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Application of reclaimed asphalt in recycled road pavements

Abstract: This paper presents the possibilities of reusing recycled materials in road pavement constructions. Waste materials came from old and damaged pavement layers. The reclaimed asphalt pavement (RAP) was used to create new layers of road surfaces - the base layers. The base layers were made of mineral-cement-emulsion mixtures (MCE). The main issue was to assess the impact of the RAP in MCE mixes on the physical, mechanical and rheological properties of the recycled base layer. The use of reclaimed asphalt in MCE mixes reduces road construction costs and allows for the ecological coexistence of the investment with the environment. The research results were developed as part of the project entitled "The innovative technology used the binding agent optimization that provides the long service life of the recycled base layer" (TECHMATSTRATEG1/349326/9/NCBR/2017) within the scientific undertaking of Strategic Research and Development Program entitled "Modern Materials Technology" (TECHMATSTRATEG I), which is financed by the National Center for Research and Development (Polish NCBiR).

Keywords: MCE mixture; Road pavement recycling; Reclaimed asphalt pavement (RAP); Cement dusty by-products

Introduction

As part of the research grant "Modern material technologies", the Department of Roads and Airports of the Wrocław University of Technology in 2018-2021 participated in the project: "Innovative technology using the optimization of a binder intended for the technology of deep cold recycling of pavement structures ensuring its operational durability". The scope of the research topic included the assessment of the impact of an innovative binder on the physical, mechanical, and rheological properties of a recycled foundation made of a mineral-binder mixture with asphalt emulsion and foamed asphalt.

Procedures for testing and assessing the properties of road mixtures containing: reclaimed asphalt, various minerals, dedicated binder (consisting of cement, lime, and dusty by-products) from cement plants, and asphalt binder in the form of asphalt emulsion or foamed asphalt were developed. The guidelines for the deep cold recycling technology with asphalt emulsion and a dedicated binder were also prepared.

One of the materials used to make the layers of the road foundation are mineral-cement-emulsion mixtures. The innovative approach to the research topic consisted of the use of an innovative binder in the composition of these mixtures as a substitute for cement in combination with reclaimed asphalt and asphalt binder. The basis of the analysis was to determine the influence of the dedicated binder on the strength parameters of mineral-cement-emulsion mixtures (MCE). The scope of the tests presented in this article included: indirect tensile strength of MCE mixtures determined by the ITS method and resistance to atmospheric factors determined by the following methods: TSR, ITSR, and AASHTO.

Recycled materials in road construction

The issue of environmental protection is very important, especially due to the progressive degradation and exploitation of the surrounding nature. In view of the declining natural material resources, the problem of reusing materials from already existing, but worn-out buildings has arisen. Re-use of used materials (recycling) is also observed in road construction.

For the construction of road and airport pavements, not only new, unprocessed materials can be used, but also those from recycling. Recycling of road surfaces enables the reuse of road materials, which, after appropriate grading and mixing with binders such as asphalt or cement with their appropriate percentage, create full-value material products.

Recycling used in road construction provides many tangible benefits: it reduces the demand for mineral resources, lowers the costs of aggregate transport, significantly reduces the number of landfills for waste from damaged road surfaces.

In scientific works in the field of construction published in the best trade journals, it was shown that layers of road structures with various types of additives and the so-called reclaimed asphalt achieves very good mechanical properties, often better than mixtures consisting only of natural ingredients [29]. Moreover, Chinese experiments confirmed the possibility of using concrete slag and bricks for the construction of the surface of highway embankments [12, 13]. Construction waste from the demolition of buildings can be used in road embankments [5, 26, 27]. The same material can be used for unbound layers of the foundation [3, 18, 30]. As a substitute for natural resources, waste materials can also be used for the construction of roadsides or unpaved roads [8]. The monitored parameters were density, bearing capacity, and frost resistance. Recycled mixtures containing aluminum waste obtained better mechanical values (compressive strength, CBR parameter) than recycled mixtures without this waste content [15].

The possibility of using mineral materials from recycled concrete pavements has also been proven. Instead of coarse natural aggregates - up to 20%, high-quality materials derived from recycling of concrete aggregates can be used [10]. The results of the tests of indirect tensile strength and modulus of elasticity showed that the addition of recycled concrete aggregate in the amount of 40% of the mineral mix to asphalt mixtures is optimal and recommended [17].

The use of used tires for mixtures with modified asphalt in the pavement structure results in significant energy saving and reduction of carbon dioxide emissions by using much less carbon [16, 32]. Car rubber in the form of crumbs as a modifier improves the rheological and mechanical properties of rubber-asphalt mixtures [16].

The research showed that the reclaimed asphalt together with the recovered substrate stabilized with cement can be used as a secondary raw material of aggregate for the preparation of cement-stabilized mixtures in cold recycling technology [23]. The mixtures with the content of recycled materials were characterized by sufficient durability and good efficiency.

Asphalt binders affect physical and mechanical parameters, such as intermediate tensile strength, creep modulus, or the content of free space, of mixtures recycled using the cold method [4, 25]. The type of binder had a significant impact on the compactability of the tested mixtures, which resulted in obtaining different values of mechanical parameters. The obtained results confirmed the possibility of applying cold recycled mixtures with foamed asphalt to the layers of pavement structures.

In addition, reclaimed asphalt can be a component of a mix with foamed asphalt (MCAS). This mixture, made by the method of processing on-site, according to cold technology, it has found its wide application in the base layer [14, 20, 31], on which a binding layer of asphalt concrete in hot technology will be directly embedded.

Another mix in which recycled material can be used is the so-called compact asphalt. It is created while laying two layers of asphalt pavement, usually binding and wearing. Tests of the pavement made on the A-2 motorway in Poland confirmed its properties in terms of durability, resistance to deformation, and connections between the layers [28].

German laboratories and contractors quite often use reclaimed asphalt for mixes for the upper construction layers [24]. In addition, reclaimed asphalt is used to harden roadsides or to build service or company roads.

Compounds containing reclaimed asphalt showed higher intermediate tensile strength (ITS) values and reduced deformation than traditional asphalt mixes [19].

Imidazolines, both rapeseed and olein, can be used as a rejuvenating agent to restore the properties of aged asphalt contained in RAP [33]. The addition of imidazoline to the "old" asphalt resulted in an increase in penetration and a decrease in the softening point and viscosity.

In addition, replacing coarse aggregate with reclaimed asphalt gives a significant improvement in mechanical properties (including Marshall stability, intermediate tensile strength) and the efficiency of hot mix asphalt compared to traditional asphalt mixes [2].

One of the methods of utilization of construction waste in road pavements may be the use of mineral-cement-emulsion mixtures (MCE). MCE mixes consist of reclaim or reclaim and mineral aggregate, cold mixed with cement and asphalt emulsion in defined proportions, under conditions of optimal humidity. These mixtures are characterized by a continuous graining [6, 23].

MCE mixes can be used in road pavement constructions as the base course. The MCE framework can be used in the following cases:

- when reconstructing existing pavements,
- when widening or repairing roadsides,
- in the construction of new pavements (base layer) as part of renovation and reconstruction [8].

The basic constituent materials of mineral-cement-emulsion mixes are: reclaim, grading aggregate, hydraulic binder, asphalt emulsion, and water.

The most common is the method of using reclaimed asphalt resulting from the milling of degraded susceptible pavements.

When recycled with the use of asphalt and cement, the pavement layers are characterized by load-bearing capacity and durability, transferring shrinkage cracks [9, 11].

The use of these ingredients, especially cement, can cause shrinkage and cracks in road layers. The authors of the study focused on reducing the cracking phenomenon in MCE mixes by using an innovative cement binder with recycled materials. The innovative cement binder based on dusty by-products from cement plants also contributes to the optimization of the recycling process in road surfaces. The research was carried out in the field of strength analyzes and resistance to weather conditions. As a result of the work, it was shown that innovative binders have a significant impact on the obtained research results. The use of innovative binders as an alternative to cement will positively affect the durability of road pavements.

Selection of ingredients for MCE mixes

The design of the MCE mix should be correlated with the design of the pavement structure and the organization of works, depending on the method of its execution. The following materials should be used to prepare mineral-cement-emulsion mixtures: reclaimed asphalt, grading aggregate, hydraulic binder, asphalt emulsion, and water.

The compositions of mineral mixtures (MM) were determined in accordance with the adopted assumptions, i.e. for two types of mixtures: fine-grained (marked with the symbol D) and coarse-grained (marked with the symbol G). The fine-grained mixture consisted of crushed grading aggregate with continuous graining 0/31.5 mm, natural grading aggregate with continuous graining 0/2 mm, and recycled aggregate - (reclaimed asphalt) 0/10 mm. The coarse-grained mixture, on the other hand, included crushed grading aggregate with continuous graining 0/31.5 mm, natural grading aggregate with continuous graining 0/2 mm, and recycled aggregate - (reclaimed asphalt) 0/31.5 mm.

The strength and deformation properties of MCE mixtures are significantly influenced by the grain size composition of the mineral mixture itself. According to the requirements [7], its grain size distribution should be within the specified range given in the Table **1**. The grain size distribution of such a mineral mixture is determined without taking into account the cement.

Tab. 1. Graining requirements for mineral mix (MM) for MCE layers [7]

Sito # [mm]	Mieszanka MCE dla KR 1÷2	Mieszanka MCE dla KR 3÷4
63,0	100	100
31,5	80 – 100	80 – 100
16,0	55 – 100	55 – 93
8,0	35 – 90	35 – 80
4,0	25 – 75	25 – 67
2,0	16 – 60	16 – 55
1,0	9 – 45	9 – 43
0,5	5 – 35	5 – 33
0,125	2 – 18	2 – 15
0,063	0 – 12	0 – 12

The conducted analyzes show that the graining curve of fine-grained and coarse-grained mineral mixes meets the conditions of the MCE boundary curves and that the percentage of its individual components (natural aggregates and reclaimed aggregate) in both types of mixes is the same, in the design of mineral mixes, the percentage of reclaimed asphalt at the level of 40%, natural aggregate 0/31.5 mm in the amount of 50% and natural aggregate 0/2 mm in the amount of 10%.

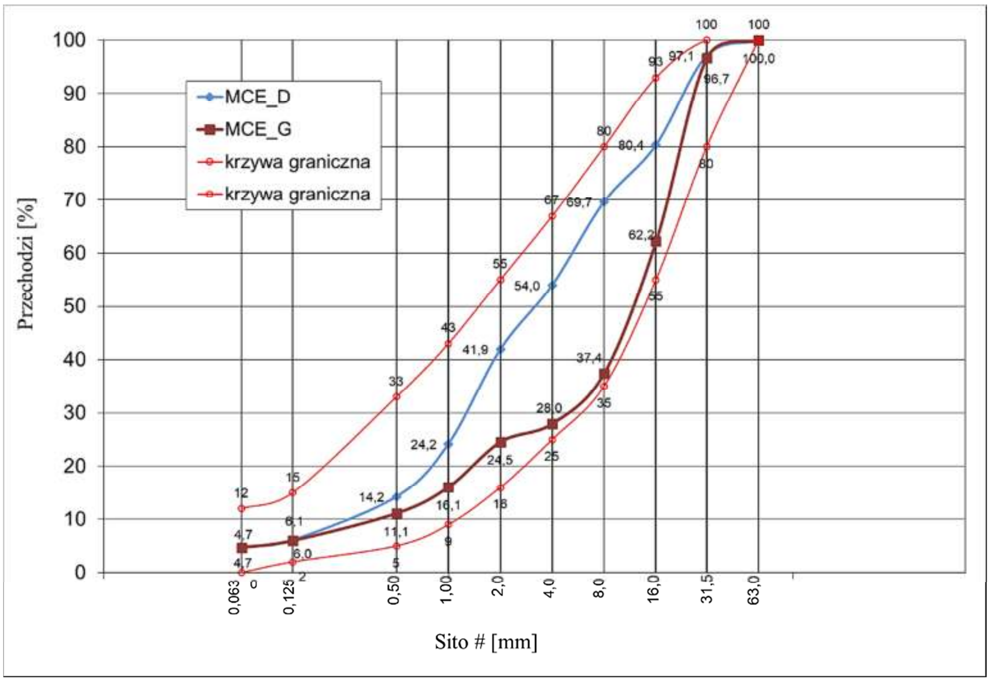
The grain size distribution of the obtained fine-grained and coarse-grained mineral mixtures is presented in Table **2** and in Figure **1**.

Tab. 2. The compositions of mineral mixes (MM)

Components of a fine-grained mix **(D)**	Components of a coarse-grained mix **(G)**	Content [%]
0/10mm reclaimed asphalt	**0/31,5mm** reclaimed asphalt	**40**
0/31,5mm grading aggregate, crushed	**0/31,5mm** grading aggregate, crushed	**50**
0/2mm grading aggregate, natural	**0/2mm** grading aggregate, natural	**10**

Both the fine and coarse mixes are grain-continuous and comply with the graining cut-off curves specified for MCE mixes intended for substructures.

The next step was to determine the composition of mineral mixes (MM), which instead of cement contained an innovative binder. Coarse-grained and fine-grained mixes containing cement binder marked respectively: MM_G_Ref and MM_D_Ref were adopted as reference mixes. Then, instead of cement, innovative road binders were used, containing cement, lime, and cement by-products (UCPP). Seven such binders were used, and they differed in different content of three components: cement, lime, and dust.



1. Particle size distribution curves of mineral mixes (MM)

This binder was designed to reduce the stiffness and ensure the service life of the MCE blend. The compositions of individual binders are presented in Table **3**.

Tab. 3. Designation and composition of the composed binders

Oznaczenie spoiw	Składnik		
	Cement	Wapno	Pyły
1V	0,20	0,20	0,60
2V	0,20	0,60	0,20
3V	0,60	0,20	0,20
4C	0,20	0,40	0,40
5C	0,40	0,20	0,40
6C	0,40	0,40	0,20
7C	0,33	0,33	0,33
Ref	1	0	0

Seven binders composed according to the experimental plan from the 1st stage of the Techmatstrateg "Modern Material Technologies" Program were used in the research.

At the stage of designing the compositions of all fine-grained and coarse-grained mineral mixes (MM) (16 mixes), the following features were determined for them: maximum bulk density, maximum skeleton bulk density, and optimal humidity. The results of these tests are presented in Table **4**.

Slight differences in the values of optimal humidity and volume densities between individual compositions result from small differences that occur in the composition of the innovative binder.

Tab. 4. Optimum humidity of MM mixes with innovative binders

Mineral mix		MM_G_1V	MM_G_2V	MM_G_3V	MM_G_4C	MM_G_5C	MM_G_6C	MM_G_7C
Optimum humidity	G	7,77 %	7,74 %	7,62 %	7,69 %	7,64 %	7,63 %	7,76 %
Maximum skeleton bulk density		2,172 g/cm^3	2,190 g/cm^3	2,176 g/cm^3	2,186 g/cm^3	2,190 g/cm^3	2,197 g/cm^3	2,185 g/cm^3
Maximum bulk density		2,341 g/cm^3	2,359 g/cm^3	2,342 g/cm^3	2,354 g/cm^3	2,357 g/cm^3	2,365 g/cm^3	2,355 g/cm^3
Mineral mix		MM_D_1V	MM_D_2V	MM_D_3V	MM_D_4C	MM_D_5C	MM_D_6C	MM_D_7C
Optimum humidity	D	7,98 %	7,94 %	7,83 %	7,91 %	7,86 %	7,85 %	7,95 %
Maximum skeleton bulk density		2,139 g/cm^3	2,153 g/cm^3	2,146 g/cm^3	2,148 g/cm^3	2,149 g/cm^3	2,156 g/cm^3	2,147 g/cm^3
Maximum bulk density		2,310 g/cm^3	2,324 g/cm^3	2,314 g/cm^3	2,318 g/cm^3	2,318 g/cm^3	2,325 g/cm^3	2,318 g/cm^3

For such defined compositions of mineral mixes (MM) with innovative binders, according to Table **4**, mineral-cement-emulsion (MCE) mixes were made. The asphalt emulsion C60B10ZM/R was used. The results of the compositions of fine-grained and coarse-grained mixes with an innovative binder are presented in Table **5**.

Tab. 5. Composition of MCE mixes

Components	Working composition of MM [%]	Composition of **MCE_D** [%]	Composition of **MCE_G** [%]
Asphalt destruct **0/10mm (D)** or **0/31,5mm (G)**	40	34,4	34,5
0/31,5mm grading aggregate, crushed	50	43,0	43,1
0/2mm grading aggregate, natural	10	8,6	8,6
Cement or binder (**1V,2V,3V,4C,5C,6C,7C**)	-	3,0	3,0
Asphalt emulsion C60B10ZM/R	-	5,0	5,0
Water	-	6,0	5,8

In the next stage of work, the analysis of the strength properties of the mineral-cement-emulsion mixes in question was started.

Research program

The tests were carried out for coarse-grained MCE mixes with various hydraulic binders with the designations: MCE_G_Ref, MCE_G_1V, MCE_G_2V, MCE_G_3V, MCE_G_4C, MCE_G_5C, MCE_G_6C, MCE_G_7C and fine-grained: MCE_D_Ref, MCE_D_1V, MCE_D_2V, MCE_D_3V, MCE_D_4C, MCE_D_5C, MCE_D_6C, MCE_D_7C.

For the implementation of the task, it was crucial to carry out the following tests: density and bulk density, free space content, water absorption, axial compressive strength, intermediate tensile strength ITS, resistance to weather conditions AASHTO and PANK, TSR, ITSR, modulus of indirect tensile stiffness IT- CY.

In this study, the resistance of the tested mixtures to atmospheric factors was analyzed in detail. Depending on the method of testing the samples, different levels of strength were obtained, used to assess the suitability of a given material for use in the layers of road pavement foundations. Three applied research methods were compared: AASHTO, TSR, and ITSR.

The idea of testing resistance to atmospheric factors using the TSR, ITSR, and AASHTO methods is analogous and the difference lies in the method of sample conditioning. In all methods, the so-called witness samples are used to compare the resistance to water and frost. "Dry samples - DRY". The ITS (indirect tensile strength) - ITSDRY - is determined for them. The ITS indirect tensile strength test was performed according to [22]. Three cylindrical samples (Marshall) with a nominal diameter of 101.5 mm and a height of 63.5 mm were used for the analysis, for each preparation and the characteristic temperature of + 25 ° C. The samples were compacted 75 strokes per side in a Marshall automatic compactor. Due to the presence of cement mixtures and hydraulic binders in the composition, the maturation period of the samples was 28 days.

During the tests, the loading force needed to destroy the sample was recorded in detail. The value of the breaking force was used to determine the intermediate tensile strength of ITSDRY dry samples.

An exemplary view of the test performed and Marshall samples is shown in Figure **2**. Tensile strength ITS was calculated from the relation (1):

$$ITS = \frac{2 \cdot \mathrm{P}}{\pi \cdot \mathrm{D} \cdot \mathrm{h}}, \quad (1)$$

where: *ITS* – intermediate tensile strength [MPa], *P* – the value of the destructive force [N], *D* – sample diameter [mm], *h* – sample height [mm].

2. Indirect tensile strength ITS specimens and test scheme

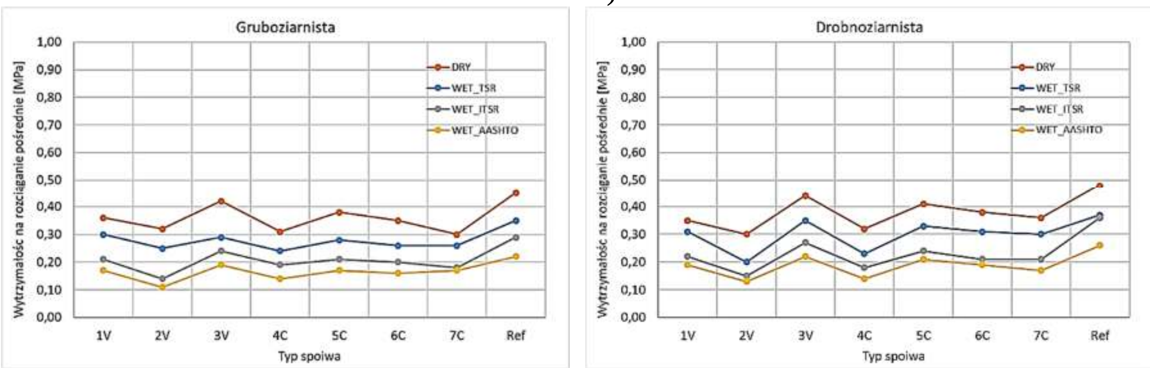
In the TSR (water resistance) method, the strength of dry ITSDRY samples is compared to the strength of samples soaked with ITSWET water for 24 hours at a temperature of + 25 °C. Three cylindrical (Marshall) samples with a nominal diameter of 101.5 mm and a height of 63.5 mm were used for the analyzes, for each test and characteristic temperature.

In the ITSR method according to the standard [21] and technical guidelines [34], the strength of dry ITSDRY samples is compared to the strength of samples soaked with water for 72 hours and subjected to one ITSRWET freezing cycle at -18 ° C for min. 16 h. For the analysis, three cylindrical (Marshall) samples with a nominal diameter of 101.5 mm and a height of 63.5 mm were used for each MCE mix.

In the AASHTO method, the strength of ITSDRY dry samples is compared to the strength of samples soaked in water under a vacuum of 200 hPa for 25 minutes. and subjected to 18 cycles of freezing and thawing in water (-18 ° C for 4 hours and + 20°C for 4 hours) - AASHTOWET [1]. To determine the strength of AASHTOWET, three cylindrical (Marshall) samples with a nominal diameter of 101.5 mm and a height of 63.5 mm were used for each MCE mix.

On the basis of the obtained detailed results, the average values of the intermediate tensile strength ITSDRY, ITSWET, ITSRWET, AASHTOWET were determined for all tested MCE mixes divided into coarse-grained and fine-grained mixes – Figure **3**.

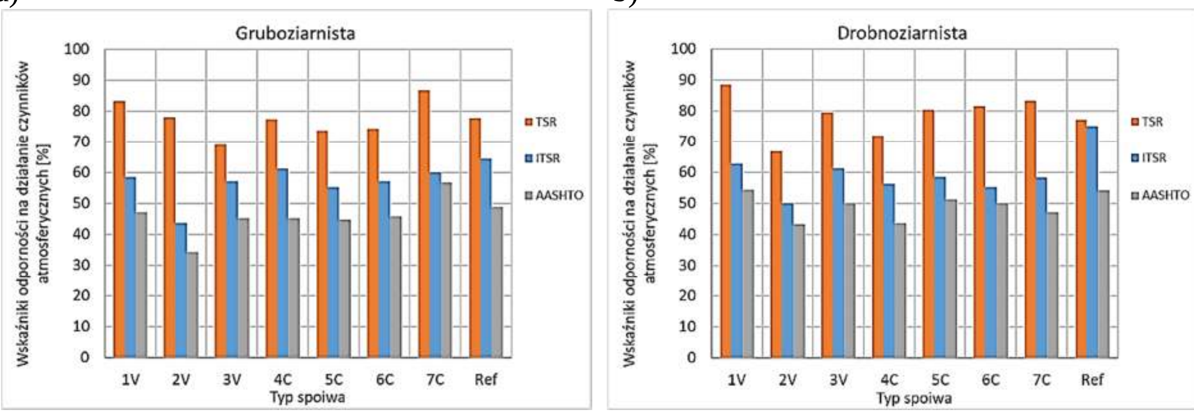
a) b)



3. Indirect tensile strength - a) coarse-grained MCE mix, b) fine-grained MCE mix

The obtained intermediate tensile strengths for "dry" ITSDRY samples and for "wet" ITSWET, ITSRWET, AASHTOWET samples were used to determine the resistance to weather conditions TSR, ITSR, AASHTO for all tested MCE mixtures divided into coarse-grained and fine-grained mixes - Figure **4**. Indicators of resistance to weather conditions TSR, ITSR, AASHTO are expressed as a percentage and indicate what part of the indirect tensile strength remained after the conditioning of the samples in comparison to the samples of witnesses, the so-called "dry".

a) b)



4. Resistance to weather conditions (TSR, ITSR, AASHTO) - a) coarse-grained MCE mix, b) fine-grained MCE mix

Based on the analyzes of the test results, it was found that the smallest drops in the intermediate tensile strength - the largest percentage of strength remaining after conditioning the samples in comparison to the "dry" samples, occur in the TSR test. Soaking the samples with water once lowers their intermediate tensile strength by 10-30%. In the case of a single soaking and freezing (ITSR method), the decrease in strength reaches 30-55%, depending on the binder used. On the other hand, in the case of soaking once and freezing and thawing 18 times (AASHTO method), the drops in strength reach up to 65% in relation to "dry" samples. In the TSR test, the lowest drops in strength were observed for mixtures with 1V and 7C binders, both fine-grained and coarse-grained. In the case of ITSR tests, the smallest drops in strength concern coarse-grained mixes with Ref, 4C, and 7C binders and fine-grained mixtures Ref, 1V, and 3V. Strength decreases in the AASHTO test were demonstrated to the smallest extent in coarse-grained mixes with the content of binders 7C and Ref, while in fine-grained mixes Ref, 1V and 5C.

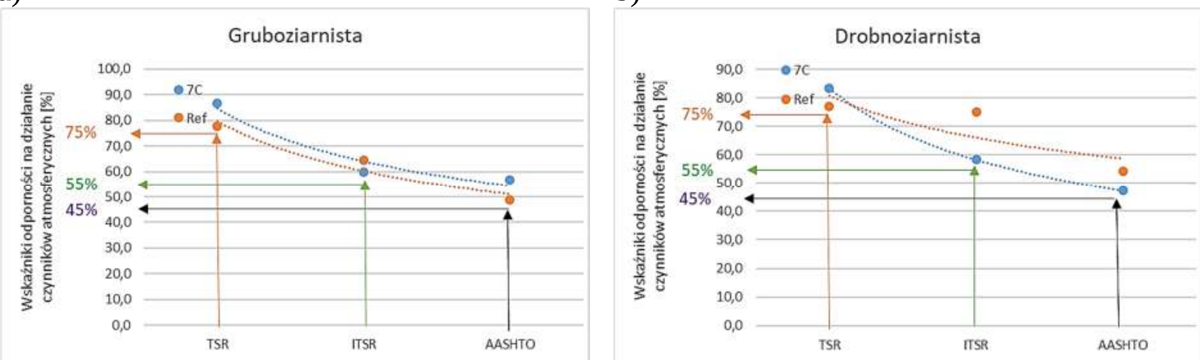
Currently, a criterion corresponding to the ITSR test is used to assess the water and frost sensitivity of conventional MCE mixtures. According to [7], the remaining intermediate tensile strength for samples conditioned in water cannot be lower than 70% or 80% depending on the current KR traffic category – Table **6**.

Tab. 6. Requirements for samples from the MCE mix [7]

Cecha	KR1-KR2 movement	KR3-KR4 movement
Water-resistance (remaining intermediate tensile strength after storing samples in water), T = + 5 ° C after 28 days, [%]	no less than 70	no less than 80

However, only water infiltration without freezing and a test temperature of + 5 ° C are used in this test. In the opinion of the authors of this study, it is more appropriate to use the method of sample care with freezing and the test temperature of + 25°C. In this way, uniform tests of water and frost resistance for MCE mixes and MMA mixes as well as adaptation to the possible actual operating conditions of the MCE layer in the pavement will be achieved. Exemplary relationships of the weather resistance index for mixes with 7C and Ref binders, both coarse-grained and fine-grained, are shown in Figure **5**. These mixes were selected due to the best, favorable strength properties demonstrated in the entire research process. At the same time, the proposed acceptable minimum criteria for assessing the suitability of MCE mixes with reclaimed asphalt for use in the layers of road pavements.

a) b)



5. Resistance to weather conditions (TSR, ITSR, AASHTO) - a) coarse-grained MCE mix, b) fine-grained MCE mix

As a result of the research, it was proposed to introduce new criteria for assessing the suitability of MCE with reclaimed asphalt, depending on the sample care method used – Table **7**.

Tab. 7. Requirements for samples from the mix of MCE with reclaimed asphalt

TSR [%] 25°C	***ITSR [%] 25°C***	***AASHTO T283 [%] 25°C***
min. 75	min. 55	min. 45

Summary

Based on the analysis of the intermediate tensile strength, it was noticed that there is an influence of atmospheric conditions on the MCE mixes with the content of a dedicated binder.

The highest resistance to atmospheric conditions is demonstrated by the samples in the TSR test, in which the intermediate tensile strength decreases in the range of 10-30%, both for coarse-grained and fine-grained mixtures, in relation to the strength obtained by the ITS method for dry samples. When determining resistance by the ITSR method, the samples decreased their strength in the range of 30 ÷ 55%, and when determined by the AASHTO method, the samples decreased their strength in the range of 45 ÷ 65%.

In the TSR test, the smallest drops in strength occur in mixes with 1V and 7C binders, both fine-grained and coarse-grained. In the case of ITSR tests, the smallest drops in strength concern coarse-grained mixtures with Ref, 4C, and 7C binders and fine-grained mixes Ref, 1V, and 3V. Strength decreases in the AASHTO test were demonstrated to the smallest extent in coarse-grained mixes with the content of binders 7C and Ref, while in fine-grained mixes Ref, 1V and 5C.

As part of the project, reclaimed asphalt was used to create new layers of road pavements, layers of the base made of mineral-cement-emulsion mixes (MCE). The use of reclaimed asphalt as waste material in MCE mixes will reduce road construction costs and will positively affect the environmental protection aspects and the ecological coexistence of the investment with the environment.

As a result of the conducted research, new criteria for assessing the suitability of MCE with reclaimed asphalt for use in the substructure layers of road pavements were developed, in terms of resistance to weather conditions, depending on the sample care method used (TSR, ITSR, AASHTO T283

The conducted tests and analyses confirmed the possibility of using a binder dedicated to the production of MCE mixes. The mixes meet the design requirements for use in construction layers of new road surfaces. MCE mixes containing an innovative dedicated binder can be used for the construction of the substructure layers of pavements with traffic up to the traffic category KR7.

The obtained test results were used to develop guidelines for the design procedures for the composition of an innovative binder (three-component) called a binder dedicated to the technology of making a layer of a mineral-binder mix with asphalt emulsion.

This article was written in connection with the implementation of research tasks in the project entitled "Innovative technology using the optimization of a binder intended for the technology of deep cold recycling of pavement structures ensuring its operational durability", as part of the joint venture "Modern material technologies" co-financed by the National Center for Research and Development.

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