WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2021.138046
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVII ISSUE 3 2021

s. 109–122

Research paper

Effect of reclaimed asphalt shingles addition on asphalt concrete dynamic modulus master curves

P. Zieliński[1]

Abstract: The paper presents the comparison of dynamic modulus and phase lag in different loading conditions for asphalt concrete mixture with or without reclaimed asphalt shingles (RAS) addition. For each mixture, 6 samples were tested using the four point bending beam method, at four temperatures and at six frequencies. The results of the study were subjected to the analysis of the statistical significance of differences between mixtures. The graphic form of results presentation includes Black curves and Cole-Cole plots. Then, matching the sigmoidal functions enabled the creation of master curves of the complex stiffness module and the phase shift angle, being a function of the load frequency. It has been observed that the mixture with the addition of RAS has higher stiffness and elasticity in the range of higher temperatures (20°C and 30°C) and lower load frequencies, which results in higher values of the complex stiffness module and lower values of the phase lag. At 0°C, the behavior of both mixtures is very similar, while at 10°C significant differences between the tested mixtures were found only for low frequency loads (up to 5 Hz). Test results have shown that mixtures with the addition of RAS have a lower thermal sensitivity in terms of the complex stiffness modulus and phase lag than the reference mixture. The above results confirmed an improvement in rutting resistance for RAS mixes observed in previous work.

Keywords: asphalt concrete (AC), reclaimed asphalt shingles (RAS), dynamic modulus master curve, Black curve, Cole-Cole plot

[1] PhD., Eng., Cracow University of Technology, Faculty of Civil Engineering, ul. Warszawska 24, 31-155 Kraków, Poland, e-mail: pzielin@pk.edu.pl, ORCID: https://orcid.org/0000-0002-3282-8430

1. Introduction

In the era of sustainable development, it is necessary to effectively manage resources, which can be implemented, among others by increasing the share of using recycled materials [1]. In the case of asphalt mixtures used in pavements, the basic recycled material is asphalt granulate, reclaimed from the old asphalt layers. The great potential is the use of reclaimed asphalt shingles (RAS) which contain about 20–35% of bitumen as well as mineral sprinkles, a supporting veil (e.g. glass), fillers or polypropylene foil (as a layer preventing shingle from sticking on the roll). Due to the content of bituminous binder (about 30%), the use of RAS is more effective in reducing the demand for fresh bitumen than in the case of RAP material (about 5%) [2]. Foxlow at al. [3] compared the properties of mixtures with RAP and RAS, finding on the basis of binder tests that mixtures with RAS are stiffer than those with RAP at high operating temperatures and perform better at low temperatures. Barry at al. [4] studied mixtures with the addition of RAS from various sources and noticed that they are stiffer than the reference mix at high temperatures and less rigid at low temperatures and have better fatigue resistance at intermediate temperatures. Baaj at al. [5] stated that the mixes containing RAP and RAS generally had higher stiffness values at intermediate and high temperatures and better fatigue properties than reference mixture. At the same time, Zhou at al. [6] found that mixtures with the addition of manufacture waste asphalt shingles (MWAS) are less sensitive to low-temperature cracks than HMA with the addition of tear-off asphalt shingles (TOAS). In addition, Darnell and Bell's studies [7] show that mixtures with RAS addition were less susceptible to changes in loading frequency and temperature. One of the most effective methods of assessing properties of asphalt mixtures over a wide range of loads (temperature and load time) is to present master curve in the form of the stiffness modulus [8]. The basic assumption used in creating the master curves is the principle of time-temperature superposition, which allows determining the stiffness of a mixture at any temperature and time of loading.

This work is a development of previous tests of asphalt mixtures containing RAS [9], the results of which showed an improvement in rutting resistance while not reducing the low temperature crack resistance. The aim of the study is to evaluate the viscoelastic changes in the asphalt mix properties after adding RAS, determined on the basis of Black curves, Cole-Cole plots and master curves of the stiffness module and phase shift angle.

2. Materials and methods

A mixture of asphalt concrete AC 16 for the bonding course with paving bitumen 50/70 was used for the test as reference mix. The results obtained on this mix were compared with the results of mixtures with the addition of 4% reclaimed asphalt shingles (RAS) and bitumen type of 50/70 (Fig. 1 shows a sample of asphalt shingles). This type of RAS was selected for testing due to the lack of aging of the binder contained in it, and its good low-temperature properties, i.e. Fraass temperature below –20°C.

Fig. 1. View of manufacture waste asphalt shingles

Testing mixtures were designed in such a way, that the total content of bitumen binders and the grading curves of both mixes were constant. Details concerning RAS and asphalt concrete properties are presented in work [9], but the test mixtures composition is given in Table 1.

Table. 1. Asphalt mixtures composition

O.N.	Components	Participation in MMA [%] for the HMA	
		AC 16 W 50/70	AC 16 W 50/70 +4% RAS
1	Limestone filler	4.3	3.8
2	Sand 0/2	9.6	9.7
3	Dolomite 0/4	26.3	23.1
4	Dolomite 4/8	17.2	17.4
5	Dolomite 8/16	38.2	38.7
6	RAS	-	4.0
7	Paving bitumen 50/70	4.4	3.3

From each mix, 2 slabs with dimensions of 405×305×100 mm were prepared in a roller compactor acc. to PN-EN 12697-33 [10], from which, with a two-disc saw, beams of 63.5×50×405 mm were cut out. Six beams were prepared for each mix, the results of the physical characteristics of the samples are given in Table 2. Because the air voids content in the samples was similar (P = 3.0% for reference mix samples and 2.7% for mix samples with RAS), the influence of the physical properties of the mix on the tested mechanical behavior can be omitted.

Table 2. Physical characteristics of AC beam samples

Parameter	Density [g/cm^3]	Bulk Density [g/cm^3]	Air Voids [%]	VMA [%]	VFB [%]
AC 16 W 50/70					
Average	2.622	2.544	3.0	14.2	79.0
St. dev.	0.006	0.002	0.1	0.1	0.4
AC 16 W 50/70 + 4% RAS					
Average	2.613	2.542	2.7	14.2	80.8
St. dev.	0.003	0.004	0.1	0.1	0.8

Then, after seasoning the samples, tests were carried out on the dynamic stiffness modulus using the four-point bending beam method at a strain level of $50 \cdot 10^{-6}$, in accordance with PN-EN 12697-26 [11]. Fig. 2 shows the four point bending beam apparatus during testing of AC beam sample. The tests were performed at 4 temperatures: 0°C, 10°C, 20°C and 30°C and at 6 frequencies: 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, 10 Hz, 20 Hz and 30 Hz. As a result, the values of the complex stiffness modulus and the phase lag for the 100-th load cycle were read.

Fig. 2. The four-point bending beam apparatus with AC beam sample

3. Results and discussion

The average values of 4-PBB test parameters at different temperatures and frequencies are given in Table 3 (complex modulus) and in table 4 (phase angle). Statistical analyses with the use of computer program Statgraphics Plus v. 5.1. [12] were performed to verify the hypothesis that the results for RAS mixture differ significantly from the results of the reference mix. Anova Table at a given confidence level equal 0.95 was used for this purpose. To determine which results differ significantly from one another, the analysis of multiply range tests with application of LSD (least square differences) option was used. It has been observed that the mixture with the addition of RAS has higher stiffness and elasticity in the range of higher temperatures (20°C and 30°C) and lower load frequencies, which results in higher values of the complex stiffness module (up to 58%) and lower values of the phase lag (up to 30%). At 0°C and 10°C, the complex stiffness module of both mixtures is very similar, the difference is below 8% and only for high frequencies (5–30 Hz) it is statistically significant. The phase lag at 0°C for both mixtures is statistically similar, but in the case of results conducted at 10°C a significant differences were found only for low frequency loads (up to 5 Hz).

Table 3. Results of significance difference tests for AC complex stiffness modulus [MPa]

Temperature [°C]	Frequency [Hz]	AC 16 W 50/70		AC 16 W 50/70 + 4% RAS		Difference	+/– limits
		Mean	St. dev.	Mean	St. dev.		
0	0.5	15750	864	15541	1023	209	1199
	1	17267	1016	16723	1413	544	
	2	18692	1195	18069	674	623	
	5	20737	1133	19116	1174	1621*	
	10	21701	1034	20300	998	1401*	
	20	22235	756	20892	940	1343*	
	30	22607	873	22142	1241	465	
10	0.5	8113	376	8405	474	–292	637
	1	9306	587	9731	507	–425	
	2	10460	525	10534	671	–74	
	5	12361	561	11708	399	653*	
	10	13811	640	12910	465	901*	
	20	15227	740	14400	330	827*	
	30	15466	812	15019	422	447	
20	0.5	2954	142	4006	125	–1052*	288
	1	3709	138	4744	154	–1035*	
	2	4651	208	5714	306	–1063*	
	5	6019	265	6615	236	-596*	
	10	7115	243	7605	254	–490*	
	20	8476	229	8623	290	–147	
	30	9244	453	9171	264	73	
30	0.5	1129	124	1787	148	–658*	211
	1	1440	67	2160	151	–720*	
	2	1924	139	2660	37	–736*	
	5	2844	198	3315	188	–471*	
	10	3511	231	3907	138	–396*	
	20	4451	226	4668	257	–217*	
	30	4850	263	5012	231	–162	

* denotes a statistically significant difference

Table 4. Results of significance difference tests for AC phase angle [°]

Temperature [°C]	Frequency [Hz]	AC 16 W 50/70		AC 16 W 50/70 + 4% RAS		Difference	+/– limits
		Mean	St. dev.	Mean	St. dev.		
0	0.5	11.9	0.7	12.2	0.9	–0.3	1.1
	1	10.9	1.1	11.4	1.1	–0.5	
	2	9.5	0.8	9.0	1.3	0.5	
	5	7.4	1.3	7.0	0.8	0.4	
	10	3.6	0.6	4.2	0.3	–0.6	
	20	0.0	0.0	0.4	0.4	–0.4	
	30	0.0	0.0	0.0	0.0	0.0	
10	0.5	22.0	1.0	19.4	1.8	2.6*	1.4
	1	20.7	1.1	17.6	1.8	3.1*	
	2	18.4	1.0	15.9	1.8	2.5*	
	5	14.6	0.7	13.1	1.0	1.5*	
	10	11.1	0.9	10.0	1.2	1.1	
	20	5.5	0.9	5.4	1.3	0.1	
	30	1.9	0.7	1.4	0.6	0.5	
20	0.5	35.6	1.0	25.6	0.7	10.0*	0.9
	1	33.9	0.9	23.5	0.7	10.4*	
	2	30.9	0.8	22.0	0.8	8.9*	
	5	25.8	0.6	18.9	0.5	6.9*	
	10	21.2	0.7	16.2	0.8	5.0*	
	20	15.2	0.8	11.7	0.5	3.5*	
	30	10.5	0.6	7.6	0.8	2.9*	
30	0.5	40.8	1.5	29.9	2.6	10.9*	1.4
	1	39.9	1.1	32.3	1.5	7.6*	
	2	38.8	1.1	30.9	1.7	7.9*	
	5	35.5	1.1	26.9	0.5	8.6*	
	10	31.7	1.0	24.4	1.0	7.3*	
	20	25.2	0.8	19.6	0.6	5.6*	
	30	20.7	0.9	16.3	0.7	4.4*	

* denotes a statistically significant difference

Fig. 3 shows the dependence of the complex stiffness modulus on the phase angle (Black curve) for the tested mixtures. This graph indicates the lower thermal sensitivity of the mixture with the addition of RAS, i.e. lower variation of the stiffness modulus and phase angle in the tested temperature range and load frequency.

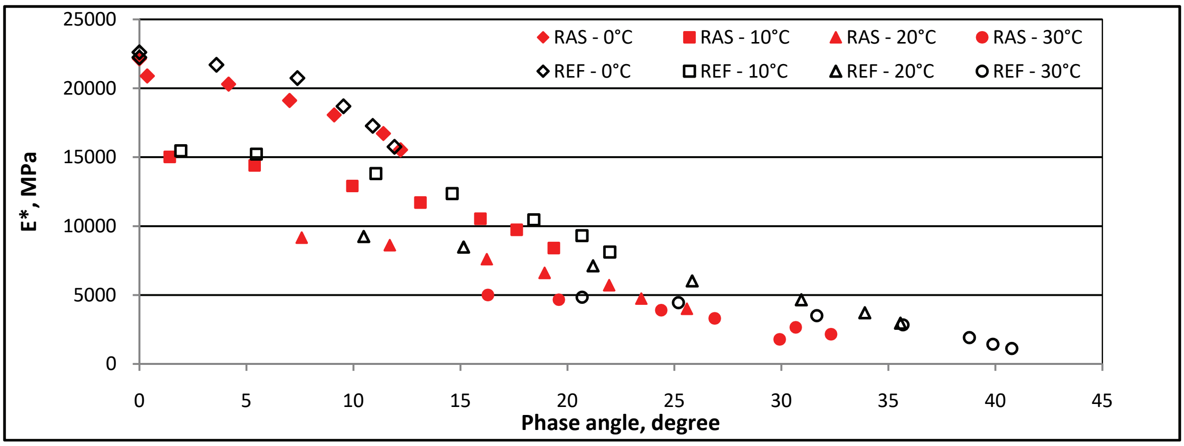

Fig. 3. Black curves for tested mixtures

Complex modulus is decomposed into two major components, the storage modulus and loss modulus as represented in Eq. (3.1). The dynamic modulus is the amplitude of the complex modulus and is defined in Eq. (3.2). The values of the storage and loss modulus are related to the dynamic modulus and phase angle (*φ)* by Eq. (3.3) and Eq. (3.4), respectively.

(3.1) $$E^* = E' + iE"$$

(3.2) $$|E^*| = \sqrt{(E')^2 + (E")^2}$$

(3.3) $$E' = |E^*| * cos\varphi$$

(3.4) $$E" = |E^*| * sin\varphi$$

Where *E'* is the storage modulus, and *E"* is the loss modulus.

The results of the relationship between the real and imaginary parts of the module are shown in Figure 4, in the form of Cole-Cole plots. The mixture with the addition of RAS shows a narrower range of both the storage modulus and the loss modulus, which confirms the conclusion that the RAS mixture is less thermally sensitive than the reference mixture.

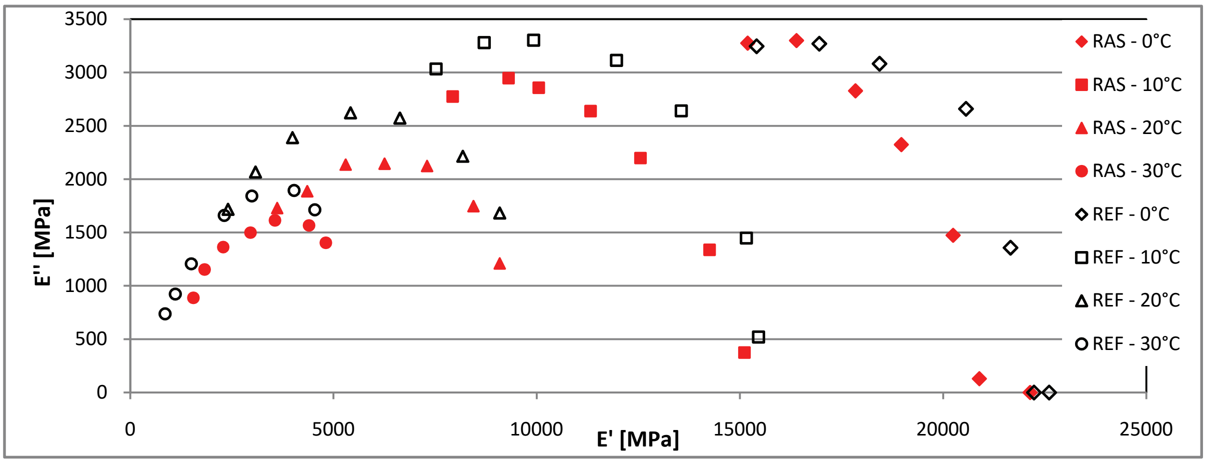

Fig. 4. Cole-Cole plots for tested mixtures

Master curves are very often used for the overall presentation of the results obtained. For this purpose, using the relation given in NCHRP 09 [13], a spreadsheet containing the solver function was used, where the complex module is expressed by Eq. (3.5). The reduced frequency is computed using the Arrhenius equation, Eq. (3.6). Substituting Eq. (3.6) into Eq. (3.5) yields the form of the master curve Eq. (3.7) that is fitted using workbook prepared by Bonaquist [14]. The shift factors for each temperature, a(T), are given by Arrhenius Eq. (3.8). The maximum limiting modulus is estimated from mixture volumetric properties using the Hirsch model and a limiting binder modulus of 1 GPa, Eq. (3.9) and Eq. (3.10).

$$log|E^*| = log(Min) + \frac{(\log(Max)-\log(Min))}{1+e^{\beta+\gamma * log\omega_r}} \tag{3.5}$$

$$log\omega_r = log\omega + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{3.6}$$

$$log|E^*| = log(Min) + \frac{(\log(Max)-\log(Min))}{1+e^{\beta+\gamma\left\{log\omega+\frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right)-\left(\frac{1}{T_r}\right)\right]\right\}}} \tag{3.7}$$

$$log[a(T)] = \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{3.8}$$

$$|E^*|_{max} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right) + 435{,}000\left(\frac{VFA*VMA}{10{,}000}\right)\right] + \frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000}+\frac{VMA}{435{,}000(VFA)}\right]} \tag{3.9}$$

$$P_c = \frac{\left(20+\frac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650+\left(\frac{435{,}000(VFA)}{VMA}\right)^{0.58}} \tag{3.10}$$

Where:

$|E^*|$ – dynamic modulus, ω_r – reduced frequency in Hz, *Max* – limiting maximum modulus in ksi, ω – loading frequency at the test temperature, T_r – reference temperature in °K, T – test temperature in °K, ΔE_a – activation energy (treated as a fitting parameter), *Min* – limiting minimum modulus in ksi, β *and* γ – fitting parameters, VMA – voids in mineral aggregates in %, VFA voids filled with asphalt in %.

Results of modulus master curves fitting for reference temperature of 20°C are shown in Fig. 5, whereas their fitting to the data are given in Fig. 6 (Reference mixture) and in Fig. 7 (RAS mixture). Final model parameters for modulus master curves are given in Table 5, but shift factor versus temperature is presented in Fig. 8. Additionally in Fig. 9 master curves of phase angle are presented. It can be seen that the maximum values of the modules of both analyzed mixtures determined from the model are very similar, while the minimum values differ quite substantially, i.e. the minimum stiffness of the mix with the addition of RAS is more than twice as high as compared to the reference mix. Therefore, it was confirmed that the mixture with the addition of RAS is less thermally sensitive, it does not worsen the behavior of the mixture at low operating temperatures, thus contributing to the improvement of MMA resistance to permanent deformations arising at high temperatures and with long load times (low speed vehicles). The lack of deterioration of the low-temperature properties of the RAS mixture can be explained by the type of additive used (manufacture waste), which was not aged, and the bitumen contained in it had a low fracture temperature, according to Fraass test. Moreover, previous TSRST results show that resistance to low-temperature cracking, for the RAS mixture is at a similar level as in the case of the reference mixture [9]. Assessing the coefficients of determination (R2) obtained for the master curves, they are quite high and amount to 94% for the reference mix and 93% for the mix with the addition of RAS. At the same time, based on Figures 6 and 7, it was observed that the estimated values are lower than those observed at 0°C, regardless of the assumed load frequency. The above observation can be explained by underestimation of the maximum values of modules limiting the leading curve determined from the Hirsch model [15]. The phase shift angle results show similar values of both mixtures at high reduced frequencies, while at low reduced frequencies the mixture with RAS content is characterized by significantly lower values of the phase shift angle in relation to the reference mixture. It means that the RAS mixture is more elastic and less viscous than the reference mixture in the case of lower load speeds and higher temperatures, whereas under conditions of quick loads and low temperatures, the behavior of both mixtures does not differ.

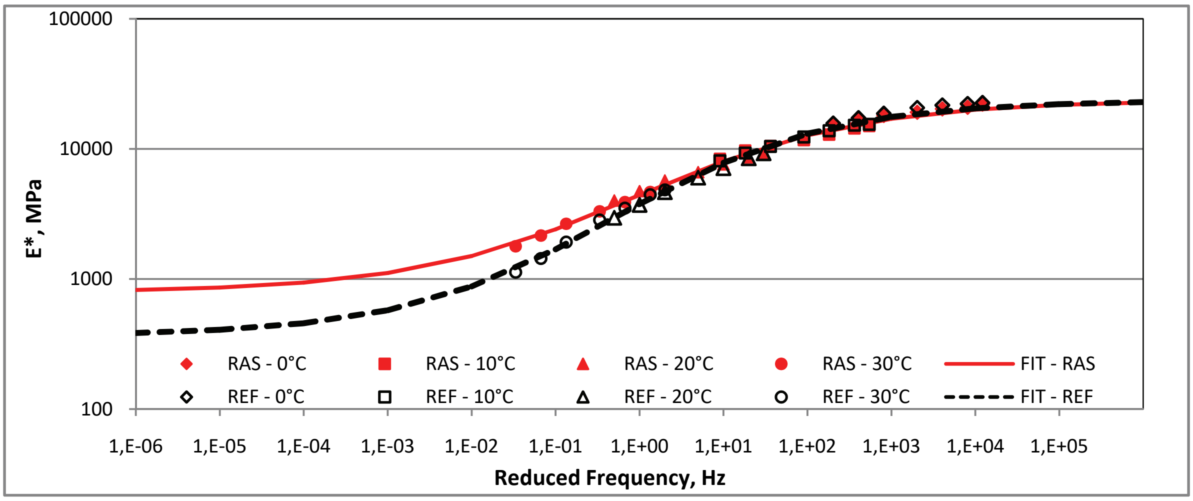

Fig. 5. Comparison of asphalt mixtures modulus master curves (20°C)

Table 5. Stiffness modulus master curves model parameters

Model parameter	AC 16 W 50/70	AC 16 W 50/70 +4% RAS
Maximum modulus, Max [MPa]	23 590	23 634
Minimum modulus, Min [MPa]	367	792
β [-]	–0.23852	–0.02513
γ [-]	–0.78351	–0.74132
EA [-]	200 000	200 000
R^2	0.9414	0.9286

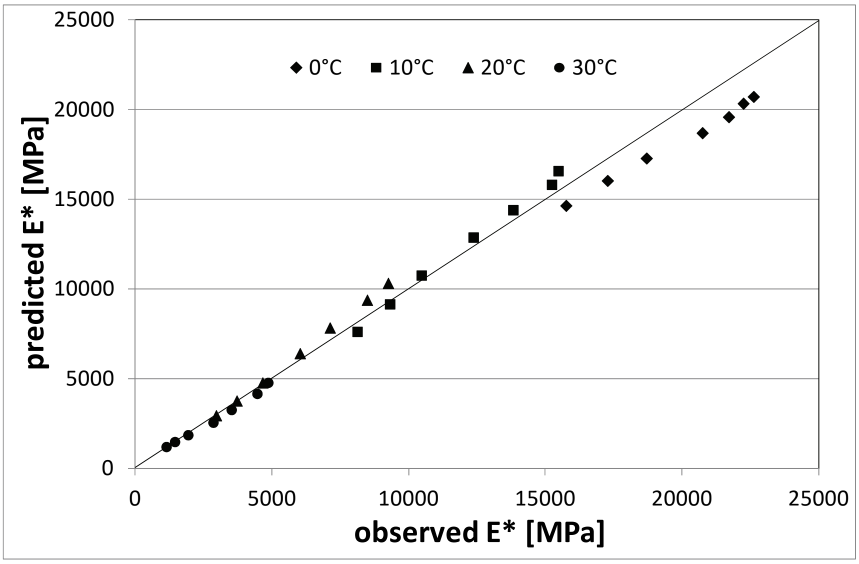

Fig. 6. Relations between observed and predicted E* values for Reference mixture

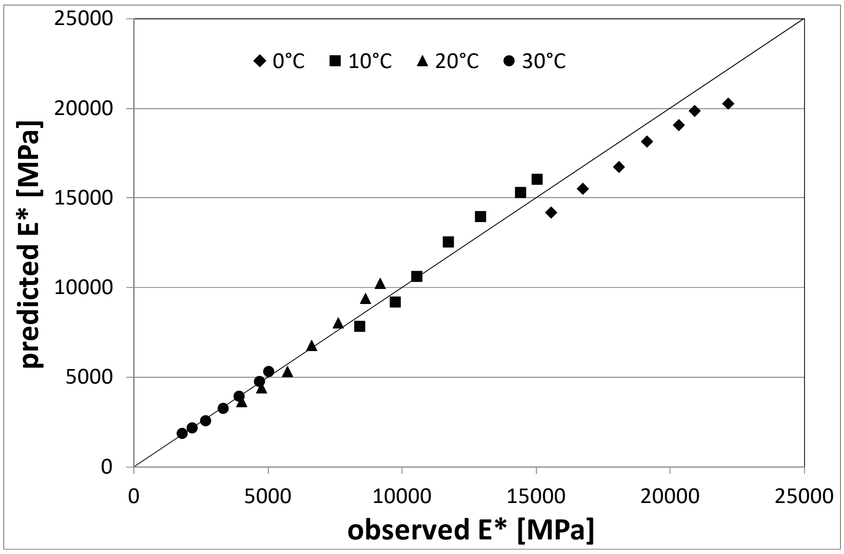

Fig. 7. Relations between observed and predicted E* values for RAS mixture

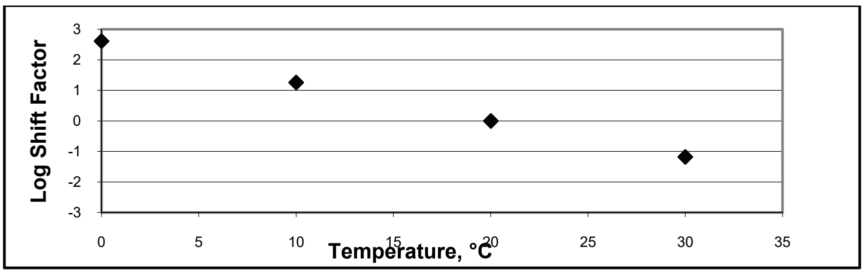

Fig. 8. Shift factor versus temperature plot for tested asphalt mixtures

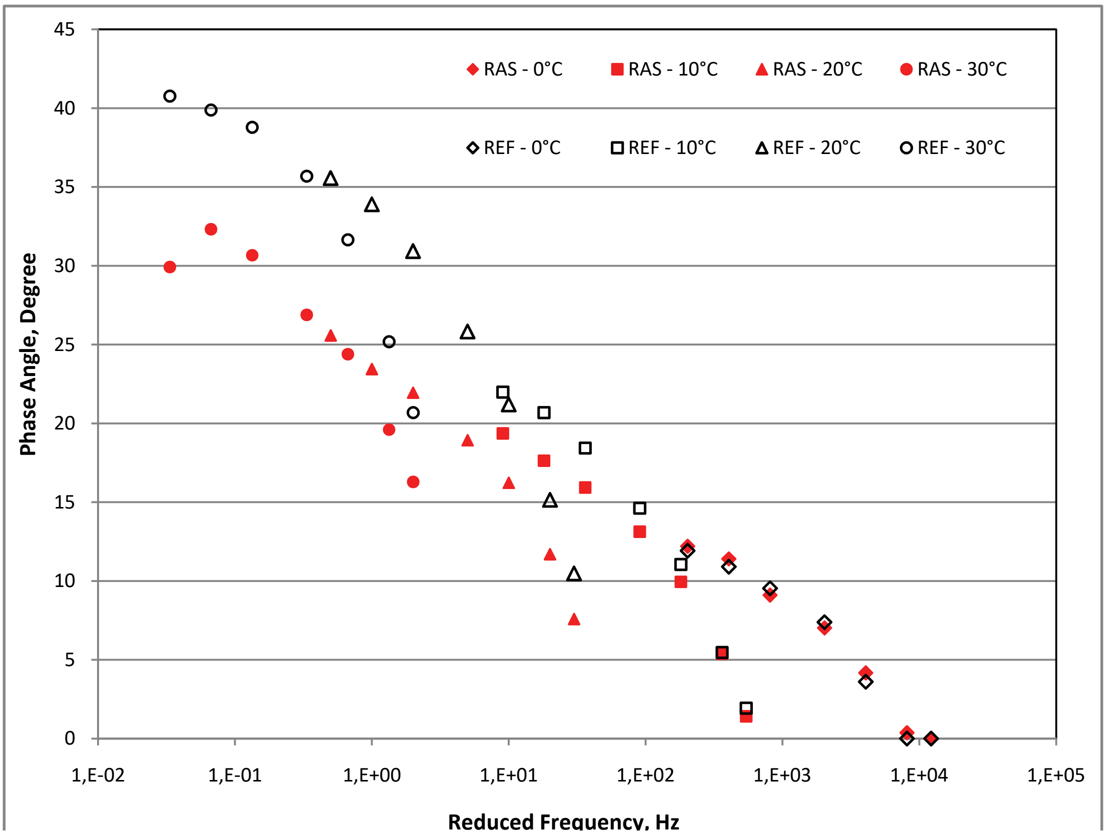

Fig. 9. Comparison of asphalt mixtures phase angle master curves

4. Conclusions

The results of Black curves, Cole-Cole plots and modulus as well as phase angle master curves showed that mixtures with the addition of RAS have lower thermal sensitivity than the reference mixture. It has been observed that the mixture with the addition of RAS has higher stiffness and elasticity in the range of higher temperatures (20°C and 30°C) and lower load frequencies, which results in higher values of the complex stiffness module and lower values of the phase lag. The highest differences were observed for the results obtained at the temperature of 30°C and the frequency of 0.5 Hz, then the mixture with RAS obtained 58% higher stiffness modulus than the reference mixture, with a simultaneous decrease of the phase shift angle by 27%. At 0°C, the behavior of both mixtures is very similar, while at 10°C significant differences between the tested mixtures were found only for low frequency loads (up to 5 Hz). Generally, mixtures with the addition of RAS show greater elasticity and stiffness at lower load speeds and higher temperatures, which is a positive effect in terms of reducing the accumulation of permanent deformations. This conclusion was confirmed in the study of rutting of these mixtures, which was presented in the paper [9]. The lack of deterioration of the low-temperature properties of the RAS mixture can be explained by the type of RAS used (manufacture waste), which was not aged, and the bitumen contained in it had a Fraass breaking temperature below –20°C. Moreover, previous TSRST results shows that resistance to low-temperature cracking, for the RAS mixture is at a similar level as in the case of the reference mixture [9]. The fatigue properties of AC with addition of RAS, despite positive results of the indirect tensile fatigue test [9], should be additionally checked in the study at a constant level of strain on beam samples.

References

[1] Pouranian M. R., Shishehbor M., "Sustainability Assessment of Green Asphalt Mixtures: A Review", Environments 2019, 6, 73, p. 55. https://doi.org/10.3390/environments6060073

[2] Williams R.C., Cascione A., Yu J., Haugen D., Marasteanu M., McGraw J., "Performance of recycled asphalt shingles in hot mix asphalt", Institute for Transportation and Iowa State University, August 2013.

[3] J.J. Foxlow, J.S. Daniel, A.K. Swamy, "RAP or RAS? The differences in performance of HMA containing reclaimed asphalt pavement and reclaimed asphalt shingles", Journal of the Association of Asphalt Paving Technologists, Volume 80, pp 347–376, 2011.

[4] Barry K., Daniel J. S., Foxlow J., Gray K., "An evaluation of reclaimed asphalt shingles in hot mix asphalt by varying sources and quantity of reclaimed asphalt shingles", Road Materials and Pavement Design, Vol. 15, No. 2, 2014, pp. 259–271. https://doi.org/10.1080/14680629.2013.861765

[5] H. Baaj, M. Ech, N. Tapsoba, C. Sauzeat, H. Di Benedetto, "Thermomechanical characterization of asphalt Mixtures modified with high contents of asphalt shingle modifier (ASM®) and reclaimed asphalt pavement (RAP)", Materials and Structures, 2013, DOI 10.1617/s11527-013-0015-7. https://doi.org/10.1617/s11527-013-0015-7

[6] Zhou F., Li H., Hu S., Button J.W., Epps J.A., "Characterization and best use of recycled asphalt shingles in hot-mix asphalt", Report No. FHWA/TX-13/0-6614-2, TEXAS A&M TRANSPORTATION INSTITUTE, USA, 2013, p. 107.

[7] J. Darnell, C.A. Bell, "Performance based selection of RAP/RAS in asphalt mixtures", Report No. FHWA/OR-RD-16-08, Oregon Dept. of Transportation, Washington, USA, p. 107, 2015.

[8] Jaczewski M., Judycki J., Jaskuła P., „Lepkoplastyczne modelowanie mieszanek mineralno-asfaltowych przy długim czasie obciążenia za pomocą krzywych wiodących i jego ograniczenia", Drogownictwo, 10/2015, pp. 336–340.

[9] P. Zieliński, "Study of the possibility of increasing manufacture waste asphalt shingles additive to hot mix asphalt", 18 International Multidisciplinary Scientific GeoConference SGEM 2018, Volume 18, 2018, pp. 191–198. https://doi.org/10.5593/sgem2018/4.2/S18.025

[10] PN-EN 12697-33 „Mieszanki mineralno-asfaltowe. Metody badań mieszanek mineralno-asfaltowych na gorąco". Część 33: Przygotowanie próbek zagęszczanych urządzeniem wałującym.

[11] PN-EN 12697-26 „Mieszanki mineralno-asfaltowe. Metody badań mieszanek mineralno-asfaltowych na gorąco". Część 26: Sztywność.

[12] Computer Program Statgraphics Plus v. 5.1, A Manugistics Inc. Product, Rockville, MD USA, 2000,

[13] R. Bonaquist, "NCHRP Report 614 Refining the Simple Performance Tester for Use In Routine Practice", Project 9–29, Transportation Research Board, Washington 2008. https://dx.doi.org/10.17226/14158

[14] źródło internetowe, https://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP09-29_mastersolver2-2.xls, dostęp: 25.03.2019r.

[15] M. Jaczewski, Ł. Mejłun, „Wyznaczanie parametrów lepkosprężystego modelu Burgersa mieszanek mineralno-asfaltowych na podstawie badania pod obciążeniem dynamicznym", Drogownictwo, 11/2013, pp. 344–348.

Ocena betonu asfaltowego z dodatkiem odzyskanej papy asfaltowej za pomocą krzywych wiodących modułu sztywności

Słowa kluczowe: beton asfaltowy, odzyskana papa asfaltowa (RAS), krzywa wiodąca modułu sztywności, krzywa Blacka, wykres Cole-Cole

Streszczenie:

W dobie potrzeby zrównoważonego rozwoju coraz częściej, także w mieszankach mineralno-asfaltowych, wykorzystuje się materiały z recyklingu. Oprócz granulatu asfaltowego pochodzącego z frezowania przebudowywanych nawierzchni innym materiałem zawierających cenne lepiszcze asfaltowe jest odzyskana papa (RAS). Zastosowanie RAS pozwala zmniejszyć zużycie nowego asfaltu a także kruszywa drobnego, przy równoczesnym spełnieniu przez mieszankę wymagań technicznych. Jak wynika z przeglądu literatury podstawowym problemem mieszanek mineralno-asfaltowych z dodatkiem RAS jest ich zachowanie w niskich temperaturach eksploatacyjnych, prowadzących do powstawania spękań nawierzchni. Równocześnie badania pokazują, że dodatek odpadowej papy asfaltowej pozwala poprawić odporność mieszanki na deformacje trwałe, powstające w podwyższonych temperaturach eksploatacyjnych. Jedną z najbardziej efektywnych metod oceny właściwości MMA w szerokim zakresie obciążeń (temperatura i czas obciążenia) jest przedstawienie w formie krzywej wiodącej modułu sztywności, co zostało wykonane w przedmiotowej pracy.

Do badań wykorzystano mieszankę betonu asfaltowego AC 16 W 50/70 z dodatkiem 4% RAS i porównawczo bez tego dodatku. Krzywa uziarnienia i całkowita zawartość lepiszcza w obu mieszankach została zaprojektowana na tym samym poziomie, aby wyeliminować ewentualny wpływ składu mieszanki na jej właściwości. Do badania z każdej mieszanki przygotowano metodą wałowania po 2 płyty o wymiarach 405×305×90 mm, z których wycięto belki o wymiarach 63,5×50×405 mm. Następnie po wysezonowaniu próbek zgodnie z PN-EN 12697-26 wykonano badania dynamicznego modułu sztywności metodą belki czteropunktowo zginanej, przy poziomie odkształceń 50×10-6. Badania przeprowadzono na 6 próbkach dla każdej MMA, w 4 temperaturach: 0°C, 10°C, 20°C i 30°C oraz przy 6 częstotliwościach: 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, 10 Hz, 20 Hz i 30 Hz. Następnie dla 100-go cyklu obciążenia odczytywano wartości zespolonego modułu sprężystości i kąta przesunięcia fazowego. Do oceny istotności różnic wyników pomiędzy badanymi mieszankami wykorzystano testy wielokrotnych porównań z wykorzystaniem kwadratów najmniejszych różnic w programie Statgraphics.

Wyniki badań przedstawione w formie krzywych Blacka pokazały, że mieszanki z dodatkiem RAS charakteryzują się mniejszą wrażliwością termiczną w zakresie zespolonego modułu sztywności i kąta przesunięcia fazowego od mieszanki referencyjnej. Badania pokazały, że mieszanka z dodatkiem RAS jest bardziej sztywna i sprężysta w zakresie wyższych temperatur (20°C i 30°C) i niższych częstotliwości obciążeń, co objawia się wyższymi wartościami zespolonego modułu sztywności oraz części rzeczywistej modułu sztywności i niższymi wartościami kąta przesunięcia fazowego oraz części urojonej modułu sztywności. W temperaturze 0°C zachowanie obu mieszanek jest bardzo zbliżone, natomiast w temperaturze 10°C stwierdzono istotne różnice pomiędzy badanymi mieszankami jedynie dla niskich częstotliwości obciążenia (do 5 Hz). Ponadto wyniki przedstawiono w formie sigmoidalnych krzywych wiodących modułu sztywności i kąta przesunięcia fazowego, wykorzystując procedurę podaną w raporcie NCHRP. Zastosowano zasadę superpozycji czasowo-temperaturowej, częstotliwość zredukowaną jak również współczynniki przesunięcia temperaturowego obliczono z wykorzystaniem równania Arrheniusa. Wartość maksymalnego modułu sztywności MMA wyznaczono z wykorzystaniem modelu Hirscha, gdzie maksymalna sztywność lepiszcza asfaltowego to 1 GPa. Uzyskane wg badań i modelu maksymalne wartości zespolonego modułu sztywności obu mieszanek są bardzo podobne, podczas gdy wartości minimalne różnią się dość istotnie, tj. minimalna sztywność mieszanki z dodatkiem RAS jest około dwukrotnie wyższa w porównaniu do mieszanki referencyjnej. Uzyskane współczynniki determinacji (R^2) dla modeli krzywych wiodących są satysfakcjonujące i wynoszą: 94% dla mieszanki referencyjnej oraz 93% dla mieszanki z dodatkiem RAS. Dla obu mieszanek zbadane wyniki zespolonego modułu sztywności dla temperatury 0°C są niższe od wyznaczonych z modelu, co można wytłumaczyć niedoszacowaniem maksymalnych wartości przez model Hirscha. W zakresie wysokich częstotliwości obciążeń dla obu mieszanek stwierdzono zbliżone wartości kąta przesunięcia fazowego, natomiast wraz ze spadkiem częstotliwości obciążeń kąt ten w przypadku mieszanki z dodatkiem RAS zaczyna być istotnie niższy w stosunku do mieszanki referencyjnej. Generalnie mieszanki

z dodatkiem RAS wykazują większą sztywność i sprężystość przy niższej prędkości obciążeń i w wyższych temperaturach, co jest pozytywnym efektem w aspekcie redukcji deformacji trwałych. Powyższe wyniki potwierdziły poprawę odporności na koleinowanie dla mieszanek z RAS, zaobserwowaną we wcześniejszych testach. W przyszłości należy rozszerzyć badania mieszanek z dodatkiem RAS także w aspekcie zmęczenia, zwłaszcza w zakresie stałego poziomu odkształcenia.

Received: 2020-11-12, Revised: 2021-01-26