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The influence of binding agents on stiffness of mineral-cement-emulsion mixtures

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Abstract

This paper attempts to determine the behavior of mineral-cement-emulsion mixture (MCE) under load, whether is it similar to asphalt mixtures (viscoelastic behavior) or to cement treated materials (elastic behavior). To answer this question nine mineral-cement-emulsion mixtures with different combinations of cement and emulsion content were tested in laboratory using Simple Performance Test (SPT). For each mixture stiffness moduli and phase angles were assessed for three different temperatures (4, 20 and 40 deg. C) and 9 load frequencies. Conducted tests revealed complex behavior of mineral-cement-emulsion mixes, which is intermediate between elastic and viscoelastic. Opposite combinations of cement and emulsion content showed either more elastic or more viscoelastic behavior. This article presents stiffness moduli and phase angles determined for all 9 mixtures and analysis of this results. The increase of cement content leaded to more elastic behavior (higher values of stiffness moduli and lower values of phase angles) and increase of emulsion content leaded to more viscoelastic behavior (lower values of stiffness moduli and higher values of phase angles). Nonetheless mineral-cement-emulsions mixtures showed more viscoelastic behavior, as their properties change significantly with the change of temperature, but their behavior is not as viscous as in asphalt concrete, as their maximum phase angle is much lower than typical for asphalt concrete.

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Keywords: viscoelastic materials, mineral-cement-emulsion mixtures, stiffness modulus, phase angle.

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1. Introduction

Deep cold in-place recycling is one of the most commonly used type of recycling of existing old flexible pavements. Different types of binding agents and their combinations are used for cold in-place recycling. In Poland the two most commonly used technologies are mineral-cement-emulsion mixtures (MCE) and mixtures with combination of foamed bitumen and cement. This two type of mixtures are described with details by Dołżycki [1], Kukiełka [2] and Iwański et al. [3].

The two main binding agents used in mineral-cement-emulsion mixtures are cement and emulsion. The reclaimed asphalt pavement used in MCE mixtures, which usually originates from old, low quality and highly deteriorated roads, has low durability. On the other hand, the requirements stated for the mixture, especially in the case of strength are very high. All this results in high amount of binding agents added to the mixture, especially cement. This approach is used in Poland [4] and neighboring countries, like Germany [5].

The properties of MCE mixture strongly depend on the proportions and interactions between the two used binding agents (Theyse et al. [6], Bocci et al. [7]). The addition of emulsion influences the increase of viscous behavior (the pavement acts more as a flexible pavement), the increase of internal integrity, decreases the risk of shrinkage cracking, increases the resistance to water and frost action and increases the fatigue life of the pavement. The excessive amount of emulsion results in decreasing the stiffness modulus of MCE mixture. The addition of cement influences the increase of stiffness modulus, tension strength and the resistance to water and frost action. Additionally it allows to achieve quite high beginning strength of MCE mixture, what is desirable for optimum usage of reconstructed pavement for the purpose of technological traffic. It also fastens the dissolution of asphaltic emulsion. On the other hand, the addition of cement increases the shrinkage of embedded mixture, what can result in shrinkage cracks of MCE layer and in the consequences in reflective cracking of asphalt layers of pavement. This problem was described by Chomicz-Kowalska et al [8], Uzarowski et al [9].

The properties of the MCE mixture are resultant of the combination of two binding agents, which are responsible for two different types of chemical bonds. Asphaltic emulsion generates asphaltic bonds, which are responsible for flexible behavior of the embedded layer. Cement generates hydraulic bonds, which are responsible for the stiffness of the layer. The behavior of the MCE layer is decided by the dominating type of bond. Asphaltic bonds should be dominating in designed MCE mixtures, as they are responsible for decreasing the risk of shrinkage cracking. On the other hand, hydraulic bonds, which are responsible for the resistance to the weather conditions, shouldn't be completely omitted.

The main aim of this study was to evaluate the influence of particular binding agents on the stiffness modulus of the MCE mixtures and the formulation of the limit of hydraulic bonds.

2. Materials

The stiffness of MCE mixtures depends on gradation of mineral mixture, the amount and type of bitumen in reclaimed asphalt pavement and on the combination of the used binding agents. To assess the influence of used binding agents the MCE mixture was designed according to Polish recommendation [4]. Single grading curve was designed on the basis of reclaimed asphalt pavement, continuously graded 0/31,5 mixture and 0/2 fine aggregate. The proportions of used aggregates are presented in Table 1 and the grading curve is presented on Figure 1. Designations of MCE mixtures were chosen as follows: "C" indicates the amount of cement and "E" indicates the amount of asphaltic emulsion. For example MCE mixture with 2% of cement and 4% of asphaltic emulsion is designated as C2E4. The tests were conducted for 9 combinations of binding agents: 2%, 4% and 6% of each binding agent. Used combinations and mixtures designation are presented in Table 2.

Table 1. The composition of used MCE mixtures.

	Mineral mixture		
	C2	C4	C6

Cement, [%]	2	4	6
Fine aggregate 0/2, [%]	10	8	6
Continuously graded aggregate 0/31,5, [%]	18	18	18
Reclaimed asphalt pavement, [%]	70	70	70

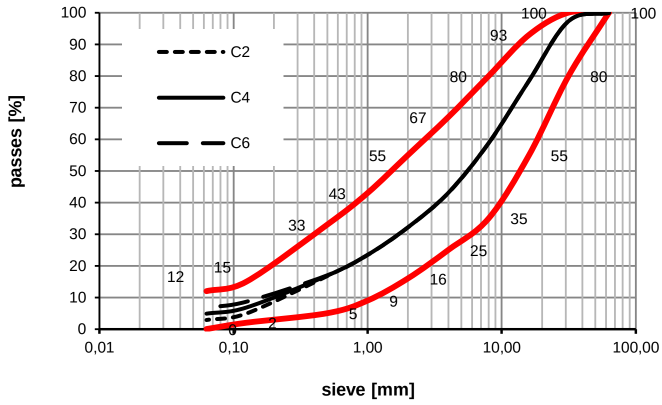

Fig. 1. Grading curve of used mineral mixtures.

C60B5R asphaltic emulsion was used in conducted research. This type of emulsion is dedicated for cold in-place recycling in Poland. As for cement, a typical CEM I 32,5R cement was used.

Table 2. Designations of mineral-cement-emulsion mixtures used in study and the combination of binding agents.

	Mineral-cement-emulsion mixture (MCE)								
Mixture designation MCE	C2E2	C2E4	C2E6	C4E2	C4E4	C4E6	C6E2	C6E4	C6E6
Cement content, [%]	2	2	2	4	4	4	6	6	6
Emulsion content, [%]	2	4	6	2	4	6	2	4	6

MCE mixture were prepared in laboratory mixer according to PN-EN 12697-35 standard. The specimens were compacted in gyratory compactor according to PN-EN 12697-31 standard. The limiting compaction ratio was set as 99%. The specimens were compacted to the following dimensions: 170 mm height and 100 mm diameter. After 14 days lower and upper surfaces were cut out to reach the specimen height of 150 mm. The stiffness modulus tests were conducted 28 days after compaction. According to AASHTO TP79 procedure, the specimens should be cut out of the specimen of 150 diameter, but it was impossible due to very low beginning strength of the mixtures and the high amount of coarse aggregates.

3. Laboratory test

Stiffness Moduli and phase angles were assessed in Simple Performance Tester according to AASHTO TP79 (2013) standard. Specimens were subjected to dynamic haversine compressive load in three test temperatures: 4°C, 20°C and 40°C. For every mixture and every test temperature 3 different specimen were tested in the controlled strain mode (100µstrain). Strain was measured with 3 LVDT sensors (gauge length of 70±1 mm) attached to the specimen. Stiffness moduli and phase angles were measured in 9 frequencies from 25 Hz to 0,1 Hz in temperatures of 4°C and 20°C. In the temperature of 40°C apart from 9 basic frequencies, stiffness moduli and phase angles were measured in additional frequency of 0,01 Hz. The view of the specimen during the test is presented on Figure 2.

4. Test results

Test results for selected frequencies acquired from SPT are presented in Table 3. Frequencies of 10, 1, 0,1 and 0,01 Hz were chosen as the most representative for presentation of the full behavior of the mixtures. Additionally the comparison of stiffness moduli and phase angles obtained for the frequency of 10 Hz and critical for the characteristics of MCE temperatures (+20°C for stiffness modulus and +40 for the phase angles) are presented respectively on Figures 3 and 4. Selected frequency is commonly used for modelling of typical traffic conditions (vehicle speed of 60 km/h).

Fig. 2. The specimen inside the simple performance tester.

Table 3. Stiffness moduli and phase angles for tested mineral-cement-emulsion mixtures.

Mixture designation	Temp. [°C]	Stiffness modulus [MPa]				Phase angle [°]			
		Frequency [Hz]				Frequency [Hz]			
		10	1	0,1	0,01	10	1	0,1	0,01
C2E2	4	5 301	4 374	3 470	-	7,27	9,02	11,13	-
	20	2 969	2 112	1 431	-	13,10	15,81	17,80	-
	40	1 258	721	441	306	20,93	21,12	19,30	15,92
C2E4	4	5 456	4 410	3 344	-	8,51	10,58	13,21	-
	20	2 662	1 758	1 089	-	15,81	18,85	21,05	-
	40	1 006	524	293	193	23,63	23,52	20,92	16,69
C2E6	4	6 139	4 727	3 392	-	9,64	12,17	15,27	-
	20	2 711	1 655	936	-	18,72	22,34	24,52	-
	40	785	374	193	138	27,28	27,18	23,72	18,68
C4E2	4	7 451	6 383	5 261	-	5,88	7,40	9,34	-
	20	4 880	3 669	2 651	-	10,38	12,64	14,22	-
	40	2 257	1 436	954	711	17,36	17,19	14,92	11,28
C4E4	4	6 993	5 740	4 513	-	7,54	9,39	11,80	-
	20	4 224	2 946	1 940	-	13,40	16,26	18,20	-
	40	1 580	918	581	423	20,57	19,70	16,71	12,14
C4E6	4	7 044	5 605	4 253	-	8,36	10,37	12,83	-
	20	3 404	2 241	1 405	-	15,43	18,50	20,51	-

	40	1 374	755	441	304	22,15	21,77	18,67	13,41
	4	9 209	8 192	6 975	-	5,05	6,32	8,01	-
C6E2	20	6 872	5 285	3 883	-	9,42	11,49	13,05	-
	40	2 828	1 942	1 419	850	14,30	13,40	11,17	8,86
	4	8 373	6 983	5 583	-	6,51	8,10	10,13	-
C6E4	20	4 997	3 604	2 485	-	11,95	14,34	15,85	-
	40	2 255	1 427	963	721	17,99	17,20	14,61	10,93
	4	7 582	6 206	4 860	-	7,39	9,18	11,38	-
C6E6	20	4 613	3 221	2 127	-	13,24	15,91	17,72	-
	40	1 722	1 023	651	476	20,17	19,41	16,36	11,68

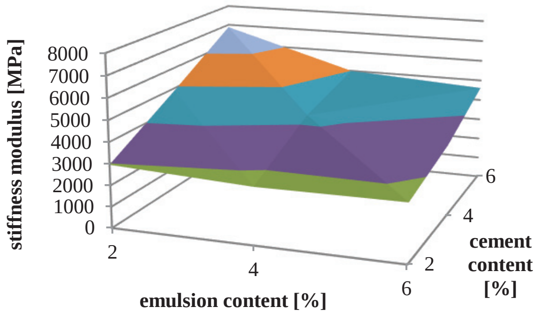

Fig. 3. Stiffness moduli of mineral-cement-emulsion mixes obtained for the temperature of 20°C and frequency of 10 Hz.

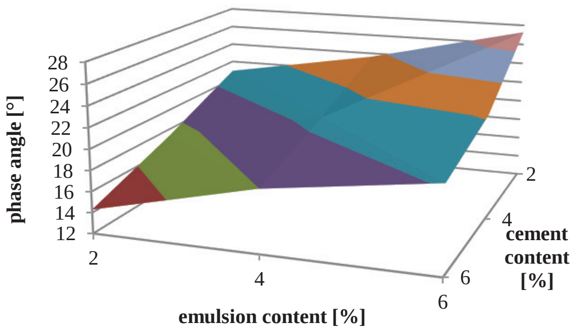

Fig. 4. Phase angle of mineral-cement-emulsion mixes obtained for the temperature of 40°C and frequency of 10 Hz.

Master Curves of stiffness modulus were developed using modified procedure presented in NCHRP 9-29 PP 02 [10] research report. The used equation (1) assumed that shift factor was calculated using Arrhenius equation.

$$\log|E^*| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log f + \frac{\Delta E_a}{19.14714}\left[\frac{1}{T} - \frac{1}{T_R}\right]\right\}}} \tag{1}$$

where: |E*| – stiffness modulus, psi; Max – limiting maximum modulus, psi; f – frequency, Hz; TR – reference temperature, K; T – test temperature, K; δ, β, γ – fitting parameters; ΔEa – activation energy (treated as fitting parameter).

Master Curves developed for tested mixtures were grouped into 6 groups depending on the combination of the binding agents. Figures 5a, 5b and 5c presents master curves for constant content of cement (respectively 2, 4 and 6%), while figures 5d, 5e and 5f presents master curves for constant content of asphaltic emulsion (respectively 2, 4 and 6%)

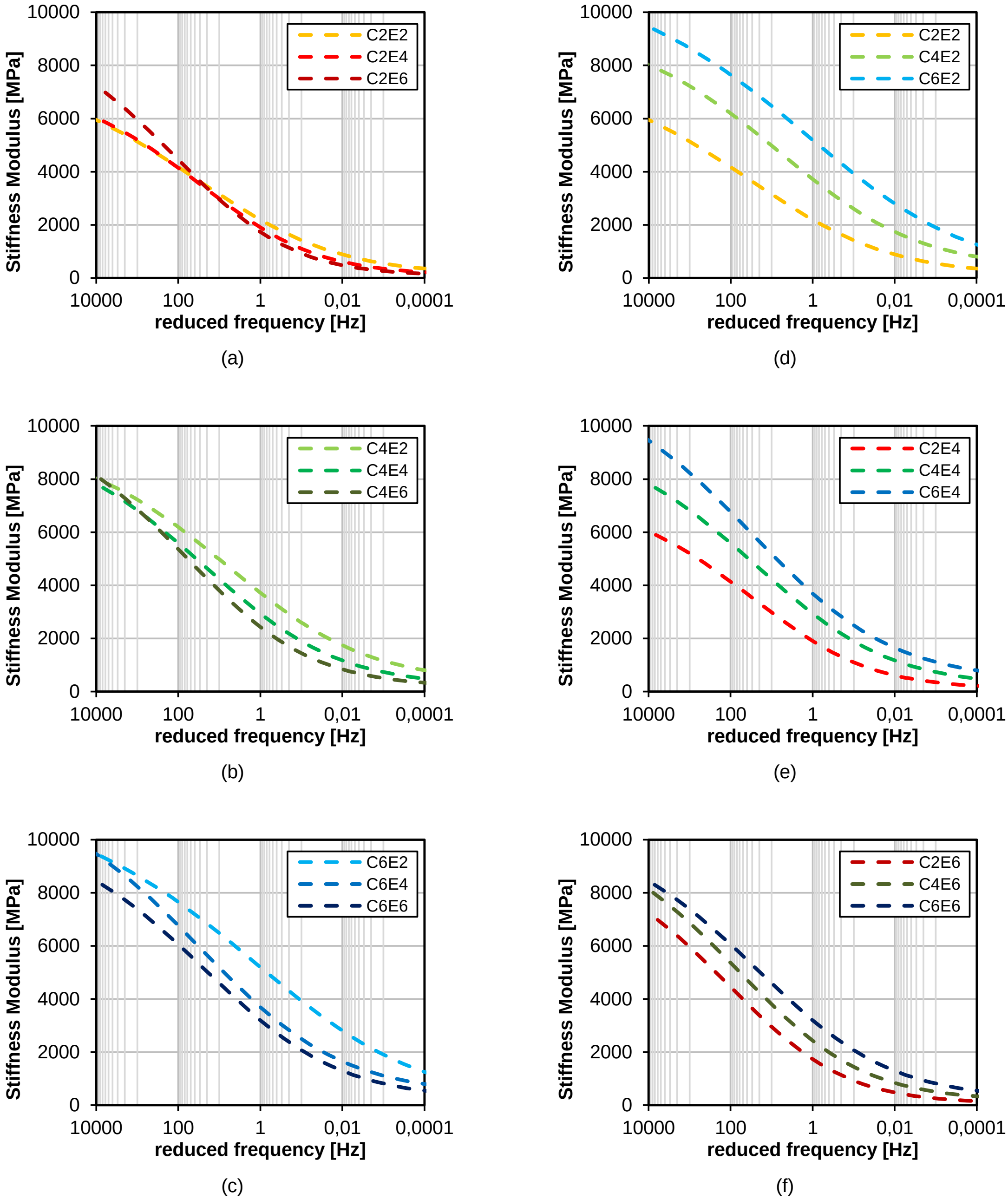

Fig. 5. Stiffness modulus master curves for mineral-cement-emulsion mixtures for constant content of: cement - a) 2% , b) 4% , c) 6% ; emulsion - d) 2% , e) 4% , f) 6%.

5. Discussion of obtained test results

Conducted laboratory test showed complex behavior of MCE mixtures. The influence of binding agents is significant and difficult for unequivocal assessment. Detailed analysis showed:

1. The properties of MCE mixtures, both stiffness modulus and phase angles for all tested combination strongly depended on the temperature and frequency (time) of loading. The observed difference between the highest and the lowest determined values was respectively in the range from 5500 to 9000 MPa in case of stiffness modulus, and from 9 to 18 in case of phase angle. This kind of behavior is characteristic for visco-elastic materials (like asphalt mixtures).
2. As was expected, the highest values of stiffness modulus were obtained for the combination C6E2, whereas the lowest values were obtained for the combination C2E6.
3. The influence of binding agents is more visible in higher temperatures, what is connected with asphaltic emulsion – the viscous ingredient of the mix.
4. In lower temperatures the behavior of the mixture is closer to hydraulically bound materials. Stiffness modulus obtained in the temperature of 4°C for the frequency of 10 Hz is from 30 to 70% higher than obtained for the frequency of 0,1Hz, whereas the stiffness modulus obtained in the temperature 40°C for the frequency of 10 Hz is from 100 to 300% higher than obtained for the frequency of 0,1 Hz. Hydraulic bonds determine the behavior of MCE mixtures stronger in lower temperatures and asphaltic bonds determine the behavior of MCE mixtures stronger in higher temperatures.
5. With the increase of the content of emulsion, the impact of amount of cement on stiffness modulus decreases. The biggest changes in stiffness modulus are visible when the amount of emulsion is equal to 2% - additional 2% of cement gives about 1500 MPa to the average stiffness modulus. This amount decreases with the amount of emulsion and is equal respectively to 1000 and 500 MPa, for 4 and 6% of emulsion.
6. The increase of the amount of emulsion, with the constant amount of cement is more complex. There are no significant differences in average modulus when the content of cement is equal to 2% - the biggest change is visible in the lowest temperature, when the influence of emulsion diminishes. Different behavior is visible for higher amount of cement (4% and higher) – the bigger change in stiffness modulus is visible when the amount of emulsion increases from 2% to 4%. With additional amount of emulsion, the change in stiffness modulus is smaller.
7. More detailed laboratory tests are necessary to properly assess the maximum modulus of MCE mixtures. As can be seen in figure 5b, for the highest reduced frequency the values of stiffness modulus of all mixtures (C4E2, C4E4, C4E6) is the same. This behavior is not that homogeneous for the amounts of cement equal to 2 and 6%. Two out of three mixtures gives similar stiffness modulus.
8. Conducted research didn’t allow to determine the straight limit of purely elastic behavior of MCE mixtures.

6. Conclusions

Conducted tests showed that behavior of MCE mixtures is very complex. Different types of chemical and physical bonds created by different binding agents do not show unequivocal influence. The clear border between domination of specific type of bound wasn’t visible, as the properties of MCE mixtures made for all combinations of binding agents depended strongly on the temperature and frequency. The stiffness of mixtures increased with the increase of the amount of cement and decreased with the increase of the amount of the asphaltic emulsion. Amidst tested binding agents cement had stronger influence on the properties of the MCE mixtures.

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