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Asphalt concrete subjected to long-time loading at low temperatures – deviations from the time-temperature superposition principle

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Abstract

The article presents the observed deviations from the time-temperature superposition principle of asphalt concretes, tested in the bending beam creep test at low temperatures for a long time of loading. In almost all tested asphalt concretes, deviations appeared after 500 seconds of loading at the temperature of −10°C. Some types of bitumen presented deviations at other temperatures – usually the harder the grade of the bitumen, the higher was the temperature of appearance of deviation. The article investigates also the impact of the following factors on the described deviations: type of bitumen, assumed time of loading and level of loading.

Keywords: low-temperature properties; master curve; viscoelasticity; creep; deviations from time-temperature superposition principle

1. Introduction

1.1. Background

The time-temperature superposition and thermo-rheological simplicity principles belong to the basic assumptions in the linear viscoelastic analysis of bitumen and asphalt mixtures. Since the first applications of these principles for polymers [1] and, later, bitumen and asphalt mixtures in the 1960s [2], they have been commonly used [3]. The concept of a single curve to describe the behaviour of the tested material for the whole temperature and time range is very useful. In most cases, especially normalised test procedures, bitumen and asphalt mixtures comply with the aforementioned principles. However, in some cases both bitumen and asphalt mixtures show results different than predicted on the basis of the time-temperature superposition principle. A few different types of deviations from these principles are known and described in the literature.

In the case of bitumen, deviations from one straight curve may be visible, especially in the case of bitumen modification with different kinds of polymers [4–11] or as a results of ageing of the bitumen [12]. These deviations are especially apparent in the black diagram as separate lines for different temperatures. Some researchers even describe this kind of behaviour, where it is possible to create one unique curve for stiffness modulus, but not in the case of phase angle, as “partial time-temperature superposition principle” [11,13]. Deviations from the thermo-rheological simplicity were also reported by [14]. Stiffness moduli of the tested bitumen predicted in the research were slightly higher than those obtained directly from the laboratory tests.

In the case of bitumen-filler mastics and asphalt mixtures it is generally accepted that materials comply with the time-temperature superposition principle and thermo-rheological simplicity. Deviations from those principles are not commonly described. Nevertheless, some researchers [15–20] reported behaviour which was not completely consistent with the commonly accepted rheological models. Laboratory tests described in the mentioned studies were conducted at moderate or elevated temperatures.

The authors of this paper observed that for long times of loading at low temperatures asphalt concretes exhibited evident deviations from thermo-rheological simplicity. In the creep test conducted on beam specimens, tested asphalt concretes behaved similarly to solid elastic materials – their creep under constant load either stopped or strongly decreased. The value of stiffness modulus in some tested cases for a long loading time was almost constant and it seemed to be independent of the time of loading. The probable explanation of this case was that the time of loading was still too short. For long loading times, when the value of stiffness modulus is almost independent from the time of loading, the validity of the time-temperature superposition principle is doubtful. While the experimental results obtained at the three tested temperatures can be shifted and the first parts of the stiffness curves (until around 500 seconds) comply completely with the time-temperature superposition principle, the values obtained for longer times will not coincide with the rest of the results. They will usually present either asymptotic behaviour (in the case of hard grade bitumen) or slope different than the stiffness modulus master curve (in the case of softer bitumen). For these longer times of loading, values determined from the constructed master curve will be much lower than those obtained from the laboratory investigation. Moreover, the deviation from the master curve increases with the increase in the time of loading [21–23]. This kind of deviation can result in generating large errors in computational analyses performed on the basis of master curve models, when long times of loading are taken into consideration [24]. Interestingly, this kind of behaviour was not noted in the long time creep tests conducted on asphalt concretes at higher temperatures [25], even when laboratory tests were made in the range of strain which strongly exceeded the assumed limit of linear behaviour.

1.2. Modelling of asphalt concrete

Literature presents numerous models used for description of behaviour of asphalt concrete under static loading [26], such as series-parallel models, spectral response functions, ladder models and mathematical models. In this analysis only the two most commonly used types of models were taken into consideration: series-parallel Burgers models and different mathematical models of master curves. In further studies application of 2S2P1D [27] for description of test data is planned.

It was assumed that materials presented and analysed in this paper can be modelled as linear-viscoelastic materials, i.e. relation between stress and strain is linear and material properties are not dependent on the level of load used or deformation of the tested specimen. Limit of application of linear viscoelasticity is given in the literature in different approaches: [28–32] suggested that the limit of linear behaviour depends on the applied stress, the test temperature and time of loading. On the other hand, [5,11,33] gave the limiting values of strain up to which behaviour of bitumen and asphalt mixture is assumed as linear. In the case of temperatures below 0°C, the tested asphalt mixture specimens complied with both of the stated requirements. At the temperature of 0°C the tested materials exceeded the limit given by Di Benedetto [11], but still presented the steady flow stage, without any signs of tertiary flow or destruction of the test specimen.

1.2.1. Series-parallel Burgers model

The Burgers series-parallel model, which was used in this paper, is presented in Fig. 1. It comprises of 2 dashpots and 2 springs. It is a linear connection of two simple viscoelastic models: Maxwell model and Kelvin-Voight model. Despite its simplicity, recent research shows that it can be used in prediction of thermal stresses with very good reliability [24,34].

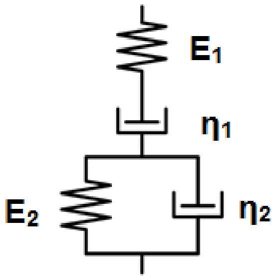


Fig. 1. The analysed series-parallel Burgers model.

The general stress-strain relationship of the model is given by the following differential equation [35]:

$$\left[\frac{d^2}{dt^2}\cdot\frac{\eta_1\eta_2}{E_1E_2}+\frac{d}{dt}\left(\frac{\eta_1}{E_1}+\frac{\eta_2}{E_2}+\frac{\eta_1}{E_2}\right)+1\right]\cdot\sigma(t)=\left[\frac{d^2}{dt^2}\frac{\eta_1\eta_2}{E_2}+\frac{d}{dt}\eta_1\right]\cdot\varepsilon(t) \tag{1}$$

where: E_1 – instantaneous modulus of elasticity, MPa, E_2 – modulus of retarded elasticity, MPa, η_1 – coefficient of viscosity of steady flow, MPa·s, η_2 – coefficient of viscosity of retarded flow, MPa·s, t – time of loading, s.

Solution of equation (1) for the case of constant load is given by equation (2).

$$\varepsilon(t)=\sigma_0\left\{\frac{1}{E_1}+\frac{t}{\eta_1}+\frac{1}{E_2}\left[1-e^{\left(-t/\lambda_2\right)}\right]\right\} \tag{2}$$

where: σ_0 – constant load, MPa, λ_2 = retardation time ($\lambda_2 = \eta_2/ E_2$), s.

1.2.2. Master curve mathematical models

Assuming that the material complies with the time-temperature superposition principle and presents linear viscoelastic behaviour, the conception of master curve enables creation of one line to describe the whole spectrum of temperatures and times of loading. Master curve is created by shifting separate stiffness curves along the time axis. The relationship between these curves is described by shift factor α_T. Master curve mathematical models used for the description of asphalt concrete are mostly sigmoidal, sinusoidal or polynomial functions, both symmetrical and nonsymmetrical [26,36]. Every function can be applied with slight modifications for both time and frequency domains. All of the commonly used master curve functions are phenomenological equations, which give the best fitting to the available laboratory test data. It is the main reason why most of them are still subject to corrections and improvements.

Shift factor α_T, which describes relationships between separate stiffness curves obtained for different temperatures, can be determined using two major approaches – free shifting or using one of the equations, such as WLF [37][38], logarithmic polynomial or Kaelble [38].

One of the most difficult issues in creation of master curves for asphalt concrete is the upper stiffness modulus asymptote, due to complex behaviour of the material. In case of bitumen, limiting value of stiffness modulus is constant and independent of the used type of bitumen – it ranges from 3 to 6 MPa [4,39]. For asphalt mixtures, either Witczak [40] or Hirsh [41,42] equations are usually taken into consideration for the assumption of the maximum modulus. This approach uses basic asphalt mixture properties and maximum value of bitumen stiffness for determination of the modulus. However, in the case of asphalt mixtures designed according to the Polish technical requirements, results obtained from laboratory tests very often exceeded those calculated from mathematical equations, probably due to the use of hard grade bitumen (usually 35/50 and even 20/30) in the mixture. In this study, results from laboratory tests (ITSM test) conducted at the temperature of −30°C were assumed as the maximum values of stiffness modulus.

Two different master curve equations were selected for the study. One of them was the CAM model [36,39,43,44], which was originally used for description of bitumen behaviour. Its basic function is given by equation (3).

$$\boldsymbol{S}(\xi) = \boldsymbol{S}_{glassy}\left[1+\left(\frac{\xi}{\lambda}\right)^{\beta}\right]^{-\frac{\kappa}{\beta}} \quad (3)$$

where: S_{glassy} – glassy state modulus (maximum stiffness modulus), ξ – reduced time, β, λ, κ – fitting parameters.

Second model selected for the analysis was the Richards function described in [38]. It is a minor modification of the equation used for Simple Performance Test [45]. Both functions differ by one parameter λ, which changes the equation into a nonsymmetrical function. In this study, instead of using Kaelble shift factor, free shifting was used to connect stiffness curves obtained at different temperatures. Richards model function modified for the purpose of this study is given by:

$$\log\left|E^*\right| = \delta + \frac{\alpha-\delta}{\left[1+\lambda e^{\beta+\gamma\log\left(1/t\right)}\right]^{1/\lambda}} \quad (4)$$

where: |E*|– complex stiffness modulus, psi/MPa, t – reduced time, δ – value of the lower asymptote (minimum value of stiffness modulus; treated as a fitting parameter), α – the value of the upper asymptote (determined from laboratory test conducted at the temperature of −30°C), λ, β, γ – fitting parameters responsible for the shape of the function.

In both cases, fitting parameters of the master curve equations were determined using SOLVER package of MS Excel software. The target function was selected according to the minimal value of the root mean square error.

2. Outline of the deviations from thermo-rheological simplicity

Figs. 2a, 2b and 2c present results typical of an asphalt mix whose behaviour is inconsistent with the principle of time-temperature superposition. Fig. 2a shows the creep curve of the mix which, after a long time of constant loading, reaches a constant (or nearly constant) value of strain or exhibits very slow viscous flow. Such behaviour is typical of "solid-type" materials and can be described with the Zener model. Most of the tested asphalt concretes showed such behaviour at low temperatures equal to or less than −10 °C. Fig. 2b shows stiffness curves for such materials on a logarithmic scale. It can be seen that after long loading time the stiffness of the mix reaches a constant value for a given temperature T_1 or T_2. After shifting along the time axis, the stiffness curves at T_1 and T_2 only partly coincide at short time of loading and do not coincide for long time of loading. Master curve obtained from the shifted stiffness curves is presented in Fig. 2c. It does not present one smooth curve, but branches into several characteristic "tails" for each testing temperature below or equal to −10°C. The described deviations from the thermo-rheologically simple behaviour were observed by the authors in most of the tested materials, regardless of the used mineral mixture or bitumen type. Some exceptions were also observed. First, in the case of hard grade 20/30 neat bitumen, where the deviations appeared at the temperature of 0°C. Second, in the case of hard grade 20/30 multigrade bitumen, in which the deviations appeared only at the temperature of −20°C.

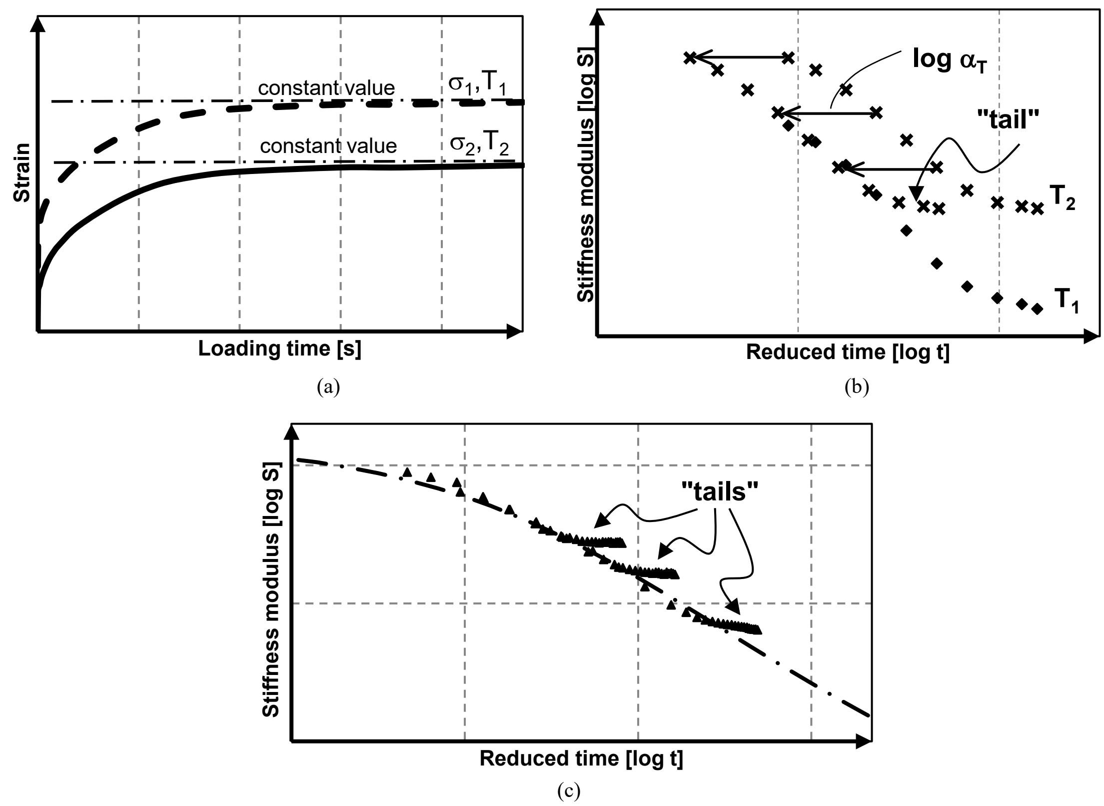


Fig. 2. The outline of the deviations from thermo-rheological simplicity: (a) creep curves, (b) stiffness moduli, (c) master curves of stiffness moduli, after [21].

3. Materials and methods

3.1. Materials and preparation

Two types of asphalt concretes were used for the purpose of this study – high modulus asphalt concrete (HMAC) used for the binder and base course with three types of bitumen (neat, polymer modified and multigrade) and, for the sake of comparison, a typical asphalt concrete (AC) used for the binder course. Finally, four different mixtures were evaluated (AC 16W 35/50; HMAC16 20/30; HMAC16 PMB 25/55-60; HMAC16 20/30 MG). All of the materials were designed in accordance with the Polish technical requirements and appropriate EN standards. Gneiss aggregate, crushed sand and limestone filler were used for the production of the mixtures. No additives were added to the asphalt mixtures. Before the compaction of the test specimens, all asphalt mixtures were subjected to the procedure of short-term ageing (acc. to SHRP-007 standard). Basic properties of the bitumen and asphalt mixtures used are presented in Tables 1 and 2 respectively. Properties presented in Table 2 were determined during the design of the asphalt mixture.

Table 1. Basic properties of the bitumen used

Property:	Type of bitumen			
	35/50	20/30	PMB 25/55-60	20/30 MG
	neat	neat	SBS-polymer modified	multigrade
Properties before TFOT ageing				
Penetration, 25°C, 0.1 mm, acc. to EN 1426	48	23	28	24
R&B temperature, °C acc.to EN 1427	53	58	62	68
Dynamic viscosity, Pa·s, acc. To EN 12596 at temp.:				
• 60°C	659.3	3063.0	not tested	not tested
• 90°C	15.9	48.5	66.6	137.0
• 135°C	0.6	1.3	1.6	2.0
• 160°C	not tested	0.4	0.5	0.5
Properties after TFOT ageing				
Penetration, 25°C, 0.1 mm, acc. to EN 1426,	45	21	26	24
R&B temperature, °C acc. to EN 1427	57	64	68	72

Table 2. Basic properties of the asphalt mixtures used

Property	Designation of the asphalt mixture			
	AC 16W 35/50	HMAC16 20/30	HMAC16 PMB 25/55-60	HMAC16 20/30 MG
Grading (passes # [mm], %)				
31.5	100	100	100	100
22.4	100	100	100	100
16	97.3	97.8	97.8	97.8
11.2	78.0	81.7	81.7	81.7
8	57.7	62.5	62.5	62.5
5	44.5	49.4	49.4	49.4
2	27.4	32.0	32.0	32.0
0.125	7.1	9.2	9.2	9.2
0.063	5.5	7.3	7.3	7.3
Binder content %, m/m	4.6	5.0	5.0	5.0
Air void content, acc. to EN 12697-8, %	4.3	3.6	3.5	3.5
VMA, %	15.2	15.5	15.4	15.4

VFA, %	71.8	76.9	77.3	77.3
Rutting Resistance, acc. to EN 12697-22,				
WTS_{Air}	0.10	0.10	0.07	0.04
PRD_{Air}	6.9	4.8	5.3	4.0

The tests were conducted on beam specimens (50 x 50 x 300 mm). Beam specimens were cut from asphalt mixture slabs (300 x 300 x 50 mm) compacted using a standard Cooper laboratory compactor. The target degree of compaction was determined in the range of 98-100% of Marshall specimen bulk density. Five specimens were cut from each compacted slab.

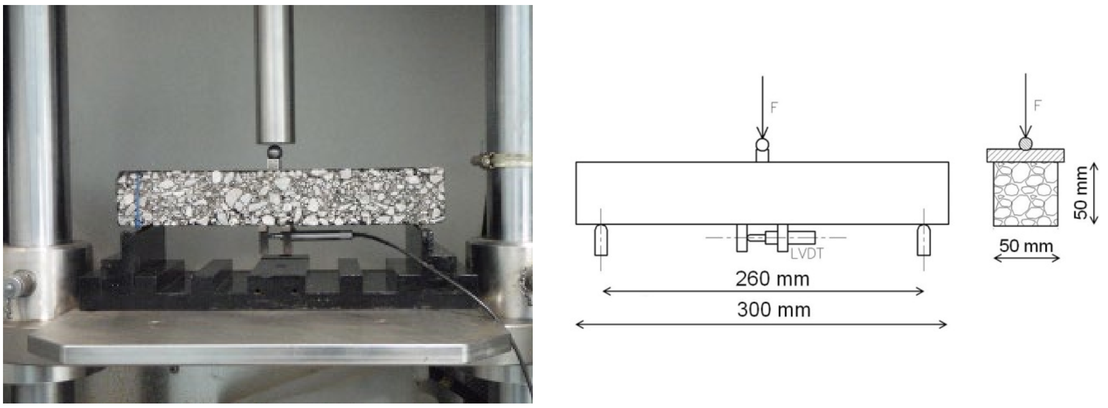
Preliminary flexural strength test for each test temperature (0°C, −10°C, −20°C) was performed on five beam specimens. The bending beam creep test for each test temperature (0°C, −10°C, −20°C) was performed on at least three specimens. Two remaining specimens from the slab were kept as a reserve for unpredictable situations (for example, if the test machine stopped due to an energy outage). For the entire planned experiment, at least six slabs of each mixture were needed (three for determination of flexural strength and three for bending beam creep test). Before the tests, specimens cut from all the six slabs of a given mixture were mixed and random five beams were chosen for specific test at each temperature. For each beam specimen, air void content was determined, in order to verify whether it was in the range of air void content determined on Marshall specimen.

3.2. Methods

To evaluate the long-time load stiffness modulus, the three point bending beam test (Fig. 3) was used [46,47]. The test was performed in a standard hydraulic press. The test consisted of two phases: in the first phase beams were subjected to constant static load for a time of 2400 seconds; in the second phase beams were left unloaded for a time of 1200 seconds. The applied load depended on the temperature at which the test was conducted. Load values were assigned as about 30% of the flexural strength. In one case (HMAC 20/30), two additional levels of loads were tested. Applied values of load are presented in Table 3. Values of applied load vary for different mixtures, depending on flexural strength determined in laboratory test. For all beams the test temperatures were −20°C, −10°C and 0°C. All specimens were conditioned at the selected temperature for 24 hours before the test. The time of conditioning was strictly controlled to avoid the influence of physical hardening [48–52] on the values of test results. The strain at the bottom of the specimen was measured with an LVDT sensor. Coefficient of variation for the measured strain test results equalled up to 20% [46,47].

Table 3. Applied values of static load

Test temperature	Flexural strength [MPa]	Value of applied stress [MPa]	Value of applied load [kN]
0°C	4.17–7.21 (mean 5.80)	1.7–2.2	0.55–0.71
−10°C	5.49–7.85 (mean 6.65)	2.7	0.86
−20°C	6.02–7.82 (mean 6.75)	2.7	0.86



(a) (b)

Fig. 3. Bending beam creep test of asphalt concrete: (a) the specimen before the test; (b) scheme of the specimen.

4. Results and discussion

4.1. Bending beam creep test results

Typical creep curves obtained from laboratory tests for the temperatures of 0°C, −10°C and −20°C are presented in Fig. 4. The results for each temperature are presented for a single specimen from the whole batch of a chosen mixture type. In this case, HMAC16 with 20/30 neat bitumen was used as an example. Apart from isolated results obtained at the temperature of 0°C, the strain values remained within the linear viscoelasticity limit given by Di Benedetto [11]. However, even in the case of the temperature of 0°C, when the limit was slightly exceeded, tested specimens showed steady flow, without any sign of tertiary flow or specimen destruction.

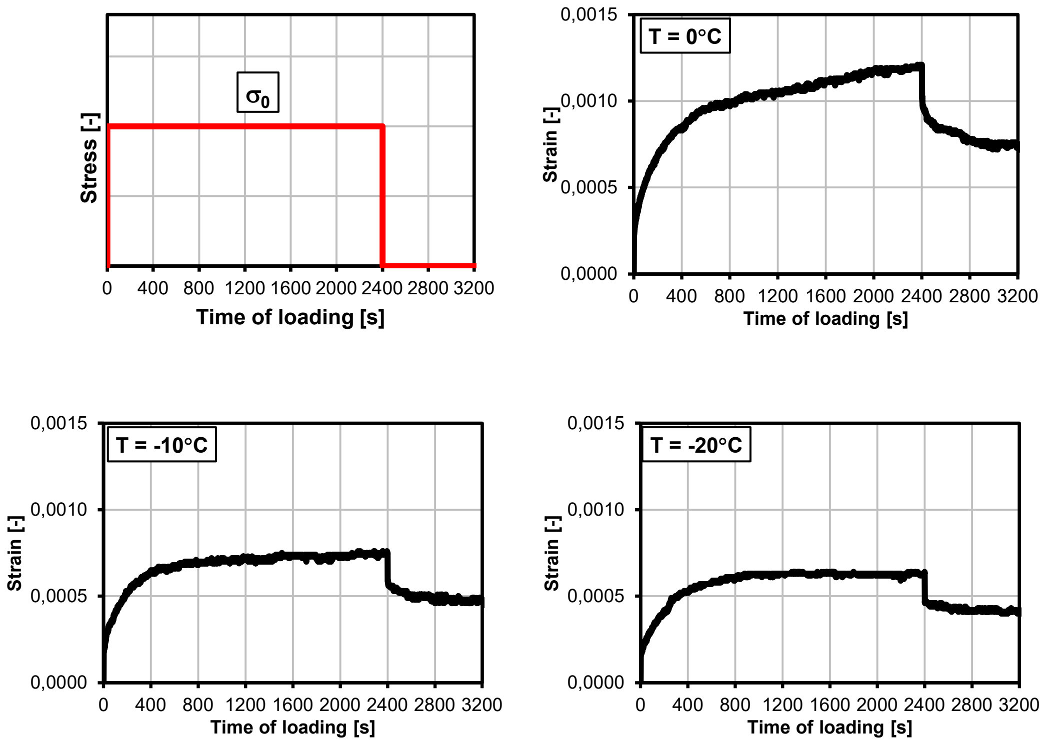


Fig. 4. (a) Applied load; (b), (c), (d) typical creep curves obtained from bending beam creep test of asphalt concrete for the temperatures of 0°C, −10°C and −20°C.

Additionally, to confirm the assumption of linear viscoelasticity, one mixture – HMAC16 with 20/30 neat bitumen – was tested at the temperature of −20°C with three different levels of stress. The results for four selected time points (8, 60, 360 and 2400 seconds) are presented in Fig. 5. Taking into consideration the variability of the test results (up to 20% [46,47]), all the results for specific time points, apart from selected results for 8 seconds for the highest applied stress, present similar values of stiffness modulus regardless of the stress used.

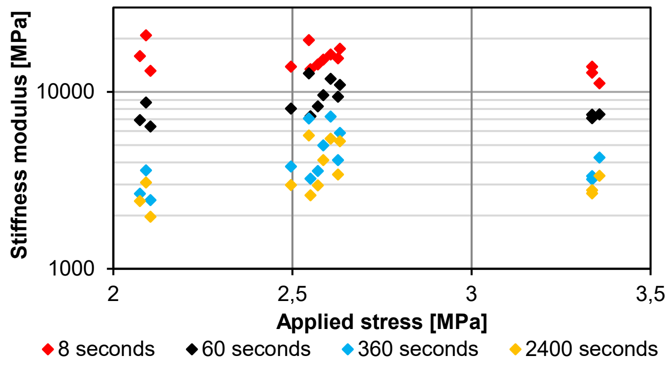


Fig. 5. Verification of the linear viscoelasticity of tested mixtures. Results for the mixture HMAC16 with 20/30 neat bitumen, test temperature −20°C, three levels of applied load.

Fig. 6 presents results obtained at the temperature of −10°C for all the asphalt mixtures analysed in this paper.

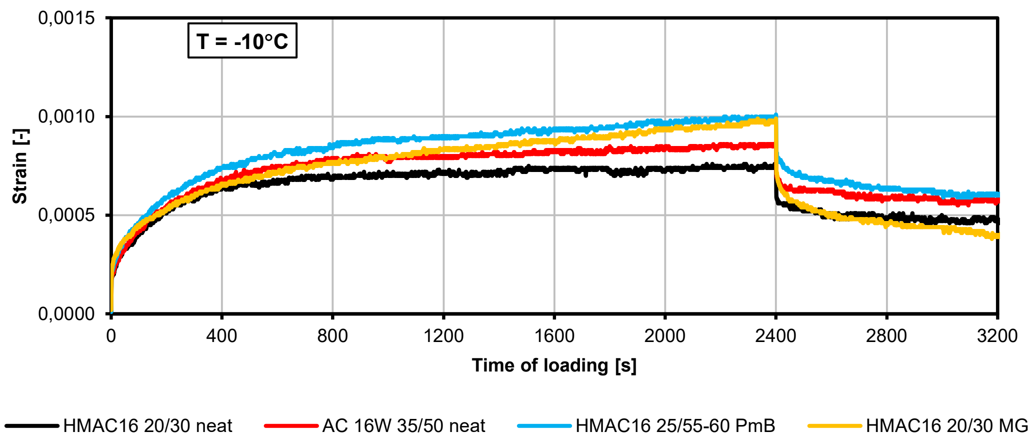


Fig. 6. Creep curves obtained from the bending beam creep test of asphalt concrete for the temperature of −10°C for all the tested mixtures.

As can be seen in Fig. 6, all the tested mixtures comply with Burgers rheological model, with all its phases: instant elastic strain and steady creep state for the loaded phase, and instant return and steady relaxation during the unloaded phase. All the tested mixtures present steady creep with time of loading. In the case of hard grade neat bitumen (20/30 neat bitumen, black line), it might seem that the steady flow stage of the creep curve flattens and almost reaches horizontal asymptote. An elongated test, which lasted 8 hours, showed that the specimen still creeps, but the rate of creep is very slow, similar to the rate typical of elastic materials, such as cement concrete.

4.2. Modelling of asphalt concrete using laboratory test results

Test results obtained from the bending beam creep test were later described using two groups of mathematical models: rheological series-parallel model and master curve mathematical models using procedures developed at the Department of Highway Engineering of the Gdansk University of Technology. In all cases the fitting was performed on the basis of root mean square error criterion.

4.2.1. Modelling using rheological series-parallel model

Modelling using rheological model was based on the fitting of equation (2) using root mean square error. Three of the four Burgers model parameters were treated as fitting parameters: E_2, η_1 and η_2. In the case of the E_1 elastic modulus, it was obtained from the unloaded phase of the creep curve, as seen in Fig. 7. E_1 elastic modulus was calculated as $E_1 = \varepsilon_1/\sigma_0$.

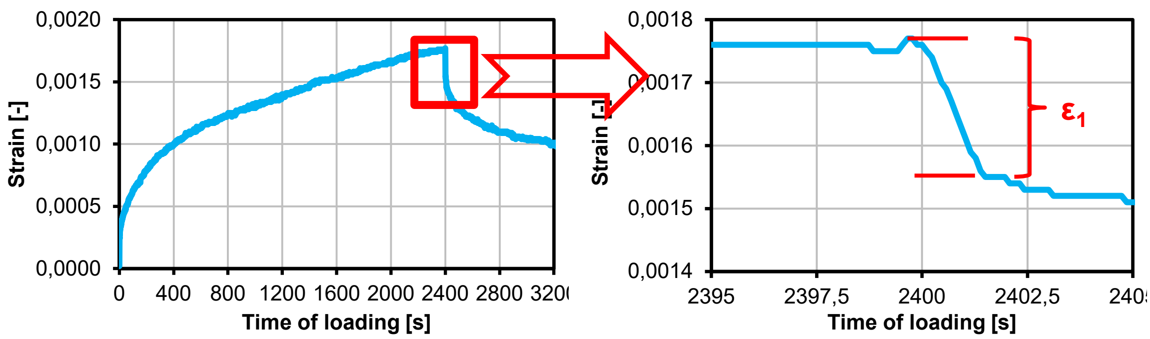


Fig. 7. Determination of the E1 elastic modulus of Burgers model.

Such a way of calculation of the E_1 parameter resulted in higher homogeneity of the obtained results and eliminated random deviations coming from the factors associated with the loading phase (especially from the fitting of steel beam used for centring of the load on the specimen). Fitting of the test results for different temperatures using described methodology is presented in Fig. 8. The determined parameters of Burgers model for all the tested asphalt mixtures are presented in Table 4.

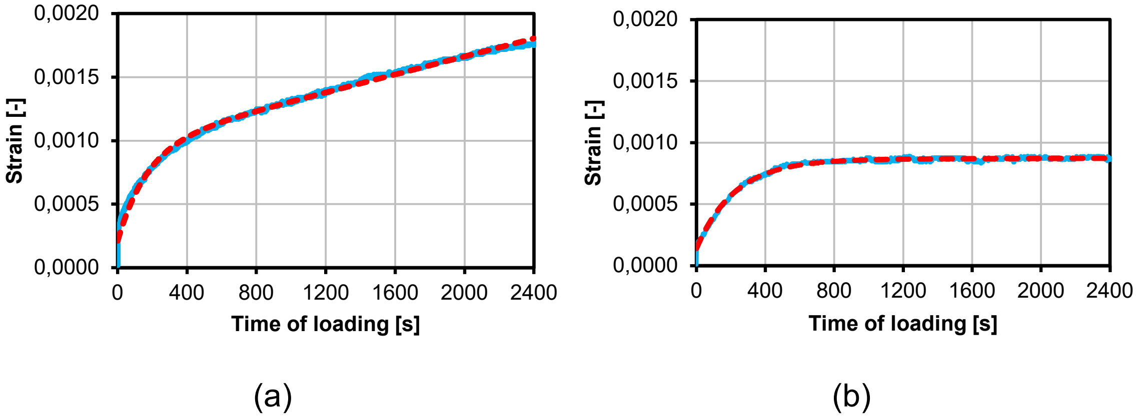


Fig. 8. Fitting of the creep curves using Burgers model: (a) temperature of 0°C, (b) temperature of −20°C (continuous line – experimental results, dashed line – fitting using Burgers model).

Table 4. Burgers model parameters for all the tested mixtures

Asphalt mixture	Temperature	Burgers model rheological parameters			
		E_1	E_2	η_1	η_2
	°C	MPa	MPa	MPa·s	MPa·s
HMAC16 20/30	0	11 666	1 811	19 303 852	327 299
	−10	16 338	4 437	128 667 390	1 000 705
	−20	20 243	7 950	261 050 362	1 801 012
HMAC16 PMB 25/55-60	0	8 107	1 989	4 512 138	434 479
	−10	13 417	4 017	32 637 170	798 762
	−20	17 514	4 331	98 703 764	890 505
HMAC16 20/30 MG	0	4 966	2 423	3 201 052	444 497
	−10	7 048	5 520	8 699 462	1 097 785
	−20	14 328	7 138	194 646 646	1 850 407
AC 16W 35/50	0	7 891	1 469	5 646 589	325 605
	−10	15 609	3 901	55 355 791	783 953
	−20	17 241	4 761	91 268 648	933 607

As can be seen in Fig. 6, the obtained creep curves are consistent with the Burgers rheological model and the obtained values are similar to those observed in other creep tests conducted for asphalt mixtures [46,53,54]. Nevertheless, some discrepancies are visible in comparison to the parameters obtained from cyclic tests, such as Simple Performance Tester. While both elastic moduli are quite similar, the biggest discrepancies are visible in the case of the η_1 parameter – coefficient of viscosity of steady flow. Results determined from cyclic tests [55–57] differ up to three orders of magnitude from the results obtained from creep tests. The reason for this discrepancy is still under research. Nevertheless, Burgers model parameters determined in this study were recently successfully used for calculation of thermal stresses in [24].

4.2.2. Modelling using master curves

Master curves were determined using the authors' modifications of the procedures used for Bending Beam Rheometer (BBR) and its later variant for testing of asphalt concrete [58–61]. In comparison to the aforementioned studies, the time of loading was extended to 2400 seconds, instead of typical 1000 seconds. Master curves were obtained on the basis of free shift of specific stiffness curves determined for the temperatures of 0°C, −10°C and −20°C. The temperature of 0°C was selected as the reference temperature. Each stiffness curve is the mean value of 3 different stiffness curves obtained from each tested specimen for a selected temperature. Each obtained master curve was later described using CAM and Richards models, under assumption that results comply with the thermo-rheological simplicity principle. During construction of the master curve, the observed deviations were not taken into consideration so as not to influence the shifting, and data points only up to 500 seconds were utilized. Master curves were constructed on the basis of results directly from the creep test, but also, separately, from the results back-calculated from rheological model parameters. The developed master curves, obtained from both direct and back-calculated results, along with mathematical description using CAM and modified Richards equations are presented in Fig. 9.

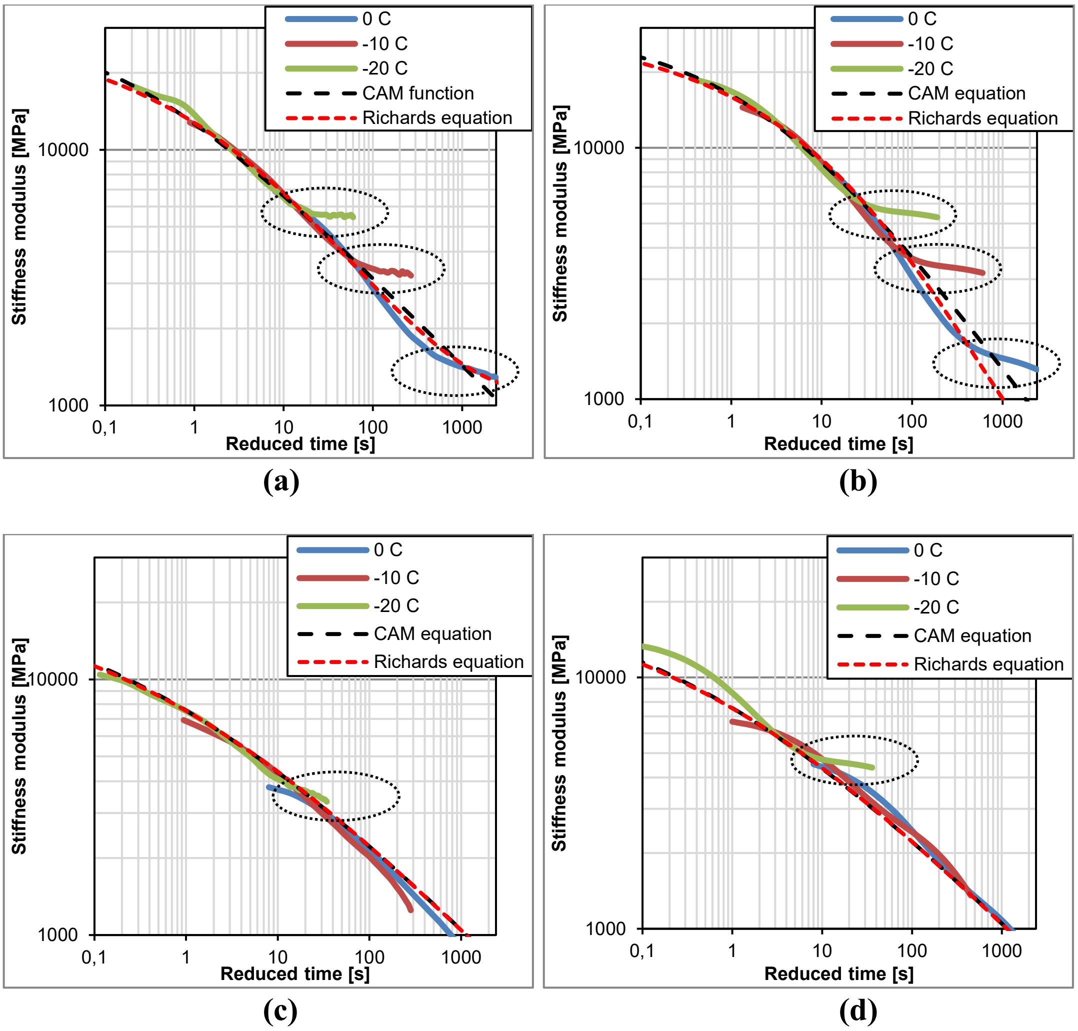


Fig. 9. Shifted stiffness curves (free shifting): (a), (c) direct results from the bending beam creep test; (b), (d) results back-calculated from the Burgers model. Deviations from the master curves are highlighted with ovals. Mixtures used: (a), (b) HMAC 20/30; (c), (d) HMAC 20/30 MG.

As can be seen in Fig. 9, for both types of data (directly from the creep test and back-calculated from the Burgers model) master curves obtained after free shifting are very similar. Nevertheless, in all cases, there are visible deviations from one continuous curve. In Fig. 9, two extreme cases are presented. In case of HMAC with 20/30 neat bitumen (Figs. 9a, 9b), horizontal deviation is visible at all the tested temperatures (from 0°C down to −20°C). In the case of HMAC with 20/30 MG, the horizontal deviation appeared only at the temperature of −20°C. In other tested cases – conventional AC and HMAC with polymer modified bitumen – the horizontal deviation appeared at the temperature of −10°C and lower.

Parameters of master curves (CAM and Richards models) of all the tested materials are presented in Table 5.

Table 5. Master curve model parameters for all the tested mixtures

Asphalt mixture	Parameters of model				
	CAM model				
	E_{max} [MPa]	λ	β	κ	
HMAC 20/30	29 723	0.168	0.506	0.348	
HMAC 25/55-60	27 018	0.203	0.587	0.360	
HMAC 20/30 MG	22 799	0.399	0.283	0.376	
AC 16W 35/50	29 885	0.044	0.857	0.332	
	Richards model				
	Max	δ [a)]	λ	β	γ
HMAC 20/30	4.473	3.027	0.001	−9.095	−0.696
HMAC 25/55-60	4.431	0.000	5.934	−0.443	−0.826
HMAC 20/30 MG	4.358	0.038	3.760	−0.582	−0.564
AC 16W 35/50	4.475	0.000	8.726	0.463	−0.980

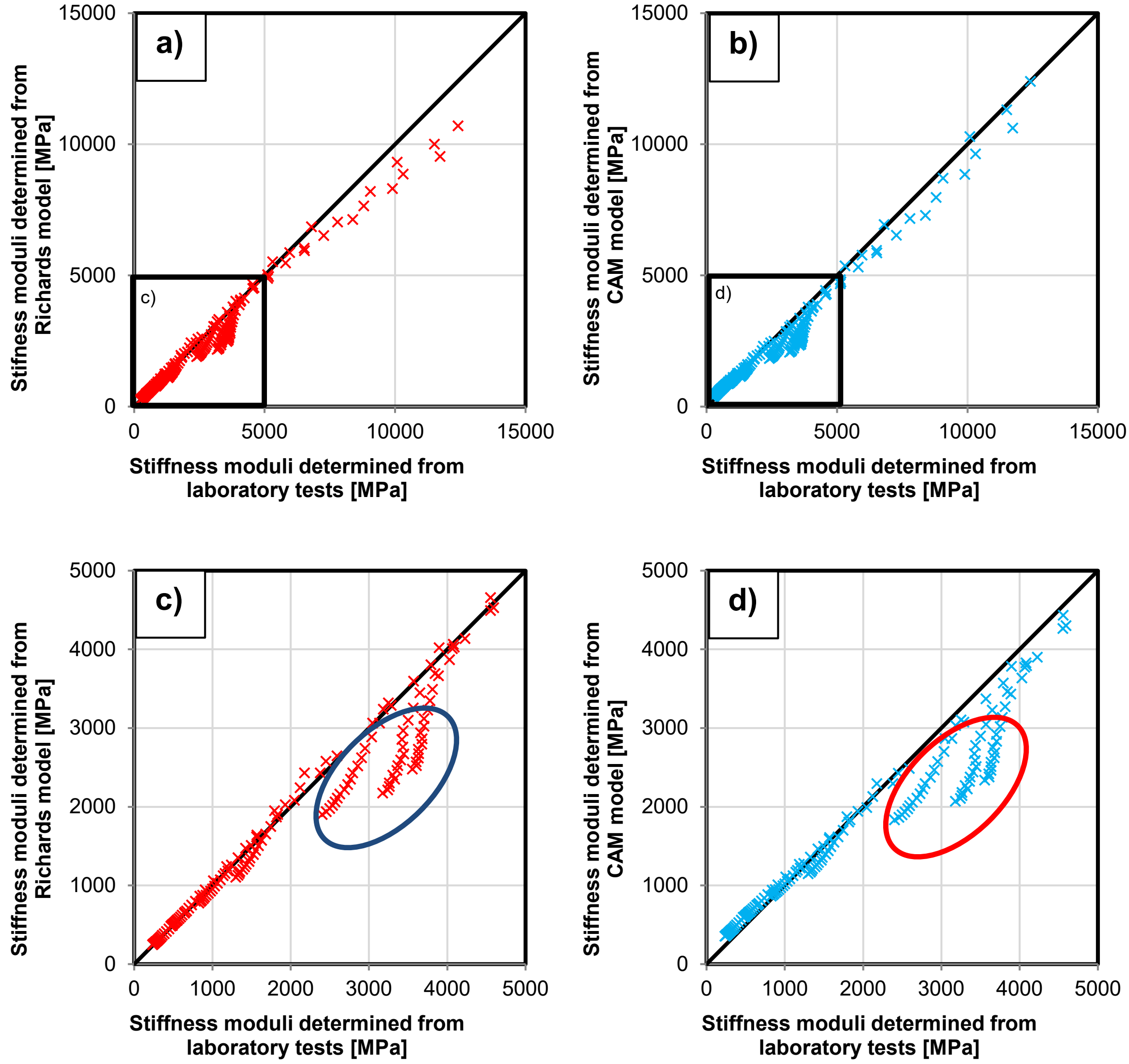
Remarks: a) δ parameter is responsible for the lower asymptote of the master curve. As can be seen from the values presented in tables, for a very long time of loading the stiffness modulus will be approaching the value of 0 MPa. While in the case of beam specimens subjected to bending this kind of situation is possible (it would be equivalent to the destruction of the specimen), from the physical point of view it is an impossibility. Therefore, values presented in the table are in this case treated as fitting parameters for the best description of the model at temperatures below 0°C and not as a physically sound general description of material's behaviour across the full spectrum of times and temperatures.

4.3. Discussion of test results

As can be seen in Fig. 8, both models gave very similar results, with similar fitting quality. Nevertheless, there are two main visible differences:

- in the case of very short reduced times, Richards model gives values lower than those obtained from the laboratory test;
- in the case of HMAC with 20/30 neat bitumen, CAM model (in contrast to Richards model), does not give any opportunity to describe the deviation from the straight section of the master curve line, as visible near the 1000s reduced time.

In one case it was also observed that for very long reduced times CAM model gave values higher than those obtained from laboratory tests. Regardless of the used model, for temperatures lower than 0°C and long times of loading, values obtained from the models are much lower than values determined from laboratory test. This situation is presented in Figs. 10b and 10d.



Remark: in figures c) and d) values obtained from both master curve models that were lower in comparison to laboratory test data are highlighted with an oval

Fig. 10. The correctness of the modelling of laboratory test data (HMAC 20/30) using two master curve models: a), c) Richards model; b), d) CAM model.

Both of the used master curve models gave similar and very good fitting of the test data, but only in the case of assumption that tested materials are thermo-rheologically simple and comply with time-temperature superposition, and time of loading used for determination of the master curve was reduced to 1000 seconds. This kind of assumption will give correct results when short-time load phenomena are modelled. In the case of long-time load phenomena, such as development of thermal stresses in asphalt pavements, values determined from the master curve will be much lower and will have strong impact on computational analyses. For example, thermal stresses calculated using that kind of data will present much lower values than those measured in the field or in the laboratory.

Authors tried to determine the main aspect which influences the appearance of the described deviations from the models used. At this stage of the research, influence of the assumed time of loading, type of bitumen and asphalt mixture composition were taken into consideration.

4.3.1. The impact of the assumed time of loading on modelling of asphalt concrete

As stated above, deviations from the models used appear at temperatures below 0°C, when the time of loading is long, usually after around 500 seconds of loading. On the other hand, typical laboratory creep test methods assume the maximum time of loading in the range from 100 to 1000 seconds [58,62,63]. As shown in Fig. 11, even when the time of loading is assumed as 1000 seconds, the deviations do not have strong impact on development of the master curve. The problem intensifies when the time of loading increases above 1000 seconds. The longer the time of loading, the more noticeable the deviations that appear. This fact is very important when master curve mathematical models are used for calculation of low temperature processes, such as thermal stresses induced in real pavements, where very long times of loading are needed, sometimes exceeding 10000 seconds. In such a case, shifted stiffness curves would be branching into multiple separate curves.

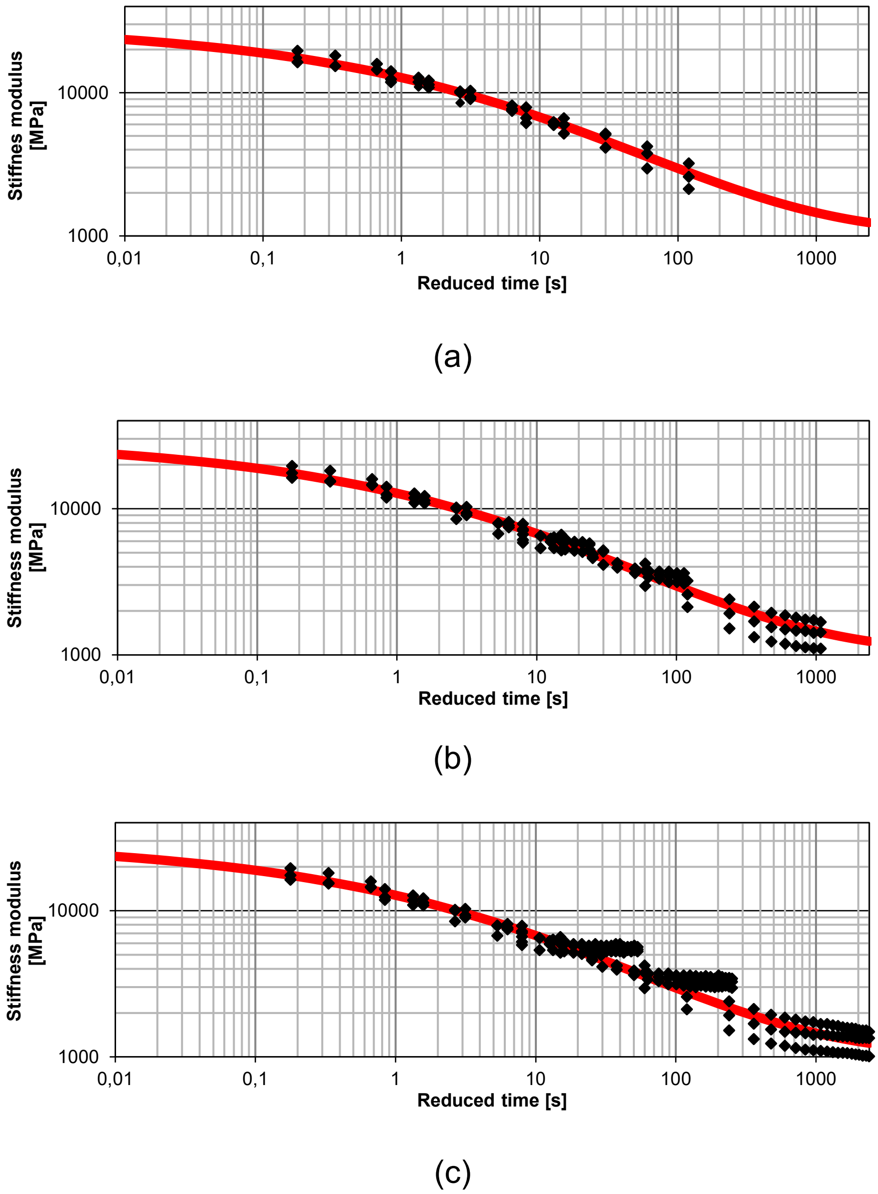


Fig. 11. The influence of time of loading on modelling of the master curve: a) 100 seconds; b) 1000 seconds; c) 2400 seconds.

In the case of temperatures higher than 0°C, deviations from the models used were not observed, even for times of loading equal to 2400 seconds. At lower temperatures, the appearance of deviation is strongly connected to the assumed time of loading. In the case of 100 seconds or even 1000 seconds, after appropriate shifting, deviations do not influence the creation of master curve. "Branching problem" appears after around 500 seconds of loading and its impact is strongly visible after 1000 seconds of loading. The type of bitumen or type of asphalt mixture did not have strong impact on the time when the "branching" of the master curve occurred.

4.3.2. Determination of the limit of the time-temperature superposition principle

To determine the time limit of application of the time-temperature superposition principle in analysis of creep test data, each of the stiffness curves was described using two logarithmic functions (see Fig. 12):

- Second order curve – for the time range from 0 to around 500 seconds, (based on an assumption that within this range the stiffness curve is mostly consistent with the time-temperature superposition principle); this part of the curve overlaps with the developed master curve for the analysed asphalt mixture.
- First order curve – for the time range in which the stiffness curve does not comply with the time-temperature superposition principle. In most cases this part of the curve approaches the horizontal asymptote.

The intersection of the two aforementioned logarithmic curves was assumed to be the time limit of the time-temperature superposition principle. Determined times (rounded up to full 20 seconds) of all the tested materials are presented in Table 6.

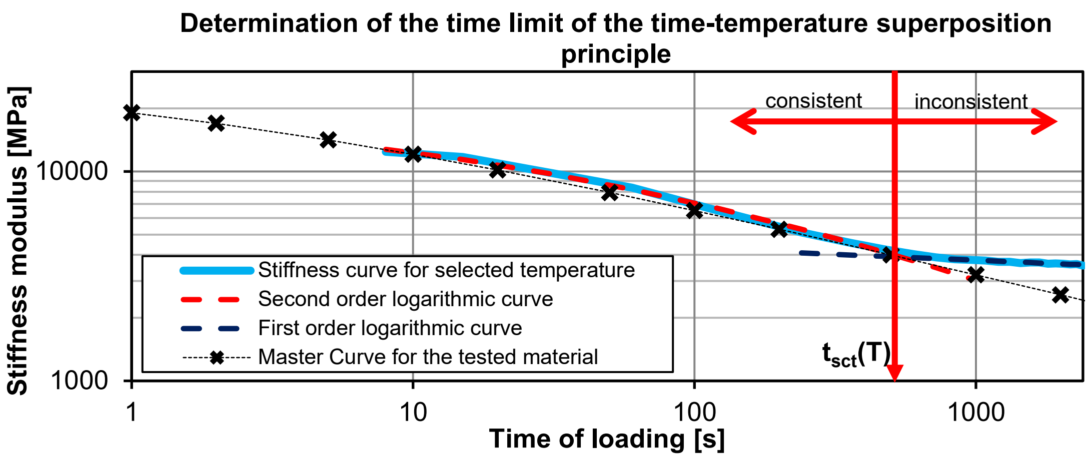


Fig. 12. Method used for determination of the limit of the time-temperature superposition principle

Table 6. The determined limit loading times in which tested materials comply with the time-temperature superposition principle

Temperature [°C]	HMAC 20/30	HMAC 25/55-60	HMAC 20/30 MG	AC 16W 35/50	AC 16W 50/70
−20	520	520	580	460	500
−10	600	440	-[a)]	580	460
0	420	-[a)]	-[a)]	-[a)]	-[a)]

a) tested specimens did not show deviation from the time-temperature superposition principle up to 2400 seconds

Time limit up to which test results were consistent with the time-temperature superposition principle at the temperature of −10°C and lower lies within the range from 400 to 600 seconds. In the described cases, master curve model covered only around 20-25% of the whole time range of the test, which is not enough for proper material description in terms of low temperature impact on asphalt mixtures.

4.3.3. The impact of type of asphalt mixture and bitumen used in asphalt concrete

Apart from the research presented in this paper, similar bending beam creep tests were conducted under other research projects carried out at the Gdansk University of Technology. Regardless of the used type of test machine or asphalt mixture [47,64] – asphalt concrete, high modulus asphalt concrete, stone matrix asphalt, porous asphalt – in all the tested cases at temperatures lower than 0°C deviations appeared after a time of loading longer than approx. 500 seconds.

It was noted that the particular type and grade of bitumen used in the asphalt mixture had a relatively strong impact on the moment of appearance of the deviations. In most cases, the first deviations appeared at the temperature of −10°C, regardless if neat or polymer modified bitumen was used. Some discrepancies were observed for two types of hard grade bitumen. First, in the case of neat hard grade 20/30 bitumen, the deviation appeared at the temperature of 0°C. This type of bitumen is characterized by a relatively high viscosity even at higher temperatures, which probably resulted in faster "stiffening" of the tested asphalt mixtures. Second case was the hard grade multigrade bitumen. In this instance, the deviation appeared much later, at the temperature of −20°C. The latter phenomenon, however, cannot be explained by the values of viscosity, as the results are similar to the values obtained for a typical polymer-modified bitumen. A probable explanation is that the viscoelastic temperature range of this type of bitumen is wider, and its behaviour is close to viscoelastic even at the temperature near 0°C. All cases are presented in Fig. 13.

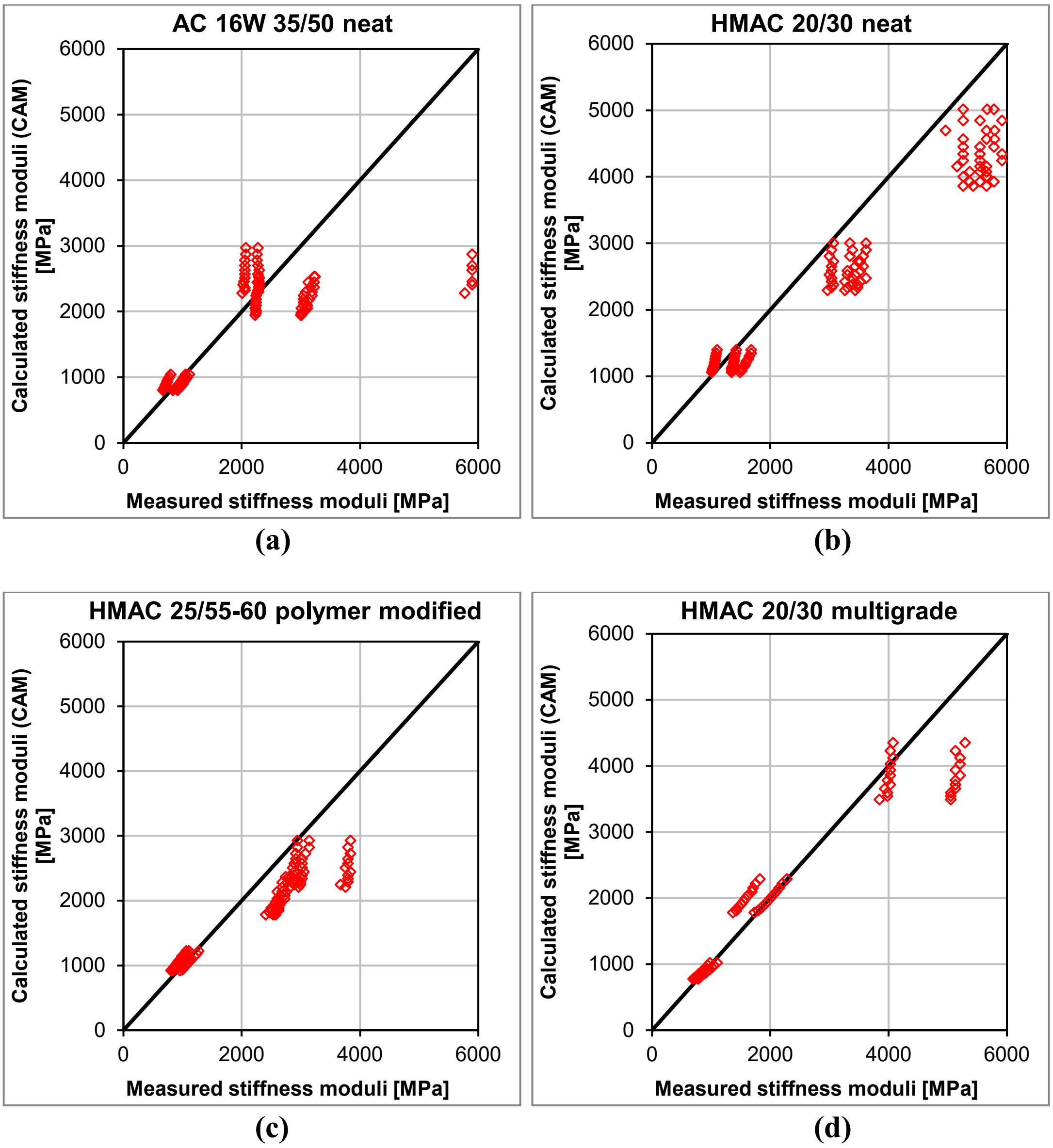


Fig. 13. Differences between calculated and measured stiffness moduli for times of loading longer than 1000 seconds: (a) AC 16W 35/50 neat bitumen, (b) HMAC 20/30 neat bitumen, (c) HMAC 25/55-60 polymer modified bitumen, (d) HMAC 20/30 multigrade bitumen.

4.3.4. The impact of the level of static loading

In most cases the value of around 30% of flexural strength was used as the constant stress that the specimen was subjected to. It was worthwhile to analyse whether the applied stress was too small to induce viscous flow. Tests with higher static load (up to 50% of flexural strength) were conducted to examine such possibility in additional research. Results of these tests are presented in Fig. 14. Creep curves measured under three static load levels (32%, 38% and 50% of flexural strength) show different limits of strain at long time of loading. For each load level two to five specimens were used. Limit of strain for static load of 50% of flexural strength is higher than for lower static loads – 32% and 38% of flexural strength – but it also reaches constant value after time of loading of about 600 to 1000 seconds. In the case of the two lower static load levels, the results of the test overlap with each other. This preliminary study on one mixture at one temperature showed that the time at which strain reaches constant limit depends on the load level and increases with higher levels of static load. A detailed investigation on different load levels at different temperatures is planned in further analyses.

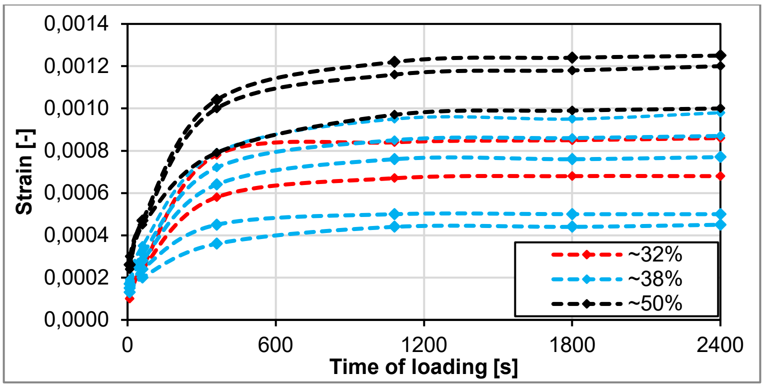


Fig. 14. Impact of different levels of static load on behaviour of asphalt mix at creep (creep curves for HMAC 20/30 neat bitumen at the temperature of −20°C), after [21] and supplemented.

5. Conclusions and further studies

The described deviations from the material models used can have strong impact on computational analyses conducted on the basis of master curves. Values of stiffness modulus determined from master curves for long times of loading are significantly lowered in comparison to the real values determined from laboratory tests. For example, in the case of calculation of thermal stresses, the calculated values can be significantly lowered or even unacceptably underestimated if only the thermo-rheologically simple part of master curve is taken into consideration. Based on the analysis, the following conclusions can be made:

- Series-parallel rheological models described each of the tested materials correctly at every tested temperature. Burgers model did not present any problems during modelling of the test data. Correctness of the data was confirmed in other studies [24].
- Neither of the master curve models described the tested materials correctly. The deviations were visible in the case of long times of loading. Under assumption of short time of loading, laboratory test data allowed to create master curves without any problems.
- It was determined that the time-temperature superposition principle limit lied within the range from 420 to 600 seconds.
- The appearance of the described deviations depended strongly on the type of bitumen used (production process and grade). The type of asphalt mixture used did not influence the appearance of the deviations.

- The level of static loading does not have strong impact on the occurrence of deviations from thermo-rheological simplicity. For the higher levels of loading the time limit of thermo-rheological simplicity principle is slightly higher.
- “Branching” model of the master curve should be created to model the complex behaviour of asphalt mixtures at low temperatures for long times of loading.

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