Durability of base courses with mineral-cement-emulsion mixes (MCEM)

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Abstract. Base courses with mineral-cement-emulsion mixes (MCEM) have been the subject of research, surveys and development of e.g. new requirements included in the Guidelines of 2014 [15]. In this paper the results of sample test and survey of road sections, assessment of transverse cracks and load-bearing capacity with FWD after 13 years of exploitation are presented. On the MCEM samples the following tests were carried out: resilient modulus using NAT, complex stiffness modulus (E*), phase shift angle at various temperatures and loading frequencies thereby obtaining master curves, fatigue life and low-temperature resistance by identifying the tensile stress restrained (TSRST) which allowed for general assessment of constructed base courses.

1. Introduction

Re-use of materials also in roads was defined by the Americans as “recycling” [10, 11, 23, 27]. The first manual in USA entitled “Basic Asphalt Recycling” was published by Asphalt Recycling and Reclaiming Association in 2001.

In England recycling with cement or asphalt emulsion was used at first [22]. A combination of both binders was introduced to the regulations after a three-year research program was completed in 2004 [1].

In 2002, German guidelines for cold “in situ” recycling were published [21] which included the recommended thickness of structural layers with the use of the material reclaimed from the old surface. The first manual in Germany entitled “The Wirtgen Cold Recycling Manual” was published in 1998.

For instance, in the French classification of 2004 [13] class 5 of the base course was adopted, 10÷30 cm thick from deep “cold” recycling and containing the total of 3÷7% of cement and asphalt emulsion. The first manual in France entitled “Fayat Recycling Book” was published in 2007.

Also, in many European countries only asphalt emulsion is used in “cold” recycling. At the end of the 20th century the total use of cement and asphalt emulsion in recycled road bases was at the experiment stage.

The need to reinforce and repair rutted road pavements in Poland was the reason for the search of an appropriate technology which would allow for re-use of the incorporated materials [3, 24, 25].

The authors of works which preceded the development of new Polish guidelines obtained information from 91 national road sections with MCEM base on the basis of a survey carried out in
2012. In Poland the most frequent are base courses with added 3% of asphalt emulsion, 4% of cement and up to 50% of aggregate improving gradation. Numerous and varied FWD tests on asphalt pavement sections with MCEM base and quite frequent transverse cracks in certain regions of Poland were also analyzed [16].

The analysis and assessment of the MMCE base course made according to ST [8] is related to the planned design, scheduled for 2018, of redevelopment national road DK 19 on the Międzyczeł - Lubartów section upgrading the road to an expressway.

2. The survey and tests of the first road sections with bases of mineral-cement-emulsion mixtures (MCEM) in the Lublin region

Elastic deflection tests with FWD plate were carried out in 2001 on a 5-kilometer section on the national road no 19 (DK 19). The subbase of MCEM base course contains tar concrete and asphalt concrete 2÷10 cm thick on a layer of crushed stone, also with variable thickness: 21÷31 cm. The 19 cm thick MCEM base made of a mix with 0/31.5 mm gradation contained 54% of reclaimed asphalt pavement, 5% of cement and 3% of cement emulsion. The 8 cm thick binder course and the 5 cm thick wearing course were made of asphalt concrete.

The results of FWD measurements at 5°C carried out in March 2001 after autumn and winter use of the road put in operation are presented on Fig. 1.

![Figure 1. FWD deflections on road no 19 measured every 100 m at 5°C on the section from 348+200 km to 353+200 (Radzyń - Kock).](image)

The deflection basin curves obtained from measurements with FWD plate demonstrate lack of shape uniformity and the maximum deflection in the load axis was approximately two times larger in relation to the minimum deflection.

In October 2001 another FWD measurement was taken in the same places after 6-month’s use. The tests were carried out at fixed spots by measuring the temperature inside the layer, and the temperature was between 4°C and 34°C. The results were not significantly different and the October measurement showed slightly lower deflections than the ones measured in March. The MCEM base underwent the process of hardening at high temperatures in the summer in 2001 and its bearing capacity was not reduced due to HGV traffic loading. Moreover, the measured deflections of MCEM base course indicate its sensitivity to temperature changes [19].

The results of elastic deflection measurements with FWD allowed calculating, using ELMOD
program, stiffness moduli for the base course and pavement courses of the road surface. The mean elastic modulus of the subbase course was $E_0 = 119$ MPa and of the top layers package and the base course layer $E_1 = 5016$ MPa at the maximum research temperature of 34°C.

In July 2013 at 20°C another measurement with FWD plate was carried out. Mean deflection in the load axis was $U_m = 242 \, \mu m$, standard deviation was $\sigma = 63 \, \mu m$ which leads to the conclusion that the variability coefficient was $\tau = 26%$. In the research carried out in 2001 at a similar temperature the mean deflection in the axis was $U_m = 195 \, \mu m$, standard deviation was $\sigma = 44 \, \mu m$ and the variability coefficient was $\tau = 22%$. After 12 years of use the deflection increased by approximately 24%. In accordance with the requirements concerning the load-bearing capacity limit state [9], road pavement structure suffers fatigue when “the value of the equivalent elastic modulus of the pavement constitutes less than 50% of the initial value”. Therefore, fatigue of the pavement structure in 2013 was much less than the limit value.

In the spring of 2017 site visit on road no 19 was conducted and on the analyzed 5-kilometer section only two transverse crack was identified. The limit state in relation to pavement cracks [9] is defined in the following way: “not less than 20% of the pavement is covered with fatigue cracks over 2 mm wide”. It may therefore be concluded that also this limit is observed, even with a considerable reserve.

The main drawback of the pavement was poor durability of the wearing course made of asphalt concrete which needed to be renovated with SMA. The new wearing course was laid in 2017.

Analysis of a 5-kilometer section on the national road no 82 (DK 82) with the MMCE base course consisted of examining the elastic stiffness modules on samples taken from the mixture in the process of implementation.

The resilient moduli with NAT made in line with the PN-EN 12697-27 and BSJ DD 231:1993 standards in the case of samples with MCEM depend on the temperature of their testing. The results of selected tests are presented in Fig. 2.

![Figure 2](image)

**Figure 2.** Dependence of the resilient moduli in NAT on the temperature of MCEM samples with added 5.5% of cement and 3% of asphalt emulsion with 0/31.5 mm gradation from a section of road no 82 after maturing for 1 year in air-dry conditions.

On the section of road no 82 (DK 82) no transverse cracks were identified in spite of the occurrence of relatively large stiffness moduli.
3. Stiffness, fatigue life and resistance to low-temperature cracks of lab samples from MCE mixes

Tests of complex stiffness modulus (E*) and of phase shift angle were carried out in line with ASTM D 3497-97 [4] in MTS press on cylindrical samples Ø 98.8x160 mm cut out of a 300x300x180 mm plate compacted by pressing. The total of 6 MCEM samples with added 5% of cement and 3% of asphalt emulsion with 0/25 mm gradation were tested.

Relatively low values of phase shift angle at different temperatures (0°C, 20°C and 40°C) and loading frequencies (0.1÷30 Hz) are presented in Fig. 3; they lead to a conclusion that the real (elastic) component (E₁) of the complex modulus has an advantage over the imaginary (viscous) component (E₂).

\[
\begin{array}{c|c|c|c|c|c}
\text{Phase shift angle [deg.]} & \text{f [Hz]} & \text{E₁ [MPa]} & \text{E₂ [MPa]} \\
\hline
0 & 0.1 & 5000 & 1000 \\
10 & 0.5 & 4000 & 800 \\
20 & 1 & 3000 & 600 \\
30 & 2 & 2000 & 400 \\
40 & 5 & 1000 & 200 \\
50 & 10 & 500 & 100 \\
60 & 20 & 250 & 50 \\
70 & 30 & 125 & 25 \\
80 & 40 & 62.5 & 12.5 \\
90 & 50 & 31.25 & 6.25 \\
\end{array}
\]

Figure 3. The results of tests of complex stiffness modulus E* of a MCE mixture sample with added 5% of cement and 3% of asphalt emulsion and with 0/25 mm gradation; a) Black’s curve, b) isotherm.

On the basis of the Cole-Cole diagram presented in Fig. 4 it may be concluded that the samples’ elasticity changes significantly depending on temperature. At 0°C the real component (E₁) of the complex stiffness modulus (E*) is approximately ten times higher compared to the imaginary component (E₂) and at least three times higher at 40°C.
Figure 4. Cole-Cole diagram showing the relations between the viscous and the elastic components of the complex modulus of MCEM samples with added 5% of concrete and 3% of asphalt emulsion with 0/25 mm gradation.

An example of master curve at the reference temperature of T=20°C of MCE mix with 0/25 mm gradation containing 5% of cement and 3% of asphalt emulsion, presented in Fig. 5, leads to the conclusion that the volume of complex stiffness modulus (E*) depends to a large extent on the loading frequency.

Figure 5. Master curve according to Medani & Huurman equation and the polynomial of the MCE mix with added 5% of cement and 3% of asphalt emulsion and with 0/25 gradation

The master curve equation by Medani & Huurman and the shift factor by Arrhenius were applied based on the example of research carried out by D. Sybilski [28, 29].

The impact of binding agents on stiffness of mixtures made in line with the Guidelines of 2014 was analyzed in the paper [7].

Tensile stresses which cause the predefined deformations in correlation with the number of loading cycles presented in Fig. 6 refer to the example of the research carried out in 2007. A characteristic feature of all the research is sudden reduction in the value of stresses and in the complex stiffness modulus during the initial period of loading. A reason may be destruction of the weakest
cement connections with MCEM. Therefore, it is justified to apply pre-loading prior to the beginning of the relevant fatigue tests until the module achieves 50% of the initial value.

The fatigue life of mixes with asphalt emulsion and cement was analyzed in the paper [18] and according to the Polish Guidelines it was the subject of publication [20]; both works were based on lab tests only.

Fatigue life tests were carried out on cylindrical samples in axial compression at defined deformation. Results of the obtained stresses in correlation with the number of load cycles are presented in Fig. 6. The fatigue life of MCEM samples with addition 5% cement and 3% asphalt emulsion rapidly falls during the initial loading period with a fixed deflection $\varepsilon_r \geq 100 \cdot 10^{-6}$, below the permissible value of 50% of the primary resilient modulus however without destruction of the sample. With deformations below $\varepsilon_r < 100 \cdot 10^{-6}$ MCEM samples meet the slope modulus criterion i.e. no more than 50% of primary resilient modulus after 1 million load cycles.

![Figure 6. Correlation between the $\sigma$ stress which causes the determined permanent deformation $\varepsilon_6=196 \mu m/m$ (sample no 1) and $\varepsilon_6=80 \mu m/m$ (sample no 2), and the number of loading cycles on MCEM samples with 0/25 mm gradation.](image)

The low-temperature resistance tests were carried out using TSRST method with restrained deformation in line with the AASHTO TP10 - 93 standard [2]. The ends of the sample were attached to steel discs fixed in the handles of MTS press. MCEM samples with added 5% of cement and 3% of asphalt emulsion and with 0/16 mm, 0/20 mm, 0/25 mm gradation were subject to tensile stresses restraining the contraction occurring when the temperature in the climate chamber is lowered (Fig. 7 and 8). The recorded maximum stresses were achieved at approx. -30°C and their level changed depending on the gradation of MCE mixes, respectively: 0/16 mm approx. $\sigma_{\text{max}}=1.2$ MPa, 0/20 mm approx. $\sigma_{\text{max}}=0.44$ MPa, while the samples with 0/25 mm gradation got destroyed after the temperature reached -8°C and the stresses $\sigma_{\text{max}}=0.44$ MPa.
MCE mixes with finer aggregate (0/16 and 0/22) are more resistant to low-temperature cracks than the coarse aggregates. However conducted tests on MCEM samples are not sufficient enough for the unambiguous determination of the low-temperature strength of these mixtures.

Transverse cracks in MCEM base courses on road sections in South-Eastern Poland were not a major problem, if reclaimed asphalt pavement contained a relatively large amount of old asphalt and the addition of asphalt emulsion also included the participation of aggregate improving gradation in the MCEM.

The structure of concrete and other composites is known from the works of A.M. Brandt [5]. The following are identified: hardened cement paste, particles, pores and voids, cracks and fractures. Micro-cracks of less than 0.1 mm are, for instance, a feature of all the cement concretes and the cracks
morphology has been presented in many research works [5, 6, 17]. Cracks length increases after exceeding the stresses which equal 0.85 cube compressive strength [12, 26]. The cracks width at the point where matrix and coarse aggregate meet in the Interfacial Transition Zone (ITZ) has a considerable impact on the propagation of cracks in concretes.

Strength of individual phases of concrete composite according to J. Hola [14] is expressed in the formula:

\[ f_{e1} > f_{e2} > f_{e3} \]

where:
- \( f_{e1} \) - aggregate strength
- \( f_{e2} \) - ITZ strength
- \( f_{e3} \) - matrix (cement paste) strength.

The transition layer is more porous and weaker than e.g. the matrix in cement concretes.

In MCEM asphalt mortar (mastic) is present on the surface of reclaimed asphalt pavement grains and of the asphalt from emulsion, and on the surface of aggregate improving gradation – only asphalt from emulsion. If the temperature of the surroundings is low, there may be no adhesion of the matrix to the aggregate, contrary to high temperatures when asphalt is soft. Lack of adhesion may be associated with linear cracks on the grain surface which are a starting point for micro-cracks and for the propagation of wing cracks in the matrix [12]. The presence of ITZ layer in MCEM may be merely fragmentary.

4. Conclusion

When designing MCEM it was common practice in Poland to add a large amount of crushed-stone aggregate improving gradation and relatively large amount of cement, as in B2 group in accordance with [21] regulations. In exceptional cases only cement (as in group C) and only asphalt emulsion (group A) were added to the mix. MCEM bases were at that time e.g. at the initial stage in France [13].

In the first decade of the 21st century MCEM mixes in Poland were made in accordance with the provisions of General Technical Specifications D-04.10.01 of 2001 [8] which complied with the requirements provided in vol. 61 of the Scientific Journals of Roads and Bridges Research Institute (RBRI) in Warsaw of 1999. Excessive requirements concerning Marshall’s stability (8÷20 kN at the temperature of 60°C), as in Scientific Journal vol. 61 RBRI and the General Technical Specifications, were very difficult to be complied with when designing MCEM while adhering to the guidelines concerning the dosage of emulsion and cement, even more so if the material was collected from the base layer being constructed.

(1) Service durability of a pavement with MCEM base course, constructed in 2000 on a 5-kilometre long section of road no 19, was evaluated on the basis of FWD tests at the temperature of 20°C in 2001 and in 2013. An increase of the mean deflection by 24% after 12 years leads to the conclusion that the load-bearing capacity limit state will occur after 25 years of use.

(2) If the reclaimed asphalt pavement contains a large amount of asphalt and a small amount of crushed-stone aggregate, as e.g. in Eastern Poland, it may be justified to increase the amount of cement in MCEM in relation to the amounts recommended in the new Instruction [15] and earlier regulations.

(3) Slow decrease of the stiffness modulus after the initial period of loading MCEM samples with 0/25 mm gradation and repeatability of fatigue life results justify the possibility to use in pavements of roads mixes of smaller particle size than recommended in the Instruction [15].

(4) The tests of complex stiffness modulus \( E^* \), phase shift angle and the obtained Cole-Cole diagrams, presented in this paper, allow to draw a conclusion that the elastic component has prevalence over the viscous one and its scale depends on test temperature.

(5) An analysis of 5-kilometers long sections of roads no 19 and no 82 with MCEM base courses which contain 5% of cement and 3% of asphalt emulsion shows that their condition complies with the design assumptions. The occurrence of two transverse cracks in section of DK 19 would require an analysis of the causes of their uprising.
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