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Research paper

Effect of filler type on non-linear viscoelastic characteristics of asphalt mastic

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Abstract: This article discusses the rheological tests and analyses based on the Schapery non-linear viscoelasticity model that were performed to study asphalt mastic behaviour under high shear stresses. Seven mineral filler types were applied in this study, including a mixed filler with hydrated lime and fillers derived from dust extraction systems. Determination of basic properties of the fillers was followed by creep and recovery tests (DSR) at different levels of shear stress conducted in accordance with a modified MSCR procedure. The first stage in the analysis was the identification of linear viscoelastic region and the non-linear viscoelasticity model parameters such as the length of the loading period, the temperature and the stress level using TTSSP (Time-Temperature-Stress Superposition Principle). Subsequent numerical simulations of strain variation with respect to stress confirmed a high degree of agreement between the non-linear viscoelasticity model and mastic sample behaviour. A strong correlation was found between the non-linear viscoelasticity parameters and mastic properties. The proposed methodology is able to quickly identify and eliminate the fillers that may contribute to HMA deformations

Keywords: non-linear viscoelasticity, asphalt mastic, mixed filler, modified MSCR, regression

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1. Introduction

Bitumen mastic is a suspension of filler in bitumen, which envelops coarser grains in mix asphalt. Mastic is the proper binder in mix asphalt, which plays a crucial role in mix asphalts' compaction and affects their durability during exploitation [1], [2]. The filler quantity has a major effect on mastic stiffness variation, thereby affecting the mechanical properties of bituminous mixtures in terms of resistance to permanent deformations and low temperatures. The literature has devoted little attention to the studies of mastic. Normally, HMA rheology analysis is the analysis of the bitumen rheology conducted through advanced experimental regression models. At high temperature ranges, the influence of bitumen on bituminous mixture rheology is low, about 40% [3]. Mastic is a composite subjected to stresses markedly exceeding the linear viscoelastic range [4], and hence, the correlation between rheological results in the linear viscoelastic range and the results of e.g., rutting tests is ineffective, especially when the non-linearity of σ-ε relationship in the mastic is significant. In practice, the behaviour of bituminous mixtures during manufacturing, placement and service will be strongly mastic-dependent [5] not the least since the specific surface area of the filler amounts to 85%÷95% of the mineral mixture.

The result of mixing bitumen and filler (<0.063 mm) ensures the correct cohesion between the primary mineral framework's components and affects the asphalt mix's stiffness. The quantity of filler substantially contributes to the change in the mastic's stiffness, which affects mix asphalts' mechanical properties in terms of resistance against permanent deformation and low temperatures [6]. Little attention is paid to studying mastic in the literature. Nevertheless, its impact on the results of rutting, where shear stress in mastic exceeds the range of linear viscoelasticity, is a lot more telling [4].

Based on the WT-1/2014 requirements and on the monograph of Professor Piłat [7], it is possible to state that the rheological properties of mastic depends on the quantity of calcium carbonate (≥70%) in the filler. The PN-EN 13043 standard provides no indications for selecting the type and amount of binder in terms of the ultimate values of mechanical parameters of the mastic or of the mixture. The most critical is the CC_{70} parameter, which defines a minimum content of calcium carbonate (≥70%). On the other hand, the authors of the NCHRP 9-45 report [8] stated that mechanical properties at low and high temperatures were mainly affected by the filler's physical properties, such as porosity and granulation. The results specified in the report confirmed the earlier results of Antunes [9], i.e. that mechanical properties are definitely affected by the content of Ridgen voids. Due to the above, this paper features a consideration about the degree to which the filler's properties will affect the mastic's strainability at different stress histories, taking into account the exceeded range of linear viscoelasticity. Therefore, as a tool to explain in article mastic rheology, one of the models of nonlinear viscoelasticity was utilized. Non-linear models application were initiated in the 60's of XX century [10] and are still being developed, especially in the design of modern polymer composites [11].

2. Materials and methods

2.1 Fillers and mastic

The study featured the use of reference "full-value" materials meeting the Polish criteria specified in the WT-1/2014 document, as well as fillers derived from the aggregate de-dusting process. According to the Polish legislation, materials derived from the de-dusting system are deemed useless in road construction. Using the suggestions specified in the NCHRP 9-45 report, mainly materials meeting the WT-2/2014 criteria and those that did not meet the criteria were used. Due to the above, the experiment featured the use of the following fillers meeting the WT1-/2014 requirements, such as the following:

- limestone dust (L),
- mixed filler: 85% limestone dust/15% hydrated lime (0.15HL/L),
- mixed filler:70% limestone dust/30% hydrated lime (0.30HL/L),
- dust of Gabbro origin (G),
- dust of Quartzite origin (Q),
- dust of Basalt origin (B),
- dust of Dolomite origin (D).
- granite dust (for validation purposes)

The study featured the use of 50/70 bitumen meeting the requirements of the PN-EN 12591:2010 standard. The filler's ratios, due to various filler densities, were determined volumetrically and amounted to F/B = 27:73.

2.2. Testing the mastic's creep and elastic recovery

Monotonic creep testing with relief (elastic recovery) was conducted with the use of the modified MMSCR procedure dedicated to evaluating the periodic creep of bitumen, taking into account the ability to test mastic in terms of linear and non-linear viscoelasticity. The basic modification included the reduction in the number of repetitions of applying load to the sample and an increase in the range of the applied shear stress. The reduction in the number of repetitions to 3 resulted from our own observations and of Shirodkar's observations [12]. The sample loading program is presented below in Fig. 1.

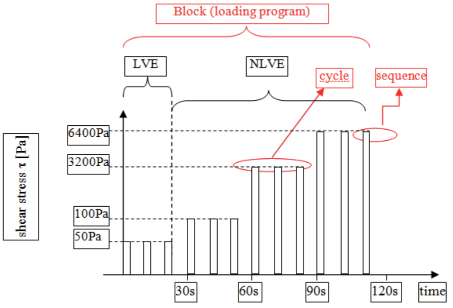

Fig. 1. Mastic samples' loading history

In the modified program, the strain measurement (sequence), the same as in the MSCR testing, was conducted during loading for 1 s (loading sequence) and then during strain for 9 s of recovery (relief sequence). The test was repeated at three temperatures: 50°C, 60°C, and 70°C to take into account the time-temperature superposition (TTSP). The estimation of the non-linear viscoelasticity parameters featured the consideration of the shape strain in the third sequence of each cycle, in which shear stress was applied.

2.3. Schapery's non-linear viscoelasticity model

The theory proposed by Schapery is one of the most commonly used methods for describing the effect of non-linear viscoelasticity, mainly for polymers [10]. It was designated based on the principles of thermodynamics for irreversible processes [13], [14]. It was assumed in the analysis that the creep function for the LVE would be best represented by the generalised model consisting of Kelvin elements combined in series and a single Hooke element. Based on earlier analyses, it was acknowledged that a system of four Kelvin elements (n=4) and a single Hooke element (GK-H) was sufficient for the correct description of the changes in the mastic's strains. It is necessary to note that the calibration of the non-linear parameters in Schapery's model requires earlier determination of the GK-H model's parameters.

Much more interesting is the final form of the numerical solution that enables forecasting the strain in the scope of linear and non-linear viscoelasticity. This solution was based on the solution of Soules, et al. [15], which assumed that the model's non-linear parameters are constant for small time increments. When using a certain mathematical formalism in the generalised GK-H model, the calculated increase in strain $\Delta\gamma_n(t)$ for a small time interval $\Delta\psi$, corresponding to an increase in shear stress $\Delta\tau$, was used to derive the following original numerical formula (2.1) [16]:

$$\Delta\gamma_n(t) = \left(g_0 J_0 + g_1 g_2 \sum_{i=1}^{n} J_n \left[1 + \frac{\Delta\tau \cdot \tau_n}{\Delta\psi}\left(\exp\left(\frac{\Delta\psi}{\tau_n}\right) - 1\right)\right]\right)\Delta\tau + \sum_{i=1}^{n}\left(\exp\left(\frac{\Delta\psi}{\tau_n}\right) - 1\right) * \gamma_n(t - \Delta t) \tag{2.1}$$

where:

J_0- instantaneous creep susceptibility,J_n - time-dependent creep susceptibility, n - number of Kelvin elements, g_0, g_1, g_2, a_σ - non-linear parameters in the stress function $\sigma(t)$, Δt - time interval, $\Delta\psi$ - time reduced by the WLF relation.

The material parameters g_0, g_1, g_2 are parameters dependent on the stress condition. The theory of non-linear viscoelasticity is in essence a generalisatin of the linear viscoelasticity model. In the case of small stress (creep testing), the parameters have the following values $g_0=g_1=g_2=a\sigma=1$. Then, the Boltzman superposition principle applies and the energy transferred into the system is recovered entirely. Parameter g_0 responds to the horizontal shifts of the (instantaneous) susceptibility J_0. On the other hand, the relation g_1g_2 is responsible for the non-linear change in the time-dependent susceptibility ΔJ caused by specific stress. Parameter g_2 refers to the stress increase rate. The last parameter a_σ is responsible for the horizontal transformation of the susceptibility function in relation to the time scale.

3. Test results

Firstly, the fillers' basic features were designated. The following structural properties were used in the testing: designation of the voids in dry and compact filler (AV_R) acc. to PN-EN 1097-4, softening point increase ($\Delta T_{R\&B}$) acc. to EN 13179-1, specific surface area (S_s) acc. to [6], and fine particles content (MB_F) acc. to PN EN 933-9. Furthermore, the fillers' functional features were taken into consideration: Bituminous number (BN) acc. to PN-EN 13179-2 and pH designation using an electronic pH meter. The test results along with the required ranges acc. to WT-1/2014 (concerning features: $\Delta T_{R\&B}$, AV_R and MB_F) are presented in Fig. 2.

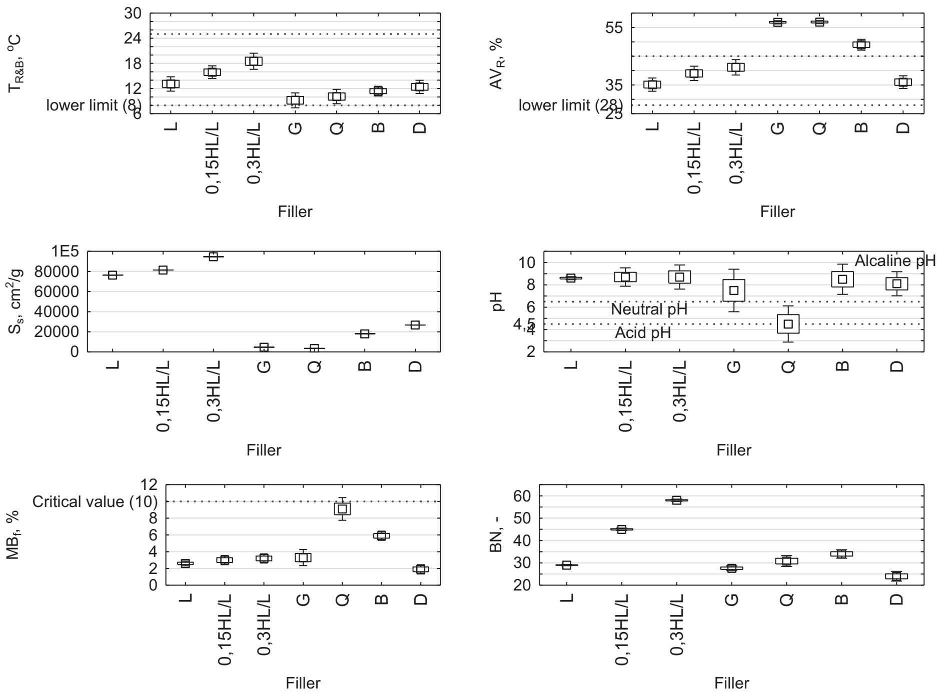

Fig. 2. Results of the mineral fillers' properties designation

The selected set of filler properties presented in Fig. 2 was used in the forecasting of ratios specifying the non-linear strain waveform based on Schapery's model. They were designated solely by using the waveform of strain during recovery. The calibration of the parameters of non-linear viscoelasticity in Schapery's model was developed based on the papers of Lai and Bekker [17]. However, the difference was that the calibration of non-liner parameters was determined for the time in which there was no complete elastic recovery. Due to the fact of measurement at various temperatures, it was required to apply the time-temperature superposition principle (TTSP) by using the WLF model. Due to the complex mathematical formalism of the calibration description, a more detailed description devoted to this notion can be found in the authors'paper [16], [18]

The Mathcad program was used for the numerical creep simulation of all mastic compositions. The constant $\Delta t = 0.1$s was adopted as the time interval. After the identification of parameters of the GK-H model in terms of LVE, as well as the parameters of non-linear viscoelasticity (2.1), a series of mastic strain simulations in a broad range of shear stress was conducted. The results are presented in Fig. 3.

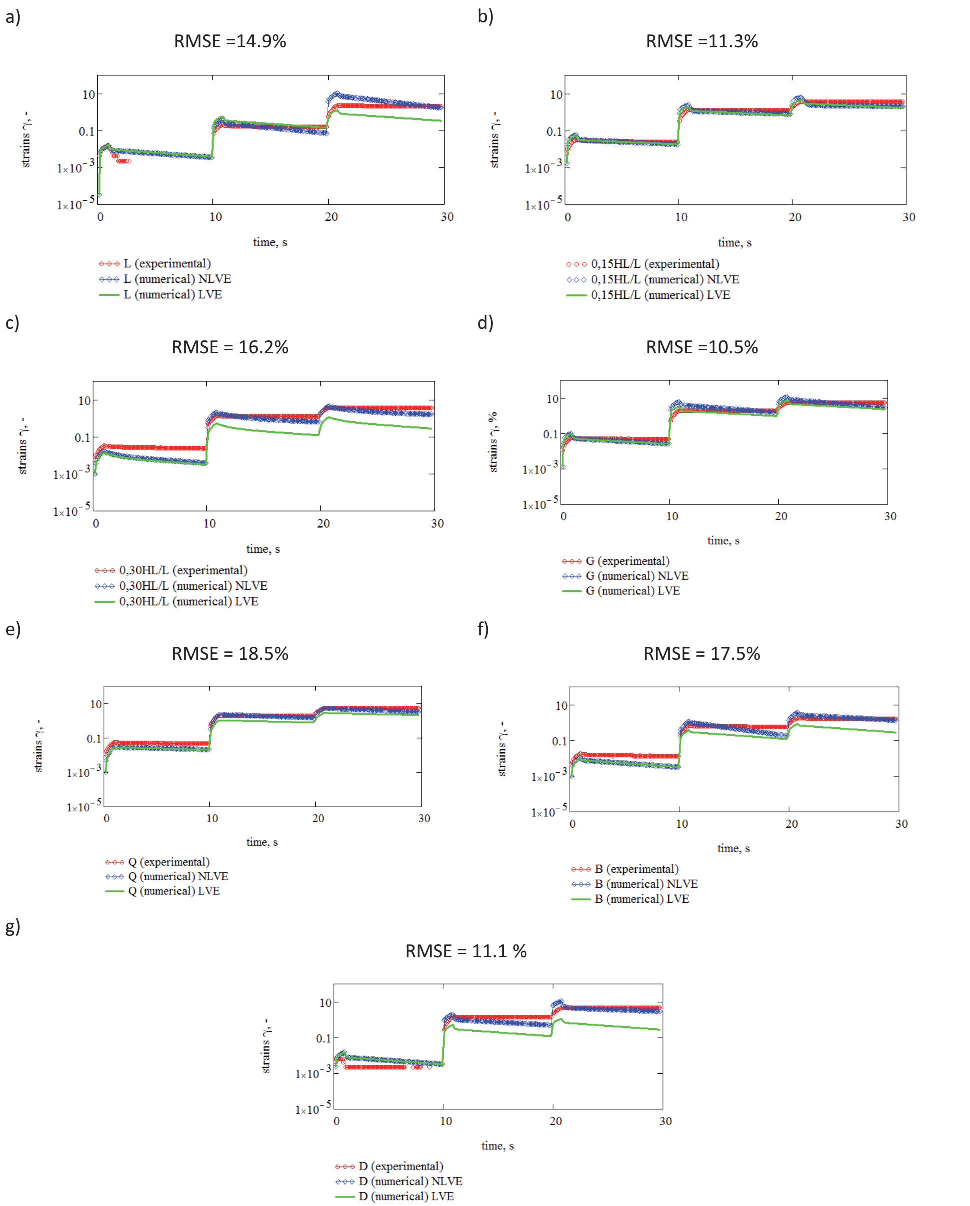

Fig. 3. Numerical simulation of strain in the scope of NLVE for all mastic compositions: a) filler L; b) filler 0.15HL/L; c) filler 0.3HL/L); d) filler G; e) filler Q; f) filler B; g) filler D.

In Fig. 3, the strain experiment results are compared with the numerical simulation results. It is necessary to note that the maximum relative error (RMSE) did not exceed 19%, which indicates a good matching of the experimental data with the model data, considering the fact that the relative error encompasses the differences in the mastic's creep and recovery stage for the LVE and NLVE models. The best matching of the model results with the experiment results were obtained for the LVE due to the minor energy dissipation and marginal irreversible strains in the mastic. Additionally, the results were enriched with the strain waveform simulation in the case of omission of the non-linear effects (green colour). It is clearly visible that the use of the LVE model does not illustrate the actual mastic behaviour for large stress values ,and thus clearly points to the lack of estimation of the actual material strain. The non-linearity of the relation τ-γ for fillers such as HL, L, B and D was observed starting at shear stress of above 50Pa. Furthermore, the conducted simulation suggests that fillers with large $CaCO_3$ content (HL, L and D) feature a favourable, higher than in the case of other samples, increase in elastic strain during recovery and low strain for LVE. Nevertheless, the deviation of the strain waveform from the LVE model suggests that such a mastic will be "susceptible" to changes in shear stress, causing changes in the filler's grain topology.

3.1 Relations between Schapery's model parameters and the mastic properties

The observed variety in the impact of particular fillers on the mastic strain waveform suggests that there are prerequisites for the statement that the fillers' physical and chemical effects can be linked to the non-linear viscoelasticity model parameters. Then, by using the fillers' properties, it will be possible to forecast the mastic strain waveform for large stresses. The relation between the non-linear viscoelasticity parameters was determined using the linear multiple regression model. The input set consisted of the results of structural and functional features (Fig. 2). The output features set featured non-linear viscoelasticity model parameters (g_0, g_1, g_2, a_σ), the values of which were estimated based on the filler features' variation. Parameter g_0 demonstrated low variation and was ultimately adopted at 1. The use of the backward elimination method, aimed at removing any excess factors, allowed for obtaining the following set of essential regression models (3.1):

$$\begin{aligned}
&\mathbf{g_1} = 1 + (0.00027 \cdot \mathrm{BN} - 0.000001 \cdot \mathrm{P_w} - 0.00023 \cdot \mathrm{AV_R} + 0.00083 \cdot \mathrm{MB_f}) \cdot \left(\frac{\tau}{\tau_0} - 1\right) + \\
&(-5.4 \cdot \mathrm{BN} + 4.1 \cdot \mathrm{P_w} + 3{,}3 \cdot \mathrm{AV_R} - 3.7 \cdot \mathrm{MB_f}) \left(\frac{\tau}{\tau_0} - 1\right)^2 \pm 0.00081 \\
&\mathbf{g_2} = 1 + (0.0000018 \cdot \mathrm{P_w}) \cdot \left(\frac{\tau}{\tau_0} - 1\right) + (0.00040 \cdot \mathrm{pH} + 0.00025 \cdot \Delta\mathrm{T_{PiK}} - 0.00031 \cdot \mathrm{MB_f}) \left(\frac{\tau}{\tau_0} - 1\right)^2 \\
&\pm 0.121 \\
&\mathbf{a_\sigma} = 1 + (0.0032 \cdot \Delta\mathrm{T_{PiK}}) \cdot \left(\frac{\tau}{\tau_0} - 1\right) - (0.000020 \cdot \Delta\mathrm{T_{PiK}}) \left(\frac{\tau}{\tau_0} - 1\right)^2 \pm 0.0092
\end{aligned} \tag{3.1}$$

2.2 Validation of the model and its scope of use

The validation of the estimated regression models was conducted by applying the strain designation results for the same loading program (Fig. 1) but using mastic that was prepared from a granite filler derived from granite sand dusting. Its functional and structural properties were as follows: AV_R = 46%; BN = 32; pH = 5; ΔT_{PiK} = 11°C; Pw = 15,704 cm^2/g; MB_f = 2.25%. For this set of granite filler features, after designating the GK-H model parameters, the following Schapery's model results were obtained: g_0=1; g_1=0.202; g_2=10.76; a_σ=0.467. Then, by applying the formula (2.1), the following strain waveform was obtained (Fig. 4):

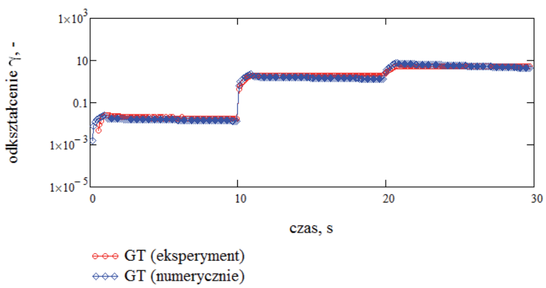

Fig. 4. Numerical simulation of strain in the scope of NLVE for mastic with a granite filler

It is worth noting that the matching of the model results with the experiment results was very good. This also clearly points to the model's high usability. Due to the above, it is possible to forecast the mastic strain based on the primary properties, which can be conducted in a quick manner. In order to specify the intensity with which each of the filler features affects the mastic's shape strain forecast result, a simulation of the strain changes for mastic with the GT filler was conducted for the stress of 3,200Pa and at a temperature of 50°C. Each of the features was increased accordingly by 25% ($\gamma_{creep25\%}$) and 50% $\gamma_{creep50\%}$), with the assumption that other features are constant (table 1).

Table 1. Impact of the filler's properties on strain after 1s of loading, caused by a stress of 3,200 Pa (a negative value means reduction).

Filler property	$\gamma_{creep25\%}$,%	$\gamma_{creep50\%}$,%
AV_R, %	-32	-40
ΔT_{PiK}, °C	-31	-41
BN	1	2
MB_f, %	4	19
Pw, cm^2/g	-29	-40
pH	-5	-5

The obtained numerical simulation results provided interesting conclusions. It is necessary to note that a 25% increase in AV_R, ΔT_{PiK} as well as porosity described by P_w cause nearly a 30% reduction in strain during loading. Nevertheless, it is necessary to note that the increase in clay fractions indicating the filler's contamination, designated by the MB_f feature, can cause an adverse increase in the mastic's strain by 19%. Furthermore, the use of a granite filler with a specific surface area greater by 50% can result in the reduction of shape strain by 40%. The increase in the filler's specific surface area and the correlated feature AV_R cause the greatest reduction in strain when compared to other granite filler features. Due to the above, the selection of a suitable filler is key in shaping the strain of the mastic, but also of the mix asphalt, especially when reading the rutting results. Furthermore, the presented analysis proves that the forecasting of mastic strainability in a broad range of stresses is possible and can be used in engineering practice.

3. Conclusions

The following conclusions were formulated based on the conducted testing and analyses:

1. Schapery's non-linear viscoelasticity model turned out to be a great tool to describe the strain of mastic which is subject to large deformations in mix asphalts. The model's validation using the strain designations of mastic made with a granite filler demonstrated the high effectiveness of the model in which the non-linear viscoelasticity parameters were designated based on the filler's properties.
2. The fillers' properties have a substantially favourable impact on the mastic's behaviour, especially during recovery. Fillers with increased $CaCO_3$ content caused the mastic to achieve a favourably higher reversible strain during the sample's loading.
3. The highest "susceptibility" to the loading time was demonstrated by the L, HL/L and D fillers. The strong adhesion between bitumen and filler from sedimentary rocks contributes to the mastic's low strainability, especially in terms of LVE. The increase in stresses above 50 Pa caused a noticeable non-linearity of the relation τ-γ in the tested fillers' set.
4. The filler's contamination by clay particles can cause an adverse increase in shape strains in the mastic with a granite filler by nearly 20%.
5. The specific surface area increase causes a substantial reduction in the mastic's strainability and reduction in the range of stresses in which the linear viscoelasticity applies.

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Wpływ rodzaju wypełniacza na nieliniową charakterystykę lepkosprężystą mastyksu

Keywords: nielinowa lepksprężystość, mastyks, wypełniacz mieszany, zmodyfikowany MSCR, regresja

Streszczenie:

W artykule przedstawiono badania i analizy efektów reologicznych mastyksu asfaltowego poddanego wysokim naprężeniem ścinającym wykorzystując model nieliniowej lepkosprężystości Schapery'ego. Docelowy materiał użyty w pracy, czyli mastyks jest efektywnym spoiwem mieszanki mineralno-asfaltowej (mma) będący produktem mieszania asfaltu i wypełniacza (<0,063 mm) zapewniającego właściwą kohezję pomiędzy składnikami zasadniczego szkieletu mineralnego. Relacja pomiędzy proporcjami składników (asfalt-wypełniacz) zdecydowanie wpływa a sztywność mma.

Na temat wpływu rodzaju wypełniacza na właściwości mastyksu jak i również mma powstało wiele prac. Nie mniej jednak z faktu złożoności zjawisk reologicznych jakie towarzyszą odkształcalności mastyksu badania nad fenomenologią mastyks wciąż trwają. Według wymagań krajowych (WT-1/2014), jako produkt pełnowartościowy, należy uznać wypełniacz o zawartości węglanu wapnia ≥70%. Z kolei autorzy raportu NCHRP 9-45 stwierdzili, że na właściwości mechaniczne w niskiej i wysokiej temperaturze miały wpływ przede wszystkim właściwości fizyczne wypełniacza takie jak: porowatość, uziarnienie. Ponadto zaobserwowali zadawalające rezultaty jakości mastyksu można uzyskać z wypełniaczami pochodzącymi z systemów odpylania kruszyw nierzadko o odczynie kwaśnym. Z faktu występowania dużych rozbieżności opinii w analizie zostały zastosowane materiały pełnowartościowe: mączka wapienna (L), wypełniacz mieszany: 85% mączka wapienna/15% wapno hydratyzowane (0.15HL/L), wypełniacz mieszany: 70% mączka wapienna/30%wapno hydratyzowane (0.30HL/L). Do dalszej ewaluacji wykorzystano materiały niespełniające kryteria jakościowe (według WT-1/2014) takie jak: pyły pochodzenia gabrowego (G), pyły pochodzenia kwarcytowego (Q), pyły pochodzenia bazaltowego (B), pyły pochodzenia dolomitowego (D) oraz pyły granitowe (do celów walidacji). O skuteczności aplikacji danego wypełniacza świadczy również zachowanie finalnego mastyksu w punktu widzenia jego odkształcalności przy wysokich naprężeniach. Dlatego też do oceny zjawiska pełzania i powrotu sprężystego wykorzystano badania monotoniczne w próbie pełzania z odciążeniem (powrót sprężysty) z zastosowaniem zmodyfikowanej procedury MMSCR. Metoda MMSCR stanowi modyfikację tradycyjnej metody MSCR (Multi Stress Creep Recovery Test) dedykowanej ocenie pełzania asfaltów poddanych cyklicznemu naprężeniu ścinającemu. Metoda MMSCR stanowi rozwinięcie metody MSCR poprzez szerszą analizę zakresu nieliniowego lepkosprężystości o wiele bardziej racjonalnego w rzeczywistej pracy mma. W zmodyfikowanym programie MMSCR pomiar odkształcenia (sekwencja), tak samo jak w badaniu MSCR, był realizowany w czasie trwania obciążenia przez 1 s (sekwencja obciążenia) a następnie odkształcenia w czasie powrotu (sekwencja odciążenia) trwającego 9 s. Badanie zostało powtórzone w trzech temperaturach, czyli: 50°C, 60°C, 70°C aby uwzględnić zasadę superpozycji czas-temperatura (TTSP). Ponadto uwzględniono trzy poziomy naprężenia ścinającego 100Pa, 3200Pa oraz 6400Pa aby wykorzystać najbardziej zaawansowaną zasadę superpozycji TTSSP (time temperature stress superposition principle).

W pracy do opisu wspomnianych zjawisk pełzania i nawrotu wykorzystano model Schapery'ego, który pozwala na dogodny opis zjawisk nieliniowych relacji naprężenie-odkształcenie w szerokim zakresie naprężeń. Model ten wymaga w pierwszej kolejności definicji podcałkowej funkcji pełzania. W początkowej fazie zakładano model potęgowy jednak ostatecznie najlepszym rozwiązaniem okazał się model złożony z szeregowo połączonych elementów Kelvina z dodatkowym elementem Hooka'e (GK-H). Wykorzystując nieliniową metodę najmniejszych kwadratów zidentyfikowano parametry modelu Schapery'ego. W końcowym etapie zaproponowano numeryczne rozwiązanie zmiany odkształcenia w

trybie kontrolowanego naprężenia oparte na rozwiązaniu Soules i inni [15] oraz zakładające, iż nieliniowe parametry modelu są stałe dla małych przyrostów czasu. Parametry modelu nieliniowej lepkosprężystości Schapery'ego g_0, g_1, g_2 są parametrami zależnymi od stanu naprężenia. Teoria nieliniowej lepkosprężystości jest w istocie uogólnieniem modelu liniowej lepkosprężystości. W przypadku małych naprężeń (próba pełzania) parametry $g_0=g_1=g_2=a_\sigma=1$. Wówczas obowiązuje zasada superpozycji Boltzmana.

Zastosowanie wyżej wymienionego modelu nieliniowej lepkosprężystości do opisu pełzania i powrotu sprężystego mastyksu okazało się bardzo dobrym narzędziem. Pozwala ona na uwzględnienie zmiany szybkości przyrostu deformacji ze względu na zmianę naprężenia oraz umożliwia oszacowanie odkształceń nieodwracalnych co w klasycznych lepkosprężystych modelach takich jak Zenera nie jest możliwe. Dopasowanie modelu Schapery'ego do wyników eksperymentu obarczone było błędem względnym <19%, który uwzględniał zakres liniowej i nieliniowej lepkosprężystości. Kolejnym ważnym elementem artykułu było poszukiwanie i ustanowienie związków korelacyjnych pomiędzy parametrami nieliniowej lepkosprężystości a właściwościami wypełniaczy. Dzięki temu w szybki sposób można określić wpływ poziomu naprężenia na mastyks wykonany ze ściśle określonym rodzajem wypełniacza.

Uzyskane wyniki symulacji numerycznej dodatkowo dostarczyły interesujących wniosków. Stwierdzono, że 25% wzrost wartości AV_R, ΔT_{PiK}, oraz porowatości P_w spowodował niemal 30% redukcję odkształcenia w fazie obciążenia. Nie mniej jednak należy podkreślić, że wzrost obecności frakcji iłowych wskazujących na zanieczyszczenie wypełniacza, określone przez cechę MB_f może spowodować niekorzystny wzrost odkształcenia mastyksu o 19%. Ponadto zastosowanie wypełniacza granitowego o 50% większej powierzchni właściwej może spowodować redukcję odkształcenia o 40%. Wzrost powierzchni właściwej wypełniacza oraz skorelowana z nią cechą AV_R spowodowała największa redukcję odkształcenia w porównaniu z innymi cechami wypełniacza. W związku z tym dobór odpowiedniego wypełniacza jest kluczowy w kształtowaniu stanu odkształcenia mastyksu, ale i również mieszanki mineralno-asfaltowej szczególnie w czasie odczytów wyników koleinowania. Ponadto przedstawiona analiza dowodzi, iż prognozowanie odkształcalności mastyksu w szerokim zakresie naprężenia jest możliwe i może być stosowane w praktyce inżynierskiej.

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