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Research paper

Warm Mix Asphalt (WMA) evaluated using different stiffness modulus measuring methods

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Abstract: This study evaluates and compares the results of two distinct stiffness measurement methods – Direct Cyclic Compression test (DCC) and Indirect Tensile test (IT-CY) – applied to warm mix asphalts (WMA) reinforced with basalt fibres intended for the construction of durable and high performance pavements, specifically surface and road base layers. The asphalt mixtures analyzed comprised surface course asphalt concrete and high modulus asphalt concrete. The production process employed reduced temperatures during both manufacturing and paving, facilitated by the use of a bio-derived fluxing additive and the foaming of the bituminous binder. These mixtures incorporated polymer modified bituminous binders and dispersed fibre reinforcement. Their performance was compared against that of traditional hot

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mix asphalt (HMA) mixtures. The findings revealed that the direct compression modulus provided a more effective differentiation of mixtures based on the impact of fibre reinforcement. Conversely, the indirect tensile stiffness test highlighted greater variability due to differences in production techniques (HMA vs. WMA) and compaction temperatures. These differences were attributed to variations in the volumetric properties of the samples, influenced by the compaction process. Regarding performance, fibre reinforcement enhanced the complex stiffness modulus across all mixtures. However, the adoption of the WMA technique significantly reduced this parameter. Laboratory test results were further compared with data obtained from samples collected from an experimental road section.

Keywords: bio-derived fluxing agent, fibre, foamed bitumen, stiffness

1. Introduction

This study compares the results of two different stiffness measurement methods (Direct Cyclic Compression test and Indirect Tensile test) of warm mix asphalts (WMA) designed to construct durable and high performance pavements, specifically surface, binding, and road base layers. The investigated production technique involves the application of reduced temperatures during production and paving, which is made possible by utilising a bio-derived fluxing additive and foaming of the bituminous binder. The enhanced performance of the mixtures was achieved through the incorporation of polymer modified bitumens and the addition of dispersed fibre reinforcement.

The reduction of processing temperatures in asphalt mixtures can be achieved by using foamed bituminous binder. This can be accomplished by foaming the bitumen using zeolites or similar materials that can encapsulate water and release it in a controlled manner [1–4] or by directly injecting water into the bituminous binder, a process commonly referred to as "mechanical foaming" [5, 6]. The injection of water for bituminous binder foaming has successfully produced warm asphalt mixtures [7–10]. Based on previous studies, no effect of water foaming on the functional properties and ageing characteristics of bituminous binders was found. The foaming process affects the viscoelastic properties of bituminous binders, the effect decreases after short-term ageing [11, 12].

Fluxing agents are employed in the production of warm mix asphalt (WMA) mixtures. The effectiveness of using a bio-derived fluxing additive (Bio-Flux) to reduce the processing temperatures of asphalt mixtures containing polymer modified bitumen was demonstrated in [13]. This additive lowers the viscosity of the bituminous binder blend, allowing for a reduction in processing temperatures during production. Over time, it increases stiffness and enhances the performance of the asphalt mixture [14]. Other notable fluxing additives derived from plants [15], as well as waste cooking oils [16–18], and tall oils [19], have also been investigated for their applications in asphalt mixtures.

Regardless of the production technique, warm mix asphalts (WMA) exhibit distinct mechanical properties compared to their hot mix asphalt (HMA) counterparts. Field studies [10] have indicated that WMA mixtures generally demonstrate a lower dynamic stiffness modulus, while the ageing of bituminous binders in these mixtures is less pronounced, partly due to the reduced processing temperatures [20, 21]. However, over time, the magnitude of these effects diminishes, and distresses in WMA test sections during medium-term service are rarely observed. These findings have been further corroborated by laboratory investigations [22–24] and additional field studies [25, 26].

The effectiveness of fibre reinforcement in enhancing the performance of asphalt mixtures has been demonstrated in numerous studies. Basalt fibre reinforcement, for instance, has been shown to increase the stiffness of asphalt mixtures at high service temperatures without adversely affecting their performance at low temperatures, thereby improving the material's fatigue life [27, 28]. Consequently, the use of basalt fibres positively impacts the service life of asphalt pavements and reduces the need for rehabilitation [29]. Similar benefits have been observed whit the incorporation of aramid fibres [30], carbon fibres, and glass fibres [31, 32] into asphalt mixtures. In the case of warm mix asphalt, fibre reinforcement further enhances stress-strain characteristics, as evidenced by improvements in resilient modulus [33], resistance to permanent deformations [33, 34], and fatigue life [33–35]. The literature suggests that fibre addition generally strengthens the composite however, it may also increase its anisotropy, potentially leading to a reduction in strength [36, 37].

2. Materials and methods

2.1. Experimental plan

This study examined two types of asphalt concrete mixtures: surface course asphalt concrete (AC-S) and high modulus asphalt concrete (HMAC). These mixtures were produced using both the conventional hot mix asphalt (HMA) technique and the warm mix asphalt (WMA) technique, which involved the use of foamed bitumen and a fluxing additive. The mixtures were compacted at standard temperatures (AC-S 145°C, HMAC 130°C) and at temperatures reduced by 15°C and 30°C. Additionally, basalt fibres were added to the mixtures covered by the tests.

2.2. Composition of asphalt mixtures

The composition of the investigated mixtures is presented in Table 1. The surface course asphalt mixtures were produced using crushed limestone and gabbro aggregates, whereas the base course mixtures utilised only crushed limestone. Limestone filler was used in all mixtures. The grading of mixtures is provided in Fig. 1, with the grading limits provided in domestic requirements [38].

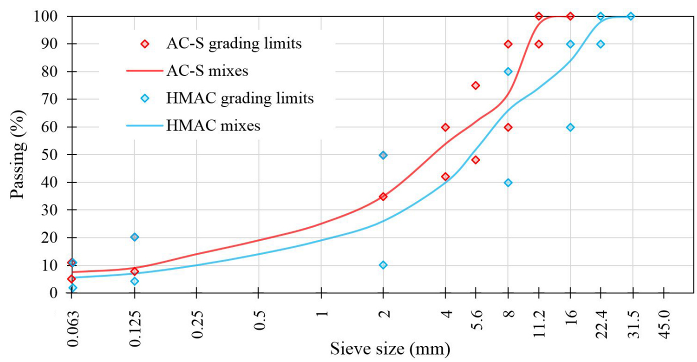

Fig. 1. Grading of the asphalt mixtures

The bituminous binder content was 5.4% and 5.0% (m/m) in the AC-S and HMAC mixtures, respectively. An adhesion promoter was added to the bitumen before mixing at a content of 0.3% by binder mass. The reinforcement in the mixtures was provided by the addition of cut basalt fibres, which differed in length depending on the mixture's maximum aggregate size: 12 mm in surface course mixes (11 mm max. aggregate size) and 24 mm in HMAC mixes (22 mm max. aggregate size). The fibres added were approx. – 0.03 mm in diameter. The content and length of the fibres were optimised during preliminary studies in hot mixtures, as were the compositions of the mixtures (grading, bituminous binder content). Basalt fibers were added to the asphalt mixture at the hot aggregate mixing stage, before the binder was injected.

Table 1. Composition of the asphalt mixtures

Component	**AC-S Ref mixes**	**AC-S Fib mixes**	**HMAC Ref mixes**	**HMAC Fib mixes**
Nominal max. aggregate size (mm)	11	11	22	22
Dusts (% m/m)	7.5	7.5	5.5	5.5
Fine aggregates (0.063–2 mm)	28.0	18.0	20.8	20.8
Coarse aggregates (% m/m)	64.5	76.3	73.7	73.7
Bituminous binder content (%, m/m)	5.4	5.4	5.0	5.0
Adhesion promoter (% m/m per bituminous binder)	0.3%	0.3%	0.3%	0.3%
Basalt fibres	–	0.3% (12 mm)	–	0.2% (24 mm)

The hot mix asphalt (HMA) mixtures involved the conventional addition of a bituminous binder to the mineral mixture. In contrast, the warm mix asphalts (WMAs) included foamed bituminous binders, which were produced and added using a laboratory-scale foaming device, as described in [39]. The foaming water content was 2%. The investigated mixtures underwent to short-term oven ageing (STOA) at a temperature of 135°C for 2 hours, with mixing performed after 1 and 2 hours, as detailed in [38]. The mixing and compaction temperatures for the HMAs were determined based on the guidelines provided by the bituminous binder manufacturer, while the production of WMAs was carried out at temperatures reduced by 20°C. Aggregates for both hot mixes were heated to 200°C. The PMB 45/80-80 neat was heated 150°C and the PMB 25/55-60 neat was heated 145°C. The compaction of WMA mixtures was conducted at temperatures 15°C and 30°C lower than those of HMAs. The compaction temperature of the AC and HMAC mixes using hot mix technology was 145°C, and in warm mix technology it was 135°C and 115°C.

For the warm mixes the bio-derived additive (Bio-Flux) bituminous binders were extra added. Detailed information on the properties and preparation of bituminous binders with the addition of Bio-Flux bituminous binders is presented in [39]. The properties of the bituminous binders are presented in Table 2. The optimal content of the fluxing additive was determined through preliminary work conducted for this study.

Table 2. Characterisation of bituminous binders

Properties	**45/80–80 neat**	**Foamed 45/80–80 +3% Bio-Flux**	**25/55–60 neat**	**Foamed 25/55–60 +2% Bio-Flux**
Asphalt concrete mixtures:	AC-S H	AC-S W	HMAC H	HMAC W
Penetration at 25°C (0.1 mm)	75	124	40	65
Softening point (°C)	95.5	81.2	63.4	58.0
Fraass breaking point (°C)	–22	–25	–13	–17
Dynamic viscosity at 135°C (Pa·s)	2.81	1.31	1.70	1.21

2.3. Methods

The study included stiffness characterisation of asphalt concrete mixtures using two methods: by determination of complex stiffness modulus in direct cyclic compression (DCC) following the AASHTO T 342 standard and by indirect tensile testing of cylindrical specimens (IT-CY) following the EN 12697-26 (Annex C) standard.

The samples for the DCC test were prepared in a gyratory compactor. The assumed value of air voids reached a value in the range of 2–4%. The tests were carried out at temperatures ranging from –10°C to 35°C with different loading frequencies ranging from 0.1 to 25 Hz. The tests were carried out using LVDTs sensors. The test was conducted in the controlled stress mode. Based on the tests, leading curves were created using the time-temperature superposition principle [40]. The data was shifted to two reference temperatures (15 and 25°C) for comparisons with the IT-CY results.

The IT-CY testing was performed on Marshall compacted specimens compacted to a height of approx. 63 mm using 2×75 blows of an automated hammer. The tests included temperatures of 5, 15, and 25°C, with the remaining test parameters in line with the EN 12697-26 (Annex C) standard.

As part of the research project, an experimental road section was constructed. Samples were collected at the production stage at the plant and cut from the road surface. Their stiffness was then tested using the IT-CY and DCC methods. Samples from the experimental road section were taken in the form of 100 mm diameter cores drilled from the pavement. Laboratory tests were performed on samples taken from the subbase layer. Due to the thickness of the wearing course (40 mm), samples from this layer were not tested.

3. Results

3.1. Complex stiffness modulus performance in DCC testing

The results obtained from measuring the complex stiffness modulus of the evaluated mixtures at 10 Hz are presented in Fig. 2. Regardless of the temperature and type of mixture, the hot produced and fibre reinforced formulations exhibited the highest values of complex stiffness modulus. For the warm mix asphalts (WMAs), in most cases, the mixtures compacted at 15°C and 30°C lower than the reference mixtures demonstrated similar values of complex stiffness modulus, particularly when assessed in the context of the obtained confidence intervals.

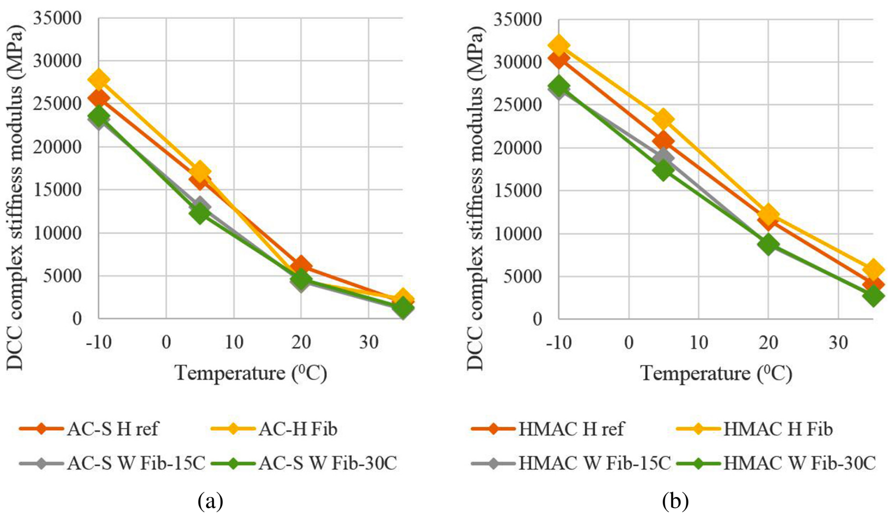

Fig. 2. The directly measured values of complex stiffness modulus (direct cyclic compression, DCC) of the investigated mixtures

The differences in performance among specific mixtures were evaluated using analysis of variance and post hoc multiple comparison tests. Based on the results of these tests, it can be concluded that, in most instances, the differences between the H Ref and H Fib mixtures, as well as between the W Fib –15 and W Fib –30 mixtures, were not statistically significant ($p > 0.05$). However, it is noteworthy that the W Fib mixtures exhibited significant differences in their dynamic modulus compared to the hot mix fibre containing mixtures. Additionally, the AC-S W Fib –30 and HMAC W Fib –30 mixtures performed similarly to the reference mixtures at two temperatures (–10°C and 20°C) and at one temperature (–10°C), respectively.

3.2. IT-CY performance with comparisons to DCC results

Figures 3 and 4 present the results of the stiffness modulus of the investigated AC-S and HMAC mixtures measured using the IT-CY and DCC methods, respectively. The values of IT-CY stiffness were obtained at 5, 15 and 25°C and the DCC at 5°C. The DCC complex stiffness modulus corresponding to the 15°C and 25°C temperatures were calculated by applying the time-temperature superposition principle to the experimental data and deriving the complex stiffness modulus master curves at these temperatures. Hence, only the 5°C DCC results are supplemented with the 95% confidence intervals.

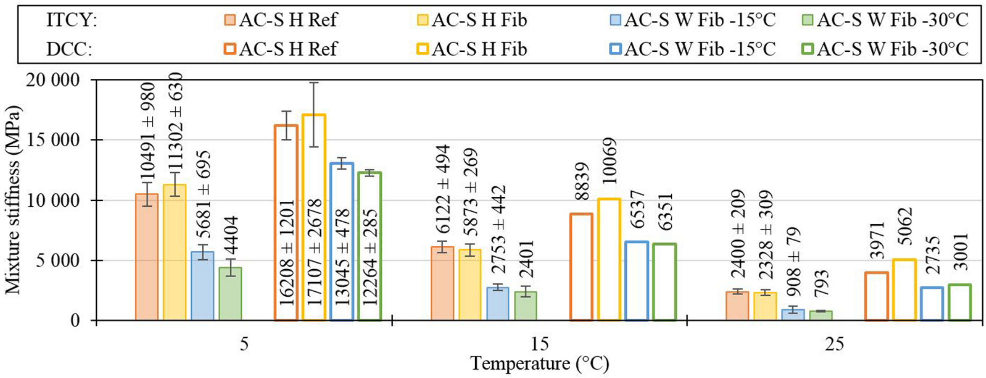

Fig. 3. The measured stiffness characteristics of the investigated surface course mixtures: IT-CY modulus (5, 15, 25°C), measured DCC complex modulus (5°C), DCC complex modulus from time-temperature shifted data (15, 25°C)

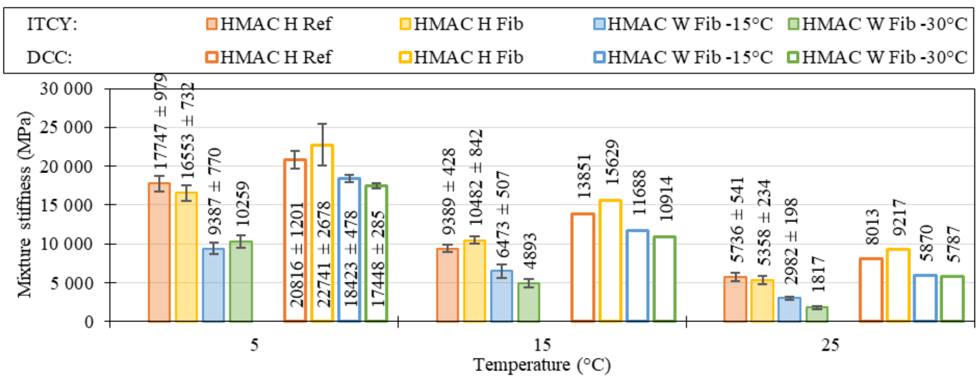

Fig. 4. The measured stiffness characteristics of the investigated high stiffness modulus asphalt concrete mixtures: IT-CY modulus (5, 15, 25°C), measured DCC complex modulus (5°C), DCC complex modulus from time-temperature shifted data (15, 25°C)

The presented IT-CY modules indicate the impact of the investigated effects: the utilisation of fibre reinforcement, warm mix production technique, and effects of compaction temperature. The impact of fibre reinforcement, as demonstrated in comparisons between the H Ref and H Fib mixtures, was statistically nonsignificant in half of the cases. Additionally, the effects of fibre reinforcement changed depending on the testing temperature. This shows that the effects of fibre reinforcement were weakly represented in the IT-CY testing, specifically when compared to the DCC testing.

Regarding the effects of the production technique of the mixtures (hot mix, warm mix), the separation between the results was significantly greater in the IT-CY results. The fine control over the density of specimens compacted using a gyratory compactor could have contributed to this result.

Lowering the compaction temperature in the case of the warm mixtures resulted in five of six cases of a decrease in the IT-CY, and these results were mostly in line with the DCC testing. In three cases, these differences were statistically significant, and the compaction level of the samples could have contributed.

By comparing the DCC and IT-CY stiffness modulus results, the relationships between the stiffness and the evaluated factors are generally similar in those two methods. The DCC method returned higher absolute values of the stiffness modulus, which can be attributed to several factors, which, among others, include different loading patterns, different loading times, inaccurate adoption of the Poisson coefficient in the calculation of the IT-CY modulus (set at 0.3), effects of air void contents in samples produced from the different mixtures (Marshall samples), effects of air void content distribution in the volume of the samples.

Fig. 5 presents the relationship between the values of stiffness modulus measured using the DCC and IT-CY methods. In both types of mixtures (AC-S, HMAC), a high degree of correlation between these parameters is present (Pearson correlation coefficient $R > 0.9$), which is even higher when they are considered jointly ($R = 0.95$).

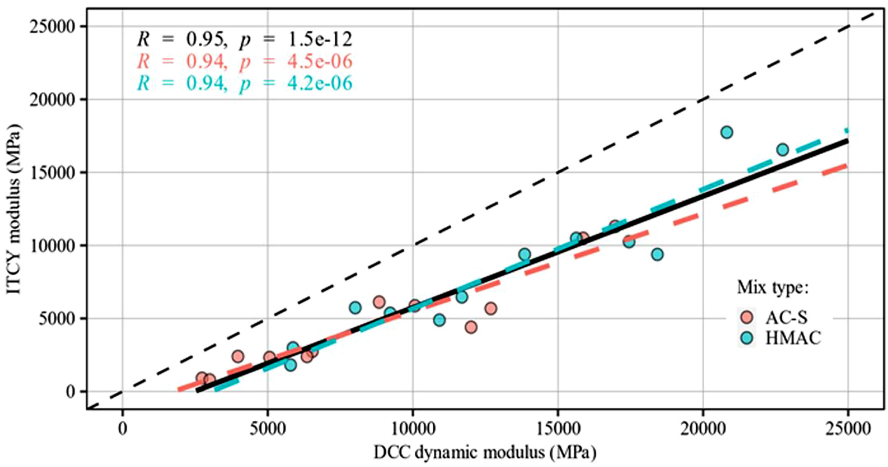

Fig. 5. Relationships between the DCC and IT-CY stiffness modulus (IT-CY = 0.763·DCC – 1883 [MPa], $R^2 = 0.901$)

As part of the project, an experimental road section was constructed. Two pavement structures were built on the traffic lanes – one containing reference mixtures and the other containing innovative mixtures intended for the wearing course and subbase, with optimal compositions determined during previous studies. The experimental section was constructed at the DUKT company location at the bituminous mixtures plant. The diagram of the built in structures is shown in Table 3.

Table 3. Road section diagram: 1) wearing course, 2) binding course and 3) subbase course

Layers	Thickness	Reference section	Innovative section
1) wearing course	4 cm	Mixture type: AC-S H Ref Sec Bitumen: 45/80-80 Fiber content: 0% Bioflux: 0% Production temp.: 180°C Compaction start temp.: 145°C	Mixture type: AC-S W Fib –30 Sec Bitumen: 45/80-80 Fiber content: 0,3% 12 mm basalt fiber Bioflux: 3% Production temp.: 160°C Compaction start temp.: 115°C
2) binding course	5 cm	Mixture type: HMAC 16 H Bitumen: 25/55-60 Production temp.: 180°C Compaction start temp.: 145°C	Mixture type: HMAC 16 H Bitumen: 25/55-60 Production temp.: 180°C Compaction start temp.: 145°C
3) subbase course	9 cm	Mixture type: HMAC H Ref Sec Bitumen: 25/55-60 Fiber content: 0%, Bioflux: 0% Production temp.: 180°C Compaction start temp.: 145°C	Mixture type: HMAC W Fib –30 Sec Bitumen: 25/55-60 Fiber content: 0.2% 24 mm basalt fiber Bioflux: 2% Production temp.: 160°C Compaction start temp.: 115°C

On both traffic lanes, an asphalt pavement consisting of three layers was built:

– wearing (AC-S 11 H Ref Sec, 4 cm and AC-S 11 W Fib –30 Sec, 4 cm),
– binding (HMAC 16 H Ref Sec, 5 cm),
– subbase (HMAC 22 H Ref Sec, 9 cm and HMAC 22 W Fib –30 Sec, 9 cm).

The analyses were performed on reference and innovative mixes from the wearing course and subbase. The binding layer was made using hot technology from a typical HMAC 16 H mix on both the reference and innovative sections and was not analysed in this paper.

The section was divided into parallel sections (traffic lanes). On one of them, layers were built using reference materials manufactured using the hot method. In the other section, layers using innovative composites developed as part of the project, characterised by reduced technological temperatures, with a water foamed binder, bio-flux and dispersed reinforcement were built. During the construction of the road surface, the weather conditions were favourable – the air temperature was above 15°C, there was no wind and no precipitation. During the construction of the section, samples of the asphalt mixtures were collected. Samples were reheated and compacted from the collected materials to test stiffness modules in the laboratory. Additionally, samples in the form of plates and cores were cut from the compacted layers for comparative tests. The location of samples taken for testing from the subbase layer is shown in Fig. 6.

(a)

(b)

Fig. 6. Construction of the experimental road section: a) Construction of the subbase layer from the HMAC mixture; b) Location of taking samples for testing from the subbase layer

Samples obtained from the corner experimental section were subjected to stiffness modulus tests using the IT-CY method. A comparison of the stiffness test results using the IT-CY method for mixtures produced and compacted in the laboratory and those taken from the pavement is presented in Fig. 7. A comparison of average air void content in samples compacted in the laboratory and cut from the pavement is shown in Table 4.

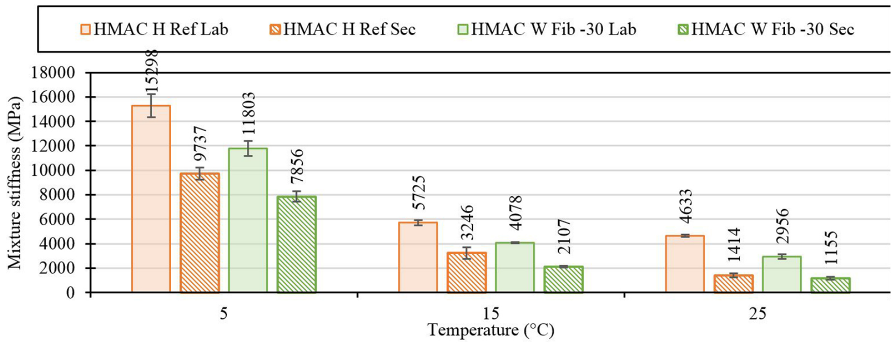

Fig. 7. IT-CY modulus at 5, 15, 25°C, specimen from laboratory and cut from the pavement section

Table 4. Comparison of average air void content in samples compacted in the laboratory and cut from the pavement section

Mixture code	Air voids content [%]	Standard deviationv[%]
HMAC W Fib –30 Lab	3.7	0.16
HMAC W Fib –30 Sec	2.9	0.24
HMAC H Ref Lab	2.9	0.11
HMAC H Ref Sec	1.8	0.26

The test results analysis shows that the stiffness modulus (IT-CY) of samples taken from the pavement differs from about 30% to 70% in relation to the samples made in the laboratory. Moreover, it was observed that with the increase of the test temperature, these differences increase.

Fig. 7 shows a difference in the test results of stiffness moduli between samples from the experimental road section, reference mixtures produced using hot technology and mixtures produced using warm technology. Lower values of stiffness moduli of mixtures by 18 to 35% were obtained using warm technology. This should be explained by the limitation of the ageing processes and stiffening of asphalt due to reduced technological temperatures. Analysing the IT-CY test results in comparison with the contents of voids, it can be concluded that the differences between the stiffness values measured for samples compacted in the laboratory and those cut out from the pavement are caused by differences in the contents of voids, which amount to about 0.8–1.0%.

Using the relationship determined based on the results of tests on mixtures compacted in the laboratory, the values of stiffness moduli were estimated according to the DCC method based on the results of the IT-CY test of samples taken from the surface of the experimental road section. Table 5 presents a comparison of the actual results of stiffness moduli determined by the DCC method at 5°C on samples compacted in the laboratory with the results obtained based on the following formula:

$$\text{DCC} = (\text{IT} - \text{CY} + 1883)/0.763 \tag{3.1}$$

Table 5. Comparison of the stiffness modulus values determined by the DCC method at 5°C with the values calculated according to the relationship (3.1)

Mixture code	**Measured stiffness lab. (DCC)**	**Calculated stiffness sec. (DCC based on IT-CY)**	**Relative error**
HMAC W Fib –30 Sec	17060	12764	25.2%
HMAC H Ref Sec	19535	15230	22.0%

In the case of results obtained for samples collected from the pavement, the differences between the measured and calculated stiffness are approximately 22–25%. This discrepancy is most likely attributable to the variation in air void content between samples compacted in the laboratory and those extracted from the experimental road section. This may also be the result of increased anisotropy of the fibre containing composite during technological processes. In future studies, special attention should be paid to the mixing, transportation, laying and compaction processes related to ensuring the homogeneity of the fibre-containing asphalt composite during mixing and compaction.

4. Conclusions

This study aimed to investigate the effects of measurement method on the stiffness modulus of the surface course asphalt concrete (AC-S) and high modulus asphalt concrete (HMAC) mixtures in three variations: reference hot mix asphalt (HMA) mixtures, fibre reinforced HMAs, and fibre reinforced warm mix asphalts (WMAs) produced with foamed bitumen and the fluxing agent. The testing methods employed included direct cyclic compression (to evaluate complex stiffness modulus) and indirect tensile stiffness tests. The summarised results of the study are as follows:

- The effects of fibre reinforcement were more pronounced and coherent in the compressive setting,
- The stiffness measurements conducted in indirect tension were influenced more strongly by the production method of the asphalt mixtures (HMA, WMA),
- The direct compression method yielded higher values of stiffness modulus in all evaluated cases,
- A strong linear relationship was found between the stiffness modulus measured in direct compression and indirect tension regardless of the type of the mixture (AC-S, HMAC),
- The values of stiffness modulus obtained for samples from the section are lower than those obtained for samples compacted in the laboratory, most likely due to the difference in air void content between samples compacted in the laboratory and those taken from the experimental road section.

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Ocena sztywności mieszanek mineralno-asfaltowych w technologii na ciepło różnymi metodami badawczymi

Słowa kluczowe: asfalt spieniony, sztywność, środek fluksujący pochodzenia roślinnego, włókna

Streszczenie:

Artykuł dotyczy innowacyjnych mieszanek mineralno-asfaltowych zbrojonych włóknami i produkowanymi w technologii na ciepło przeznaczonych do budowy trwałych i odpornych na zniszczenia nawierzchni drogowych. W pracy dokonane zostało porównanie i ocena wyników modułów sztywności uzyskanych na podstawie dwóch różnych metod pomiaru sztywności – bezpośredniego cyklicznego ściskania (DCC) oraz pośredniego rozciągania (IT-CY). Prace obejmowały dwie mieszanki mineralno-asfaltowe przeznaczone do budowy trwałych i odpornych na zniszczenia nawierzchni drogowych: beton asfaltowy do warstwy ścieralnej oraz beton asfaltowy o wysokim module sztywności do warstwy podbudowy.

Mieszanki zastosowane w badaniach produkowane były w technologii na ciepło (WMA). W obu mieszankach zastosowano zbrojenie włóknami bazaltowymi. Proces produkcyjny prowadzono w obniżonych temperaturach zarówno podczas wytwarzania, jak i wbudowywania mieszanek mineralno-asfaltowych dzięki zastosowaniu dodatku upłynniającego pochodzenia roślinnego i spienianiu lepiszcza asfaltowego. W obu mieszankach zastosowano polimeroasfalty. Wykonany zostałeksperymentalny odcinek drogowy z konstrukcją nawierzchni z tymi mieszankami mineralno-asfaltowymi. Właściwości analizowanych mieszanek wytwarzanych w technologii na ciepło (WMA) porównano z tradycyjnymi mieszankami w wytwarzanymi w technologii na gorąco (HMA). Wyniki badań laboratoryjnych porównane zostały także z wynikami modułu sztywności uzyskanymi z próbek pobranych z eksperymentalnego odcinka drogowego. Wyniki badań wykazały, że moduł sztywności uzyskany w teście bezpośredniego ściskania (DCC) lepiej różnicuje mieszanki mineralno-asfaltowe ze względu na wpływ zastosowanego zbrojenia włóknami. Wyniki modułu sztywności w teście pośredniego rozciągania (IT-CY) wykazały większą zmienność, wynikającą z różnych właściwości objętościowych próbek związanych z procesem zagęszczania. Pod względem właściwości mechanicznych, zastosowanie zbrojenia włóknami poprawiło moduł sztywności we wszystkich mieszankach, natomiast zastosowanie technologii WMA znacząco obniżyło modułsztywności. Wartości modułu sztywności uzyskane dla próbek z eksperymentalnego odcinka drogowego były niższe od wartości uzyskanych dla próbek zagęszczanych w laboratorium.

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