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Evaluation of properties of mineral-cement-emulsion mixtures after 10 years of performance in field test sections

Abstract: In recent years, cold recycling using mineral-cement-emulsion (MCE) mixtures has become a common practice in the reconstruction of the old, deteriorated roads. The course made of MCE mixture, similarly to other materials used in pavement engineering, changes its properties with time. While the properties of such mixtures are currently quite well known, the biggest issue of their properties after many years on the pavement, when the layer is subjected to traffic and climate, remains. This article presents an evaluation of the properties of six road sections with an MCE base layer after around 10 years of service life. Sections located on Voivodship Road No. 172 differed in the amount of binding agents (cement/emulsion) used. Results of mechanical properties determined in 2023 in the laboratory on core specimens were compared with properties determined during the construction of the sections. Additionally, the results of the Falling Weight Deflectometer (FWD) test (deflection, deflection bowl, and backcalculated modulus) were analyzed considering the combinations of binding agents. Results and analysis indicated that stiffness moduli did not decrease significantly during ten years of pavement service life; simultaneously, Indirect Tensile Strength *ITS* increased up to twofold for some sections. The obtained results show that the behavior of the MCE mixtures in the field is not as unambiguous as in the laboratory and needs further research.

Keywords: cold recycling, field test, FWD test, MCE, reclaimed asphalt pavement (RAP).

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1. INTRODUCTION

Polish roads with small and medium traffic are very often in a bad technical condition. Roads in these conditions should be either renovated or reconstructed [1]. Most of the sections require structural reconstruction which is related to the deterioration of asphalt courses due to very long service life and subjection to varied climatic conditions. One of the techniques that improves the bearing capacity of the pavement is cold recycling using mineral-cement-emulsion mixtures or cold recycling using foamed bitumen [2-6]. This technology has been used in Poland since the 1990s, and from this time it has been constantly adjusted and improved. Currently, it is one of the most common techniques in reconstruction or renovation of low- and medium-volume roads [7-9].

Cold recycled mixtures can be designed using two approaches: a) designing the new pavement using a typical construction from the catalogue [10], or b) when the reconstruction or renovation is planned, designing the pavement individually. While the first case is quite easy, in the second case, one of the biggest issues is determining of long-term modulus of the MCE course. Catalogue [10] could be some help, but it does not differentiate the modulus depending on the mixture composition.

While the mechanical and rheological properties of early-aged MCE (after compaction or after 28 days) are well known and thoroughly researched in the laboratory, it is still not known how these properties change with time, and on what level are the value of properties after long-term usage in the pavement under typical traffic and climatic conditions. Presented study is one of the few cases to answer questions about what values we should use for the mechanistic design of the pavement. This issue is very important, as when we compare the values of modulus of MCE mixtures obtained in the laboratory 28 days after compaction (4000-8000 MPa) and presented in the Catalogue [10] (1500 MPa), the difference seems significant. But one should remember, that MCE mixtures, like all other materials in the pavement, degrade with time. Despite the addition of emulsion and cement, it is still a very brittle material and loses its bearing capacity due to numerous passes of vehicles and climatic cycles over the years. The Polish approach suggests using middle or end-of-life properties for such materials during design. This approach is used in Poland for cement-treated materials (II or crushed state) and cold recycled mixtures (both mineral-cement-emulsion and mixtures with foamed bitumen).

The main purpose of this article is the evaluation of the properties of MCE base layer after 10 years of exploitation in the field and an attempt to evaluate the changes which take place in their properties. This fills a research gap in the literature where access to long-term studies of test sections with an MCE mixture base is limited. It's important to emphasize that MCE mixes contain relatively small amounts of binders (up to a few percent of cement and emulsion), significantly less than in the case of recycled hot-mix asphalt. Given this, proper design of a durable pavement structure requires understanding the material's characteristics based on analysis of long-term experimental sections.

2. VOIVODSHIP ROAD NO. DW 172

2.1. GENERAL INFORMATION REGARDING RECONSTRUCTION

Voivodship road No. DW 172 is located in West-Pomerania and connects Połczyn-Zdrój and Szczecinek. The field sections are situated near Radacz in the vicinity of Szczecinek. The field sections were constructed with the help and agreement of West-Pomerania Voivodship Road Administration. The contractors were COLAS and SCHMITASPHALTECHNIK. Location of the field sections is presented in Fig. 1.

Fig. 1. Location of field sections on Voivodship Road No. DW 172

Existing pavement structure was typical for the voivodship roads constructed in the northern part of Poland and consisted of 10 cm of old deteriorated bituminous mixtures, 15-20 cm unbound base with the addition of larger rocks and clay. The bottom part of the bituminous courses contained tar. The following works were conducted:

1. Processing of old bituminous courses and construction of MCE mixture course with 15-20 cm thickness.
2. Embedding the anti-cracking composite on the surface of the MCE course.
3. Construction of 10 cm of asphalt pavement (6 cm of AC W asphalt concrete binder course and 4 cm of SMA stone mastic asphalt wearing course).

Designed construction was like new construction with a cold recycled base course for low traffic (KR1-KR2 traffic) according to the current typical catalogue [10].

Works were performed using in-situ mixing with a combination of independent devices. The process of reconstruction is presented in Fig. 2. The works consisted of the following stages:

1. Milling of the old bituminous pavement with leaving material on the road (Fig. 2a).
2. Adding water (to obtain optimum fluid content) and spreading of cement directly in front of the recycler (Fig. 2b).
3. Mixing of materials using WIRTGEN WR2000 recycler. Emulsion was added directly to the recycler (Fig. 2c).
4. Forming of the pavement slopes using a grader (Fig. 2d)
5. Compaction of the MCE course using a heavy roller (Fig. 2e).

The compacted MCE course after the described process is presented in Fig. 2f.

Fig. 2. Preparation of the field sections located on the Voivodship Road No. DW 172

The basic job mix formula of the MCE mixture was as follows: 3% of C65 B3 RC bituminous emulsion, 3% of CEM I 32.5 cement, 94% of RAP + unbound base. The recipe did not include additional aggregate to improve the grading curve, which was not a typical approach. In the following project, it was decided to use only recycled materials to decrease the depletion of mineral aggregates.

During the reconstruction process, it was found that in some locations, due to the thinner bituminous layers, part of the unbound aggregate course was also mixed into the MCE mixture. It is typical during such reconstructions, but it also leads to higher inhomogeneity of the final properties of the MCE mixture course.

2.2. DESCRIPTION OF THE FIELD SECTIONS

Field sections were constructed in two stages, first in 2012 and second in 2013. In 2012 field sections with different proportions of cement and emulsion were constructed. The following 3 sections were constructed:

- Section 1/1; 3% cement 3% emulsion – reference section, acc. to job mix formula,
- Section 1/2; 1% cement, 3% emulsion,
- Section 1/3; 1% cement, 5% emulsion.

In 2013 second stage of the field sections was constructed with a constant amount of emulsion and a varied amount of cement. The following 3 sections were constructed:

- Section 2/1; 3% cement, 3% emulsion – reference section, acc. to job mix formula,
- Section 2/2; 5% cement, 3% emulsion,
- Section 2/3; 7% cement, 3% emulsion.

Each section length was around 50 m. Location of each section is presented in Table 1.

3. LABORATORY TESTS PERFORMED DURING FIELD TEST CONSTRUCTION

Selected laboratory tests were performed during the construction stage. Due to the long distance from the construction site to the laboratory preparation of the specimens was very difficult, and a smaller quantity of them was compacted. Material for the specimens was taken directly from the field after passage of the recycler, just before final compaction. Specimens were compacted using Marshal hammers in the road laboratory in Koszalin. From each field section 9 specimens were compacted. Compacted specimens were later transported to the Road Research Laboratory of Gdańsk University of Technology, where they were cured and tested. 28 days after compaction following tests were performed:

- Stability and Flow using Marshall test, acc. to [11],
- Stiffness Modulus *ITSM* IT-CY scheme according to PN-EN 12697-26,
- Indirect Tensile Strength *ITS* acc. to PN-EN 12697-23.

Marshall test was performed at three temperatures: +20°C, +40°C for specimens conditioned in air, and +60°C for specimens conditioned in water. During this time, it was a typical test for quality control of Mineral-Cement-Emulsion mixtures. The ITSM and ITS tests were performed at two temperatures: +5°C and +20°C (conditioned in air). Results are presented in Table 2.

Additionally, from sections 1/1, 1/2, and 1/3 after 28 days cores were taken for additional tests. From each section 9 cores were drilled. Results are presented in Table 3.

At that time FWD tests were not performed.

Table 1. Description of the field sections

Construction period	Section	Location of the section at km	Length of the section [m]	Cement [%]	Bituminous emulsion [%]
September 2012	1/1*)	from 25 + 369 to 25 + 433	64	3	3
	1/2	from 25 + 433 to 25 + 482	49	1	3
	1/3	from 25 + 482 to 25 + 535	53	1	5
June 2013	2/3	from 30 + 150 to 30 + 200	50	7	3
	2/2	from 30 + 200 to 30 + 250	50	5	3
	2/1*)	from 30 + 250 to 30 + 300	50	3	3

*) test sections constructed according to the job mix formula

Table 2. Results of laboratory tests performed on specimens compacted from material from field sections

Section	*C/E**)	Stiffness modulus *IT-CY* [MPa]		Indirect tensile strength *ITS* [MPa]		Marshall stability [kN]			Marshall flow [mm]		
		+5°C	+20°C	+5°C	+20°C	+20°C	+40°C	+60°C	+20°C	+40°C	+60°C
1/1	3/3	14,480	9,832	1.043	0.826	33.8	27.5	18.4	1.3	1.8	1.7
1/2	1/3	7,030	1,374	0.557	0.286	18.1	11.5	4.7	1.8	1.5	2.3
1/3	1/5	5,343	1,830	0.602	0.395	16.9	10.0	4.6	2.4	2.6	2.3
2/3	7/3	4,818	1,850	0.680	0.243	17.8	9.0	4.7	1.7	1.5	1.5
2/2	5/3	4,874	2,493	0.687	0.281	18.7	7.9	3.1	1.9	2.1	1.3
2/1	3/3	5,724	3,354	0.733	0.314	19.5	9.8	4.8	1.6	1.5	1.1

*) *C/E* – amount of cement [%] / amount of bituminous emulsion [%]

Table 3. Results of laboratory tests performed on cores obtained from field sections

Section	*C/E**)	Stiffness modulus *IT-CY* [MPa]		Indirect tensile strength *ITS* [MPa]		Marshall stability [kN]			Marshall flow [mm]		
		+5°C	+20°C	+5°C	+20°C	+20°C	+40°C	+60°C	+20°C	+40°C	+60°C
1/1	3/3	6,605	6,098	0.431	0.515	20.0	13.4	13.8	3.8	4.1	3.8
1/2	1/3	4,785	1,607	0.524	0.335	16.1	7.4	3.3	4.8	3.6	3.7
1/3	1/5	3,667	1,391	0.747	0.372	13.1	9.5	3.3	4.0	4.2	4.0

*) *C/E* – amount of cement [%] / amount of bituminous emulsion [%]

4. LABORATORY AND FIELD TESTS PERFORMED 10 YEARS AFTER CONSTRUCTION OF THE SECTION

4.1. BACKGROUND

Repeated laboratory tests after 10 years were performed in March 2023 and consisted of research that allowed for the evaluation of the stiffness modulus of the MCE course. The scope of the research included: deflection measurement using FWD and coring of the specimen for IT-CY stiffness modulus tests and indirect tensile strength ITS test. The research was performed under the IDUB ARGENTUM project financed by Gdańsk University of Technology.

4.2. FIELD TESTS – DEFLECTION MEASUREMENT

Deflections of the pavement were measured using FWD equipment. Due to the short length of the test sections (around 50 m each), deflections were measured every 2 meters. Additionally, 4 cores were drilled from each test section (both asphaltic and MCE courses were obtained). Air temperature during the FWD test was around 5-6°C. The measured temperature of the asphalt courses was equal to 6°C. Due to the quite low temperature of the pavement, the dynamic load under the plate was increased to 65 kN. Standardized deflection for the sections 1/1, 1/2, and 1/3 are presented in Fig. 3, and for sections 2/3, 2/2, and 2/1 in Fig. 4. The calculated reliable deflection results and the condition ratios of the pavement are presented in Table 4. Ratios were taken after the DSN [12] system for traffic of KR1-2 and KR3. Measurements were normalized to a load of 50kN, and a temperature of 20°C. The following factors were included: temperature according to the equation: $f_T = 1 + 0.02 \cdot (20 - T_{asf})$, season $f_S = 1.0$, and base material $f_P = 1.1$.

Based on deflection measurements elastic moduli of the asphalt courses, MCE course, and subgrade were backcalculated using ELMOD 6 software. A three-layered model was used, in which thicknesses were determined from the cored specimen. Calculations were performed for the temperature of 6°C. Determined values are presented in Table 5.

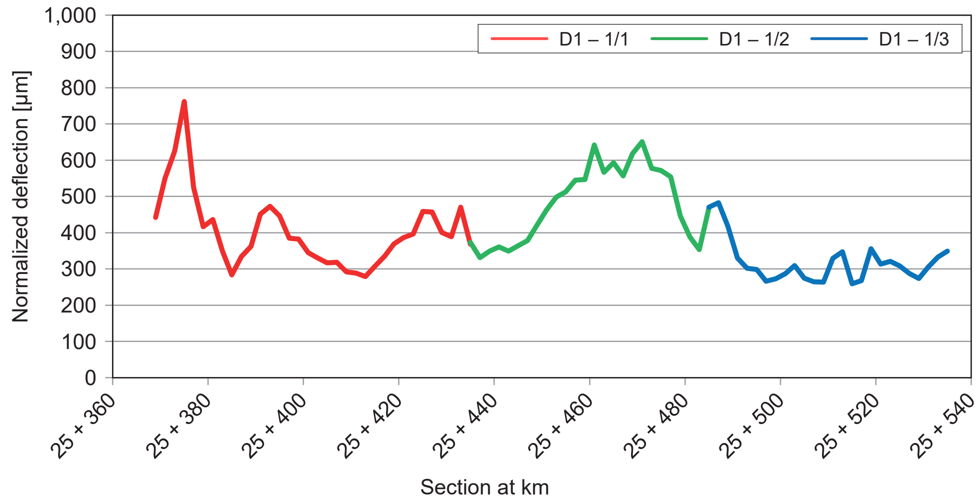

Fig. 3. Normalized deflections determined using FWD, sections from 2012

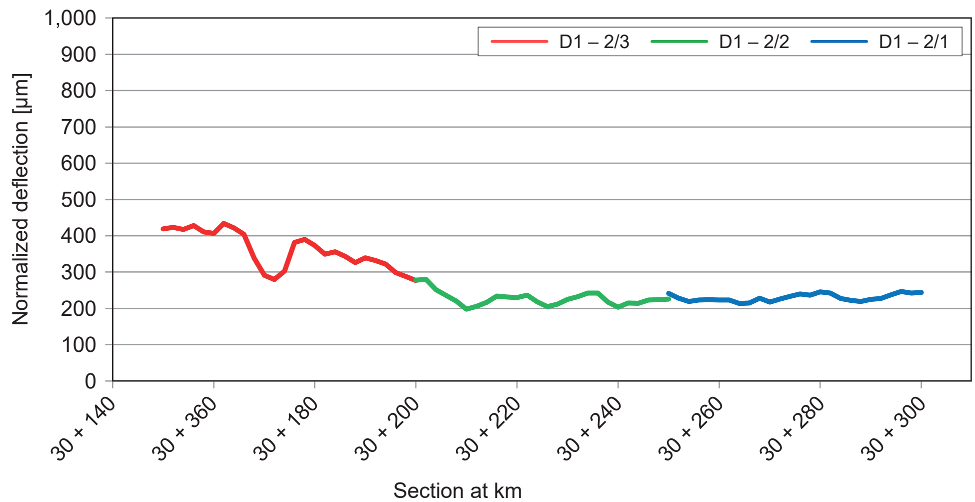

Fig. 4. Normalized deflections determined using FWD, sections from 2013

Table 4. Results of FWD measurements compared to DSN bearing capacity classes

Section	Location of the section at km	*C/E*[*)]	Reliable deflection D1 [μm]	DSN class acc. to Deflection Class		Reliable SCI_{300} [μm]	DSN class acc. to Deflection Bowl Class	
				KR1-KR2	KR3		KR1-KR2	KR3
1/1	from 25 + 369 to 25 + 433	3/3	506	A	B	212	C	D
1/2	from 25 + 433 to 25 + 482	1/3	584	B	C	212	C	D
1/3	from 25 + 482 to 25 + 535	1/5	378	A	A	101	A	B
2/3	from 30 + 150 to 30 + 200	7/3	412	A	B	136	B	C
2/2	from 30 + 200 to 30 + 250	5/3	247	A	A	74	A	B
2/1	from 30 + 250 to 30 + 300	3/3	240	A	A	61	A	A

[*)] *C/E* – amount of cement [%] / amount of bituminous emulsion [%]

Table 5. Results of backcalculations of elastic moduli of specific courses using ELMOD6

Section	Location of the section at km	*C/E**)	E1 (asphalt courses) [MPa]		E2 (MCE base) [MPa]		E_{SUB} (subgrade) [MPa]	
			mean	*P* 80%**)	mean	*P* 80%**)	mean	*P* 80%**)
1/1	from 25 + 369 to 25 + 433	3/3	3,278	1,129	7,487	6,723	196	164
1/2	from 25 + 433 to 25 + 482	1/3	5,234	1,308	4,717	4,188	155	122
1/3	from 25 + 482 to 25 + 535	1/5	14,116	4,856	5,070	3,971	175	165
2/3	from 30 + 150 to 30 + 200	7/3	14,304	7,336	4,294	3,420	207	186
2/2	from 30 + 200 to 30 + 250	5/3	19,182	14,263	4,328	3,881	243	226
2/1	from 30 + 250 to 30 + 300	3/3	15,529	10,702	8,490	7,739	250	243

*) *C/E* – amount of cement [%] / amount of bituminous emulsion [%]; **) *P* 80% – 20% percentile

4.3. LABORATORY TESTS

Laboratory tests were performed on specimens cored from the pavement. Due to a smaller number of specimens, only stiffness modulus and indirect tensile strength tests were performed. In the case of sections 1/1, 1/2 and 1/3 on which 10 years ago modulus and strength tests were performed, the location for obtaining specimens were selected as near as possible to previous ones (Fig. 5a). Test results are presented in Table 6.

Table 6. Results of laboratory tests performed on core specimens

Section	*C/E**)	Stiffness modulus *IT-CY* [MPa]		Indirect tensile strength *ITS* [MPa]
		+5°C	+13°C	+5°C
1/1	3/3	7,550	7,737	0.86
1/2	1/3	4,731	3,156	1.12
1/3	1/5	4,064	1,910	0.99
2/3	7/3	3,804	2,707	0.54
2/2	5/3	4,324	2,912	0.69
2/1	3/3	7,909	6,449	0.85

*) *C/E* – amount of cement [%] / amount of bituminous emulsion [%]

a)

b)

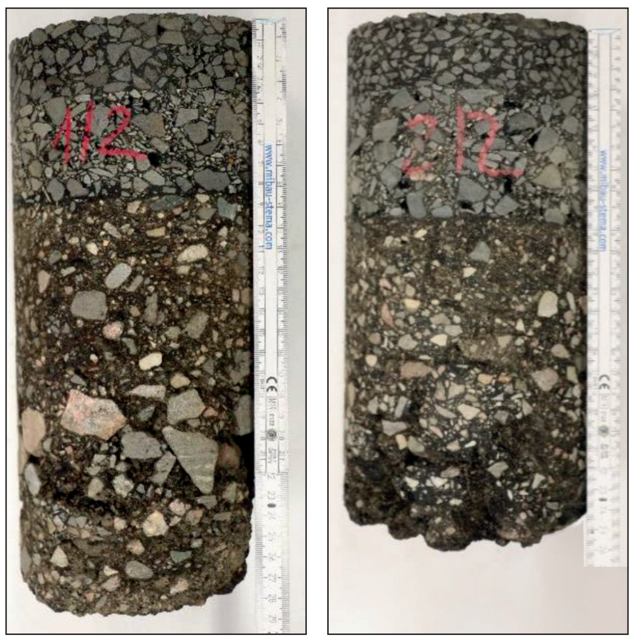

Fig. 5. Cores obtained from the field sections after 10 years of exploitation: a) exemplary location of the coring, b) examples of the field cores drilled 10 years after compaction

5. ANALYSIS

5.1. LABORATORY TEST RESULTS PERFORMED DURING THE CONSTRUCTION STAGE

Based on test results obtained from specimens tested during the construction stage following observations and conclusions can be stated:

1. Tests performed for the section constructed using the same job mix formula (reference, sections 1/1 and 2/1) one year after the construction differ from each other for all performed tests (ITSM, ITS, and Marshall).
2. Decreasing of cement amount with increasing of emulsion amount (sections 1/1, 1/2, 1/3) resulted in a decrease in stiffness and other properties of MCE mixtures. On the other hand, increasing in emulsion content (sections 1/2, 1/3) did not differ the properties.
3. Change of cement content (sections 2/1, 2/2, 2/3) did not have influence on mixture performance.
4. In the case of results obtained on cores from sections 1/1, 1/2, and 1/3 the performance was similar to specimen compacted from a loose mixture, but the difference between results was smaller.
5. Test performed on material mixed and compacted on the road proved that the difference in the amount of binding agents does not show a clear relationship. In real conditions the influence of the binding agents is much smaller than in the case of laboratory compacted specimens, and inhomogeneity of the base materials has a stronger influence.

5.2. TESTS PERFORMED 10 YEARS AFTER PAVEMENT CONSTRUCTION

Analysis of the test results obtained on specimens cored 10 years after section construction allows to formulate the following observations and conclusions:

1. The condition of the pavement can be described as satisfactory. The pavement does not show any signs of structural damage. Only local, surface course deteriorations were observed.
2. Reliable deflections showed varied performance. Five of six sections are in class A (for KR1-2 traffic) and the last one showed class B. Such results show that the renovation of the pavement was successful.
3. Comparison of stiffness moduli determined using different approaches (IT-CY tested at +5°C, FWD tested at +6°C) are presented in Fig. 6. Results for specific sections from different time periods and methods are of a similar level.
4. Results for specimens compacted in the laboratory showed higher values of stiffness in comparison to cored specimens or field-measured values.
5. Stiffness moduli values obtained right after pavement construction and 10 years after construction were on similar levels.
6. Comparison of Indirect Tensile Strength *ITS* values tested at a temperature of +5°C are presented in the Fig. 7. Results determined for the first test sections (1/1, 1/2, and 1/3) increased 2 times, while for the last three sections (2/1, 2/2, and 2/3) showed only a minimum increase.
7. Results of tests performed on specimens compacted in the laboratory after pavement constructions were similar to those obtained on cores obtained 10 years after pavement construction, and two times higher than for cores obtained in 2012.
8. Comparison of both laboratory and field test results does not show any clear relations, taking into consideration the amount of binding agents. It can be assumed that the influence of raw materials inhomogeneity (mixing of bituminous courses with unbound aggregate with clay) could have a stronger impact on mechanical properties than the amount of binding agents.

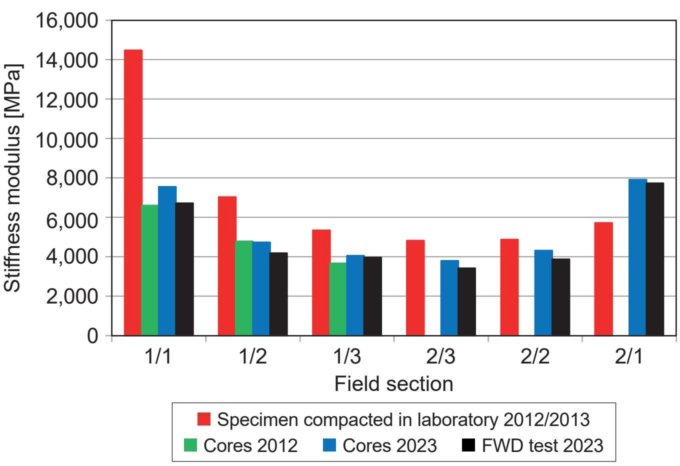

Fig. 6. Comparison of stiffness modulus from laboratory and field measurements (IT-CY tested at +5°C, FWD tested at +6°C)

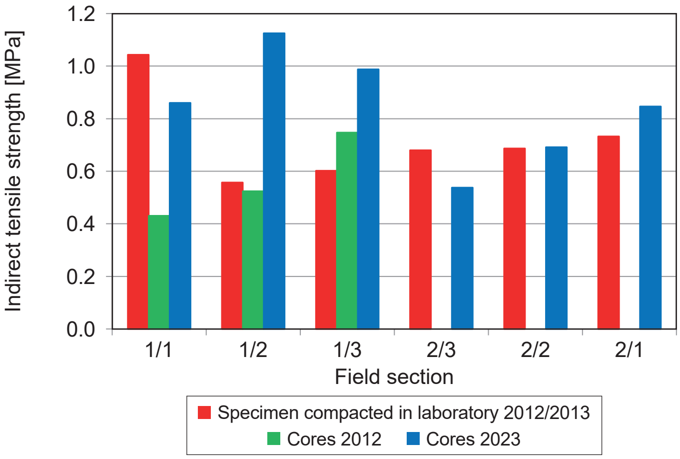

Fig. 7. Comparison of results of the Indirect Tensile Strength test *ITS* tested at +5°C

6. CONCLUSIONS

Presented test results performed on specimens obtained from different field sections proved that in real construction conditions it is almost impossible to predict mechanical and rheological properties of MCE mixture courses, especially in the case of recycling asphalt layers, including unbound sub-base. While the test sections differed in the amount of binding agents, no clear relations could be found, as it can be seen in the laboratory prepared and cured specimens. It could be related to varied factors present only in the field, which cannot be repeated in the laboratory.

Tests performed on all test sections proved a high bearing capacity of the pavement, which did not change significantly after 10 years of usage.

Performed tests showed that values obtained in the field for the middle of the life period for cold recycled materials are much higher than assumed during the design period. This observation should be confirmed on further field tests and analyses. The observations concern a single location and the reconstruction of a single pavement structure. Further research and observations are necessary using data from various structures, particularly those differing in the composition of recycled mixtures, not just in the combination of binders. A larger database of field results and observations is necessary to formulate more definitive conclusions.

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Ocena parametrów mieszanek mineralno-cementowo-emulsyjnych po 10 latach eksploatacji odcinków badawczych

Streszczenie: Technologia recyklingu głębokiego na zimno z zastosowaniem mieszanek mineralno-cementowo-emulsyjnych (MCE) jest coraz powszechniej stosowaną technologią w trakcie przebudów starych, zniszczonych dróg. Wykonana warstwa podbudowy z mieszanki MCE, tak jak pozostałe materiały drogowe, zmienia swoje parametry mechaniczne w czasie eksploatacji nawierzchni. O ile cechy materiału określone bezpośrednio po wykonaniu warstwy są dość dobrze rozpoznane to mniej znana jest zmiana parametrów mieszanek MCE w długim okresie czasu spowodowana eksploatacją nawierzchni oraz oddziaływania czynników klimatycznych. Publikacja przedstawia wyniki badań sześciu mieszanek MCE po około 10 latach eksploatacji nawierzchni. Odcinki badawcze usytuowane na drodze wojewódzkiej nr 172 różniły się zawartością poszczególnych środków wiążących. Wyniki badań cech mechanicznych wyznaczone w laboratorium w roku 2023 porównano z wynikami badań wykonanymi w trakcie budowy sekcji testowych. Dodatkowo przeanalizowano wyniki badań aparatem FWD (ugięcia, czasze ugięć oraz moduły wyznaczone z obliczeń odwrotnych) w zależności od proporcji środków wiążących. Analiza uzyskanych wyników zachowania się mieszanki MCE okazała się niejednoznaczna w stosunku do wyników uzyskiwanych w laboratorium i potwierdza konieczność dalszych badań.

Słowa kluczowe: badania terenowe, FWD, granulat asfaltowy, MCE, recykling na zimno.