Materials Physics and Mechanics 21 (2014) 222-229 Received: September 17, 2014

EROSION OF ASPHALT AS A RESULT OF AUTOMOBILE TIRE STUDS IMPACTS

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Abstract> The main objective of the presented research is to develop a model in order to predict fracture of asphalt road surface impacted by an automobile tire stud. As a result of the analysis it is demonstrated that the critical automobile speed leading to creation of fracture in asphalt does depend on combination of asphalt mean elastic modulus and special dynamic strength characteristics responsible for the incubation process of microcracking caused by impacts. It is shown that in certain conditions smaller elastic moduli combined with bigger ductility of compound and increased dynamic strength can result in greater threshold car velocities giving brittle damage to asphalt. At the same time larger elastic moduli can provide better performance of asphalt layer undergoing quasistatic loading (slow heavy traffic). One of the practical solutions to maximize durability of highways is to use different asphalt mixtures in right (slower) and left (faster) traffic lanes. This can be, for example, achieved by addition of plasticizers into asphalt mixture used to cover high-speed traffic lanes. FEM simulation is giving a quantitative prediction of critical vehicle velocities leading to initiation of fracture in asphalt.

1. Introduction

It is often believed that the main contribution to fracture and deformation of asphalt covered road surfaces is made by heavy weight traffic. Indeed, for low speed traffic, heavy vehicles (lorries, buses etc.) create loads on the road surface, which significantly exceed loads created by much lighter motorcars. In this case the road surface is loaded *quasistatically*. The process of road surface deformation and fracture in this case is well studied. The situation can be significantly different if one allows for high-speed traffic. Moving on Russian high speed motorways it can be observed that the main damage to the road surface is concentrated at left (high-speed) traffic lanes. It is also seen that this damage is caused by erosion-type fracture of the asphalt surface (fracture connected with material removal). At the same time heavy trucks are rarely or never moving in these lanes. Obviously, fast-moving motorcars induce this damage. For a car moving at the speed of 110 km/h time of interaction between the tire and the road is around 5 milliseconds. An impact of a tire stud on the road surface is 2-3 microseconds long and the energy of this impact is increasing as the square of the vehicle velocity. It is believed that the main reason for the erosion-type damage in the left traffic lanes on high-speed roads is the result of impacts of tire studs of vehicles moving at high speeds.

2. Fracture criterion

Adequate choice of fracture criterion is one of the central problems in order to create a model predicting erosion-type fracture of asphalt impacted by automobile tire studs. Nowadays it is known and generally recognized that classical fracture criteria (critical stress criterion, critical

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stress intensity factor criterion, etc.) are normally inapplicable in order to predict fracture cased by dynamic high-rate loads. Incubation time fracture criterion [2-3] can be utilized for correct and robust prediction of critical conditions leading to fracture of material loaded by impact loads. This criterion for fracture at a point *x*, at time *t*, reads as:

$$\frac{1}{\tau}\int_{t-\tau}^{t}\frac{1}{d}\int_{x-d}^{x}\sigma(x',t')dx'dt' \le \sigma_{\mathrm{c}}, \tag{1}$$

where τ is the microstructural time of a fracture process (or fracture incubation time) – a parameter characterizing the response of the material to applied dynamical loads (i.e. τ is constant for a given material and does not depend on problem geometry, the way a load is applied, the shape of a load pulse or its amplitude). Parameter *d* is the characteristic size of a fracture process zone and is constant for the given material and chosen scale; σ is stress at a point, changing with time, and σ_{c} is its critical value (ultimate stress or critical tensile stress found in quasistatic conditions).

Assuming

$$d = \frac{2}{\pi}\frac{K_{\mathrm{IC}}^2}{\sigma_{\mathrm{c}}^2}, \tag{2}$$

where K_{IC} is the critical stress intensity factor for mode I loading (mode I fracture toughness), measured in quasistatic experimental conditions, it can be shown that within the framework of linear fracture mechanics, for the case of fracture initiation in the tip of an existing crack, (1) is equivalent to:

$$\frac{1}{\tau}\int_{t-\tau}^{t}K_{\mathrm{I}}(t^*)dt^* \le K_{\mathrm{IC}}\,.$$

Condition (2) arises from the requirement that (1) is equivalent to Irwin's criterion ($K_{\mathrm{I}} \ge K_{\mathrm{IC}}$), in the case of $t \to \infty$.

As it was shown in many previous publications, criterion (3) can be successfully used to predict fracture initiation for brittle solids (ex. [4-5]). For slow loading rates and, hence, times to fracture that are much bigger than τ, condition (3) for crack initiation gives the same predictions as Irwin's criterion of a critical stress intensity factor. For high loading rates and times to fracture comparable to τ all the variety of effects experimentally observed in dynamic experiments (ex. [6-8]) can be obtained using (3), both qualitatively and quantitatively [9]. Application of condition (3) to predict real experiments or usage of (3) as the critical fracture condition in finite element numerical analysis gives a possibility for better understanding of the nature of fracture dynamics (ex. [10]), and even predicts new effects typical for dynamic processes (ex. [11-12]). There is also a possibility to predict other highly transient processes on the basis of the general incubation time approach [9]. Using this ideology one can successfully model effects typical for electrical breakdown in insulators under high-rate pulsed voltage, cavitation in liquids, plasticity and phase transformations under high rate loads, detonation, etc., that are difficult to describe within the framework of classical approaches.

All this motivates the choice of fracture criterion for the current investigation.

3. Fractured material (asphalt)

The following estimations will require material parameters for the fractured material. The choice is not obvious: there is a big number of different asphalt mixtures widely used in practice. Their mechanical and strength properties vary significantly depending on the properties of mixture components and their proportions. Moreover, for this class of materials there is a significant dependency of material properties on temperature.

The current research is focused on brittle fracture of asphalt impacted by tire studs. It is known that lower temperatures are normally leading to “more brittle” behaviour of material (probability of brittle fracture is increased).

As a reference temperature of asphalt layer we accept temperature equal to -5 Celsius, which is a normal winter temperature for the European part of Russia. Higher temperatures will result in lower probability of brittle fracture (higher critical motorcar speeds leading to asphalt fracture). Lower temperatures will have opposite influence.

Based on the available experimental data [13-15] the following material properties typical for asphalt used for construction of top layer of Russian motorways at -5 Celsius were used:

- Young's modulus (E) $1.1 \cdot 10^9$ Pa;
- Poisson's ratio (ν) — 0.3;
- Density (ρ) 2100 kg/m^3;
- Ultimate stress (σ_c) $45 \cdot 10^5$ Pa;
- Critical stress intensity factor (K_{IC}) $114 \cdot 10^3$ Pa m$^{1/2}$;
- Brittle fracture incubation time — 12 microseconds;
- Structural size d for this material can be calculated using (2) and is equal to 0.4 mm.

This reference material will be compared to “modified” asphalt mixtures. It is assumed that there is a possibility to change material elastic modulus (Young’s modulus) of asphalt (for example, by introduction of plasticizer). Effect of elastic modulus change on other material parameters can be evaluated on the basis of the previous research [2, 11, 12].

Following [16] it is supposed that ultimate stress and critical stress intensity factor are not significantly affected by the change of the elastic modulus. Thus, structural size d is neither affected significantly. In [17] it is demonstrated that the incubation time for many materials is proportional to the structural size d and back proportional to the speed of waves in the fractured material.

Thin rod elastic wave speed is given by $c_s = \sqrt{E/\rho}$. Assuming that the material density is not significantly changed, it can be received that in the studied case the fracture incubation time should be back proportional to the square root of the elastic modulus.

4. Spall fracture

The first approximation used in order to assess influence of change of asphalt elastic modulus on its dynamic strength is the problem of spall fracture in a plate made of asphalt. Suppose the impact has a rectangular time shape (this time shape is close to time shape of pressure created by a stud impacting the surface). Duration of the load is given by the stud linear size. Its amplitude is given by the impact initial velocity.

The problem can be solved analytically using the incubation time criterion (1) in order to predict fracture. As a result, critical load parameters, leading to spall fracture in asphalt plate can be calculated.

Taking into consideration that the usual length of an automobile tire stud is 16 mm and longitudinal wave speed in steel is around 5000 m/s, it can be found that duration of the stud impact is about 3.1 microseconds. Impact amplitude will depend on the stud initial velocity.

The solution is received as a sum of an incident and the reflected waves. The incident wave is given by:

$$\sigma_+ = -P\left[H(t+\frac{x_2}{c_1}) - H(t+\frac{x_2}{c_1}+T) \right],$$

where P is the load amplitude; T is its duration; H is the Heaviside step function; t is the time;

t=0 is the time when the incident wave is arriving to the sample boundary; x_2=0 is the plate boundary reflecting the wave. The reflected wave is given by:

$$\sigma_- = P\left[H(t - \frac{x_2}{c_1}) - H(t - \frac{x_2}{c_1} + T) \right].$$

The solution can be found as $\sigma = \sigma_+ + \sigma_-$.

Fracture criterion (1) is used to find critical load leading to asphalt rapture. Taking into account that incubation time τ is exceeding load duration T, critical condition can be received as: $PT \leq \sigma_c \tau$.

When this inequality is not fulfilled a rapture of asphalt takes place. Equality of the right and the left part corresponds to the critical load amplitude, i.e. critical stud velocity corresponding to a motorcar's critical speed. Thus:

$$P_c = \frac{\sigma_c \tau}{T}.$$

Figure 1 shows critical load amplitude P_c as a function of asphalt elastic modulus.

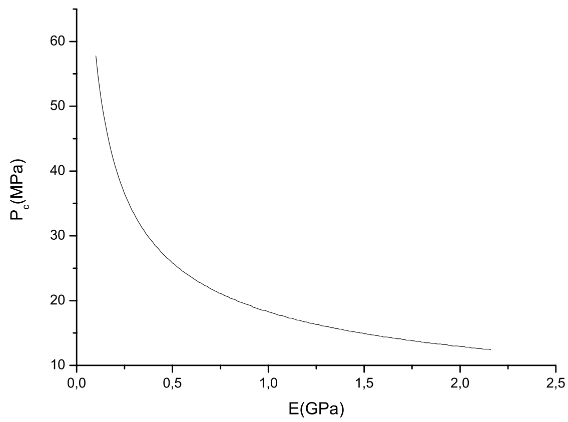

Fig. 1. Critical load amplitude as a function of asphalt elastic modulus.

As it follows from Fig. 1, lower elastic moduli of asphalt result in higher critical motorcar velocities, i.e. material with lower elastic modulus is more suitable to be used for high-speed traffic.

5. Hertz model of a cylinder impacting half-space

As a much closer approximation to the problem of a tire stud impacting asphalt layer, Hertz problem of an impact of a rigid cylindrical particle on a boundary of a half-space can be considered.

Consider rigid cylindrical particle with a radius R and a length l=4/3R, impacting boundary of an elastic half-space with initial velocity v_0. Using the approximation of the classical Hertz theory, it is supposed that the particle motion is given by [4, 18]:

$$m\frac{d^2h}{dt^2} = -F, \tag{3}$$

where m is the particle mass. F is given by:

$$F(t) = k(R)h(t); \quad k(R) = \frac{2RE}{1-\upsilon^2}. \tag{4}$$

At the moment preceding interaction between the particle and the half-space (t=0):

$$h(t) = 0; \quad v(t) = v_0. \tag{5}$$

Solving (3)-(5) for h, one can receive:

$$h(t) = h_0 \sin\left(\frac{\pi t}{t_0}\right), \qquad h_0 = \frac{v_0 t_0}{\pi}, \qquad t_0 = \sqrt{\frac{m}{k}}\pi. \tag{6}$$

where h_0 is the maximum particle penetration and t_0 is the duration of the contact between the particle and the half-space.

Maximum of the tensile stresses can be approximated by [18]:

$$\sigma(v_0, R, t) = \frac{1-2\nu}{2}\frac{F(t)}{\pi R^2} = \frac{(1-2\upsilon)E}{\pi(1-\upsilon^2)}\frac{h_0}{R}\sin\left(\frac{\pi t}{t_0}\right).$$

Fracture condition (1) for this case can be rewritten as:

$$\int_{t-\tau}^{t} \sigma(v_0, R, s)ds \le \sigma_c \tau.$$

The following condition corresponds to critical situation leading to raptures in the half-space:

$$\max_t \int_{t-\tau}^{t} \sigma(v_0, R, s)ds = \sigma_c \tau. \tag{7}$$

Utilising (7), one can find threshold velocity v_0 of the particle leading to initiation of fracture in the area of asphalt impacted by a cylinder.

Cylinder mass is taken to be equal to 2.1 g, being the mass of a standard tire stud. Standard stud length is 16 mm, giving R=12 mm.

Solving (7) for v_0 (initial particle velocity), critical stud velocity can be found as a function of asphalt elastic modulus. Figure 2 presents the received dependency.

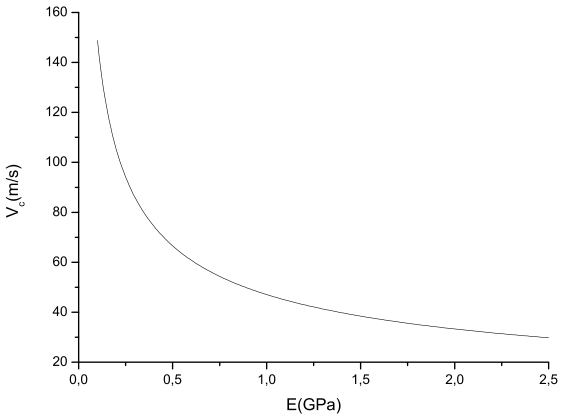

Fig. 2. Critical stud velocity can be found as a function of asphalt elastic modulus.

As it follows from Fig. 2, lower elastic moduli of asphalt result in higher critical motorcar velocities, i.e. lower elastic modulus provides an increase in the material dynamic strength properties. The received dependency should qualitatively coincide with dependency of critical velocity of an automobile tire stud fracturing asphalt layer (erosion-type fracture).

6. Numerical simulations

Predictions of asphalt fracture closest to real process can be received on the basis of FEM modelling. Axisymmetric contact problem of a steel cylinder (tire stud) impacting half space (asphalt) will be solved. Displacements for the problem are given by:

$$\rho u_{i,tt} = (\lambda + \mu) u_{j,ji} + \mu u_{i,jj} \ . \tag{8}$$

where "," refers to the partial derivative with respect to time and spatial coordinates; ρ is the mass density, and the indices *i* and *j* assume the values 1 and 2. Displacements are given by u_i in the directions x_i respectively. T stands for time, λ and μ are Lame constants. Stresses and strains are coupled by the Hooke's law:

$$\sigma_{ij} = \lambda \delta_{ij} u_{k,k} + \mu (u_{i,j} + u_{j,i}) \ . \tag{9}$$

where σ_{ij} represents stresses in direction *ij*, and δ_{ij} is the Kronecker delta assuming value of 1 for *i*=*j* and 0 otherwise. For *t*=0 half space representing asphalt is stress free and velocities of all half space points are 0:

$$\sigma_{ij}\big|_{t=0} = u_{,t}\big|_{t=0} = 0. \tag{10}$$

Cylindrical striker representing the stud for *t*=0 is free from stresses and has an initial velocity *v*:

$$\sigma_{ij}\Big|_{t=0} = 0; \ \ u_{,t}\big|_{t=0} = -v. \tag{11}$$

The stud is modelled as linear elastic cylinder with properties of steel (see previous sections for properties). The cylinder is 16 mm long and 2.4 mm in diameter. The mass of the cylinder is equal to 2.1 grams, which is a typical mass of a tyre stud. Execution of fracture condition (1) is controlled for all of the points of the body representing the fractured asphalt media. As the fracture criterion is executed creation of a new surface would take place. Fracture condition (1) for this problem can be rewritten as:

$$\frac{1}{\tau}\int_{t-\tau}^{t} \sigma_{ii}\,(t')dt' \geq \sigma_C, \tag{12}$$

where *i* is taking values of 1 and 2. Spatial integration can be removed as a result of an appropriate FE mesh choice – nodal stresses are already the average stresses on a distance approximately equal to the element size (*d*).

The problem is solved for *y*<0. ANSYS finite element method software was utilized to solve the problem of linear elasticity. Execution of condition (12) at every node was controlled by an external program. When the fracture condition was executed somewhere in the body, sample geometry was updated accounting for newly created surface. Figure 3 shows typical distribution of horizontal stresses in the process of modelling. Figure 4 shows a typical history of stresses on the asphalt surface at a point adjacent to the stud impact area.

Computations were performed for a number of asphalt mixtures with different properties (standard mixture and several modified mixtures). For every of the examined mixtures a set of simulations were performed in order to establish critical (threshold) stud velocity leading to initiation of fracture in the asphalt media. I.e. impacts with velocities lower than the critical one are not producing any fracture whilst higher velocity impacts lead to implementation of fracture criterion (12) somewhere within the modelled area).

H. Zubeck et al. [1] claim that the velocity of an automobile stud prior to contact to the pavement surface can be estimated as 1/10 of the vehicle velocity. Thus, one can roughly estimate critical (minimal) vehicle velocities that will lead to initiation of fracture in asphalt. Figure 5 gives critical vehicle velocity as a function of asphalt elastic modulus.

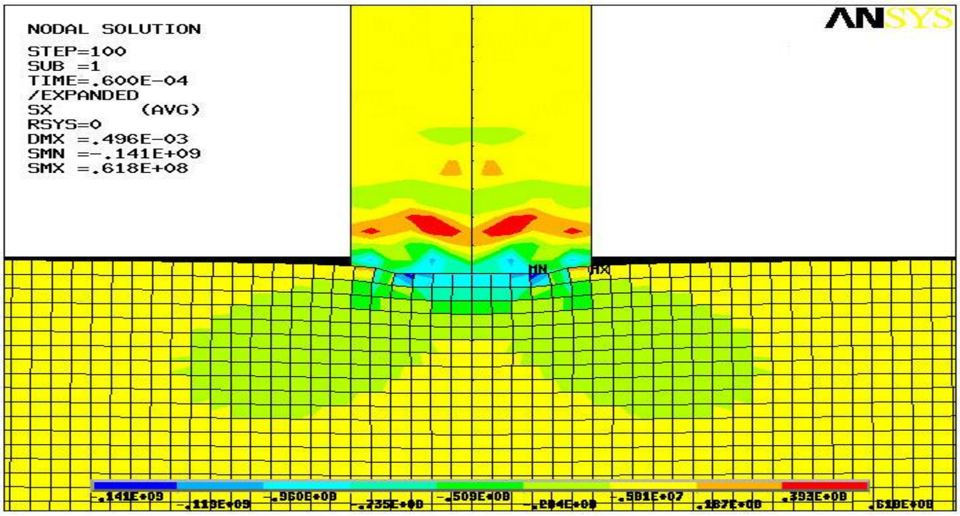

Fig. 3. Typical field of the horizontal stresses in the process interaction of a stud with asphalt media.

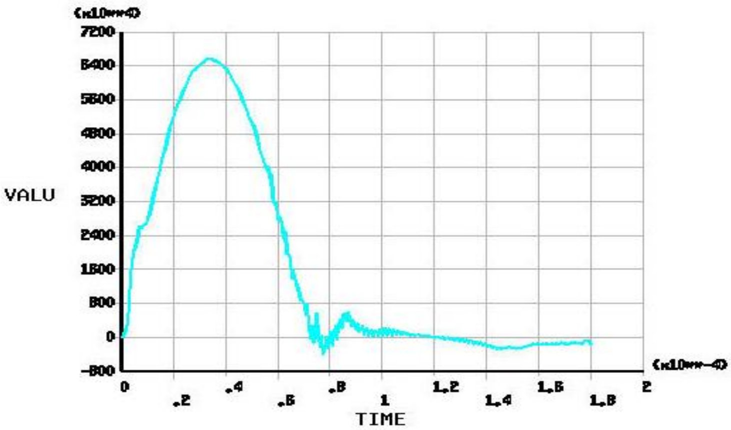

Fig. 4. Typical history of stresses on the asphalt surface at a point adjacent to the stud impact area.

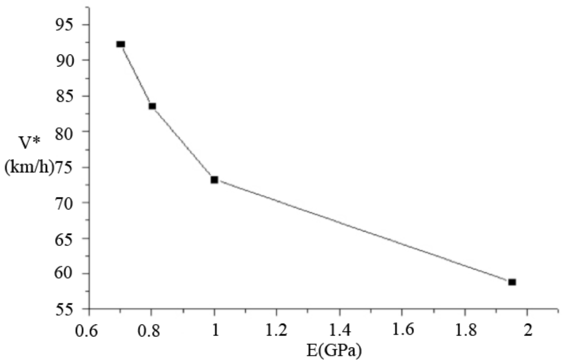

Fig. 5. Critical (minimal) vehicle velocity leading to initiation of fracture in asphalt as a function of asphalt elastic modulus.

7. Summary

Two analytical models serving as qualitative approximation to the process of automobile tire stud impacting asphalt layer are analysed. Using these models an important effect is demonstrated: decrease in the elastic modulus of asphalt can lead to a significant increase of the critical stud (or motorcar) velocity leading to initiation of asphalt rapture.

FEM being a much better approximation of a real process is used to predict critical vehicle velocities leading to creation of ruptures in asphalt layer. The received dependency of critical automobile velocity as a function of asphalt layer elastic modulus is providing a possibility to quantitatively assess the effect of the asphalt elastic modulus change on the asphalt strength. Critical velocity of automobile for "standard" asphalt (74 km/h) is very close with the value evaluated experimentally [19] and the speed limit of 80 km/h imposed on cars with studded tyres in some of the European countries (Switzerland, Lichtenstein, Austria).

One of the practical solutions to maximize durability of highways is to use different asphalt mixtures in right (slower) and left (faster) traffic lanes. This can be, for example, achieved by addition of plasticizers into asphalt mixture used to cover high-speed traffic lanes. Presented simulations are giving a quantitative prediction of critical vehicle velocities leading to initiation of fracture in asphalt.

Acknowledgements
The authors acknowledge Saint-Petersburg State University for a research grant 6.39.319.2014. The research and publication preparation was also supported by RFBR research grants 14-01-00814 and 13-01-00598, the President Grant for Government Support of Young Russian Scientists MK-5890.2013.1 and the academic programs of the Russian Academy of Sciences.

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