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# Modelling of asphalt mixes under long time creep at low temperatures

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**Abstract**

Proper description of asphalt mixtures behavior under long time load is one of the most important factors in analyses of strain and stress relations at low temperatures both from traffic and environmental loads. For example different models of thermal stress accumulation require different approaches of description of asphalt concrete. But in all cases it is required to describe its behavior under long time loading, which in some cases may be even longer than 10 000 seconds.

This paper presents advantages and disadvantages of three different models used for description of the asphalt mixes behavior in low temperatures. The authors have chosen three following approaches: generalized models, which describe asphalt mixtures using one parameter – the stiffness modulus – designated for a specific temperature and time of loading; rheological models (represented by Burgers rheological model), which describe asphalt mixtures using two or more parameters at a discrete range of temperature but at a continuous range of time of loading and master curves models which describe asphalt mixtures in a continuous range of both temperature and time of loading.

Parameters of presented models were obtained from laboratory three-point bending creep tests conducted on different asphalt mixtures: high modulus asphalt concretes (HMAC), conventional asphalt concretes (AC), stone matrix asphalt (SMA) and porous asphalt (PA). The bending creep tests were conducted at three temperatures: 0 °C, -10 °C and -20 °C for the time of loading of 2400 seconds according to the procedure developed at Gdansk University of Technology. In this study the authors presented parameters only for HMAC.

Commonly used models assume that asphalt mixture is linear viscoelastic and thermorheologically simple material. Authors found that those assumptions were not always valid for long time loads at low temperatures, especially for asphalt mixes made with hard grade bitumen.

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As the conclusions the authors presented a comparison of parameters calculated for each analysed model, advantages and disadvantages of each model and the impact of a chosen model on asphalt pavement analyses at low temperatures.


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*Keywords:* high modulus asphalt concrete; rheological models; master curve; low temperature

## 1. Introduction

Proper description of asphalt concrete behavior under long time load is one of the most important factor in low temperature computational analysis. Many thermal cracking models require stiffness or relaxation moduli for long time of loading. Values used in computational analysis are acquired through various models from laboratory tests. The range of used data from laboratory tests varies with type of model. The main aim of this article is to evaluate existing models and to find a suitable model for description of asphalt concrete low temperature behavior under long time load. Proper model should be easy to implement in computational methods and should give correct values for every possible combination of temperature and time of loading.

In preliminary study authors have chosen three different commonly used models:

- generalized models, which describe asphalt mixtures using one parameter – the stiffness modulus – designated for a specific temperature and time of loading; used for example in Hills and Brien (1965) method,
- rheological models (represented in this article by Burgers rheological model), which describe asphalt mixtures using two or more parameters at a discrete range of temperature, but for a continuous range of time of loading,
- master curves models which describe asphalt mixtures in a continuous range of both temperature and time of loading; master curves are also classified as a generalized model.

**Nomenclature**

| | |
|---|---|
| $\sigma$ | stress (MPa) |
| $\varepsilon$ | strain (-) |
| $S(T,t)$ | stiffness modulus at any time t and at any temperature T (MPa) |
| $S(T_0,t_0)$ | stiffness modulus at reduced time $t_0$ and at reference temperature $T_0$ (MPa) |
| $\alpha_T$ | shift factor |
| $\alpha, \beta, \delta, \gamma, \lambda$ | master curve coefficients |
| $E_1, E_2, \eta_1, \eta_2$ | Burger's model parameters |

### *1.1. Generalized models – stiffness modulus*

Stiffness modulus is calculated directly from the test data using following equation:

$$S(T,t) = \frac{\sigma}{\varepsilon(T,t)} \tag{1}$$

where:
$S(T,t)$ – stiffness modulus, calculated for temperature "T" and time of loading "t" (MPa),
$\sigma$ – stress during test (MPa),
$\varepsilon(T,t)$ – strain for the temperature "T" and time of loading "t".

*1.2. Rheological models (represented by Burgers model)*

Burgers model is a 4-parameter rheological model, which consists of two spring elements and two dashpot elements. Scheme and behavior of the Burgers model under constant load are presented on figure 1. Relation between strain and stress during constant load phase is given by equation 2.

$$\varepsilon(T,t) = \sigma_0 \cdot \left\{ \frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2}\left[1 - e^{\left(-t/\lambda\right)}\right] \right\} \quad (2)$$

where:

$$\lambda = \frac{\eta_2}{E_2} \quad (3)$$

$E_1$, $E_2$, $\eta_1$, $\eta_2$ – Burgers model parameters,
t – time of loading, s
$\sigma_0$ – constant stress during load phase, specific for each temperature, MPa.

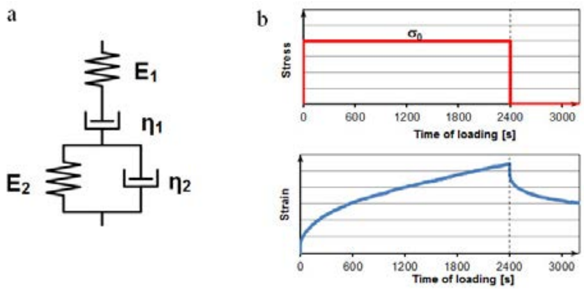


Fig. 1. (a) Scheme of the Burgers model; (b) behavior of the Burgers model under constant load.

*1.3. Generalize models – Master Curve models*

Master Curve describes stiffness modulus of asphalt mixture with one line for the whole range of temperatures and time/frequency of loading using time-temperature superposition principle. Literature (e.g. Ferry (1965), Marasteanu and Anderson (1999), Rowe et al.(2009), MEPD-G (2004), Zofka et al. (2008a, 2008b)) presents plenty of models, which can be used to describe laboratory test results. For the purpose of this article, authors chosen one model of master curve (based on the fitting accuracy done as a part of a prepared Jaczewski Ph.D. thesis) – Richards model (Rowe et al.(2009)), and one model of the shift factor $\alpha_T$ – WLF model (Williams et al. (1955); also chosen based on the fitting accurcy). Richards model is given by the equation:

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

where:
f – reduced frequency, Hz
α, δ, β, γ, λ – master curve fitting parameters.

WLF model is given by the equation:

$$\log \alpha_T = \frac{C_1 (T - T_0)}{C_2 + (T - T_0)} \tag{5}$$

where:
$\alpha_T$ – shift factor,
$C_1$, $C_2$ – WLF model fitting parameters
T – test temperature, K
$T_0$ – reference temperature, K

## 2. Used materials and testing method

For the purpose of the study three different type of asphalt mixtures were used:

- AC 16W asphalt concrete for binder course with 35/50 and 50/70 neat bitumen,
- SMA8 stone matrix asphalt for wearing course with PmB 45/85-60 SBS modified bitumen,
- HMAC16 high modulus asphalt concrete for binder and base courses with 20/30 neat bitumen, PmB 25/55-60 SBS modified bitumen and 20/30 multigrade bitumen.

For the purpose of this article, only HMAC16 with 20/30 neat bitumen results are presented as an exemplary. Remaining mixtures showed similar behavior for long time of loading in low temperatures.

Presented mixtures were designed according to Polish Technical Requirements (2014) and tested in three point bending test developed by Judycki (1991) and improved by Judycki et al. (2001, 2014). Specimen during the test in NAT (Nottingham Asphalt Tester) apparatus is presented on figure 2.

Fig. 2. Specimen during bending test mounted in Nottingham Asphalt Tester apparatus.

## 3. Test results and analysis

Exemplary test results for temperature range from -20 °C to 0 °C are presented on figure 3. Presented graph shows behavior of HMAC with 20/30 neat bitumen under constant load.

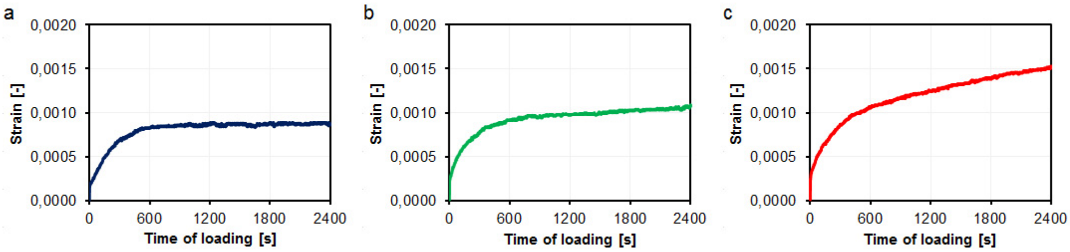


Fig. 3. Results of three point bending test for temperatures: (a) -20 °C, (b) -10 °C and (c) 0 °C.

The main information acquired from laboratory tests are relations of stiffness modulus with time of loading and temperatures. The range of low-temperature data acquired for long time of loading for chosen models is presented in the next paragraphs.

### *3.1. Stiffness modulus*

As presented in paragraph 1.1 basic conception of stiffness modulus can describe only one chosen time of loading of the whole test. This specific time of loading is chosen based on the cooling gradient used in calculations of thermal stresses. Selected values of models are valid only for simple computational analyses, which do not require information about relaxation processes. Calculation of thermal stresses for real environmental data requires very time consuming calculation, in which stiffness modulus values are determined from laboratory test for each gradient of cooling. Figure 4 presents relation of stiffness modulus with temperature acquired for the cooling gradient of 3 °C/h and the range of data used by this model (only one point- marked on fig. 4b with red “X”). As it could be seen it is not a very efficient model.

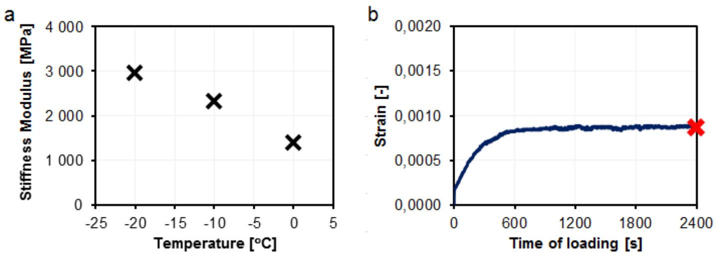


Fig. 4. Basic stiffness modulus model: (a) Relationship between stiffness modulus and temperature; time of loading 2400 s, (b) usage of the test data obtained from laboratory tests for temperature of -20 °C.

### *3.2. The Burgers Model*

Rheological models, such as the Burgers model, are so far the most accurate type of modeling of asphalt concrete behavior under long time load (usage of the test data is presented on fig 5c with red crosses). Exemplary parameters of Burgers model are presented in table 1. Main parameters ($E_1$, $\eta_1$) show quite good relations with the change of temperature (fig 5a, b), so it is possible to interpolate results for other temperatures with high confidence.

But there are also many problems with that kind of models. Firstly there are a lot of different rheological models, which are used to describe asphalt and asphalt concrete behavior (Judycki (1984), Olard et al. (2003), Di Benedetto et al. (2004), Iwański and Mazurek (2012), Iwański and Chomicz-Kowalska (2013)). Some of the have various restrictions, usually connected with the range of temperature for which they are valid. For example even Burgers model is not accurate in modeling plasticity or behavior in glassy state. The variety of rheological models are also the reason why there aren't any commonly used programs for computational analyses. Another reason is different behavior under different kind of loading. For example there could be different model parameters in specific temperature for static and dynamic type of loading. For the purpose of thermal stresses analysis, only data from static test could be used. Data from dynamic laboratory test used for example in various design method has too short period of time of loading to give correct values for viscous parameters. Even with many inconveniences rheological models are the most accurate for modeling behavior in low temperatures. But to acquire valid test results it is very important to perform laboratory tests with much attention for the test conditions.

Table 1. The Burgers model parameters (exemplary test results HMAC with 20/30 neat bitumen).

| Temperature [°C] | $E_1$ [MPa] | $E_2$ [MPa] | $\eta_1$ [MPa·s] | $\eta_2$ [MPa·s] |
|---|---|---|---|---|
| 0 | 8 447 | 2 529 | $9.9\times10^6$ | $5.5\times10^5$ |
| -10 | 13 388 | 5 052 | $6.9\times10^7$ | $9.9\times10^5$ |
| -20 | 17 627 | 4 115 | $1.6\times10^8$ | $9.4\times10^5$ |

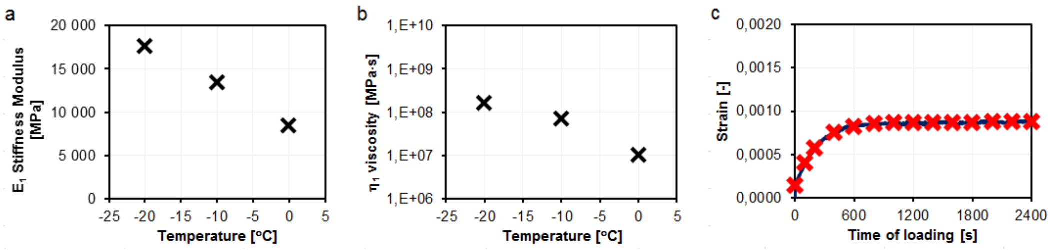


Fig. 5. The Burgers model: (a) Relationship between $E_1$ stiffness modulus and temperature, (a) Relationship between $\eta_1$ viscosity and temperature (c) usage of the test data obtained from laboratory tests for temperature of -20 °C.

### *3.3. Master Curves*

Conception of Master Curves allows to describe behavior of asphalt concrete with single equation for whole range of temperatures and time or frequency of loading. This process is possible only for materials which comply with time-temperature superposition principle (TTSP) – their behavior is linear and thermorheologically simple. TTSP principle is used in many European and American technical standards. American design guide MEPD-G uses master curves in design of flexible pavements. But there are some problems with using master curve for the purpose of low temperature behavior description. Table 2 presents exemplary results of Richards model parameters obtained from the series of creep tests. Laboratory test results and their description with single master curve equation are presented on figure 6. As it could be seen, that kind of modelling is accurate only for short time of loading (movement of a vehicle) and in moderate temperatures in which their behavior is very linear. In the case of long time loading in low temperatures the results of modeling and observations in the laboratory are drifting from each other (Jaczewski and Judycki (2014)). Depending on the type of asphalt mixture and grade of bitumen, the drift of results can appear even in the temperature as high as 0 °C (in the case of hard grade bitumen). Usually this deviation appears in temperatures of -10 °C or lower and it is growing with the elongation of time of loading and with decreasing of temperature (fig 6c).

Table 2. Master curve and shift factor parameters (exemplary test results HMAC with 20/30 neat bitumen)

| α | δ | λ | β | γ | WLF shift factor |
|---|---|---|---|---|---|
| 4.473 | 0.000 | 1.536 | -1.709 | -0.449 | $C_1$ = 6.569<br>$C_2$ = -79.018 |

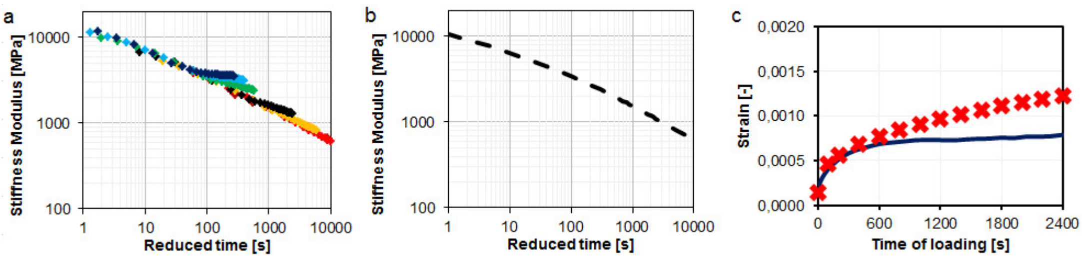


Fig. 6. (a) Laboratory tests results shifted into one line, (b) master curve developed from laboratory tests results, reference temperature 0 °C, (c) usage of the test data obtained from laboratory tests for temperature of -10 °C.

### *3.4. Master Curve modification for low temperature description*

Observed deviation from the thermorheological simplicity leaded to modification of presented Richards model. It was very important, as data obtained from master curve was used directly in calculation of thermal stresses. Using data obtained from basic model resulted in understating values of calculated stresses.

For each temperature, for a reduced time range in which deviation appeared additional set of parameters was calculated (table 3). In current stage of research strict relations between master curve parameters and test temperatures have not been found and parameters used in calculations were changed by hand.

Proposed model of modified master curve with changeable parameters is presented on figure 7a. Dividing one master curve into series of lines in the case of low temperatures gives very good correlation with test data (fig 7b). But the process of using modified master curve is still very crude. In further stages either new model of master curve needs to be developed or relations between material properties (e.g. type of the bitumen, type of asphalt mixture, etc.), test temperature and time of loading should be found.

Table 3. Modified master curve and shift factor parameters (exemplary test results HMAC with 20/30 neat bitumen).

| Temperature | α | δ | λ | β | γ | WLF shift factor |
|---|---|---|---|---|---|---|
| 5 °C and above | 4.473 | 0.000 | 1.536 | -1.709 | -0.449 | |
| 0 °C | 4.473 | 2.775 | 0.063 | -4.088 | -0.554 | $C_1$ = 6.569 |
| -5 °C | 4.473 | 3.275 | 0.060 | -3.776 | -0.686 | $C_2$ = -79.018 |
| -10 °C | 4.473 | 3.485 | ~0.000[a)] | -8.616 | -0.836 | |
| -15 °C | 4.473 | 3.531 | ~0.000[a)] | -8.599 | -0.898 | |

NOTICE: a) value of λ parameter is slightly higher than 0. Creating Master Curve with value of λ = 0 is impossible.

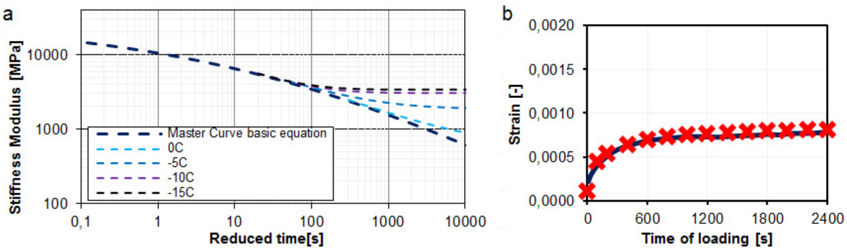


Fig. 7 (a) Modified Master Curve developed from laboratory tests results, reference temperature 0 °C, (b) usage of the test data obtained from laboratory tests for temperature of -10 °C.

## 4. Conclusion

As it could be seen neither of models commonly used in literature is ideal. Each of them have their advantages and disadvantages. For the present time, according to authors opinion the most valid results are obtained using rheological models. Burgers model chosen for the purpose of this article gives the best description of the test data and possibility to extrapolate data for the longer times of loading, without losing reliability. But it gives results only in discreet range of temperatures. And it is hard to predict behavior in temperatures lower than the test temperature with good reliability.

The next model is master curve, which describes behavior of asphalt mixture continuously and it is possible to interpolate and extrapolate stiffness modulus with quite good reliability in majority of range of temperatures and times of loading. But as it could be seen in the 3rd paragraph in the case of low temperatures deviations from thermorheologically simplicity are visible. Values calculated from master curve are understated in comparison to laboratory test data.

As a result of the conducted studies authors presented initial modification of Richards model of the master curve, which should be further developed and improved. But similarly to Burgers model, in present stage of research it can be used only for a discreet range of low temperatures. With further improvements that kind of model, not necessarily Richards model, could be a good solution to describe behavior in low temperatures, even taking into account other phenomenon, like physical hardening.

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