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A Model of DSR Performance to Evaluate the Rutting Parameter of Bitumen at High Temperatures

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Abstract

Rheological properties of bituminous materials are normally measured using a dynamic shear rheometer (DSR). In this paper, a model of DSR incorporation into the finite element method (FEM), based on prony series, by existent simulation facilities in ABAQUS, is presented. To try this work, the dynamic shear modulus (G^*), phase angle (δ) and $G^*/\sin\delta$ (to check the superpave rutting indication) of aged and un-aged bitumen and modified bitumen with Polybutadiene rubber (PBR), at high temperatures were measured by DSR and then were calculated using stress-strain values of ABAQUS output. Afterwards, the model and DSR results of G^* and $G^*/\sin\delta$ were compared. The comparison has shown that the utilization of such numerical analysis technique is useful for the evaluation of rutting parameter of bitumen.

Key words: Bitumen, DSR, Dynamic shear modulus, Rutting parameter, ABAQUS.

Introduction

The rheological properties of bituminous binders including bitumen are typically determined by means of dynamic mechanical analysis (DMA) using an oscillatory type, dynamic shear rheometer (DSR) tests (Airey, 2002). The procedure in DSR involves to evaluate a value of the complex shear modulus ($\mathbf{G}^*$, the materials resistance to deformation) and the phase angle (δ, the time lag between applied stress and resulting strain) (Remišová, Zatkaliková and Schlosser, 2016). The principle used with the DSR is to apply sinusoidal, oscillatory stresses and strains to a thin disc of bitumen, which is sandwiched between the two parallel plates of the DSR (Yusoff, Shaw and Airey, 2011). A sinusoidal angular displacement of constant angular frequency is applied to the top plate so that it oscillates back and forth. This oscillation comprises one smooth, continuous cycle which can be continuously repeated during the test (Rahman, 2004). The sinusoidal stress, the resulting strain, the complex shear modulus, and the absolute complex shear modulus, called dynamic shear modulus can be shown respectively by the fallowing formulas (Airey, 1997);

$$\sigma(t) = \sigma_0 sin\omega t \text{ (a)}, \quad \gamma(t) = \gamma_0\, sin(\omega t + \delta) \text{ (b)}, \quad G^* = \frac{\sigma_0}{\gamma_0} e^{i\delta} \text{ (c)}, \quad |G^*| = \frac{\sigma_0}{\gamma_0} \text{ (d)} \qquad (1)$$

Where σ_0 is the peak stress (Pa), γ_0 is the peak strain, ω is the angular frequency (rad/s), t is the time (second) and δ is the phase angle of the measured material response in degrees. Herein, $|G^*|$ is shown by G^*, in meaning of dynamic shear modulus.

The superpave methodology can indicate major stresses observed in asphalt paving such as permanent deformation (rutting) through the rheological parameter $G^*/\sin\delta$ (rutting parameter). The increase in $G^*/\sin\delta$ value means that the binder becomes more shift (higher rutting resistance). In superpave specification in order to minimize the permanent deformation the parameter $G^*/\sin\delta$ must be greater than or equal to 1.00 kPa for un-aged binders and 2.20 kPa for aged binders that undergo ageing processes via the rolling thin film oven test (RTFOT), at the frequency of 10 rad/s (Naskar et al., 2013).

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To describe the viscoelastic behavior of a material, ABAQUS assumes that a Prony series expansion adequately describes the material response with respect to time (Generalized Maxwell finite element model). ABAQUS can calculate the terms in the Prony series using time-dependent relaxation test data (Simulia, 2011). The shear and bulk relaxation moduli $G(t)$ and $K(t)$, assuming the constant Poisson's ratio and fitted into the Prony series as a Generalized Maxwell Solid model are shown as the fallowing (Wang, 2011);

$$G(t) = G_0(1 - \sum_{i=1}^{m} G_i\,(1 - e^{-\frac{t}{\rho_i}})), \qquad K(t) = K_0(1 - \sum_{i=1}^{m} K_i\,(1 - e^{-\frac{t}{\tau_i}})) \qquad (2)$$

Where G_0 and K_0 are instantaneous shear and volumetric elastic moduli, G_i, K_i, τ_i and ρ_i Prony series parameters and t is the time. ABAQUS assumes that $\tau_i = \rho_i$. On the other hand, the number of terms in bulk and shear is fixed previously in frequency domain with Prony series model calibration (Hammoum et al., 2009). For the modulus of elasticity E and the Poisson's ratio ν, there are the fallowing equations (Abbas, Papagiannakis and Masad, 2004; Elseifi, Al-Qadi and Yoo, 2006);

$$E(t) = G(t)/2(1+\nu) \quad \text{(a)}, \qquad K(t) = 2G(t)(1+\nu)/3(1-2\nu) \quad \text{(b)} \qquad (3)$$

In continuation, a model of DSR is presented. To form and analyze of the model, the Prony series in equation (2), were used. Although the model and simulation are not exactly identical with DSR and its behavior, but numerical analysis results show that the model can work instead of DSR for some rheological properties of bitumen.

Main section

In this section, at the first part, the experimental test of bitumen by DSR is explained and the results, G^*, δ and $G^*/\sin\delta$ are shown. At the second part, the modelling scheme is described. Then, Using equations of the introduction and DSR results, prony parameters calculated with Solver (of excel in Microsoft Office software) and the other necessary fitted parameters of the ABAQUS time-dependent relaxation model are presented. Finally, the calculated shear modulus, phase angle and rutting parameter, according to the outcome (stresses and strains) of the model, are exhibited for aged and un-aged bitumen and Polybutadiene rubber (PBR) bitumen.

Experimental Procedure

In the experiment, the pure and base bitumen was a 60/70-penetration grade bitumen (performance grade 58). Polybutadiene rubber was used as a 2.3 percent rubber for making the modified bitumen, PBR bitumen (performance grade 64). The temperatures of tests were 52, 58 and 64 (°C) for pure bitumen and 52, 58, 64 and 70 (°C) for PBR bitumen. Test sample of bitumen was placed between parallel plates of DSR with 25 mm in diameter and a gap of 1 mm. The frequency of experiments were 10 rad/s and the total time of each test was 1 minute. The ageing of bitumen and PBR bitumen was processed via RTFOT. The values of G^*, δ and $G^*/\sin\delta$, after averaging of all values of G^* and δ from DSR results at each temperature for pure, aged pure, PBR and aged PBR bitumen were obtained. The achieved results are presented in table 1.

Table 1. DSR results for bitumen and PBR bitumen, un-aged and aged

DSR results	δ [°]	$\mathbf{G^*}$ [Pa]	$\mathbf{G^*/\sin\delta}$ [Pa]	T [°C]
Bitumen	76.9578	3627.810	3723.871	52.0000
	78.4734	1676.487	1710.994	58.0000
	79.7938	808.3552	821.3520	64.0000
Aged bitumen	77.0789	6203.489	6364.649	52.0000
	80.7860	2706.826	2742.209	58.0000
	82.9823	1194.429	1203.444	64.0000
PBR bitumen	72.2852	5814.021	6103.427	52.0000
	73.7797	2842.897	2960.750	58.0000
	74.7260	1332.435	1381.224	64.0000
	75.9781	719.5970	741.6973	70.0000
Aged PBR bitumen	72.2988	10438.53	10957.30	52.0000
	74.7624	4872.371	5049.905	58.0000
	77.4255	2188.101	2241.876	64.0000
	79.5407	1100.286	1118.877	70.0000

With respect to table 1, the values of $G^*/\sin\delta$ for bitumen and PBR bitumen (also aged bitumen and aged PBR bitumen) at temperatures 64 and 70 (respectively) are lesser than the accepted superpave rutting parameter indicators, 1.00 kPa for un-aged binders and 2.20 kPa for aged binders. To approach the aim of modelling, this result must be a consequence of the model, too.

Table 2. Considered values of $\mathbf{G_0^*}$

G_0^*				
T [°C]	Bitumen	PBR bitumen	aged bitumen	aged PBR bitumen
52.0000	3646.195	5762.045	6199.723	10311.42
58.0000	1694.861	2844.724	2716.925	4951.319
64.0000	793.0574	1334.27	1173.435	2211.936
70.0000		696.8675		1092.616

The first obtained value of measured G^*s (by DSR) of each bitumen at each temperature is assumed as G_0^* (the instantaneous shear modulus) of that bitumen at that temperature (table 2). These values are some requirement values in the modelling process that also can be calculated by equation (a) of (3), if E is available instead of G^*.

Modelling and analysis

In a DSR test, one cycle is completed when as in figure 1 (a), the top plate goes from point A to point B, then reverses direction and moves past point A to Point C, followed by a further reversal and movement back to Point A. This oscillation comprises one smooth, continuous cycle which can be continuously repeated during the test. In the model of DSR, it is assumed that a cycle is completed when as in figure 1 (b), the top plate goes from point B to point C and then come back in reverse direction.

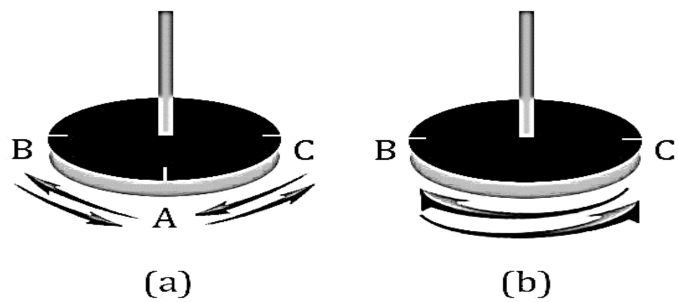

Figure 1. The movement directions of DSR (a) and the model (b) in each cycle

For the model, steel plates and bitumen layer were constituted. The steel requirement properties for the modelling are density and elastic properties of steel. The elastic properties include the young's modulus (E) and Poisson's ratio (ν). The bitumen layer requirement properties are density, elastic and viscoelastic properties of bitumen. The viscoelastic properties include shear (g_i), bulk (k_i) and relaxation time (ρ_i) parameters, that are the prony series parameters. The density of bitumen and PBR bitumen are 1027 kg/m^3 and 1000 kg/m^3, respectively. Steel plates have a density equal with 7800 kg/m^3, Young's modulus 21×10^9 and Poisson's ratio 0.3. Notice that for temperatures greater than 10 (°C), bitumen is usually assumed to be an uncompressible body, then Poisson's ratio is 0.5 (Hammoum et al., 2009). But 0.5 is not a passable value for Poisson's ratio in the analysis (it causes an infinity bulk modulus, with respect to equation (b) of (3)). Therefore, some proximate values of 0.5 were chosen for Poisson's ratios of bitumen materials. Each shear Modulus G_0^* given by DSR experiment was converted into a Young modulus, by equation (a) of (3) using a Poisson' ratio. Prony parameters were obtained via Solver, by prony series in equation (2) with m=5. Density, elastic and viscoelastic properties of bitumen materials are presented in table 3.

For ABAQUS adjustments, the contact of steel plate and bitumen layer was elected normal in explicit, dynamic, tangential behavior and frictionless. Two plates were considered in rigid body with a kinematic coupling tape. The down plate was fixed (ENCASTRE) and the up plate rotated at UR3, in a periodic amplitude with circular frequency 10 rad/s. Figure 2 is a picture of the completed model after running.

The upshot of the model was regulated for the maximum and minimum stresses and strains at each 0.1 second. The absolute of obtained maximums and minimums were considered as the requirement maximums and minimums for the next calculations. The Phase angles were calculated by equation (b) of (1), using minimum strains. The average of all phase angles of a bitumen at a temperature was assumed as the phase angle of that bitumen at that temperature. The dynamic shear modulus of bitumen at a temperature was calculated by equation (d) of (1), with the average of maximum stresses and the average of maximum strains. Finally, rutting parameters were obtained by the dynamic shear modulus and the phase angle. In table 4, all calculated dynamic shear moduli, phase angles and rutting parameter values are presented.

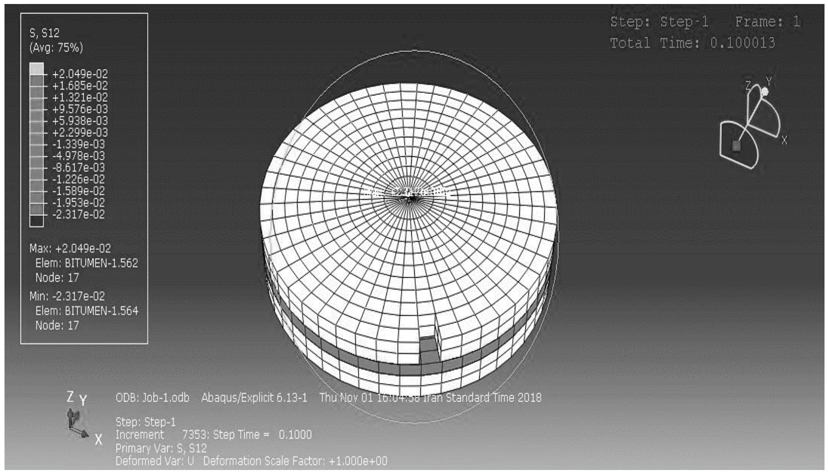

Figure 2. A picture of the model

Table 3. Requirement properties of materials

	Bitumen			PBR bitumen				Aged bitumen			Aged PBR bitumen			
T [°C]	64.000	58.000	52.000	70.000	64.000	58.000	52.000	64.000	58.000	52.000	70.000	64.000	58.000	52.000
ν	0.495	0.496	0.497	0.49	0.492	0.493	0.494	0.495	0.496	0.497	0.49	0.492	0.493	0.494
E (Pa)	2377.586	5081.193	10931.29	2083.634	3989.467	8505.725	17228.51	3517.958	8145.341	18586.77	3266.922	6613.689	14804.44	30831.15
g_1	-0.260167863	-0.080936005	0.02609502	0.254856914	-0.215157578	0.191865821	0.185003267	0.125997852	-0.033739025	-0.279255522	0.238826628	0.000107881	-0.192534995	-0.011941429
g_2	-0.018065855	-0.060353626	0.057069428	-0.223884661	0.342932835	0.131987331	0.145592383	-0.1322428	-0.126451132	-0.040265761	-0.017136536	-0.031455041	0.15285255	-0.160972317
g_3	0.179328077	-0.135710727	-0.051780322	-0.081342193	-0.104381874	-0.060273031	-0.333686574	0.062257818	-0.035689705	0.148794766	-0.404269108	0.162516157	0.184137826	0.262590301
g_4	0.036412983	-0.040196252	0.117625479	0.183414425	0.008434199	-0.109426918	-0.014973945	-0.092722295	0.224101237	0.367848256	0.066015919	-0.05444925	0.12500219	-0.123652537
g_5	0.035562606	0.335497827	-0.136438892	-0.184395795	-0.035787884	-0.151097776	0.004381882	0.00985909	-0.034381496	-0.199142307	0.108283305	-0.067636243	-0.246098014	0.013555545

ρ_1	ρ_2	ρ_3	ρ_4	ρ_5
0.017949841	0.026913222	0.045137821	0.051512834	0.080023331
0.024128937	0.027398716	0.02784242	0.071950661	0.08659651
0.020349224	0.047139738	0.061088093	0.0748057	0.079470044
0.003087962	0.00995438	0.049238286	0.062730773	0.088768855
0.035628482	0.05060066	0.067791605	0.078398502	0.085207407
0.012344794	0.034874069	0.055673189	0.055673184	0.072406607
0.017949841	0.026913222	0.04513782	0.051512834	0.080023391
0.023323623	0.027003574	0.039328508	0.053712429	0.087965675
0.016118821	0.029473194	0.033096408	0.052500502	0.079737123
0.0000001	0.049486228	0.051977417	0.073641876	0.074061664
0.015642677	0.021954501	0.053099914	0.068395758	0.075183011
0.027445416	0.027623154	0.054203768	0.073876197	0.074574326
0.024541367	0.070401674	0.074868328	0.083676993	0.084185248
0.030638983	0.047662097	0.053567428	0.079321991	0.079875164

With respect to table 4, the values of $G^*/\sin\delta$ for bitumen and PBR bitumen (also aged bitumen and aged PBR bitumen) at temperatures 64 and 70 (respectively) are lesser than the accepted superpave rutting parameter indicators, 1.00 kPa for un-aged binders and 2.20 kPa for aged binders. Thus, the model causes to acceptable results about the evaluation of rutting parameter, in this study.

Table 4. The model calculated results

DSR results	δ [°]	G^* [Pa]	$G^*/\sin\delta$ [Pa]	T [°C]
Bitumen	61.6812501	3639.3575	4134.1202	52.0000
	50.3676665	1716.66986	2228.99730	58.0000
	59.15420	809.4645	942.8271	64.0000
Aged bitumen	52.91886	6241.0116	7822.9491	52.0000
	61.69698	2741.99559	3114.30326	58.0000
	54.47971	1181.21847	1451.28917	64.0000
PBR bitumen	62.74284	5799.23009	6523.61270	52.0000
	52.03776	2836.14516	3597.26868	58.0000
	54.8436	1339.90430	1638.85955	64.0000
	60.49011	690.845528	793.828302	70.0000
Aged PBR bitumen	60.49011	10395.15086	13190.3498	52.0000
	61.6413009	4982.6677	5662.17906	58.0000
	63.0743384	2230.09326	2501.24075	64.0000
	54.625294	1066.391128	1307.84004	70.0000

Conclusion

In this study, one kind of bitumen and modified bitumen in un-aged and aged states were used for the modelling and numerical analysis of DSR results, at high temperatures, by ABAQUS. Prony series, Poisson's ratios and young's modulus were fitted to requirement properties for the analysis. Accordingly, calculated dynamic shear moduli of the model are near to obtained dynamic shear moduli of DSR. But, phase angles of the model are not similar to phase angles of the experiment. Anyway, using the calculated dynamic shear modulus and phase angle to calculate the rutting parameter of a bitumen at a temperature, causes the true result about the superpave rutting parameter indicator, for that bitumen at that temperature. Therefore, the model is useful for obtaining the dynamic shear modulus and evaluating the rutting parameter of bitumen at high temperature performance.

References

Abbas, A. R., Papagiannakis, A. T., & Masad, E. A. (2004). Linear and nonlinear viscoelastic analysis of the microstructure of asphalt concretes. Journal of Materials in Civil Engineering, 16(2), 133-139.

Airey, G. (1997). Rheological characteristics of polymer modified and aged bitumens (Doctoral dissertation, University of Nottingham).

Airey, G. D. (2002). Use of black diagrams to identify inconsistencies in rheological data. Road Materials and Pavement Design, 3(4), 403-424.

Elseifi, M. A., Al-Qadi, I. L., & Yoo, P. J. (2006). Viscoelastic modeling and field validation of flexible pavements. Journal of engineering mechanics, 132(2), 172-178.

Hammoum, F., Chailleux, E., Nguyen, H. N., Erhlacher, A., Piau, J. M., & Bodin, D. (2009). Experimental and numerical analysis of crack initiation and growth in thin film of bitumen. Road Materials and Pavement Design, 10(1), 39-61.

Naskar, M., Reddy, K. S., Chaki, T. K., Divya, M. K., & Deshpande, A. P. (2013). Effect of ageing on different modified bituminous binders: comparison between RTFOT and radiation ageing. Materials and structures, 46(7), 1227-1241.

Rahman, M. (2004). Characterisation of dry process crumb rubber modified asphalt mixtures (Doctoral dissertation, University of Nottingham).

Remišová, E., Zatkaliková, V., & Schlosser, F. (2016). Study of rheological properties of bituminous binders in middle and high temperatures. Civil and Environmental Engineering, 12(1), 13-20.

Simulia, D. S. (2011). ABAQUS/Standard Version 6.12 User's Manual. Dassault Systèmes Simulia Corp., Providence, RI.

Wang, H. (2011). Analysis of tire-pavement interaction and pavement responses using a decoupled modeling approach (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Yusoff, N. I. M., Shaw, M. T., & Airey, G. D. (2011). Modelling the linear viscoelastic rheological properties of bituminous binders. Construction and Building Materials, 25(5), 2171-2189.