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Numerical Simulation of Asphalt Mixtures Fracture Using Continuum Models

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Abstract. The paper considers numerical models of fracture processes of semi-circular asphalt mixture specimens subjected to three-point bending. Parameter calibration of the asphalt mixture constitutive models requires advanced, complex experimental test procedures. The highly non-homogeneous material is numerically modelled by a quasi-continuum model. The computational parameters are averaged data of the components, i.e. asphalt, aggregate and the air voids composing the material. The model directly captures random nature of material parameters and aggregate distribution in specimens. Initial results of the analysis are presented here.

INTRODUCTION

The limitation of damage processes of road pavements due to common traffic is crucial for their economic and safe design. In order to improve asphalt mixtures versatile laboratory tests are conducted due to strength parameters, abrasive resistance, durability and others. Variable temperature and load levels are provided for the tests. Initiation and the cracking process of asphalt mix are the main issues here. Fracture parameters of the mineral-asphalt mixtures should be consecutively incorporated in the pavement design procedures [1, 2, 3].

The laboratory tests should be supported by numerical computations. The finite element method (FEM) modelling of a material structure may be performed on various levels, e.g.: mesoscale, multiscale, continuum approaches and others [4 – 11]. The laboratory specimen case makes it possible to implement a mesoscale modelling, leading to an accurate mixture image. This approach requires advanced material models, a non-standard computational software and highly efficient computers. Moreover, laboratory tests do not assure material parameters of all asphalt mix ingredients, keeping in mind a highly complicated bitumen-aggregate contact definition. Hence, simplified multiscale models are applied. To implement them the mixture should be homogenized in order to estimate smeared material parameters, to further define simple, homogenized, continuum models. Such a solution is feasible in real road pavement analysis, due to complex load acting.

Novel, objective constitutive relations require a representative volume element (RVE), the lowest heterogeneous material volume to reflect global material features [4, 12 – 15].The experimental test results of mixtures detect random nature [16] which should be reflected in numerical computations [4, 10, 13, 14, 17 – 20]. This results from random character of material parameters and random aggregate location in the volume. Thus non-deterministic numerical analysis is relevant here.

The paper introduces a quasi-continuum model, its structure together with material parameters are randomly generated on the finite element level. Attention is paid to crack propagation modelling in asphalt mixture specimens. The standard constitutive models included in the ABAQUS package were applied here. The material parameters were assessed on the basis of laboratory tests. The experimental results were determined due to various material mixtures and notch sizes at temperatures below zero centigrade. High diversity of results was observed, to be further reflected

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in the FEM model. Random approach is the only one to provide it. Thus such a quasi-continuum model may be called a Monte Carlo constitutive model. The optimal RVE is investigated to properly reflect the experimental results.

LABORATORY TESTS

The laboratory at the Road Construction Division at the Faculty of Civil and Environmental Engineering, Gdańsk University of Technology conducts experiments to estimate fracture parameters of a mineral-asphaltic mix [16]. The semi-circular test pieces subjected to three-point bending (Figure 1) are in use. The original test methodology described by the standard PN-EN 12697-44 was appropriately modified. Vertical deflections *d* and forces *F* were measured experimentally. The displacement rate was 1 mm/min. Specimen and loading frame during the test were located in thermostatic chamber of the press to achieve a constant desired test temperature −20°C. The tests were performed with three notch depth, i.e. *a* =10 mm, 20 mm, 30 mm, and on two types of asphalt mixtures for wearing course, i.e. stone matrix asphalt SMA 8 and porous asphalt PA 8 (Figure 2, Table 1). The aggregate skeleton was designed according to the Polish Technical Guidelines WT-2 2010 [21].

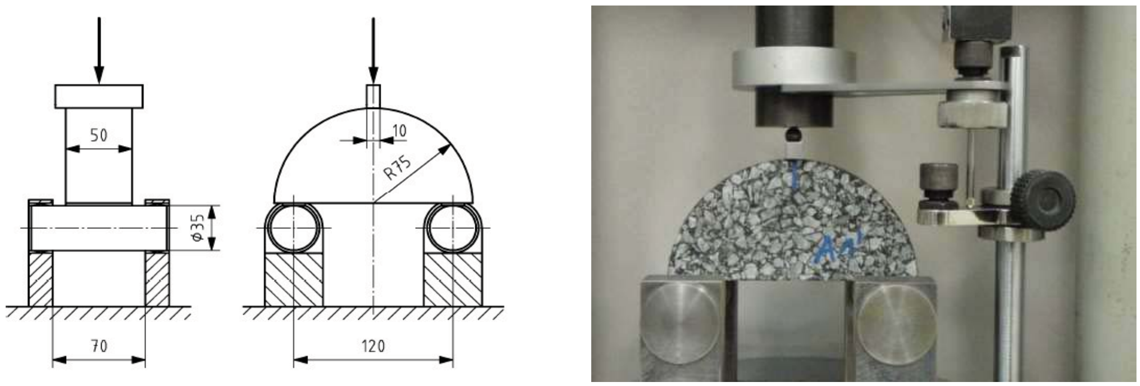

FIGURE 1. Semi-circular specimens

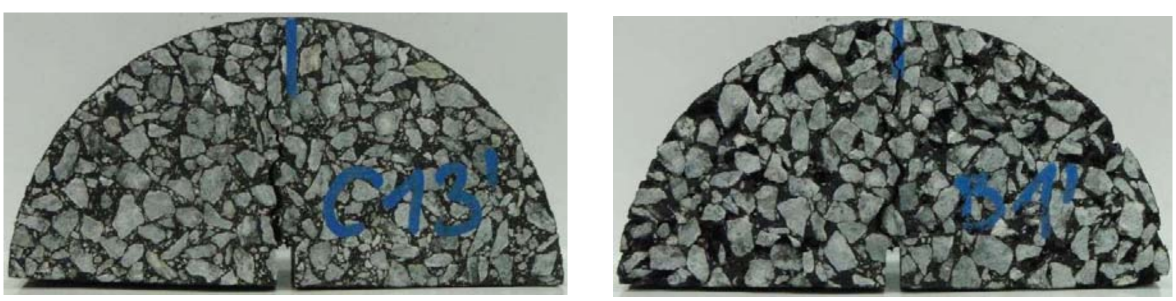

FIGURE 2. Semi-circular specimens: stone matrix asphalt SMA 8 and porous asphalt PA 8

Table 1. Composition of tested asphalt mixtures

	Passes # [mm]	SMA8 Mixture	PA8 Mixture
Aggregate	11.2	100	100
	8	94.2	91.2
	5.6	41.2	13.4
	2	25.6	6.7
	0.125	11.9	4.8
	0.063	9.7	4.1
	type of aggregate	gneiss, granodiorite and limestone	gneiss, granodiorite and limestone
Bitumen	optimum content [%]	7.0	6.5
	type of bitumen	45/80-55 PmB	45/80-65 PmB

Four samples were tested in each case. Summary of the laboratory test results are shown in Table 2. Figure 3 presents load F vs. deflection d curves for all tested samples with 20 mm notches.

The results in Table 2 show high dispersion in maximum forces F in the experiment and the linear part slope of the force–deflection ($F - d$) diagram, to be observed in Figure 3 (Tan α). It is reflected in standard deviations (SD) and coefficients of variation (CV).

For example, the case of mixture PA8 and a 20 mm notch result in the maximum force variation from 2700 N to 3280 N (coefficient of variation equal 0.08), and the linear slope of the diagram, representing the specimen stiffness, from 9740 N/mm to 13305 N/mm (coefficient of variation equal 0.13). The entirety of experiments results in the envelopes of $F - d$ curves varying in the range of 1.5 standard deviation.

Table 2. The results of fracture toughness test at -20°C

Asphalt mixture	a [mm]	F_{max} [N] sample	mean	SD	CV [%]	Tanα [N/mm] sample	mean	SD	CV [%]
SMA 8 45/80-55	10	11881 9939 11326 10333	10870	892	8	26037 41200 41371 69449	44514	18111	41
	20	7939 6851 6990 6659	7110	569	8	33015 48086 36794 33233	37782	7084	19
	30	5423 5099 5173 5362	5264	153	3	28890 30099 24365 25660	27254	2687	10
PA 8 45/80-65	10	4894 5550 5678 4756	5220	462	9	17594 26718 30013 19259	23396	5933	25
	20	3280 2700 2902 2988	2968	241	8	11552 12829 13305 9740	11857	1593	13
	30	807 1741 1816 1703	1517	475	31	10131 4626 7850 10278	8154	2658	33

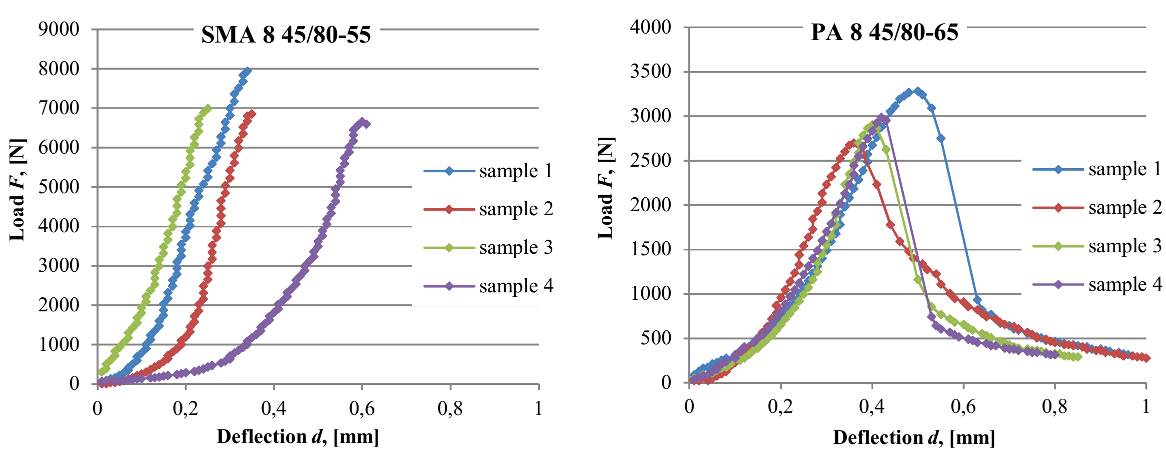

FIGURE 3. Laboratory test results for notch depth 20 mm

NUMERICAL MODELS

It has been assumed that the computations should be conducted in the standard ABAQUS package [22]. The advanced models to capture aggregate distribution require dedicated, advanced software [4]. It should be pointed out that even such models are not intended to fully consider detailed aggregate specification, features of bonding asphalt and the interface of both materials.

Two distinct material models were considered in the computations. The smeared crack model and the cohesive joint and element model were chosen here. Both models are based on a proper constitutive material description (Figure 4), obtained from the laboratory tests.

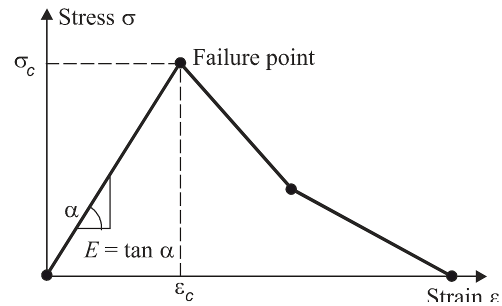

FIGURE 4. $\sigma-\varepsilon$ constitutive relation in tension

The smeared crack model does not indicate the fracture course (Figure 5), the cohesive models allows to analyse the process more precisely (Figure 6). The smeared crack model should capture the non-local character of constitutive relations. Both models can be adjusted to the laboratory scale specimen analysis, but the smeared crack model is the only one allowing simulation of larger pavement parts. The joints or cohesive elements may be easily introduced in the regions of detected crack course. The laboratory test specimens relevantly represent the class of detected crack propagation directions. Random character of material parameters is another key issue here.

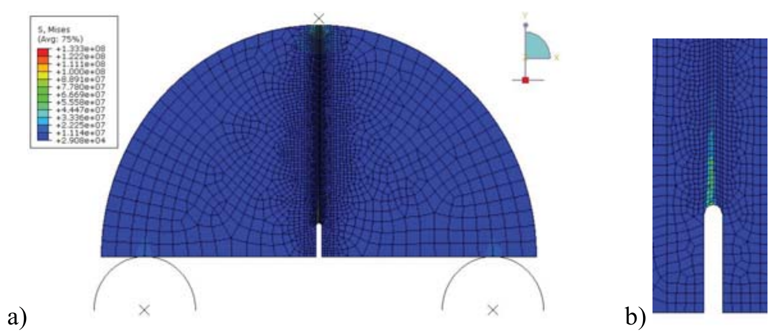

FIGURE 5. Smeared crack model sample mesh (a), and propagation of crack (b).

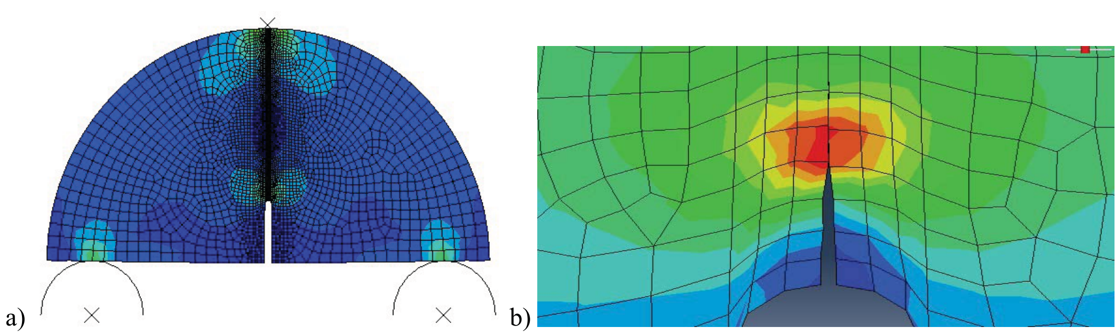

FIGURE 6. Cohesive element crack model: sample mesh (a), and propagation of crack (b).

The work includes a preliminary, simplified fracture analysis of asphalt mixtures. Firstly, computations were made for the PA8 mix specimen with a 20 mm notch. The laboratory test results (Figure 3) suggested about the simplest elastic-brittle material model. The asphalt mix was assumed homogeneous. The results in Table 2 led to the following averaged continuum parameters: E = 1 GPa, ν = 0.2. The cohesive element parameters are as follows: traction separation behavior $K_{nn} = K_{ss} = K_{tt} = 10^{-12}$, total plastic displacement = 0.0001, damage stabilization (viscosity coefficient) = 0.0001. In fact only the elastic material parameters are directly laboratory-based, while cohesive element parameters are obtained by trial and error method. The obtained, satisfactory results for the 20 mm notch are shown in Figure 7.

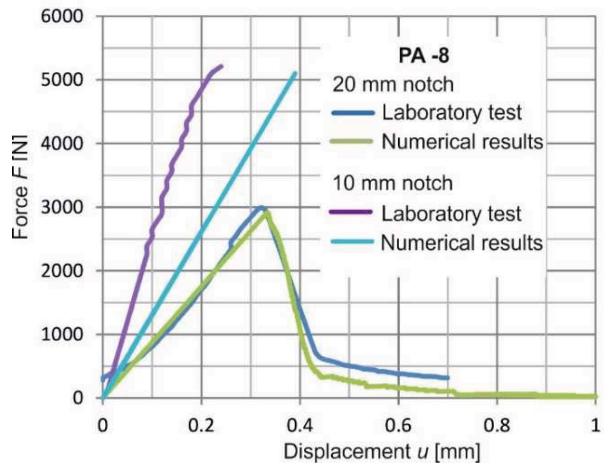

FIGURE 7. Comparison of experimental results and FE calculations – diagram F-d for the PA-8 asphalt mixture

The same input material data were applied for a mechanical modelling of a specimen made of the same mixture, but the notch half its previous value, i.e. 10 mm. The expected response was an improper mapping just in the elastic case (Figure 7). The reason was the scale effect, magnified by a high impact of aggregate distribution in a relatively small crack propagation zone.

In order to reflect the laboratory results random description of asphalt mixtures is required. A numerical experiment was conducted, to randomly characterize the finite elements with three material components: aggregate, bitumen mortar and air voids. A compressed element was assumed, corresponding to a part of a semi-circular specimen (Figure 6a). The density of a FE mesh also corresponds to the model used in previous computations. Variation of a global Young's modulus was investigated, for various proportions of ingredients. The aggregate distribution in the specimen was assumed uniform. A dedicated procedure was built, it incorporated the ABAQUS data. The following material data were assumed: Young's modulus of aggregate E_{ag} = 80000 MPa (constant), Young's modulus of bituminous mortar E_m = 8000 MPa, 800 MPa, 80 MPa, percent of aggregate content from 100% to 50 %. The material data were assumed according to [4]. Table 3 shows results for various percentage of aggregate content.

Table 3. Global E calculation with regard to various percentage of aggregate content

Nr	% of aggregate	E_m= 8000 MPa	E_m= 800 MPa	E_m= 80 MPa
0	100	80000	80000	80000
1	95	72060	69860	69200
2	90	65330	60980	59990
3	85	56690	44230	38850
4	80	49270	33420	28680
5	75	43410	24930	17510
6	70	35810	17550	10700
7	65	30680	8397	2469
8	60	27820	7184	1647
9	55	23690	4566	766
10	50	20040	2004	413

Next the dispersion was checked for of a global Young's modulus E assuming different aggregate distributions generated. Figure 8 presents stress distributions for four random samples. The stress transformation process is observable, caused by randomly distributed aggregate. Thus simulation of real mechanical performance of asphalt mixtures may be conducted. The following parameters are applied: E_{ag} = 80000 MPa, 60% of aggregate content, E_m = 80 MPa. The results are: E = 1647, 1838, 1616, 2105 MPa, Young's modulus mean value 1802 MPa, and standard deviation 225 MPa. The generation can be sequentially repeated, to finally get the material model of an averaged Young's modulus and its standard deviation, both based on experiments. Thus the process can be described as a Monte Carlo simulation-based constitutive relations.

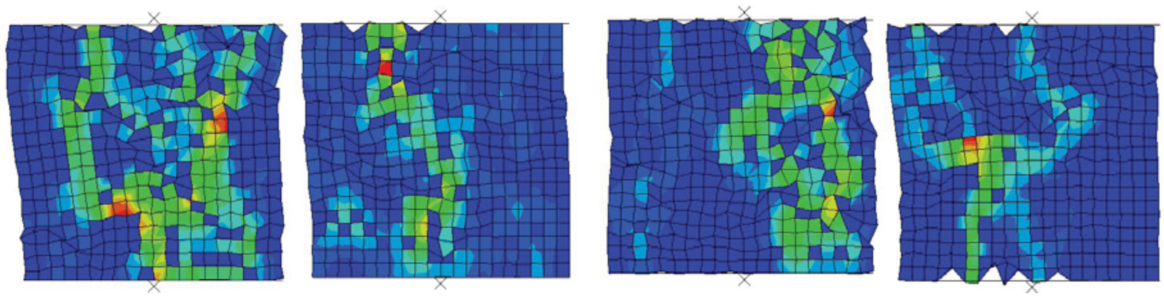

FIGURE 8. Samples of generated aggregate dispersions - stress fields under uniform compression

The computations were based on the mean E = 1000 MPa and its standard deviation σ_E = 130 MPa. These values were determined on the variance basis of laboratory test data (Tab. 2) The Young's modulus generation was conducted in the interval 400 – 1600 MPa. The following values 1500 MPa, 1000 MPa and 800 MPa were assumed, corresponding to the 10, 20 and 30 mm notches, respectively. Other parameters of the cohesive materials were left unchanged. Figure 9 presents the bending test results of PA8 specimens, regarding three notch cases.

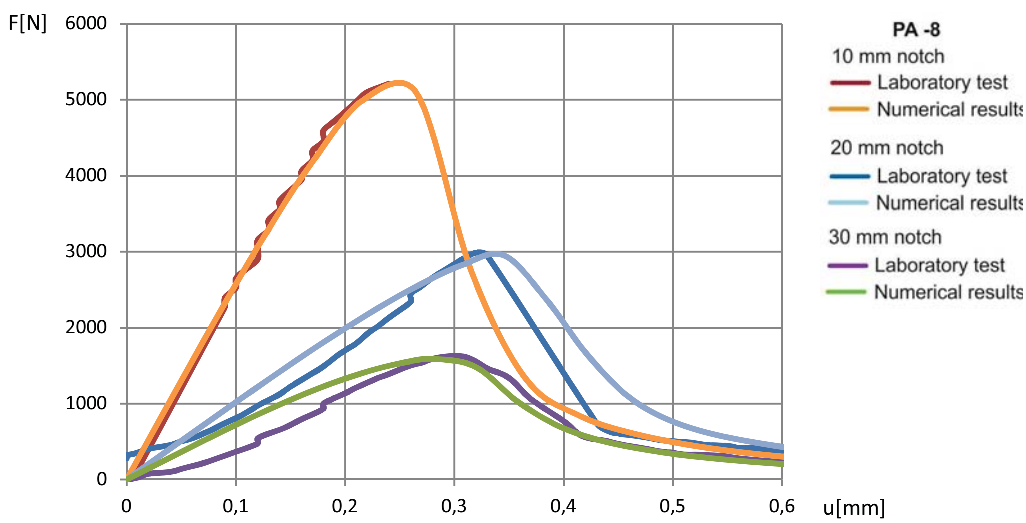

FIGURE 9. Comparison of experimental results and FE calculations – diagram F-u – PA8 mixture, 10, 20 and 30 mm notches

The preliminary character of the computations is pointed out here. Selected cases were chosen only, not backed up by a comprehensive statistical background. This comes out of an indirect Young's modulus assessment, based on the bending laboratory tests. The proposed computational algorithm should be complemented by standard deviation assessment of experimental uniform tension results. The computational results should refer to the averaged values and their deviations, not to distinct experimental cases.

CONCLUSIONS

The character of both laboratory testing and numerical analysis is preliminary. The models requires calibration, considering the notch dimensions, mixture content diversity and the specimen dimensions. An additional issue may concern the temperature impact on the damage process. It is required for the material models to calibrate parameters, by means of averaging the material parameters of components.

The following conclusion can be formulated:

- the asphalt mix may be analysed by continuum models, incorporating standard software,
- the quasi-continuum models allow to consider random uncertainty of parameters,
- a numerical experiment which randomly characterizes the finite elements helps to get better correlations between numerical and laboratory results,
- material parameters of cohesive joints should be based on experimental research.

The preliminary computations allow to state that the proposed Monte Carlo constitutive model is a useful tool to analyse nonhomogeneous materials like asphalt mixtures.

REFERENCES

1. T. L. Anderson, *Fracture mechanics fundamentals and applications*(Taylor & Francis, 2005).
2. Y. R. Kim, *Modelling of asphalt concrete*(ASCE Press Mc GrawHil, 2009).
3. L. Wang, *Mechanics of asphalt Microstructure and micromechanics*(ASCE Press Mc GrawHil, 2011).
4. J. Wimmer, B. Stier, J.W. Simon and S. Reese, Finite Elements in Analysis and Design **110**, pp. 43–57 (2016).
5. H. Wang, J. Wang, J. Chen, Engineering Fracture Mechanics **132**, pp. 104–119 (2014).
6. T. You, R. K. A. Al-Rub, M. K. Darabi, E. A. Masad and D. N. Little, Construction and Building Materials **28**, pp. 531–548 (2012).
7. K. H. Moon, A. C. Falchetto and J. W. Hu, Construction and Building Materials **53,** pp. 568–583 (2014).
8. E. Mahmoud, S. Saadeh, H. Hakimelahi and J. Harvey, Road Materials and Pavement Design **15**(1), pp. 153-166 (2013).
9. A. Yin, X. Yang, S. Yang and W. Jiang, Engineering Fracture Mechanics **78**, pp. 2414-2428 (2011).
10. T. Schüler, R. Jänicke and H. Steeb, Construction and Building Materials, pp. 96-108 (2016).
11. X. Li and M. O. Marasteanu, International Journal of Fracture **136** pp. 285–308 (2005).
12. M. Galouei, A. Fakhimi, Computers and Geotechnics **65** pp. 126–135 (2015)
13. .T. Kanit, S. Forest, I. Galliet, V. Mounoury, D. Jeulin, International Journal of Solids and Structure **40** pp. 3647–3679 (2003).
14. M. Ostoja-Starzewski, Probabilistic Engineering Mechanics **21** pp. 112-132 (2006).
15. T. Pellinen, E. Huuskonen-Snicker, P. Eskelinen, P. O. Martinez, Journal of traffic and transportation engineering **2**(1), pp. 30-39 (2015).
16. C. Szydłowski, J. Judycki, Highway Engineering **10**, pp. 348–353 (2015) (in Polish).
17. S.-J. Lee, G. Zi, S. Mun, J. S. Kong, J.-H. Choi, Engineering Fracture Mechanics **141** pp. 212–229 (2015).
18. A. Yin, X. Yang, H. Gao, H. Zhu, Engineering Fracture Mechanics **92** pp. 40–55 (2012).
19. X. F. Wang, Z. J. Yang, J. R. Yates, A. P. Jivkov, C. Zhang, Construction and Building Materials **75** pp. 35–45 (2015).
20. X. Wang, Z. Yang, A. P. Jivkov, Construction and Building Materials **80** pp. 262–272 (2015)
21. WT:2-2010. Technical Guidelines, Asphalt Pavements on State Roads, Asphalt Mixes. General Directorate for National Roads and Motorways, 2010. Warsaw, Poland. (in Polish).
22. ABAQUS. ABAQUS analysis user's manual, Habbit, Karlsson & Sorenson Inc. 2010.