Dynamic Fracture of Asphalt as a Result of Automobile Tire Studs Impacts

Vladimir Bratov[1,2,a] and Yuri Petrov[1,2,b]

[1] IPME RAS, Bolshoj pr. V.O., 61, 199178, St.Petersburg, Russia

[2] St.Petersburg University, Universitetskaya nab. 7/9, 199034, St.-Petersburg, Russia

[a] Vladimir@bratov.com, [b] YP@yp1004.spb.edu

Keywords: Dynamic fracture, asphalt wear, studded tires, highways.

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. Two analytical approximations of the process are studied. The first one is spall fracture of asphalt. The model is not very close to the real process studied, but the solution is simple and is providing a possibility to analyze effect of asphalt properties on critical impact speeds leading to asphalt fracture. The second analytical model is based on the known Hertz-type solution for a cylinder impacting half-space. This model is much closer to the real stud impact process and is providing a possibility to estimate the effect of asphalt elasticity modulus on critical stud velocity, leading to fracture of the asphalt surface. Fracture criterion for all the studied models is based on the incubation time theory for brittle fracture.

As a result of the analysis it is demonstrated that the critical automobile speed, leading to creation of fracture in asphalt does depend on asphalt elastic modulus. This dependency is received both qualitatively and quantitatively. It is shown that larger elastic moduli are resulting in smaller critical car velocities giving damage to asphalt. At the same time larger elastic moduli are providing better performance of asphalt layer undergoing quasistatic loading (slow heavy traffic). Practical solution 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.

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 Russia 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 microseconds. An impact of 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.

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 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:

$$\frac{1}{\tau}\int_{t-\tau}^{t}\frac{1}{d}\int_{x-d}^{x}\sigma(x,t)dxdt \geq \sigma_c\ , \tag{1}$$

where t 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. t 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). d is the characteristic size of a fracture process zone and is constant for the given material and chosen scale. s is stress at a point, changing with time, and s_c is its critical value (ultimate stress or critical tensile stress found in quasistatic conditions).

Assuming

$$d = \frac{2}{\pi}\frac{K_{IC}^2}{s_c^2}, \tag{2}$$

where K_{IC} is a 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:

$$\frac{1}{\tau}\int_{t-\tau}^{t}K_{\mathrm{I}}(t^*)dt^* \leq K_{\mathrm{I}C}\ .$$

Condition (2) arises from the requirement that (1) is equivalent to Irwin's criterion ($K_{\mathrm{I}} \geq K_{IC}$), 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 t, 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 t 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 the description of real experiments or usage of (3) as the critical fracture condition in finite element numerical analysis gives a possibility of 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 of describing 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 of liquids, plasticity and phase transformations under high rate loads, detonation, etc., that are difficult to describe within the framework of classical approaches.

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

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” behavior 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) 1.1e9 Pa
- Poisson's ratio (ν) — 0.3
- Density (ρ) 2100 kg/m^3
- Ultimate stress (σ_c) 45e5 Pa
- Critical stress intensity factor (K_{IC}) 114e3 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 $c_s = \sqrt{\frac{E}{\rho}}$. 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.

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 16mm and longitudinal wave speed in steel is around 5000m/s, it can be found that duration of the stud impact is about 3.1microseconds. 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 – its duration, H is standing for the Heaviside step function, t is 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:

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

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

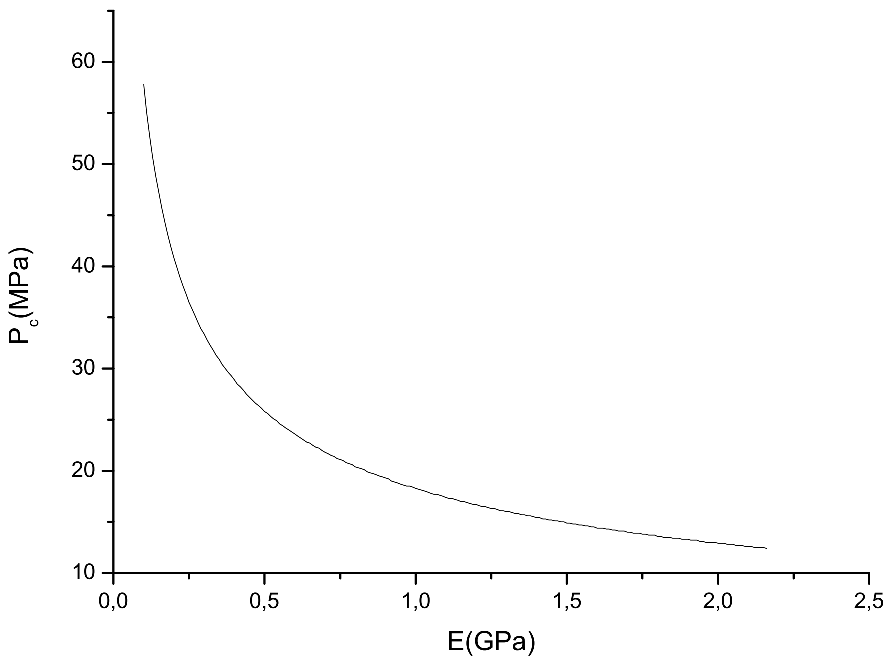

Fig. 1
Critical load amplitude as a function of asphalt elastic modulus

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.

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:

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

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. Fig. 2 is presenting the received dependency.

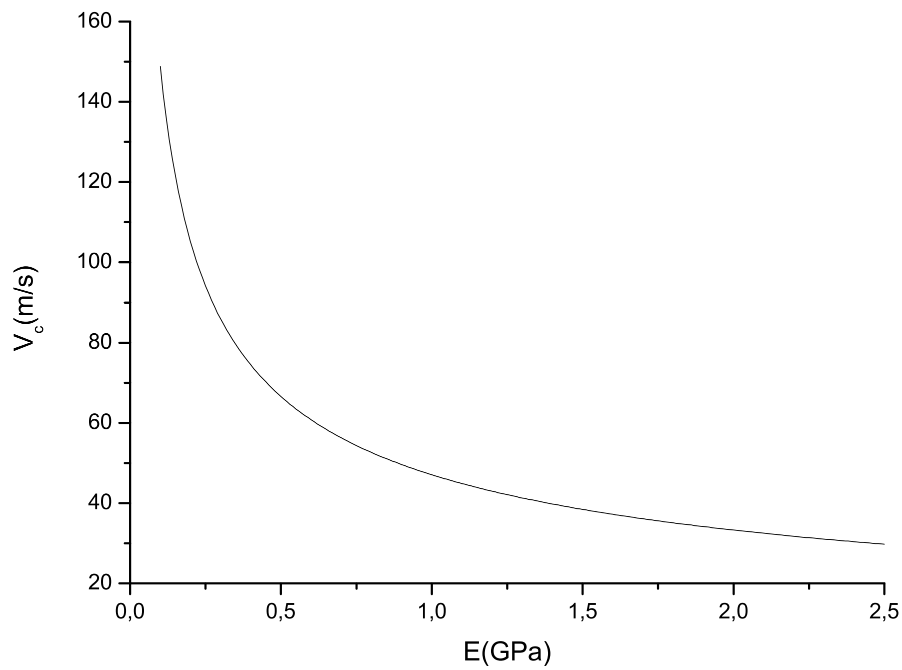

Fig. 2
Critical stud velocity can be found as a function of asphalt elastic modulus.

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 tyre stud fracturing asphalt layer (erosion-type fracture).

Summary

Two 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.

These results indicate a possibility to optimise material (asphalt mixture) parameters for different traffic conditions by addition of plasticizers into asphalt mixture.

References

[1] Hannele Zubeck, Lynn Aleshire, Susan Harvey, and Stan Porhola, Eric Larson: SOCIO-ECONOMIC EFFECTS OF STUDDED TIRE USE IN ALASKA, EXECUTIVE SUMMARY, University of Alaska Anchorage, April 26, (2004)

[2] Petrov, Y.V., Morozov, N.F.: On the modeling of fracture of brittle solids. Journal of Applied Mechanics vol. 61, (1994), pp. 710-712

[3] Morozov, N., Petrov, Y.: Dynamics of Fracture. Springer-Verlag, Berlin-Heidelberg-New York, (2000)
[4] Petrov, Y.V., Morozov, N.F., Smirnov, V.I.: Structural micromechanics approach in dynamics of fracture. Fatigue and fracture of Engineering Materials and Structures, vol. 26, (2003), pp.363-372
[5] Petrov, Y., Sitnikova, E.: Temperature dependence of spall strength and the effect of anomalous melting temperatures in shock-wave loading. Technical Physics vol. 50, (2005) , pp. 1034-1037
[6] Ravi-Chandar, K., Knauss, W.G.: An experimental investigation into dynamic fracture: I. Crack initiation and arrest. International Journal of Fracture vol. 25, (1984), pp.247-262
[7] Kalthoff, J.F.: Fracture behavior under high rates of loading. Engineering fracture Mechanics vol. 23, (1986), pp.289-298
[8] Dally, J.W., Barker, D.B.: Dynamic measurements of initiation toughness at high loading rate. Experimental Mechanics vol. 28, (1988), pp. 298-303
[9] Petrov, Y.V.: Incubation time criterion and the pulsed strength of continua: fracture, cavitation, and electrical breakdown. Doklady Physics vol.49, (2004), pp.246-249
[10] Bratov,V., Gruzdkov, A., Krivosheev,S., Petrov, Y.: Energy Balance in the Crack Growth Initiation under Pulsed-Load Conditions. Doklady Physics vol. 49 (2004), pp. 338-341
[11] Bratov, V., Petrov, Y.: Optimizing energy input for fracture by analysis of the energy required to initiate dynamic mode I crack growth. International Journal of Solids and Structures, vol. 44, (2007), pp. 2371-2380
[12] Bratov, V., Petrov, Y.: Application of incubation time approach to simulate dynamic crack propagation. Int. J. Fract. Vol. 146, (2007), pp. 53-60
[13] J.M.M. Molenaar, X. Liu, A.A.A. Molenaar: RESISTANCE TO CRACK-GROWTH AND FRACTURE OF ASPHALT MIXTURE, Delft University of Technology, (2001)
[14] McQuillen, J.L., and Hicks, R.G.: Construction of rubber- modified asphalt pavements. American Society of Civil Engineers, Journal of Construction Engineering and Management, Vol: 113, issue: 4, (1987), pp. 537-553.
[15] M. A. Mull, K. Stuart, A. Yehia: Fracture resistance characterization of chemically modified crumb rubber asphalt pavement, Journal of Materials Science, vol. 37(3), (2002), pp. 557-566
[16] Gruzdkov, A.A., Morozov N.F., Petrov Y.P.: The Principle of Equal Powers for Multilevel Fracture in Continua , Mechanics of solid state, vol 6, (2006), pp. 198-203.
[17] Yu. V. Petrov, A. A. Gruzdkov, and N. F. Morozov. The Principle of Equal Powers for Multilevel Fracture in Continua, Doklady Physics, vol.50, Issue 9, (2005), pp.448-451.
[18] Lawn B.R., Wilshaw T.R., Indentation Fracture: Principles and Application, Journal of Material Science, vol.10, (1975), 1049-1081