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STIFFNESS OF MCE MIXTURES BASED ON CEMENT DUSTY BY-PRODUCTS AND RECYCLED AGGREGATE

SZTYWNOŚĆ MIESZANEK MCE NA BAZIE UBOCZNYCH CEMENTOWYCH PRODUKTÓW PYLASTYCH I KRUSZYWA Z RECYKLINGU

STRESZCZENIE. SŁOWA KLUCZOWE: W artykule przedstawiono możliwości powtórnego zastosowania materiałów pochodzących z recyklingu w konstrukcjach nawierzchni drogowych. W pracy analizowano wpływ destruktu asfaltowego i ubocznych cementowych produktów pylastych (UCPP) na sztywność mieszanek mineralno-cementowo-emulsyjnych (MCE). Destrukt asfaltowy może być wykorzystany jako surowiec wtórny do przygotowania mieszanek stabilizowanych cementem w technologii recyklingu na zimno. Zastosowanie w nawierzchniach drogowych mieszanek MCE jest jednym ze sposobów utylizacji odpadów budowlanych. Badania mieszanek MCE z UCPP miały na celu potwierdzenie możliwości zastosowania tych materiałów do warstw konstrukcji nawierzchni, poddanych recyklingowi na zimno. Istotą była ocena wpływu innowacyjnego środka wiążącego UCPP na właściwości mechaniczne mieszanek MCE. Analizowano sztywność przedmiotowych mieszanek. Badania wykonano dla mieszanek: drobnoziarnistej i gruboziarnistej. Badania sztywności w pośrednim rozciąganiu (IT-CY) wykonano wg normy PN-EN 12697-26. Badanie wytrzymałości na rozciąganie pośrednie (ITS) wykonano wg PN-EN 12697-23. Zastosowanie innowacyjnych spoiw pozwoliło na redukcję sztywności poszczególnych mieszanek MCE w porównaniu do mieszanek referencyjnych, zawierających klasyczny cement, przy zachowaniu ich odpowiedniej trwałości. Opracowane zależności pomiędzy sztywnością IT-CY a wytrzymałością ITS pozwolą na optymalizację procesu projektowania i wykonywania mieszanek MCE w nawierzchniach drogowych. Stosowanie UCPP zmieniło właściwości mechaniczne mieszanek MCE, ograniczając ich sztywność. Przyczyni się to do zwiększenia odporności na pękanie podbudowy i zwiększenie jej trwałości zmęczeniowej. Innowacyjny materiał został wykorzystany na odcinku doświadczalnym i jest monitorowany.

SŁOWA KLUCZOWE: mieszanka MCE, destrukt asfaltowy, recykling.

ABSTRACT. This paper presents the possibilities of reusing recycled materials in road pavement constructions. This study analyses the effects of reclaimed asphalt pavement (RAP) and cement dusty by-products (UCPP) on the stiffness of mineral-cement-emulsion (MCE) mixtures. Asphalt waste can be used as a secondary raw material for the preparation of cement-stabilised mixtures in cold recycling technology. The use of MCE mixtures in road pavement construction is one way of disposing of construction waste. Testing of MCE mixtures with UCPP was aimed at confirming the applicability of these materials for cold recycled pavement structure layers. The purpose was to evaluate the effect of the innovative UCPP binding agent on the mechanical properties of MCE mixtures. The stiffness of the mixtures in question was analysed. Tests were carried out for fine- and coarse-grained mixtures. The stiffness modulus in indirect tension test on cylindrical specimens (IT-CY) was carried out according to EN 12697-26. Indirect tensile strength (ITS) testing was carried out according to EN 12697-23. The use of innovative binders has made it possible to reduce the stiffness of individual MCE mixtures compared to reference mixtures containing conventional cement, while still maintaining adequate durability. The relationships developed between IT-CY stiffness and ITS strength will allow the design and execution of MCE mixtures in road pavements to be optimised. The use of UCPP changed the mechanical properties of MCE mixtures by reducing their stiffness. This will contribute to the cracking resistance of the base and sub-base layers and increase their fatigue life. The innovative material was used in the experimental section and it is being monitored.

KEYWORDS: mineral-cement-emulsion mixture, innovative road binder, recycling, fatigue durability, fracture toughness.

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1. INTRODUCTION

1.1. REUSE OF MATERIALS IN CIVIL ENGINEERING

Recycling of road pavements manifests itself in the protection of the natural environment, based on the reuse of used materials in the process of producing new conglomerates.

Due to decreasing natural material resources, the problem of reusing materials embedded in existing road pavements is actual and increasingly used during the modernization of the existing road network in Poland and worldwide [1, 2, 3, 4, 5]. This reduces the consumption of natural resources and the amount of waste. The main reason for using recycling is decreasing availability of natural stone materials and elimination of waste landfills from damaged road pavement constructions. One of the recycling solutions is the use of asphalt emulsion and cement as a binder for aggregates recovered from building and road structures.

There is research which is carried out around the world to verify the technical properties of recycled materials and their suitability for use in industry. Recycling of building materials allows to reuse these materials in manufacturing processes in the economy. Construction and demolition waste (CDW), together with appropriate technologies, is useful as a new construction material [6]. Waste materials from landfills can be used as a component of the subgrade [7] or for the construction of road shoulders and unpaved road constructions [8]. Mineral mixtures based on aggregates recovered from the demolition of houses, including walls and foundations, are suitable for use in layers of road pavements unbound with binder [9]. Construction waste and material from the demolition of buildings [10, 11] as well as concrete slag and bricks [12, 13] can be used as a component of road embankments. Research according to [14, 15, 16] confirms the use of waste materials from demolition in unbound base layers (CDW).

The building materials industry has developed technologies and processes for integrating ashes into final products such as concrete and various building components. Waste drilling fluid (WDF) from the petroleum industry is another material which offers recycling opportunities. According to [17], both coal ash and WDF combine well with clay and can be used in mixtures for the production of building materials.

One of the relatively new recycling by-products used in building process is sand obtained during the process of rinsing demolition materials [18]. Recycled washed sand can be used, for example, to construct new filtration base layers in the road pavement constructions.

It is possible to use recycled waste materials for asphalt mixtures, such as rubber granulate [19] and plastic waste granulate [19, 20]. Large energy saving and reduction of carbon dioxide emission can be achieved by using the material from used tires, in mixtures with modified asphalt, in pavement construction [21, 22]. The use of polymer fibres from used car tires is a new phenomenon in recycling. In this case, polymer fibres from tires partially replace PVA fibres [23], which allows to reduce the costs of producing this material.

In cement composites, the addition of fibres does not significantly change the stiffness modulus and compressive strength of these materials.

Reclaimed asphalt together with the recovered cement-stabilized subgrade, according to Chinese researchers [24], can be used as an aggregate raw material to prepare cement-stabilized mixtures in cold recycling technology. These mixtures showed sufficient durability.

Tests on recycled concrete aggregate were also carried out in Hong Kong. Mixtures consisting of recycled fine aggregate and coarse recycled concrete aggregate [25] were subjected to durability tests. The results of tests confirmed the possibility of using this type of waste in building structures.

In work [26], the authors, based on several hundred designs of mixtures containing recycled concrete and natural aggregate, showed that for concrete with a compressive strength of up to 45 MPa, the type of applied aggregate was not significant.

1.2. MCE MATERIALS

One of the utilisation methods of construction waste is to use the mineral-cement-emulsion (MCE) mixtures in road pavements. The MCE mixture can be used e.g. for the sub-base layer in road pavement constructions. MCE mixtures consist only of reclaimed material or reclaimed material and mineral aggregate (improving gradation), cold mixed with cement and asphalt emulsion, in specific proportions, in optimal moisture conditions. These mixtures are characterized by continuous graining [27].

The most common method is the use of reclaimed asphalt, obtained by milling the devastated flexible pavements. The use of cement with the addition of asphalt emulsion has a positive effect on the stiffness and on the elasticity of such mixtures [28].

According to [29], single hardening conditions are positive for reducing the air void content and increasing the indirect tensile strength (ITS) in recycled mixtures with asphalt emulsion with low cement content. However, mixing and hardening can reduce the air void content and significantly increase the indirect tensile strength of recycled mixtures with high cement content.

The addition of rubber powder to MCE mixtures reduces the stiffness modulus and the force value in indirect tension tests [30], but it meets the national requirements.

The large amount of concrete waste that may soon appear from existing and damaged concrete road pavement indicates to the need of developing a technology for using reclaimed concrete (cement concrete) in cold recycling for new road pavements. Reclaimed concrete can also be used in MCE mixtures. Its content of 45% allows to obtain the optimal graining of the mineral mixture and maximum strength characteristics of this type of the mixture [31]. This type of solution will significantly reduce the number of so-called reflected cracks on the surface of the road pavement [32].

1.3. THE IMPACT OF WASTE ON DURABILITY AND STIFFNESS MODULUS

The addition of waste to mineral-cement-emulsion mixtures may affect the strength and stiffness of these conglomerates. Better values of mechanical properties (compressive strength, CBR parameter) were obtained for recycled mixtures containing aluminium waste in comparison to recycled mixtures without this waste [33].

In Denmark [34], the environmental impact of ash in road constructions was estimated. An improvement in stiffness and no decrease in strength of asphalt concrete containing electrical furnace dust was shown [35].

The authors of work [36] showed that the addition of 10% of rubber waste in combination with concrete waste didn't reduce the strength parameters of road mixtures.

In [37] it was shown that small pieces of rubber mixed with soil provide better values of elastic deformation and improve shear strength. The rheological and mechanical properties of rubber-asphalt mixtures are improved by rubber in the form of crumbs as a modifier [38].

Reclaimed asphalt pavement (RAP) can be successfully used for new mineral-asphalt mixtures. After additional use of bio-oil, RAP acquires better properties. Such recycled asphalt mixtures have good water resistance and fatigue durability, better rutting resistance at high temperatures and better low temperature cracking resistance, comparing to typical RAP mixtures [39].

Not in all cases, the use of RAP is beneficial for the road pavement construction layer properties. However, after applying an appropriate mixing process, compared to the conventional mixing procedure, it was found that the hot recycled mixture obtained better stability in water, resistance to cracking at low temperature, and fatigue durability [40]. In this method, part of the new asphalt is mixed with aggregate and the remaining part of the new binder with RAP. Then both mixtures are combined together.

Reclaimed asphalt may negatively affect the fatigue life of mineral-cement-emulsion mixtures. However, there are methods to improve the fatigue durability of mineral-cement-emulsion mixtures containing RAP, by using the so-called microcapsules. Microcapsules based on methyl ether resin allow for the so-called self-healing of mixtures during their lifetime [41]. Microcapsules allow the asphalt binder to re-bind the aggregate grains when a micro-crack appears, and ensure their proper cooperation.

Replacing limestone aggregate with reclaimed asphalt by up to 25% increased the stability of road mixtures according to [42]. The asphalt emulsion content of up to 4% of the mixture does not reduce the value of dynamic modulus [43].

It was shown that concrete mixtures made of high-quality recycled concrete aggregate had very similar strength to samples made only of natural aggregate. This applies to both rolled concrete and steel fibre reinforced concrete mixtures [44]. Moreover, in [45] it was proven that construction waste can be used as an additive to road mixtures, however, in that case the stiffness of the material can be higher.

There is a possibility of using recycled concrete aggregate (RCA) to produce new concrete mixtures [46]. The analyses concerned three basic mechanical properties (compressive strength, bending strength and modulus of elasticity) and two parameters of volume constancy (drying shrinkage and limited shrinkage cracks).

Tests of indirect tensile strength and elastic modulus have shown that the addition of recycled concrete aggregate in the amount of 40% of the mineral mixture is optimal and recommended [47].

Belgian research proves that up to 20% of coarse natural aggregates as a component of concrete mixtures can be replaced with high-quality materials from RCA [48]. This is confirmed by tests of abrasion resistance and freezing resistance.

Mechanical parameters of road mixtures, such as indirect tensile strength or dynamic modules, are influenced not only by their ingredients, including the type of waste used, but also by the order and method of mixing, mixing conditions and compaction [49, 50, 51]. Additionally, it is suggested that the cement and emulsion should be fully mixed together before contact with the aggregate [52]. The appropriate type of mineral aggregate and its size together with a recycled aggregate (construction rubble) with the addition of 3% cement have a positive effect on the mechanical parameters of road mixtures [53]. The authors of work [54] showed good stiffness of mixtures containing RAP and recycled cement concrete. In [55] a slight increase (from 9% to 14%) in the value of dynamic modules was observed.

Mixtures containing the addition of RCA and RAP have required values of indirect tensile strength and stiffness modules. The type of asphalt binder has an impact on the compaction of the mixtures and their mechanical parameters. The obtained tests results confirmed that there is a possibility to use such mixtures for the cold recycled pavement construction layers [31, 56].

Another way to improve the properties of asphalt mixtures containing RAP is to use innovative cement binders based on dusty by-products (UCPP) [56]. The hydraulic binder in the form of cement increases the stiffness of MCE mixtures. Cement binder containing UCPP allows to reduce the stiffness of MCE mixtures and to increase the durability during their lifetime.

In this study the influence of RAP and cement dust by-products (UCPP) on the stiffness of mineral-cement-emulsion (MCE) mixtures was analysed.

2. MATERIALS AND TEST METHODS

2.1. THE PURPOSE OF TESTS

The essence of the research presented in the paper is the impact of the innovative UCPP binder on the mechanical properties of MCE mixtures containing recycled material. The stiffness of MCE mixtures containing reclaimed asphalt and UCPP was analysed. The stiffness of MCE mixtures can be determined by various methods. Basic laboratory tests include the stiffness modulus in indirect tension test on cylindrical specimens (IT-CY) and the indirect tensile strength test (ITS). Stiffness is also represented in four point bending test on prismatic specimens (4PB-PR), weather resistance tests (PANK), crack propagation tests (SCB) and shrinkage tests. The aim of the current analyses was to show the relationship between different stiffness testing methods (IT-CY) and (ITS). The tests included fine and coarse-grained materials with contents of UCPP. The influence of the type of innovative binding agent on the material properties was analysed, compared to mixtures containing classic cement.

2.2. COMPOSITION DESIGN

The following materials were used to produce mineral-cement-emulsion mixtures: reclaimed asphalt, improving gradation aggregate, hydraulic binder, asphalt emulsion and water.

The compositions of mineral mixtures in accordance with the adopted assumptions, for two types of mixtures: fine-grained and coarse-grained, were presented in Table 1. The fine-grained mixture consisted of natural improving gradation aggregate 0/31.5 mm (melafir), natural aggregate with continuous grain size 0/2 mm (washed sand) and recycled aggregate (RAP) 0/10 mm. The coarse-grained mixture contained improving gradation aggregate 0/31.5 mm (melafir), natural aggregate with continuous grain size 0/2 (washed sand) and recycled aggregate (RAP) 0/31.5 mm. The grain size of the obtained fine-grained and coarse-grained mineral mixtures was shown in Fig. 1.

Table 1. Composition of mineral mixtures

Coarse mineral mixture ingredients (c)	Fine mineral mixture ingredients (f)	Quantity [%]
0/2 mm natural aggregate improving the gradation - sand	0/2mm natural aggregate improving the gradation – sand	10
0/31.5 mm reclaimed asphalt	0/10mm reclaimed asphalt	40
0/31.5 mm crushed aggregate improving the gradation – melaphyr	0/31.5mm crushed aggregate improving the gradation – melaphyr	50

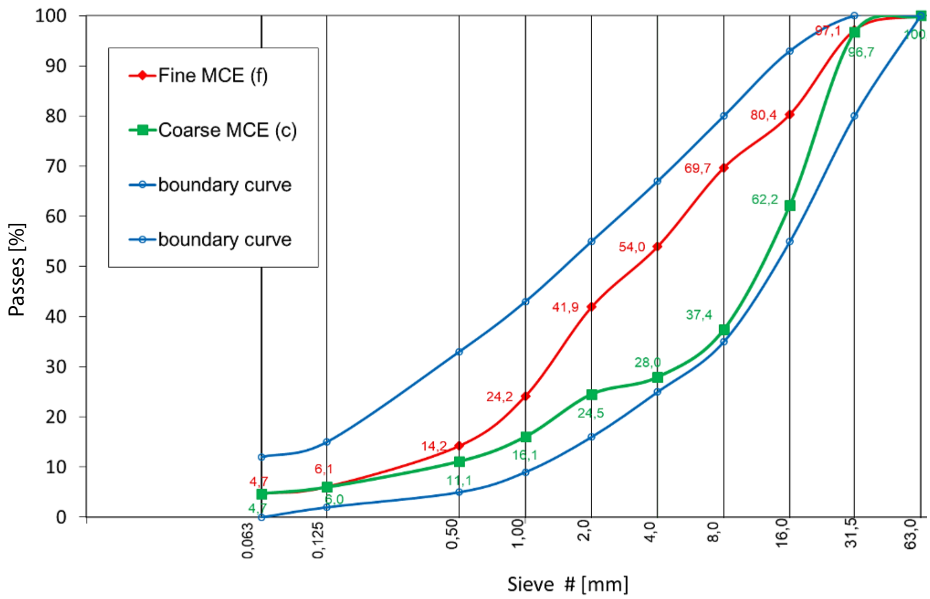

Fig. 1. Graining curves of mineral mixtures (MM)

Based on the research results presented in [57, 58, 59] and on the basis of author's experience [60, 61, 62], a 3% cement content was assumed in the design of MCE mixtures. For the tests a Portland cement CEM II 32.5 class was used.

The optimal moisture and maximum bulk density of the mixture skeleton were indicated by the Proctor method, based on the standard [63].

For a fine-grained mixture, the optimal moisture was 8.0%, and for a coarse-grained mixture, the optimal moisture was 7.8% [64, 65].

For the analysed MCE mixtures a cationic emulsion C60B10 R was used with the requirement of the standard [66]. Additionally, it is recommended to use 50/70 or 70/100 asphalt in the emulsion, according to [27].

Using authors' experience [60, 61, 62] and information in world literature [67, 68, 69], the percentage of asphalt emulsion 60/40 was set at level of 5%. The emulsion content allowed the total binder content to be 5.1% in fine-grained mixtures and 4.9% in coarse-grained mixtures (taking into account the binder in the emulsion and RAP).

The next step was to determine the composition of MCE mixtures with an innovative binding agent (binder) instead of cement. Seven binders were used with different content of three components: cement, hydrated lime and cement dusty by-products. As a result 16 different binders were made, 8 binders each for fine grain and coarse grain type mixture. Compositions and names of the designed binders were presented in Table 2.

Table 2. Compositions of designed binders

Symbol of binder	Binder components		
	Cement [-]	Lime [-]	UCPP [-]
1S	0.20	0.20	0.60
2S	0.20	0.60	0.20
3S	0.60	0.20	0.20
4S	0.20	0.40	0.40
5S	0.40	0.20	0.40
6S	0.40	0.40	0.20
7S	0.33	0.33	0.33
Ref	1	0	0

The percentages of individual ingredients for MCE mixtures containing an innovative binding agent (binder) were presented in Table 3.

Table 3. Compositions of MCE mixtures

Ingredients	Mineral mixture [%]	Coarse Mineral-Cement-Emulsion Mixture (c) [%]	Fine Mineral-Cement-Emulsion Mixture (f) [%]
0/2mm natural aggregate improving the gradation – sand	10	8.6	8.6
0/31.5mm (c) reclaimed asphalt or 0/10mm (f) reclaimed asphalt	40	34.5	34.4
0/31.5mm crushed aggregate improving the gradation – melaphyr	50	43.1	43.0
Cement or cement binder (1S, 2S, 3S, 4S, 5S, 6S, 7S)	-	3.0	3.0
Asphalt emulsion 60/40	-	5.0	5.0
Water	-	5.8	6.0

2.3. STIFFNESS MODULUS TESTS USING THE IT-CY METHOD

The stiffness modulus in indirect tension test on cylindrical specimens (IT-CY) was determined according to [70]. Four cylindrical (Marshall) samples with a nominal diameter of 101.5 mm and a height of 63.5 mm were used for analysis, for each batch and characteristic temperature. The compaction of the samples was carried out in an automatic Marshall impact compactor with 75 blows on each side of the sample. The curing period of the samples was 28 days due to the presence of cement and hydraulic binders in their composition. The Marshall samples were shown in Fig. 2.

Fig. 2. Marshall samples

The stiffness modulus was determined by recording the vertical loading force and horizontal displacement. The modulus values were calculated from the equation (1):

$$E_{IT-CY} = \frac{F \cdot (v + 0.27)}{(z \cdot h)} , \qquad (1)$$

where:
E_{IT-CY} –IT-CY stiffness modulus [MPa],
F – maximum vertical force [N],
ν – Poisson ratio [-],
z – displacement amplitude [mm],
h – height of the sample [mm].

Tests were performed in the testing machine. The loading scheme was shown in Fig. 3.

Using the results obtained for individual samples, the average values of the stiffness modulus in indirect tension test IT-CY were determined for all tested MCE mixtures. The results were grouped for coarse-grained and fine-grained mixtures. The tests were carried out for five temperature levels: -10°C, +5°C, +13°C, +25°C and +40°C.

Fig. 3. Loading scheme in IT-CY tests

2.4. INDIRECT TENSILE STRENGTH TESTS (ITS)

The indirect tensile strength test was carried out according to [71]. Three cylindrical samples (Marshall samples) with a nominal diameter of 101.5 mm and a height of 63.5 mm were used for analysis, for each batch and characteristic temperature.

The samples were compacted in the same way and in the same Marshall compactor as the IT-CY stiffness modulus samples. The curing period of the samples was also 28 days. A view of the Marshall samples was shown in Fig. 4.

Fig. 4. Samples for ITS tests

A universal testing machine was used for the tests. The value of the breaking force, which was recorded during the test, was used to determine the indirect tensile strength of dry samples. The loading scheme was shown in Fig. 5. From equation (2), the ITS tensile strength was calculated:

$$ITS = \frac{2 \cdot P}{\pi \cdot D \cdot h}, \tag{2}$$

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

Fig. 5. Scheme of ITS tests

Using the results obtained for individual samples, the average values of the indirect tensile strength were determined for all tested MCE mixtures. The results were divided into coarse-grained and fine-grained mixtures. The tests were carried out for five temperature levels, i.e.: -10°C, +5°C, +13°C, +25°C and +40°C.

3. TEST RESULTS AND DISCUSSION

3.1. IT-CY ANALYSES

Depending on the grain size, type of the binder 1S, 2S, 3S, 4S, 5S, 6S, 7S and cement (Ref), MCE mixtures may have different material properties.

Knowing the test results for individual samples, the average values of the stiffness modulus in IT-CY tests were determined. It was done for all types of MCE mixtures in the applied temperature range. The results were grouped for coarse-grained and fine-grained mixtures and were presented in Fig. 6 and Fig. 7.

Based on the test result analyses, it was found that the values of the IT-CY stiffness modulus of MCE mixtures change with the changes of the test temperature. As the test temperature increases, the stiffness of the mixtures decreases. Depending on the grain size and type of the binder (1S-7S or cement), MCE mixtures had different material specificity. The application of innovative binders resulted in a reduction in the stiffness of individual MCE mixtures comparing to reference mixtures containing only classic cement. These dependencies were observed for the entire temperature range.

For fine-grained and coarse-grained mixtures, the use of an innovative binder allowed to reduce the modulus values to 30÷95% of the reference mixture modulus, containing only cement. This range of the reduction concerned all considered binders. Fine-grained and coarse-grained mixtures containing the same type of the binder obtained similar modulus values.

In both coarse-grained and fine-grained mixtures, the greatest decrease in the stiffness was achieved after the application of 2S, 4S and 7S binders.

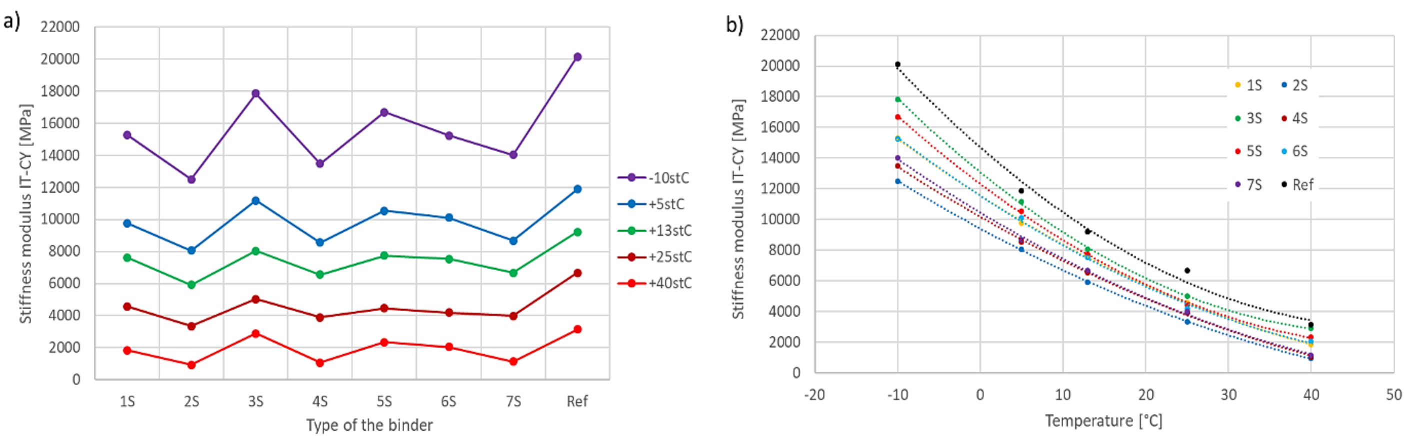

Fig. 6. IT-CY Stiffness modulus – coarse-grained MCE mixture: a) binder dependency; b) temperature dependency

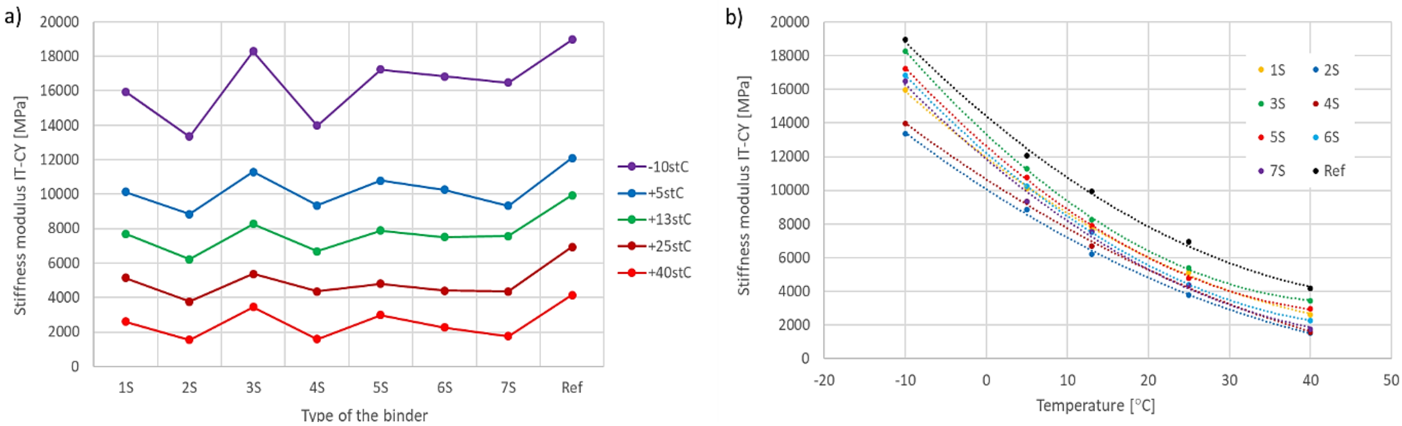

Fig. 7. IT-CY Stiffness modulus – fine-grained MCE mixture: a) binder dependency; b) temperature dependency

The use of innovative binders allowed for a reduction in the stiffness of MCE mixtures comparing to reference mixtures containing classic cement. These dependencies were shown in Fig. 8, for coarse-grained mixtures and in Fig. 9, for fine-grained mixtures.

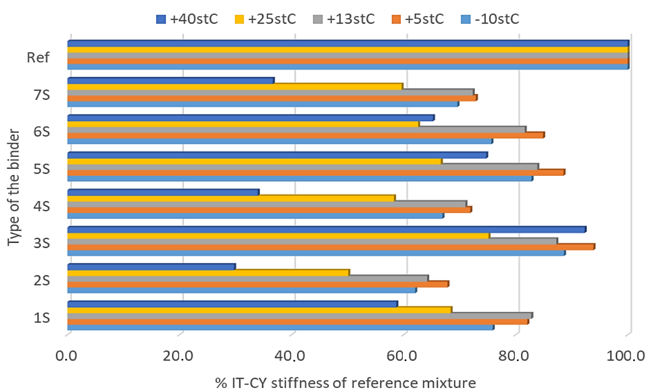

Fig. 8. Reduction of the IT-CY stiffness modulus – coarse-grained MCE mixture

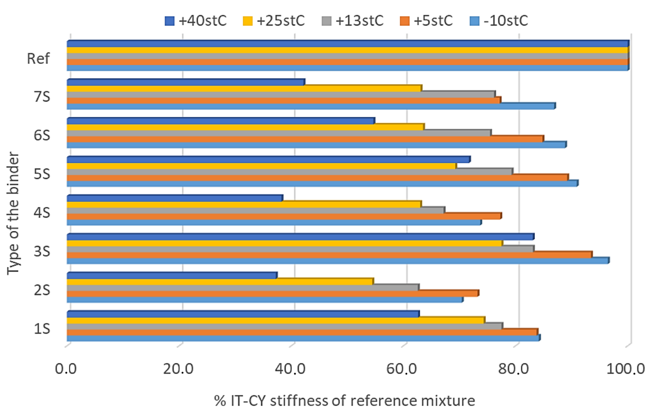

Fig. 9. Reduction of the IT-CY stiffness modulus – fine-grained MCE mixture

3.2. ITS ANALYSES

Similarly to the tests of the IT-CY stiffness modulus, depending on the grain size and type of the binder 1S, 2S, 3S, 4S, 5S, 6S, 7S or cement (Ref), MCE mixtures had different material specificity.

Based on the test results, average values of the indirect tensile strength were determined. It was done for all types of MCE mixtures in the applied temperature range. These dependencies were shown in Fig. 10, for coarse-grained mixtures and in Fig. 11, for fine-grained mixtures.

As the test temperature increased, a decrease in indirect tensile strength was observed. Moreover, the use of innovative binders allowed for a reduction in the indirect tensile strength comparing to reference mixtures containing only classic cement. The obtained values were from 5% to 40% lower than the strengths for mixtures containing only cement as a binder. These results for coarse-grained mixtures were shown in Fig. 12, and for fine-grained mixtures in Fig. 13.

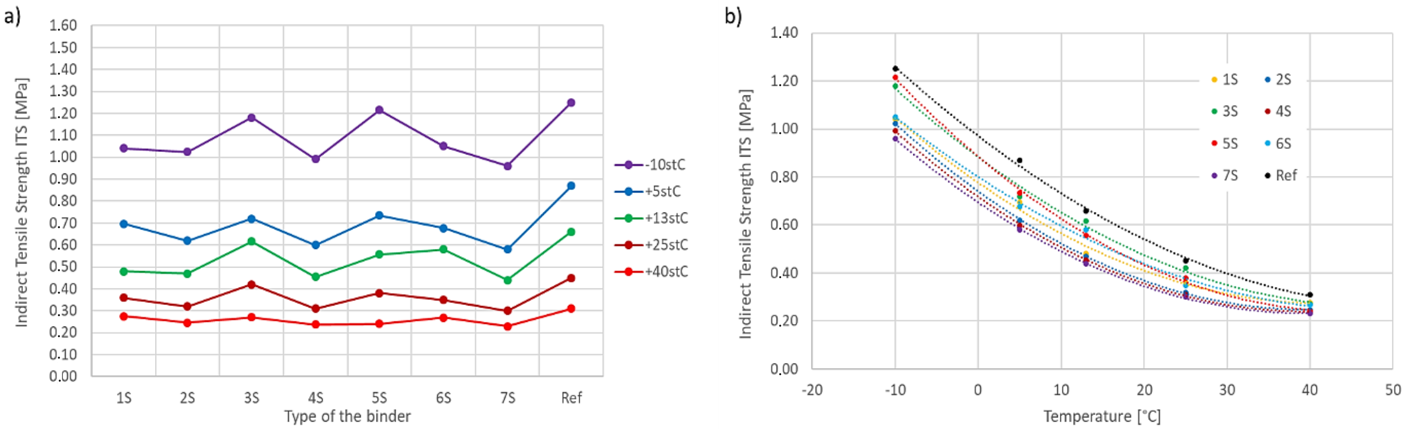

Fig. 10. Indirect tensile strength – coarse-grained MCE mixture: a) binder dependency; b) temperature dependency

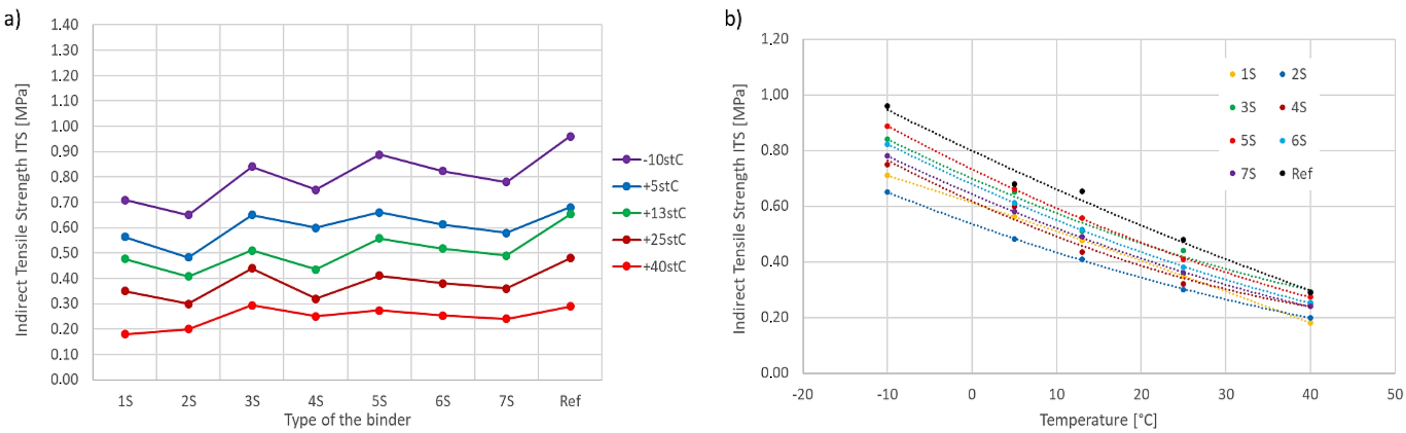

Fig. 11. Indirect tensile strength – fine-grained MCE mixture: a) binder dependency; b) temperature dependency

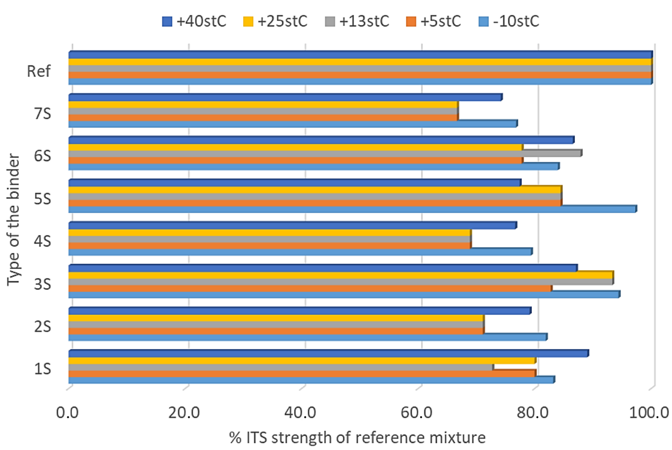

Fig. 12. Indirect tensile strength – coarse-grained MCE mixture

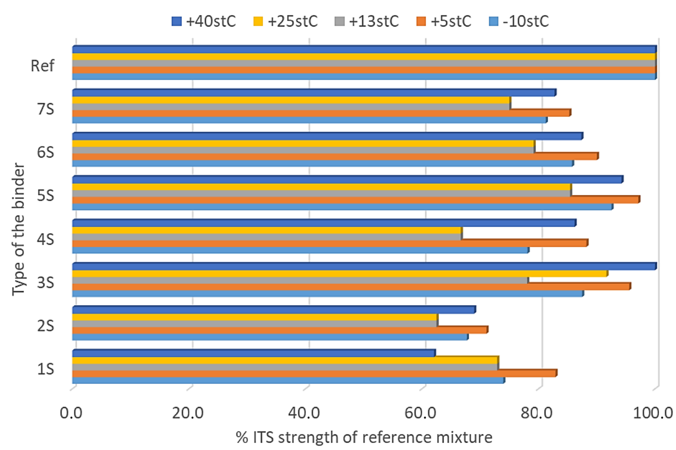

Fig. 13. Indirect tensile strength – fine-grained MCE mixture

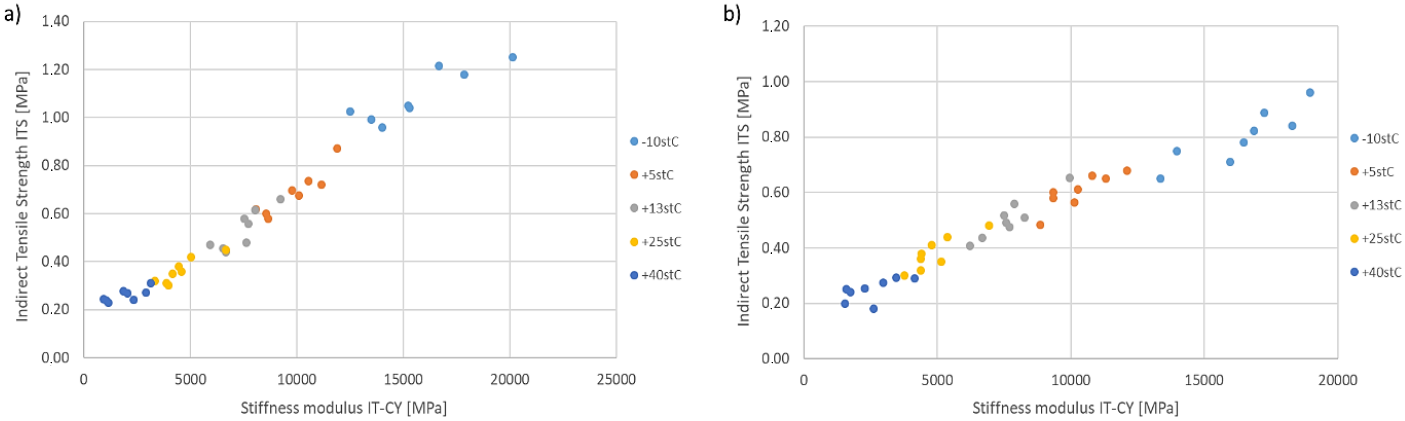

Fig. 14. Dependence of the indirect tensile strength (ITS) on the stiffness modulus (IT-CY) MCE mixture: a) coarse-grained; b) fine-grained

3.3. CORRELATION OF THE RESULTS

As a result of the tests, it was possible to determine the relationship between the stiffness IT-CY of the tested material and the indirect tensile strength ITS for various temperatures – Fig. 14.

As a result of the analyses, a systematic relationship between the stiffness of the mixtures and the indirect tensile strength was observed in a wide temperature range – Fig. 15.

For a coarse-grained mixture, the indirect tensile strength as a function of the IT-CY stiffness modulus was expressed by the formula (3):

$$ITS^c = 0.00006 \cdot E^c_{IT-CY} + 0.1115 \ , \tag{3}$$

where:

ITS^c – indirect tensile strength for a coarse-grained mixture [MPa],

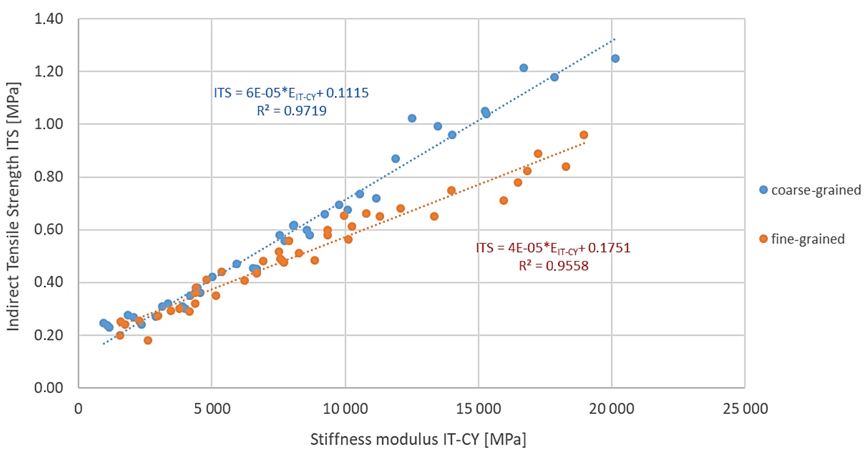

Fig. 15. Dependence of the indirect tensile strength (ITS) on the stiffness modulus (IT-CY) for coarse-grained and fine-grained MCE mixtures in the tested temperature range

E^c_{IT-CY} – stiffness modulus for a coarse-grained mixture [MPa].

For a fine-grained mixture, the indirect tensile strength as a function of the IT-CY stiffness modulus was expressed by the formula (4):

$$ITS^f = 0.00004 \cdot E^f_{IT-CY} + 0.1751 \ , \tag{4}$$

where:

ITS^f – indirect tensile strength for a fine-grained mixture [MPa],

E^f_{IT-CY} – stiffness modulus for a fine-grained mixture [MPa].

The presented relationships indicated good mutual correlations. The coefficients of determination R^2 were equal to: $R^2 = 0.9719$ for ITS_c and $R^2 = 0.9558$ for ITS_f. Such correlation gives the possibility to estimate the *ITS* strength value based on the knowledge of the IT-CY modulus value for a given type of MCE mixture grain size. The relationship between IT-CY stiffness and ITS strength will allow to optimise the process of designing and embedding MCE mixtures in road pavements. Strength characteristics of mineral-cement-emulsion mixtures may constitute important information for predicting the fatigue life of road pavement constructions at various temperatures. It was found that selected MCE mixtures based on UCPP had appropriate stiffness, which allows to use these materials in road pavement construction with traffic loads KR1-KR7.

4. CONCLUSIONS AND RECOMMENDATIONS

The implementation of UCPP waste instead of classic cement changed the mechanical properties of the MCE mixture, limiting the stiffness modulus in indirect tension test on cylindrical specimens (IT-CY). Examinations of indirect tensile strength (ITS) also showed a reduction in stiffness. The obtained results concern both coarse-grained and fine-grained mixtures. Different temperature values at which the tests were carried out did not cause any changes in the characteristics of the MCE mixtures. The correlation between ITS and IT-CY stiffness of MCE mixtures, for various mineral compositions and at various test temperatures, was very good. This property will improve designing process of MCE mixtures for the base layers of road pavement constructions. The obtained results can be used to predict the fatigue life of road pavement constructions during the operation at various temperatures. The test results indicate that the use of UCPP binder in MCE mixtures will reduce the stiffness of MCE mixtures, which will result in increasing the cracking resistance of the base layer and increasing its fatigue life. The innovative material was used in an experimental road section and now it is monitored.

ADDITIONAL INFORMATION

The paper was developed as part of the project entitled "An innovative technology using binding agent optimization that provides long service life of cold-recycled pavement construction" (TECHMATSTRATEG1/349326/9/NCBR/2017), within the joint undertaking "Modern Materials Technology" (TECHMATSTRATEG I), which is co-financed by the National Center for Research and Development.

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