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Rheo-mechanical model for self-healing asphalt pavement

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Abstract. Examining the rheological properties of different asphalt mixtures at different temperatures, pressures and deformation conditions on the combined rheo-tribometers the authors have found that the generally used Burgers-model doesn't explain the deformation properties of asphalt mixtures and pavements under loading forces and loading pressures. To understand better the rheological and deformation properties of such complex materials like asphalt mixtures and pavements the authors used Malvern Mastersizer X laser granulometer, Bruker D8 Advance X-ray diffractometer, Hitachi TM 1000 Scanning Elektronmicroscope, Tristar 3000 specific surface tester and the combined rheo-tribometer developed and patented by the authors. After the complex investigation of different asphalt mixtures the authors have found a new, more complex rheological model for the asphalts including self-healing asphalt pavements.

1. Introduction

In our days rheology is playing very important role in examination of biological and polymer systems and materials science [1-4] also in development of ceramics and construction materials with required properties [5-8]. Knowledge of rheological properties is particularly important in processing and application of asphalt mixtures [9-13] as one of the most popular building materials in the world, thanking to the urbanization and increasing traffic by day to day. In spite of this popularity there are some shortages in explanation of the physical and mechanical properties of asphalt pavements made from different local bitumen and minerals using the traditional Burgers rheological model [14-19]. The reason is that using this rheological model the Maxwell element cannot explain the resistance of pavement to the mechanical loading forces especially in changing climatic conditions like winter and summer. To add this when construction engineers would like to prepare self-healing asphalt the wetting of surface of mineral raw material particles and fillers by binders like bitumen, is playing very important role [12, 20, 21].

The physical, chemical, mechanical and rheological properties of asphalt mixtures and consolidated asphalt pavements are very strong depend not only on working temperature, but on mineralogical composition, grain size distribution, filler containment and microstructure of used raw materials and the type and proportion of the used binders. It is also important the role of chemicals used for asphalt mixtures to increase wetting properties of bitumen binders [22-25]. The goals of this research are:

- understand the phenomena of rheo-mechanical properties of complex material systems like asphalt mixtures and pavements,
- understand the influence of temperatures, filler types and grain size distributions, and loading forces on the mechanical behavior and rheological properties,
- create new rheological model which can better support engineers in development more durable asphalt mixtures as well as self-healing asphalt pavements if possible.

2. Materials and experimental procedures

Asphalt is a mixture of coarse (graves and sands) and fine (fillers) aggregates with hydrocarbon binders like bitumen the structure of which is shown in Fig.1.

Figure 1. Structure of asphalt

Gezentsvei [26] was the first in 1950s who described the mechanical properties of this kind of material structure by rheological model of Burgers (Fig.2). He was also one of the first scientists who emphasized and underpinned the importance of temperature, granular structures on rheological properties of fresh asphalt mixtures and their behavior during compacting under the road roller [27].

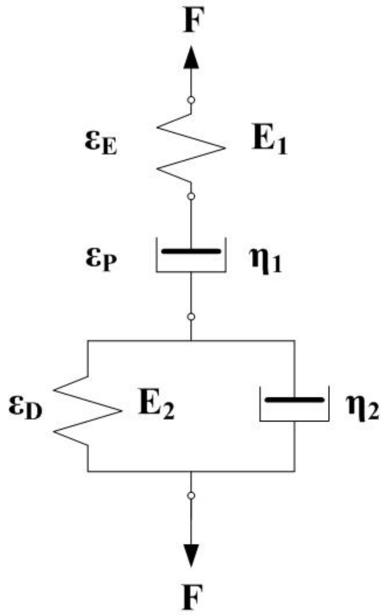


Figure 2. Rheological model of the Burgers-materials

It is obvious from the Burgers-model that these kinds of materials will have a residual and further permanent deformation in each case when an outstanding loading force will develop in it a mechanical stress:

$$\sigma > 0 \tag{1}$$

The deformation response function of this kind of materials was described by [28] as:

$$\varepsilon_0(t) = \varepsilon_1(t)\varepsilon_m(t) + \varepsilon_{k0}(t) \tag{2}$$

where:

$\varepsilon_1(t) = \sigma/E_1$ – the deformation response function of Hooke-element
$\varepsilon_1(t)$ -deformation response function of Newton-element
$\varepsilon_1(t)$ - deformation response function of Voigt-Kelvin-element

On the basis of Burgers-model the irreversible deformation of asphalt pavement is:

$$\varepsilon_m(t) = \sigma\tau/\eta_1 \tag{3}$$

and the value of which will permanently grow and never will reversible in time thanking to the new loading forces of car wheels on the road.

Generally there are three different asphalt pavements are used to prepare the roads. They are dense (closed), semi-dense (semi-closed) and light (open). All of them have different density depending on volumes of pores and gaps between the mineral particles. So the dense (closed) asphalt pavement can be characterized as:

$$\sum_{i=1}^{n} V_{ci} + \sum_{j=1}^{k} V_{pj} \leq 5\%V_0 \tag{4}$$

the semi-dense as:

$$5\%V_0 < \sum_{i=1}^{n} V_{ci} + \sum_{j=1}^{k} V_{pj} \leq 15\%V_0 \tag{5}$$

and the light as:

$$\sum_{i=1}^{n} V_{ci} + \sum_{j=1}^{k} V_{pj} > 15\%V_0 \tag{6}$$

where:

V_0 – the total volume of the examined asphalt pavement specimen (Marshall-probe)
V_{ci} – the volume of i-th elementary capillary
V_{pj} – the volume of j-th elementary pore
n – number of elementary capillaries in the examined asphalt pavement specimen
k –number of elementary pores in the examined Marshall-probe specimen

For examination the rheological properties of asphalt pavements at different temperatures under different loading forces the Marshall-probe specimens were prepared using the following five different fillers:

- Limestone filler 1
- Limestone filler 2
- Andesite + dolomite filler mixtures (50-50%)
- Andesite filler
- Basalt filler

The grain size distribution of dolomite filler is shown in Fig.3 and the specific surfaces of the fillers are shown in Table 1.

The typical microstructures of the filler components used for preparing Marshall-probe specimens of asphalt pavements are shown in Fig.4.

The rheological properties of Marshall-probes made from asphalt mixtures with different mineralogical, granular and bitumen compositions were examined on the new developed and patented [29] combined rheo-tribometer which is shown in Fig. 5. During the rheological tests the Marshall-specimens were put into the specimen holder (9), pressed with pneumatic cylinder (10) and heated through thermostat (14). The variable speed (v) of shear plate (6) was kept in a constant value depending on the experiment plan.

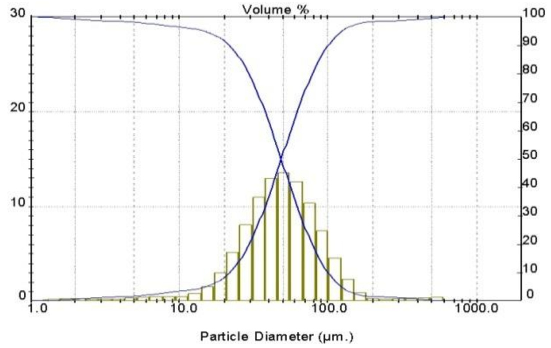
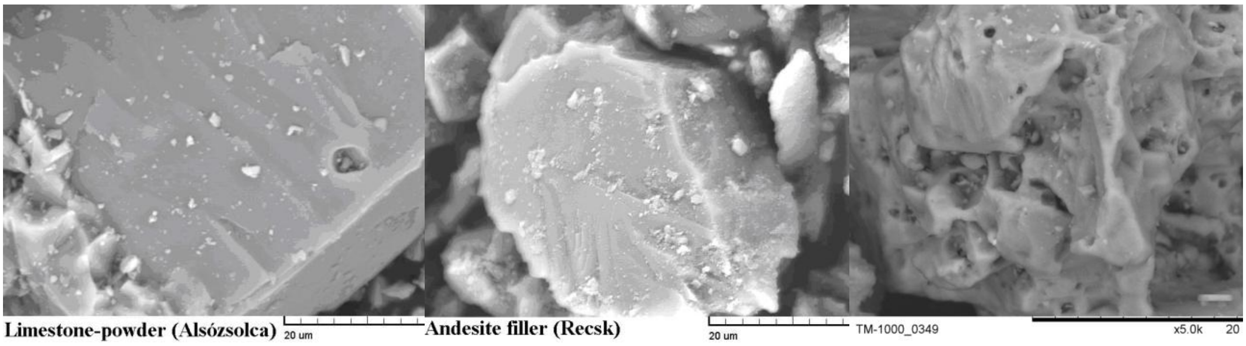


Figure 3. Grain size distribution of dolomite filler

Table 1. Specific surfaces of the used fillers

Name	pore volume	pore surface	outer surface	spec. surf. BET	spec. surf. Langmuir	spec. surf. single
	cm^3/g	m^2/g	m^2/g	m^2/g	m^2/g	m^2/g
1	0,000082	0,2185	2,0177	2,2362	3,0931	2,168
2	0,000095	0,2335	1,8329	2,0664	2,8455	2,0114
3	0,000906	2,0391	5,3887	7,4278	10,0959	7,339
4	0,000223	0,6263	7,0661	7,6924	10,5022	7,4422
5	0,000296	0,6826	1,7184	2,401	3,2578	2,3639



Limestone filler Andesit filler Dolomite filler

Figure 4. Microstructures of the filler components

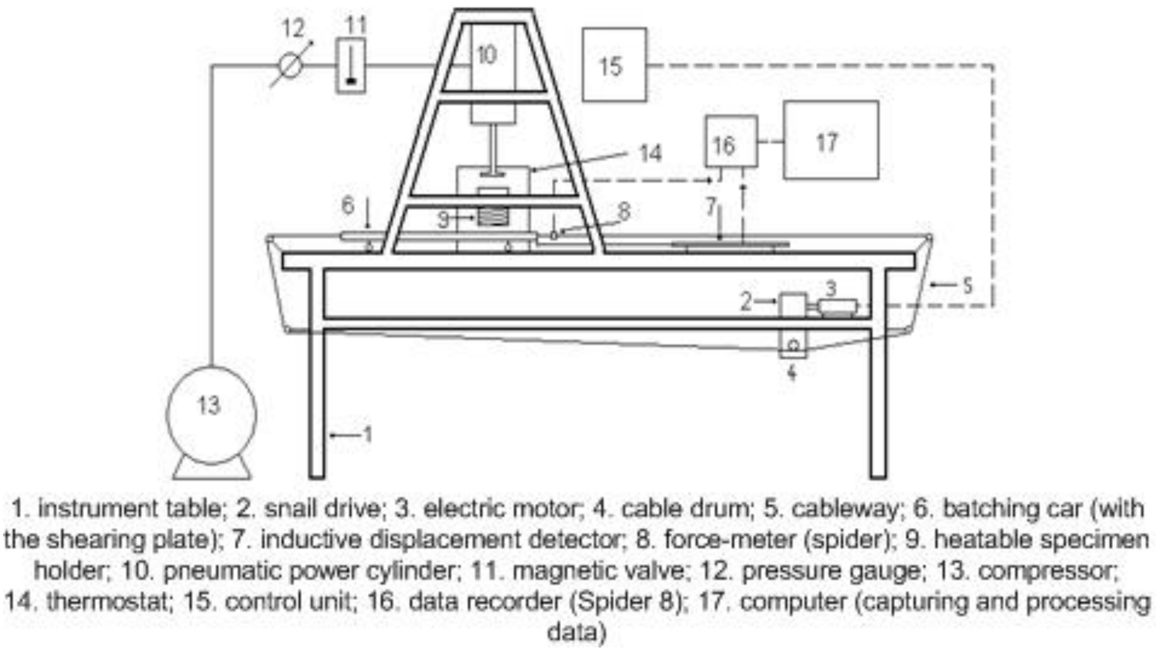


Figure 5. Combined rheo-tribometer [29]

The operation scheme of the developed by author instrument is shown in Fig. 6.

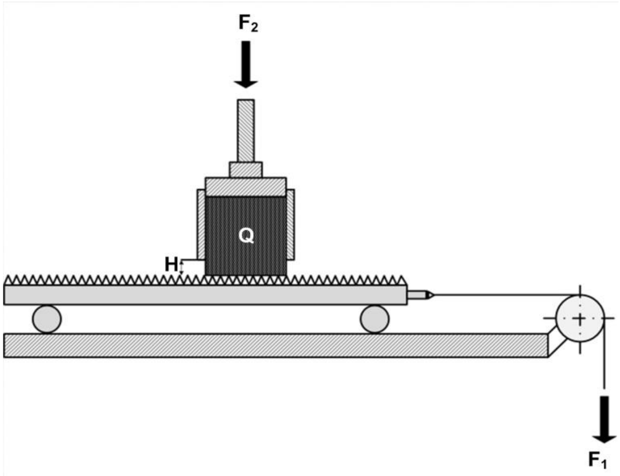


Figure 6. Operation scheme of the combined rheo-tribometer
$\mathbf{F_1}$ – moving force, $\mathbf{F_2}$ – loading force, **H** – working gap

Using this instrument we could measure the shear stress through the force meter (8) and fix it through the data recorder spider (16) by the computer (17). So we could measure and fix the developed shear stresses in Marshall-specimens as:

$$\tau = f(p, Q, T, v) \text{ [MPa]} \tag{7}$$

where:
p – the pressure effected on surface of Marshall-specimens [MPa];
Q – the material compositions of Marshall-specimens;
T – the temperature of Marshall-specimens during the shear tests [^{o}C];
v – the speeds of shear or deformations [m/s].

During the rheological tests of Marshall-specimens we were able to create the curves of specific deformation as function of time at different loading forces as it is shown in Fig. 7.

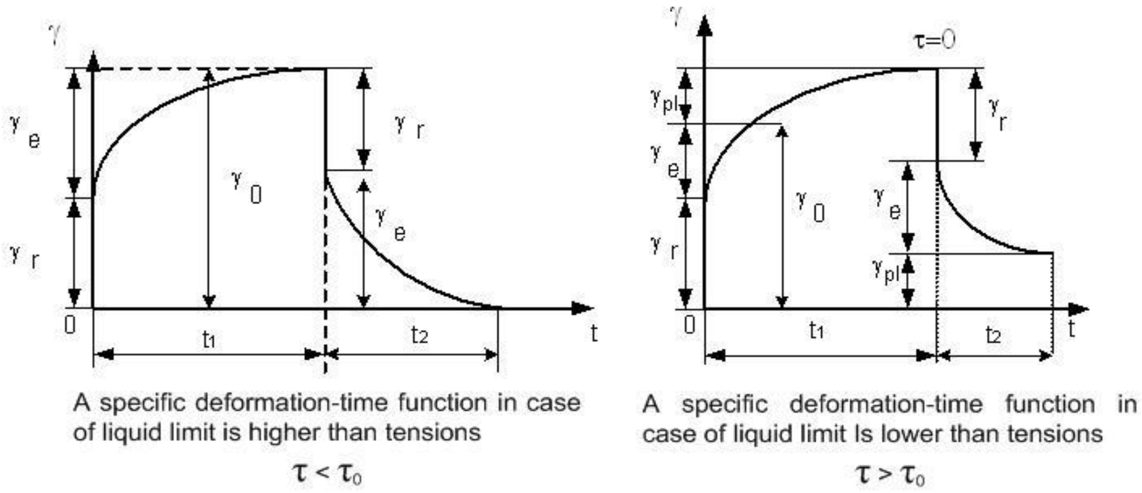


Figure 7. The specific deformation of asphalt pavements as function of time at different loading forces

3. Results and discussion

There are several papers about self-healing materials including also building materials in the last 8-10 years [30-35]. In accordance to the self-healing asphalts the scientist of The Netherland have achieved remarkable results under the supervision of professors A.A.A. Molenaar [36-40] and Erik Schlangen [41-44]. There are several methods to increase the self-healing capabilities of the asphalt pavements including application of fired nano clay particles, micro steel wools [45] and so on, but the most important from them is the application of microcapsules containing oily rejuvenator [46-49] to enhance the self-healing ability of aged bitumen. Using only locally available aggregates in Latvia researchers could successfully develop high performance asphalt concrete. In order to achieve resistance against deformations at a high ambient temperature, a hard grade binder was used [50]. Workability, fatigue and thermal cracking resistance, as well as sufficient water resistance is achieved by low porosity (3-5%) and higher binder content compared to traditional asphalt mixtures To intensify the self-healing process generally necessary to add additional energy to asphalt pavement through increasing its temperature [36, 51] locally. All these additives and temperature will influence on the rheological parameters and properties of the asphalt pavements considerably, including also their rheo-mechanical model [28].

Using the developed by us combined rheo-tribometer (Fig. 5) we were able to measure the elastic modulus of Hooke's and Voigt-Kelvin's components of the asphalt pavements at different normal loading pressures at temperatures of 50, 60 and 80°C (Fig. 8).

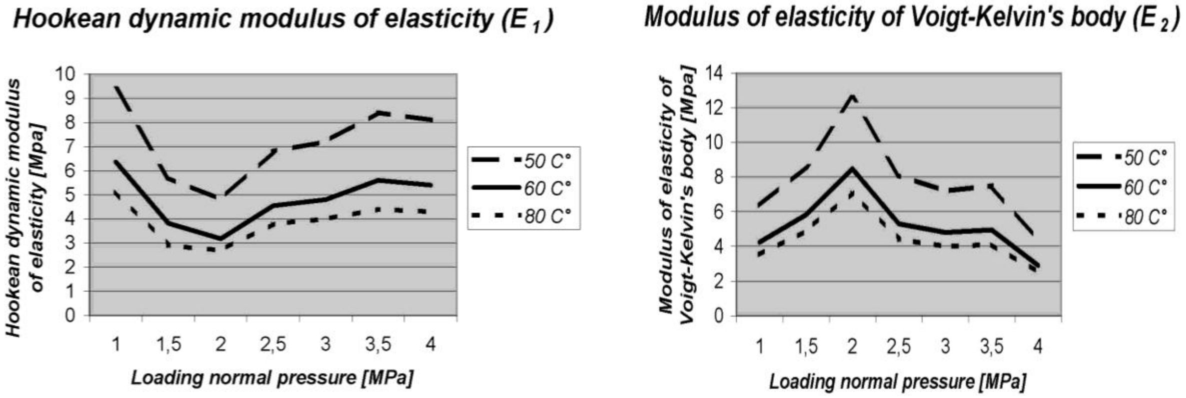
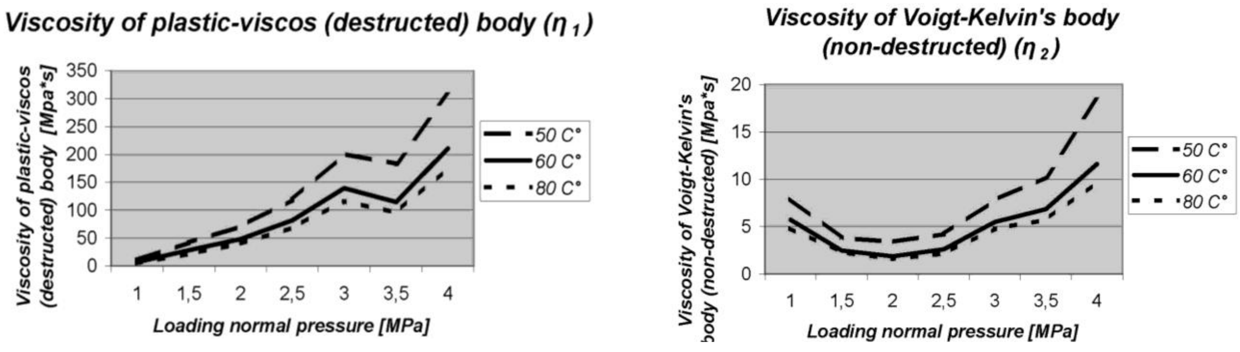


Figure 8. Hooke's (**E$_1$**) and Voigt-Kelvin's modulus of elasticity of the tested asphalt specimens as function of normal pressure at different temperatures measured with the combined rheo-tribometer

Comparing the values of elastic modulus of Hooke's body with Voigt-Kelvin components of asphalt pavement we can underline that the Hooke element has minimal value at 2 MPa loading normal pressure meanwhile the Voigt-Kelvin element has maximum value at this pressure. Further increasing the loading pressure the Hooke's elastic modulus is growing meanwhile the values of Voigt-Kelvin's elastic modulus are decreasing. This interesting co-working of different elastic modulus of asphalt components are measured and determined first thanking to the new developed instrument. The combined rheo-tribometer gave us an opportunity to measure and determine the values of viscosities of destructed (Fig. 9a) and non-destructed Voigt-Kelvin (Fig. 9b) components of asphalt pavements.



a **b**

Figure 9. Viscosity of destructed (a) and non-destructed (b) components of asphalt pavements as function of loading normal pressures at different temperatures

During the rheological test we found that viscosities of destructed components of self-healing asphalts are increasing continuously with increasing the values of loading normal pressures meanwhile the viscosities of non-destructed Voigt-Kelvin's components have local minimum at 1.5-2.5 MPa loading normal pressures. When the loading normal pressures are higher than 2.0-2.5 MPa the viscosities are increasing. These viscous and elastic properties of bitumen based asphalt mixtures together with the temperature very strong influence on the self-healing process of asphalt pavements.

The patented combined rheo-tribometer [29] gave us opportunity also to determine the static yield point of asphalt pavements (Marshall-specimen) as function of loading normal pressures at temperatures of 50, 60, 80^{o}C (Fig. 10).

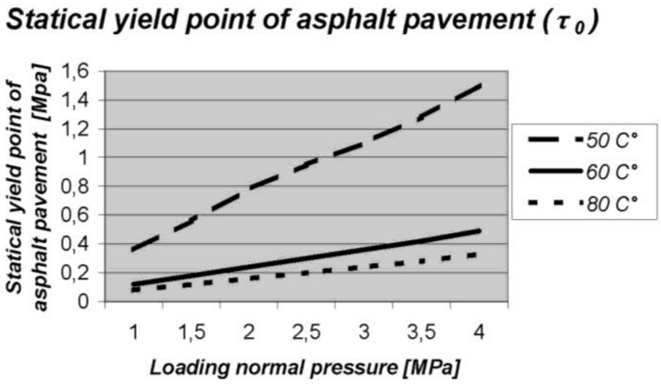
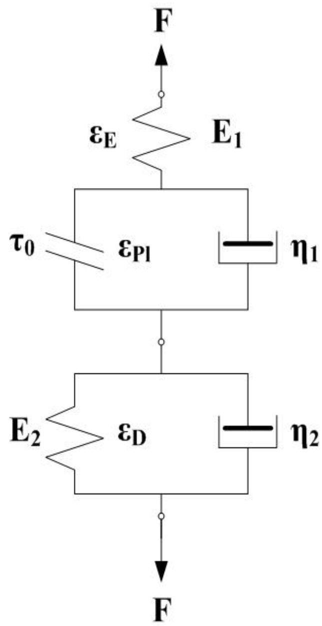


Figure 10. Static yield points of self-healing asphalt pavements as function of normal loading pressures at different temperatures

From Fig. 10 it is obvious that the self-healing asphalt mixtures – asphalt pavements – have excellent yield properties at normal climate conditions when the temperatures are less than 50^{o}C, as increasing the loading normal pressures on them their static yield points are increasing considerably. So, their values of plasticity together with destructed and non-destructed viscosities and modulus of elasticity are increasing together with loading pressures. This means that as larger the mechanical load, as larger the mechanical resistance. The materials with these mechanical properties can be rheological modeling by Fig. 11, and their effective viscosity can be determined by eq. (8) which first time was published in Hungarian in 1983 [52]:



- E_1: Hookean dynamic modulus
- E_2: Elasticity modulus of the Voigt-Kelvin component
- ε_E: Actual elastic deformation
- ε_{Pl}: Plastic viscous deformation
- ε_D: Delayed elastic deformation
- η_1: Viscosity of the Newton component
- η_2: Viscosity of the Voigt-Kelvin component
- τ_0: static yield point of the plastic-viscous component

Figure 11. The rheological model of the self-healing asphalt mixtures and pavements

$$\eta_e = \frac{\tau_0+\eta_1\dot{\gamma}+\eta_1 n_\gamma\ddot{\gamma}}{\dot{\gamma}+n_\tau+n_\gamma\ddot{\gamma}+\dot{\gamma}\left[n_\tau+n_\gamma\left(1+\frac{\eta_1}{\eta_2}\right)\right]} \tag{8}$$

where

- η_1, η_2, τ_0 – as in Fig. 11
- n_γ – the delayed time of elastic deformation and can be determined as: $n_\gamma = \eta_2/E_2$
- n_τ – the stress relaxation time, and can be determined as: $n_\tau = \eta_1/E_1$
- $\dot{\gamma}$ - the total value of shear rate (the sum of shear rates of destructed and non-destructed components)
- $\ddot{\gamma}$ - derivative of total shear rate

The description of effective viscosity by equation (8) give us a better understanding of rheological properties – rheological requirements – of self-healing materials including self-healing asphalt mixtures and pavements.

4. Conclusion

The Burgers rheological model (Fig. 2) cannot explain the self-healing properties of bitumen bonded asphalt mixtures and pavements, but using the rheological model developed and described above (Fig. 11) can help us to better understand the self-healing process which very strong depends not only on mechanical pressures and temperatures but on stress relaxation times also (eq. 8).

Understanding the rheological properties of components can help us not only to prepare self-healing asphalt mixtures but keep better maintenance of asphalt pavements, roads and constructions.

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