transferring to the surface layers of the road structure. Repairing this type of damage is labour-intensive and expensive.

Modification technology can lead to a reduced risk of cracking. Research conducted by Krasowski J. [23] show a positive effect of polymer modification. Moreover, a study by Buczyński [6] also found no effect on the value of axial compressive strength [24] which is the main factor analysed in this type of mixture. Positive results of polymer modification were presented by Buczyński and Iwański in their publication [4] also presented in the case of studies on mineral-cement mixtures with foamed bitumen (FB-RCM). The use of redispersible polymer powders (RPPs) was found to have a beneficial effect on the densification process. A comparison of physical and mechanical properties, as well as water and frost sensitivity, confirmed that the RPP modifier increased waterproofing. The use of RPPs had a positive effect on the mechanical properties. The modification contributed to an increase in cohesion and elasticity without stiffening the base layer, i.e., no increase in elastic modulus was observed. The application of the modification extends the visco-elastic range of the FB-RCM mixture. The obtained results paint a positive picture of polymer modification in the case of deep cold recycled mixes and may be indicative of the formation of a mineral-cement-polymer composite microstructure [25]. Such an effect can have a positive impact on the other parameters of the mixtures.

Numerous research papers focusing on cold mixtures do not provide answers to the topic related to the influence of individual components on the properties of the mixture. Because of this, it is necessary to present the influence of the binding agent on the properties of cold mixtures. This publication therefore focuses on this issue. The scope of the tests, the type and composition of the mixes were chosen to fully show the impact of the binding agent on the properties of the cold mixes.

2. PURPOSE AND SCOPE OF RESEARCH

The aim of the study was to show the influence of the binding agent on the properties of cold mixtures. An assessment of the influence of the type of binding agent on properties of the cold mixture was carried out by evaluating the following mixtures:

- two mixtures bound by a hydraulic binder (CBGM);
- three mixtures bound by a polymer modified hydraulic binder (CBGM+P);
- three polymer modified mineral-cement-emulsion mixtures (BE-RCM+P);
- three mineral-cement mixtures with polymer-modified foamed bitumen (FB-RCM+P);
- asphalt concrete for the base course (AC 22 P).

All mixes, with the exception of the asphalt concrete, were made using a common mineral skeleton. This made it possible to eliminate the influence of the mineral mix composition on their properties.

The test methods used to assess the influence of the type of binder on the cold mix properties are presented in Table 1.

Table 1. Research methods used to evaluate mixtures

Properties	Test standard
Void content (V_m)	PN-EN 12697-8 [26]
Indirect tensile strength (ITS) – cohesion	PN-EN 12697-23 [27]
Water resistance (TSR)	Wirtgen [10, 12]
Stiffness modulus S_m	PN-EN 12697-26 [28] (in the ITC-CY system)
Axial compressive strength (R_C)	PN-EN 13286-41 [24]

2.1. Design of mixtures produced through deep cold recycling

The premise of the design was to produce a universal mineral mixture, meeting the grain size requirements for CBGM, BE-RCM and FB-RCM mixtures [29, 30]. The mineral skeleton was based on aggregates commonly used in road construction and material from road surface demolition. Natural aggregates of continuous grain size, asphalt waste, cement, road asphalt and asphalt emulsion were used. Some of the mixtures have undergone polymer modification.

Figure 1 shows the grain size curve of the mineral mixture, which was the same for all the cold mixtures analysed.

By adopting a uniform mineral skeleton, it will be possible to assess the effect of individual binding agents on the properties of the mixtures. Table 2 shows the composition of the mixtures analysed. All mixtures, have been divided and assigned to the appropriate analytical group, depending on their composition. The starting mixture was a cement-bound mixture (CBGM), which was then polymer-modified to produce a polymer modified cement-bound mixture (CBGM+P). Based on the modified mixture (CBGM+P), BE-RCM and FB-RCM mixtures were made. The content of foamed bitumen and asphalt emulsion in the mixtures was chosen so that the mixtures had the same amount of dosed asphalt. Therefore, the amount of asphalt in the mixtures was equal. The mixtures designed in this way demonstrate the influence of the bonding agent dosing method on the properties of the final mixture.

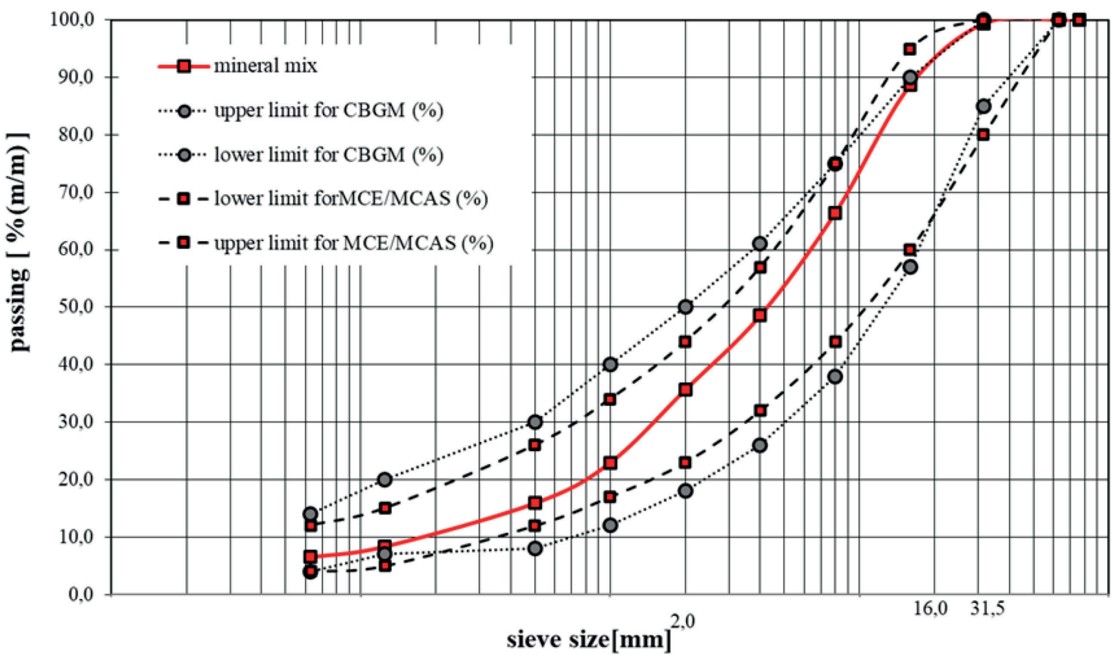

Fig. 1. Grain size curve of the universal mineral mixture

Table 2. Composition of the analysed test mixtures based on a universal mineral mixture

Mixture type	Mixture code	CEM I 42.5R Cement	Polymer (RPP)	Asphalt emulsion C60B10ZM/R	Foamed asphalt 70/100
		[%]	[%]	[%]	[%]
CBGM	C2	2.0	0.0	0.0	0.0
CBGM+P	C2+P0.5	2.0	0.5	0.0	0.0
BE-RCM+P	C2+P0.5+E5	2.0	0.5	5.0	0.0
FB-RCM+P+P	C2+P0.5+AS3	2.0	0.5	0.0	3.0
CBGM+P	C2+P3.5	2.0	3.5	0.0	0.0
BE-RCM+P	C2+P3.5+E5	2.0	3.5	5.0	0.0
FB-RCM+P+P	C2+P3.5+AS3	2.0	3.5	0.0	3.0
CBGM	C3.5	3.5	0.0	0.0	0.0
CBGM+P	C3.5+P2	3.5	2.0	0.0	0.0
BE-RCM+P	C3.5+P2+E5	3.5	2.0	5.0	0.0
FB-RCM+P+P	C3.5+P2+AS3	3.5	2.0	0.0	3.0

2.2. Design of the asphalt concrete mix

For comparison purposes, the test plan used asphalt concrete designed for sub-base layers with a grain size of up to 22.4 mm. A mix recipe was made for (AC 22P) KR 3-4 traffic intensity. The mineral skeleton consisted of the local aggregates summarised in Table 3.

Table 3. Mineral materials used to produce the AC 22P KR 3-4 mix

No.	Grain size	Rock name	Density ρ_a
1	16/22.4	dolomite	2.71
2	8/16	dolomite	2.70
3	2/8	dolomite	2.70
4	0/4	dolomite	2.68
5	Filler added	limestone	2.70

Mineral mixture, subjected to dust extraction during the production process. The share of dust decreased by 25%. This resulted in a slightly altered grain size. The final shape of the mineral mixture is shown in Figure 2.

For the project, 35/50 penetration road asphalt was also used. Table 4 shows the basic properties of asphalt.

An asphalt content of 3.9 per cent was used for the mix, which meets the minimum bonding agent content of the mix [32].

The mixture also includes an amine-based adhesion agent. This material is characterised by its high stability at mix production temperatures. The manufacturer recommends using an additive of 0.3% in relation to the asphalt content.

Table 5 provides a summary the mixture design.

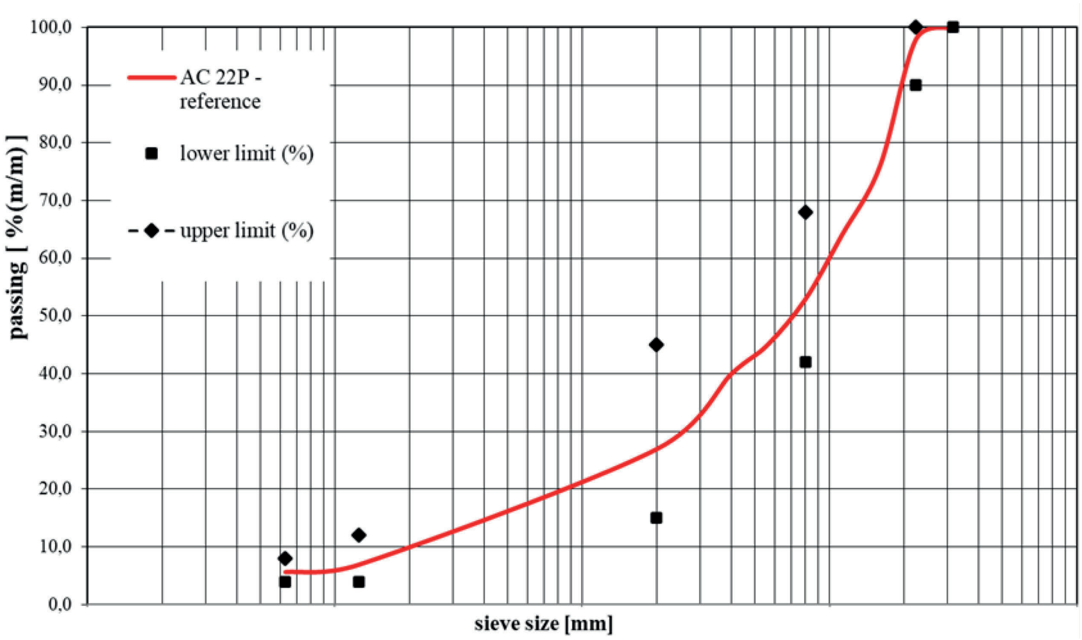

Fig. 2. Mineral mixture grain size curve

Table 4. Basic properties of 35/50 road asphalt [31]

Property	Research method	Unit	Parameter value
Penetration at 25°C	PN-EN 1426	0.1 mm	35–50
Softening temperature	PN-EN 1427	°C	50–58
Fracture temperature According to Fraass	PN-EN 12593	°C	(-14.1) – (-11.1)
Density at 15°C	PN-EN 15326	kg/m³	1026

Table 5. Summary of the mixture design

No.	Material	Share in % (m/m)	
		mm	mma
1	16/22.4	24.0	23.1
2	8/16	23.0	22.1
3	2/8	18.0	17.3
4	0/4	33.0	31.7
5	Mineral filler – limestone	2.0	1.9
6	Road asphalt 35/50	–	3.9
7	Adhesive agent	–	0.1
	Total	100	100

3. TEST RESULTS FOR COLD RECYCLED MIXTURES

An assessment of the influence of the type of binding agent on the properties of the cold mixture was carried out according to the adopted scope of the study presented in Table 1. The scope covers the basic properties of cold-produced mixtures. The scope of the work, the testing methodology and the execution of the samples were carried out in accordance with the norms and guidelines used in Poland.

3.1. Void content – V_m

A determination of the void content V_m was carried out for the mixtures analysed. This parameter plays a very important role and determines, among other things, resistance to the damaging effects of water, frost or the formation of permanent deformations. The void content is a fundamental parameter defining a given mixture. The test was performed on Marshall samples with a diameter of 101.6 mm and a height of 63.5 ±2 mm. The samples were compacted with a Marshall tamper 2x75 strokes. Figure 3 shows the results obtained during the study.

Analysing the presented graph of void content V_m in the mixture, it can be clearly seen that the asphalt concrete mixture has the lowest values. The V_m factor of the AC 22P mix is 5.6%. Another group of mixtures are CBGM mixtures that have undergone polymer modification. The results obtained are significantly lower than those of traditional hydraulic binder-bound mixtures. Classic CBGM mixtures have a significantly higher ratio than polymer-modified bound mixtures. The C3.5 mix contains 12.4% voids, while the C3.5+P2 mix contains 8.6% voids. This may be due to the improved workability of the material as a result of the polymer modification. This phenomenon was observed in traditional cement concrete [22]. The use of an asphalt bonding agent affects the V_m factor. Adding foamed bitumen sequentially increases the voids in the mixture compared to the bound mixture undergoing modification. In comparison, the C3.5+P2+AS3 mixture contains 12.7% voids. The foamed bitumen combines with the fines to close the voids in the mix. The use of asphalt emulsion changes the void values. Mixtures made using BE-RCM technology have the highest void content of all those analysed. The twin mixture to the previously mentioned C3.5+P2+E5 has a void content of 13.9%. The influence of the bonding agent dosing method is therefore apparent. Each of the mixtures made with BE-RCM and FB-RCM technology has identical asphalt content. This means that the use of foamed bitumen technology results in a reduction in the void content and therefore a tighter seal of the mixture and more precise filling of the voids.

Like modified CBGM mixtures, mixtures containing FB-RCM foamed bitumen have a low V_m factor. This

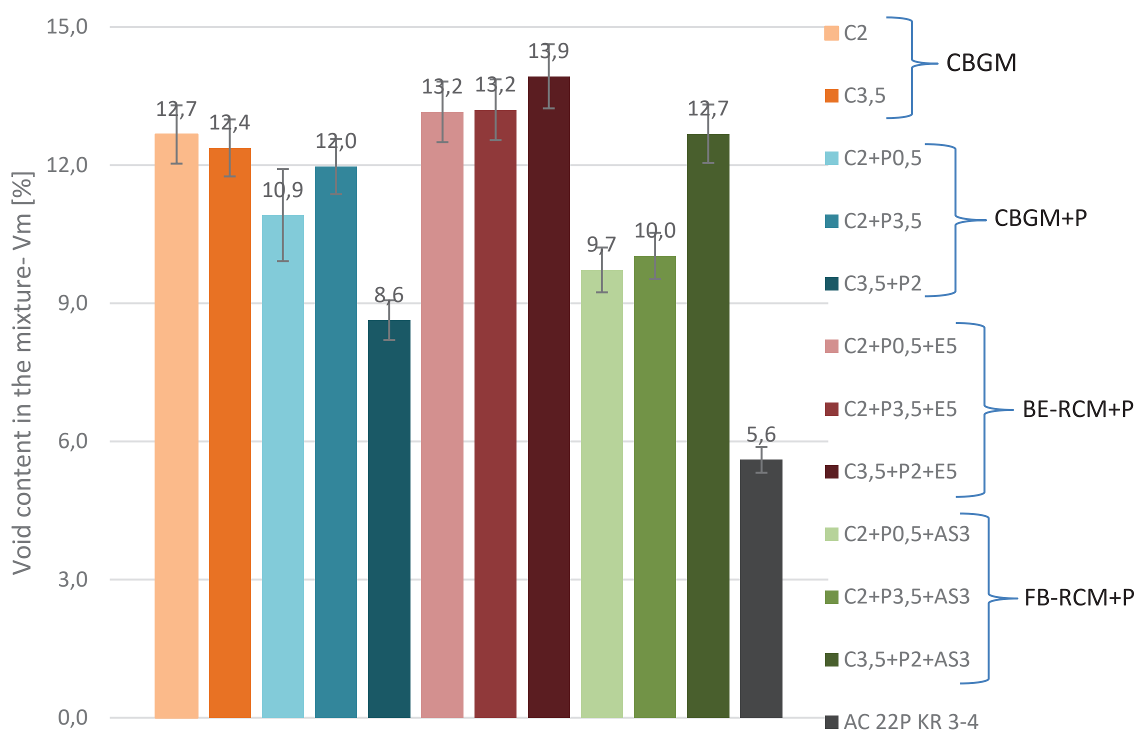

Fig. 3. Void content V_m in the mixtures

means that the mixtures are well workable, well compactible, and that the bonding agent and fine particles of the mineral material fill the voids formed between the coarse grains of the mineral skeleton.

3.2. Indirect tensile strength – ITS_{dry}

An indirect tensile strength ITS_{dry} determination of mixtures was performed. This parameter is extremely important for mixtures in road pavement construction, in the context of predicting fatigue life. Road subbase work in the tensile range, therefore the analysis of the ITS parameter is extremely important. The test was carried out at a temperature of 25°C. Figure 4 shows the results obtained for the mixtures.

Considering the results shown in Figure 4, it should be noted that mixes containing 3.5% cement binder have the highest ITSdry value. The initial C3.5 mixture is characterised by an ITS dry coefficient of 1537.5 kPa. The addition of polymer powder at 2% leads to a decrease in the coefficient, and the C3.5+P2 mixture has an indirect tensile strength of 1370.2 kPa. A decrease in the coefficient value is also seen when asphalt bonding agent is added to the mixture. The use of 5% asphalt emulsion leads to a decrease in the ITS_{dry} value, and the mixture with a C3.5+P2+E5 designation has a strength of 1163.3 kPa. In comparison, the use of foamed bitumen at 3% causes a greater drop in strength than asphalt emulsion. The C3.5+P2+AS3 mixture has a strength of 930.7 kPa. The mix of asphalt concrete has an indirect tensile strength of 1440.8 kPa. Summarising the results obtained for the mixes produced by the deep cold recycling process, it can be seen that the highest values in each group were characterised by mixes bound with CBGM cement (C2 and C3.5). On each occasion, a decrease in the parameter was noted following the addition of redispersible polymer powder, and the loss of strength was proportional to the amount of additive used in the form of RPP. A decrease in the parameter with the use of an asphalt bonding agent can be seen further down. The BE-RCM and FB-RCM mixtures had inferior strength parameters, compared to pure cement and cement-polymer mixes. The ITS_{dry} values obtained for the mixtures using foamed bitumen and asphalt emulsion were convergent, but the mixtures with foamed bitumen had the lowest value of the analysed parameter. The smallest ITS_{dry} parameter value of 345.1 kPa corresponded to the C2+P3.5+AS3 mixture. The main reason for this low result was the use of 3.5% redispersible polymer powder in the mixture's formulation. The highest ITS_{dry} value was achieved by a C3.5 mix bound only by cement at 3.5%. 1537.5 kPa was recorded. This is approximately 4.5 times higher, compared to the C2+P3.5+AS3 mixture.

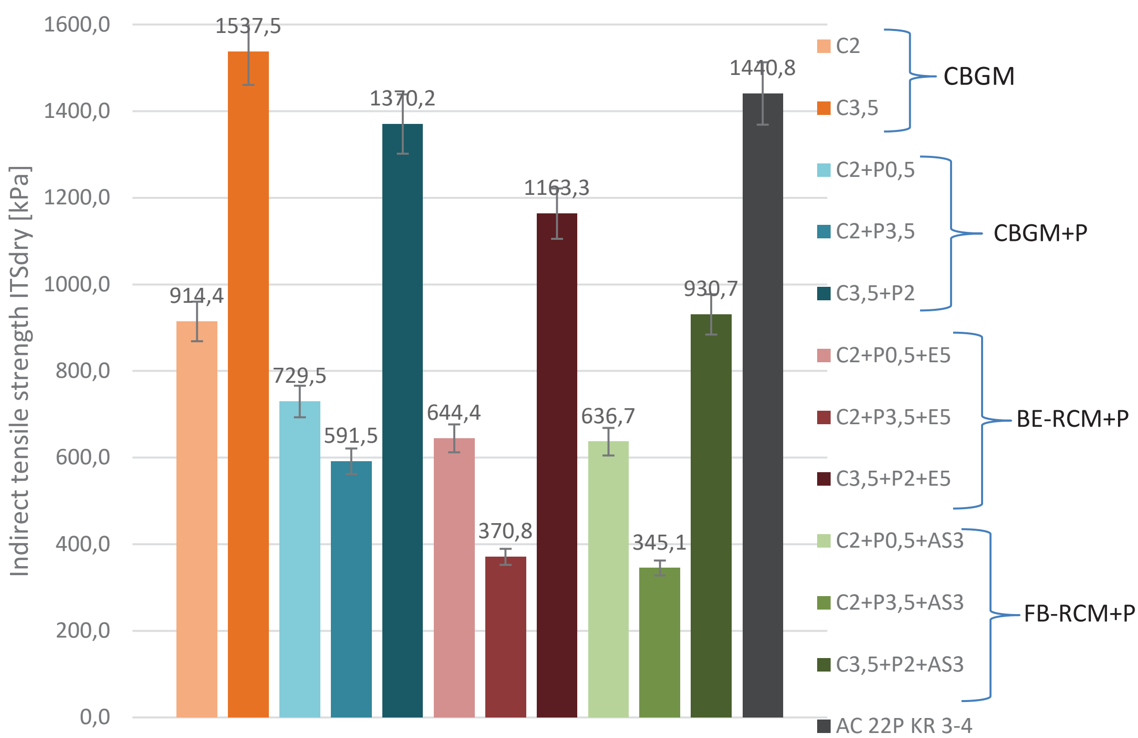

Fig. 4. Indirect tensile strength ITS_{dry}

3.3. Water resistance – TSR

A water resistance determination was carried out for the mixtures analysed. This is a test of the water resistance of the mixture in indirect tension. Road pavement construction layers are exposed to moisture, so for mixtures subjected to harmful effects of water, the parameter of resistance in indirect tension is a very important factor in determining the mixture. Figure 5 shows the results obtained during the study.

Analysing Figure 5, it should be noted that the mixtures containing asphalt bonding agent and an increased content of polymer powder have the highest resistance to water. Mixtures containing only 0.5% polymer have lower water resistance. This is evident in the C2+P0.5+E5 and C2+P3.5+E5 mixes. The former mixture has a resistance of 85%, while the twin mixture with increased polymer content has a resistance of 97%. This implies a strong effect of the polymer modification on the water resistance of BE-RCM mixtures. This is identical for FB-RCM mixtures. The slight effect of the asphalt bonding agent dosing method on the resistance of the TSR mixtures is also apparent, as shown [5]. Mixtures made with asphalt emulsion achieved higher resistance compared to mixtures with foamed asphalt. In comparison, the asphalt concrete mix has a water resistance of 95%. In the case of mixtures bound only by cement, the influence of the cement binder content is apparent. A C3.5 mix containing 3.5% cement in its composition has a resistance of 86%. In comparison, the C2 mix achieved a resistance of 83%. Adding polymer powder to the mix bound only by cement had a positive effect in each case. A slight increase in resistance was achieved.

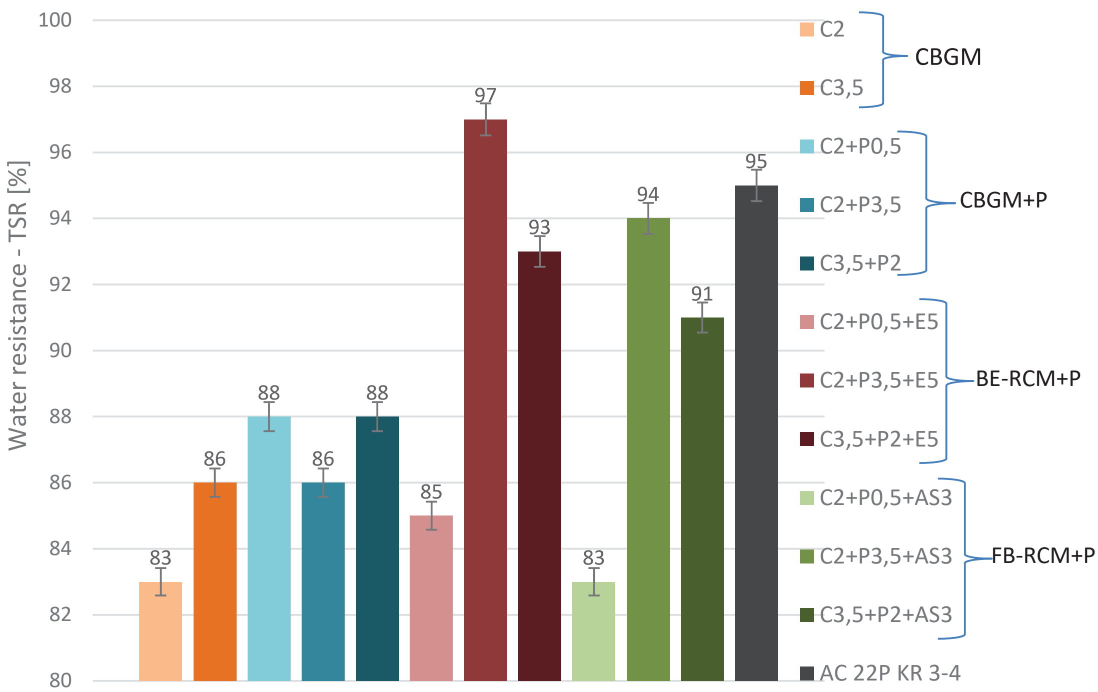

Fig. 5. TSR water resistance of the analysed mixtures

3.4. Elastic stiffness modulus – IT-CY

The results of the determination of the stiffness modulus S_m of the mixtures will be discussed below. An IT-CY test was performed at temperatures (-10°C, 5°C, 13°C, 25°C, 50°C). This makes it possible to evaluate the performance of the mixture under varying environmental conditions, depending on the season. This means that it is possible to observe the performance of the mixture in winter conditions, the gradual thawing and the exposure of the mixture to permanent deformations created at high temperatures. The results obtained are shown in Table 6.

It can be seen from Table 6 that the highest value of the stiffness modulus among the mixtures analysed was recorded for AC 22P at -10°C. The next highest recorded was the C3.5+P2 mixture. It is a substructure bound with 3.5% cement and 2% redispersible polymer powder. When analysing the other polymer-modified CBGM mixtures, it should be noted that they have the highest stiffness modulus values over the entire temperature range. Importantly, the effect of the bonding agent dosing method on the stiffness modulus value was also observed. Mixtures containing foamed bitumen in their composition have a higher stiffness

Table 6. Values of the stiffness modulus S_m of the analysed mixtures

Mixture type	Code of the mixture	Mixture stiffness modulus S_m [MPa], at the temperature of determination				
		-10°C	5°C	13°C	25°C	50°C
CBGM	C2	15674.0	12167.5	6543.3	3579.0	–
	C3.5	23915.3	21053.8	17884.8	14635.5	4771.0
CBGM+P	C2+P0.5	19378.5	19205.0	17014.5	12276.5	6062.3
	C2+P3.5	21596.0	20158.7	17772.7	11449.7	4905.7
	C3.5+P2	29892.5	30048.3	27032.0	23361.5	16330.3
BE-RCM +P	C2+P0.5+E5	11500.0	8963.0	4754.3	2737.7	2141.3
	C2+P3.5+E5	12084.8	7170.5	5965.3	2972.8	1855.3
	C3.5+P2+E5	16214.3	15795.8	12065.0	8076.5	2487.0
FB-RCM +P	C2+P0.5+AS3	14785.3	12241.5	8622.5	4435.5	753.3
	C2+P3.5+AS3	16129.5	15389.5	12681.5	7591.3	2083.3
	C3.5+P2+AS3	20870.8	18569.3	18017.3	13892.3	7537.0
AC	AC 22P KR 3-4	28863.0	19677.0	14440.0	6608.0	752.0

modulus. It should be noted that at high temperatures the asphalt concrete mixture has low stiffness. For comparison, at 50°C the AC22P mixture has a stiffness modulus of 752.0 MPa, while the C3.5+P2 cement-polymer mixture has a stiffness modulus of 16330.3 MPa. Importantly, the initial C3.5 mixture had a stiffness modulus of 4771.0 MPa. The significant impact of the polymer MIXTURE modification is therefore apparent. This phenomenon is apparent even at the smallest polymer contribution. The C2 mixture HAd a stiffness modulus of 3579.0 MPa at 25°C. After adding a 0.5% polymer powder and creating a C2+P0.5 mixture, 12276.5 MPa was recorded. A significant effect of the bonding agent dosing method on the recorded stiffness modulus values can also be deduced from Table 6. The C3.5+P2+E5 mix recorded a stiffness modulus in the range 16214.3 – 2487.0 MPa. The twin mix with C3.5+P2+AS3 foamed bitumen achieved a stiffness modulus of 20870.8 – 7537.0 MPa.

3.5. Axial compressive strength – Rm_{28}

Another parameter considered was the axial compressive strength after 28 days of conditioning. The results obtained are shown Figure 6.

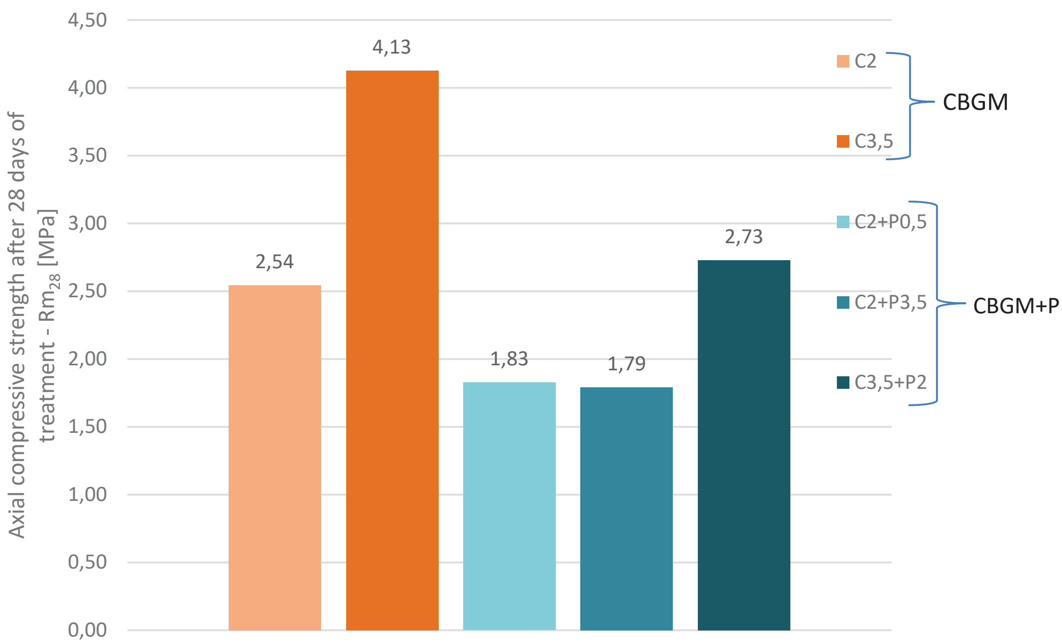

Fig. 6. Axial compressive strength after 28 days of treatment – Rm_{28}

Analysing Figure 6, it is clear that the classic hydraulically bound mixtures have the highest axial compressive strength of those shown. The substructure designated C2, bound with 2% cement, has a strength of 2.5 MPa. The C2+P0.5 mixture presented next, containing 2% cement and 0.5% redispersible polymer powder, achieved a lower compressive strength value. A decrease in the analysed parameter of 0.6 MPa was recorded. After increasing the RPP content of the mix, a C2+P3.5 mix with a strength of 1.7 MPa was obtained. The highest ranked mixture turned out to be C3.5. As a result of the test, its strength was determined at 4.1 MPa. After adding a 2% modifier and creating a C3.5+P2 mixture, 2.7 MPa was recorded.

After reviewing the results presented, it is important to note the significant effect of the cement content of the mix on the axial compressive strength. Increasing the binder content improves the analysed parameter. In the case of the polymer modifier, a reduction in the strength of the mixture is achieved. The addition of 0.5% powder resulted in a loss of strength of 24% of the initial value. However, with the addition of 3.5%, there was a 32% decrease in strength. As can be seen from this example alone, the decrease is significant, but it is not possible to demonstrate a linear relationship of strength decrease with increasing modifying agent content. In comparison, in a mixture bound with 3.5% cement, there was a 34% drop in strength when 2% RPP was added.

4. CONCLUSIONS

Summing up the analysis of the research results:

1. The BE-RCM mixtures presented are characterised by a higher void content than the modified CBGM mixtures. This represents an increase in the parameter as a result of the use of asphalt emulsion. In addition, a difference in the coefficient is apparent depending on the method of asphalt dosing. Mixes with foamed bitumen contain fewer voids than their counterparts made with asphalt emulsion.
2. The void content of the CBGM mix decreases as a result of polymer modification. The initial C3.5 bound mix has a void content of 12.4%. The addition of 2% polymer powder resulted in a decrease in voids. For the C3.5+P2 mix, the parameter was 8.6%. The polymer powder leads to better workability and better filling of voids.
3. The smallest ITS_{dry} parameter value of 345.1 kPa corresponded to the C2+P3.5+AS3 mixture. The main reason for this low result was the use of 3.5% cent redispersible polymer powder in the mixture's formulation. The highest ITS_{dry} value was achieved by a C3.5 mix bound only by cement at 3.5%. 1537.5 kPa was recorded. This is approximately 4.5 times higher, compared to the C2+P3.5+AS3 mixture.
4. The FB-RCM mixture with the C2+P3.5+E5 designation achieved a better TSR value than the asphalt concrete mixture. This is due to the sealing of the mix by the asphalt foam and the resulting polymer film.
5. It should be noted that hydraulic binder-bound mixtures subjected to the polymer modification process achieve different values to the classic CBGM mixture. The modification alters the values obtained, and the mix itself is characterised by intermediate performance, sitting between traditional cement-bound mixtures and mineral-cement mixtures with FB-RCM foamed asphalt.
6. The influence of the method of dosing the bonding agent into the mix is also important. This is evident in the case of the BE-RCM and FB-RCM mixtures under consideration. It should be noted that in both cases the final bonding agent content was identical.

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