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ELASTIC PROPERTIES OF TYRES AFFECTING CAR COMFORT, DRIVING AND RIDING

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The present paper focuses on an elastic properties analysis of new and depreciated tires. The research was carried out using two different methods, field and numerical, respectively. The purpose of the study is to check whether there is a change in the elastic properties of a tire during its depreciation and to what extent the process affects the comfort of driving and riding. The experimental tests were conducted on a hydraulic test stand and by applying strength and deformation analysis the effect of its structure deformation was additionally considered. The investigation was performed on a vehicle-based tire test stand to find out stress-strain and tire deformation was with different vertical loading according to FEM. The numerical solution was reached by implementing SolidWorks - Simulation and Abaqus. The obtained results are graphically compared, and the average value of the elastic constant for a new and depreciated tire has been determined.

Key words: hydraulic test stand, rubber elasticity, FEM, SolidWorks, Abaqus.

1. Introduction

An important safety and comfort characteristics for the car, considered as a system of elements, is the pneumatic tire. Its significance mostly stems from the influence of external factors, such as the external forces generated by the uneven road surface, the coefficient of friction, the elastic and damping properties of the tire, etc. To evaluate each one of them, it is necessary to create experimental stands, taking into account the influence of the given characteristics and with minimal error parameters. Therefore, the implementation and creation of experimental stands related to the study of these factors (Bo *et al.* [1]; Dihua *et al.*[2]; Yam*et al.* [3]) is of crucial importance.

A major component in the study of suspension as a part of the car is the study of the elasticity of the car pneumatic tires. It is connected with both safety and comfort. The tire is an element of suspension and affects due to its characteristics directly the stable behaviour of the car in motion along different types of road surfaces. (Guo and Liu [4]; Svendenius and Gäfvert [5]; Shang *et al.* [6]). Examples of pneumatic tires with different geometric dimensions, at different internal pressures and mileage depreciation are considered. In the present paper, one of the examples shown is carried out on a Michelin brand pneumatic tire, size 205/55R16.

It is a well known fact that the pneumatic tire provides continuous interaction of the vehicle with the road surface. Practically, all operational properties of the car in the study depend on the characteristics of the pneumatic tire. It is considered as an elastic element and the analysis is performed by considering deformation under radial loading. The characteristic of the elastic constant is a hysteresis type with a difference in the transition from *0* to the maximum magnitude of the force and vice versa. The force is a linearly variable on loading and unloading, keeping a precise reading of the deformation. Pneumatic tires of the same type at different mileage depreciation and the influence of material aging and fatigue are compared. The maximum load force for all investigated tires is the same value, observing the height of the board.

Studying the absorbing and smoothing ability, its coefficients of elasticity are obtained. In real operating conditions, the elasticity of the pneumatic tire depends on a number of factors - dimensions, internal pressure, material properties, speed of movement, static and dynamic loads.

The linear deformation of the tire characterized by a certain elasticity is determined from the static load (Fraggstedt, [7]; Korunović *et al.* [8]; Kulikowski and Szpica, [9]). The magnitude of the load depends on the limit deformation, after the passage of which there are occurrences of an unstable condition in the construction of the tire, in which destruction of the skeleton, which has low elasticity, or tears on the sides and tread are possible.

Based on the normal deformation, which is determined by the pressure in the tire, the ability of the tire to absorb shock loads in the process of motion without destroying its structure has been determined.

2. Experimental study of rubber tire elasticity

A hydraulic test stand rig for the investigation of the elastic constant of passenger car tires was constructed (Fig.1).

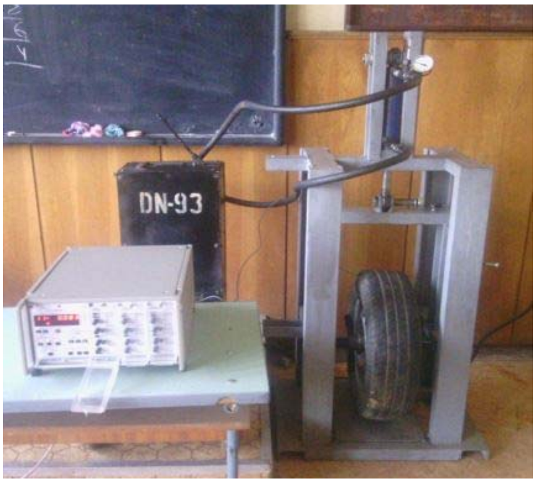


Fig.1. Photo of the test stand and the measuring devices.

The stand for determining car tire elasticity consists of elements that allow the realization of pre-set linear loads of different sizes.

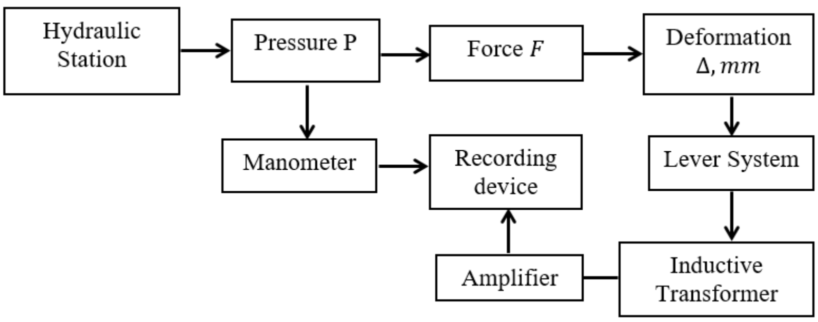


Fig.2. Block diagram for determining car tire elasticity.

The elements comprise a hydraulic power cylinder with pre-selected stroke, diameter and dimensions of the stand construction; hydraulic station, allowing the necessary pressure for the operation of the cylinder and change of load direction; high pressure hydraulic hoses providing the connection between the cylinder and the hydraulic station. A pressure gauge was directly installed at the inlet of the upper chamber of the cylinder. The deformation of the tire is taken into account by the linear displacement of an inductive transducer with a suitable lever system in a corresponding ratio. The signal from the sensor is converted by an amplifier and recorded on a suitable device - an oscilloscope. At the inlet and outlet of the power cylinder, one-way hydraulic chokes are installed, allowing a reduction of the speed of the fluid supplied to the cylinder, respectively pressure. They help to gradually increase and decrease the force on the cylinder piston in the chambers, which makes it easy to measure. The block diagram below exemplifies the algorithm of the described measuring system (Fig.2).

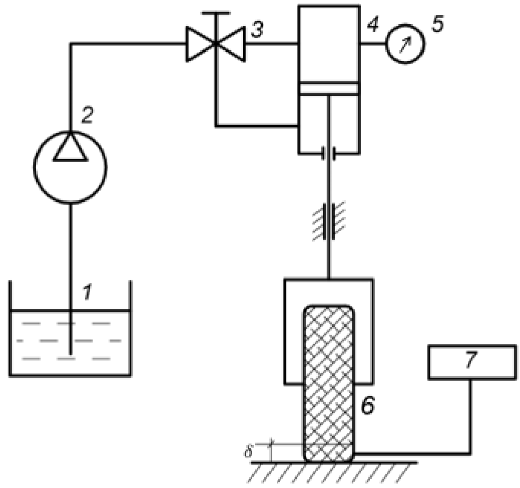


Fig.3. Measurement schematic diagram: 1 - reservoir; 2 - pump; 3 - regulator; 4 - cylinder; 5 - manometer; 6 - pneumatic tire; 7 - measuring device.

Fig.4. Photo of the hydraulic station DN-93.

The elements of the block diagram are:

- HS hydraulic station - representing a system of hydraulic pump connected to a three-phase induction motor with suitable characteristics for the pump drive. The pump is connected and supplies pressure to a four-way three-position distributor by manual control, supplying pressure to the power cylinder, operated manually, by the measuring operator (Fig.3).
- Pressure *P* - exerted and applied fluid pressure from the hydro station in *MPa*, is converted into load force, *N*, by the hydraulic cylinder. Depending on the diameter of the cylinder base, which in this case is *50 mm*, the force is calculated according to the dependencies:

$$F_N = P \cdot S\,. \tag{2.1}$$

$$S = \frac{\pi D_B^2}{4}. \tag{2.2}$$

- Force F applied by the power hydraulic cylinder to the movable frame of the rig lead to axially symmetrical loading in the tire axle system.
- Deformation Δ - caused by the front two components of the rig and evident in linear movement of the axle together with the tire. It is measured in mm and read by the measuring device.
- Inductive converter. An inductive transducer and amplifier are used as a measuring device, which take into account the linear displacement by Hottinger (HBM), the world's foremost provider of precision measurement. HBM Force Transducers have high accuracy and high sensitivity when changing the measured value, which makes them extremely convenient for such measurements.

The linear translation parameter that the transducer can reach (*12 mm*) makes it necessary to reduce the linear deformation by means of a lever system.

- Lever system - due to the lack of a suitable inductive converter in the material base, it was important to develop a lever system that will reduce the reported linear displacement within the measuring range of the converter we have.

In the design and analysis phase of the most widely used tires, a required load of up to *700 kg* and a maximum deformation of the order of *50 mm* are reported. Therefore, the creation of a lever system was required (Figs 5 and 6).

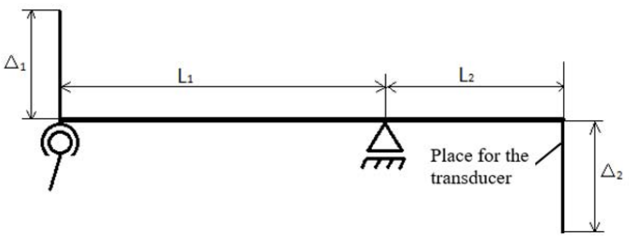


Fig.5. Lever system for measuring linear deformation, Δ *mm*.

When working with such a lever system, it is important to derive the dependencies and the gear ratio of the system depending on the required conversion, as follows

$$\frac{L_1}{L_2} = \frac{\Delta_1}{\Delta_2} \tag{2.3}$$

- Reading manometer. A dry-type pressure gauge with a reading scale of up to *60 bar* was used to read the pressure in the upper chamber. The reading was performed up to the middle of the scale of the manometer, which ensures minimal reading error (Fig.7).
- Amplifier. An amplifier was used for the input quantities, suitable for operation with the inductive converter and allowing the necessary settings during operation (Fig.8).

Fig.6. Photo of the lever system and the inductive converter mounted to it.

Fig.7. Photo of the manometer, throttles and power cylinder and their place on the rig.

Fig.8. Photo of the amplifier used in the measurements.

2.1. Results of the field experiment of measuring and determining the elasticity of depreciated and new tires.

A Michelin tire of size 205/55R16 was used in the field experiment (Taneva and Katsarov [10]). The purpose of the measurement is to take into account linear deformation (Δ, [*m*]) and inducing force created by the pressure in the cylinder in (*MPa*). The force at which linear deformation is taken into account corresponds to the increase of the pressure in the cylinder from *4* to *30 MPa*. Graphical dependence of the deformation on the force causing it $\left(\Delta = f\left(F\right)\right)$ is compiled in relation to the reported force *F* in [*N*] (Fig. 9).

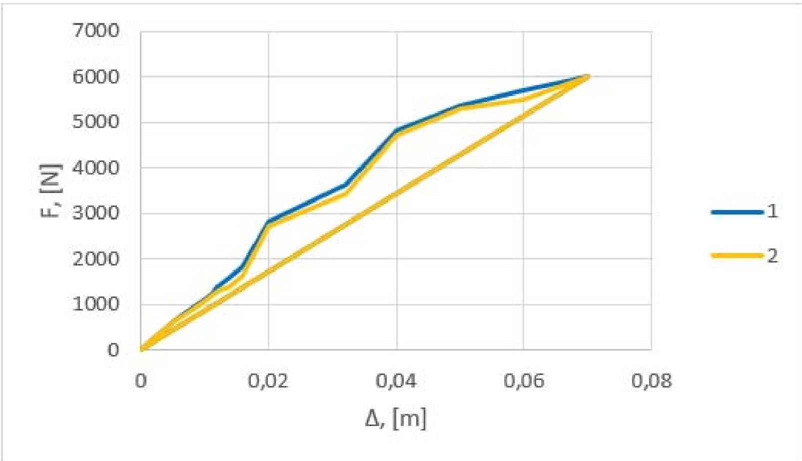


Fig.9. Modification of the deformation of a tire of size 205/55R16.
1 - tire depreciation; 2 - new tire.

After measuring the linear deformation and the force causing it, the elasticity of the tire at a pressure of *2.1* bar is determined by the following dependence (Tab.1).

$$c = \frac{F}{\Delta}, \left[N/m \right] \tag{2.4}$$

where *c* is the elastic constant of the tire;

F is the force, applied by the power hydraulic cylinder to the movable frame of the rig leading to axially symmetrical loading in the tire axle system;

Δ is the deformation, caused by the front two components of the rig and evident in linear movement of the axle together with the tire.

Table 1. Data from the experimental studies of the elastic constant of rubber under radial loading.

№	Tire depreciation			New tire		
	$F\,[N]$	$\Delta\,[m]$	$C\,[N/m]$	$F\,[N]$	$\Delta\,[m]$	$C\,[N/m]$
1	*266*	*0.0020*	*133000*	*250*	*0.0020*	*125000*
2	*641*	*0.0050*	*128200*	*620*	*0.0050*	*124000*
3	*840*	*0.0070*	*120000*	*800*	*0.0070*	*114286*
4	*1030*	*0.0091*	*113187*	*1010*	*0.0091*	*110989*
5	*1240*	*0.0110*	*112727*	*1190*	*0.0110*	*108182*
6	*1410*	*0.0120*	*117500*	*1310*	*0.0120*	*109167*
7	*1610*	*0.0140*	*115000*	*1410*	*0.0140*	*100714*
8	*1840*	*0.0160*	*115000*	*1640*	*0.0160*	*102500*
9	*2830*	*0.0200*	*141500*	*2710*	*0.0200*	*135500*
10	*3640*	*0.0320*	*113750*	*3440*	*0.0320*	*107500*
11	*4810*	*0.0400*	*120250*	*4710*	*0.0400*	*117750*
12	*5360*	*0.0500*	*107200*	*5310*	*0.0500*	*106200*
13	*5699*	*0.0600*	*94983*	*5499*	*0.0600*	*91650*
14	*6010*	*0.0700*	*85857*	*6010*	*0.0700*	*85857*

Figure 10 shows the change in the elastic constant of a new and depreciated tire, size 205/55R16.

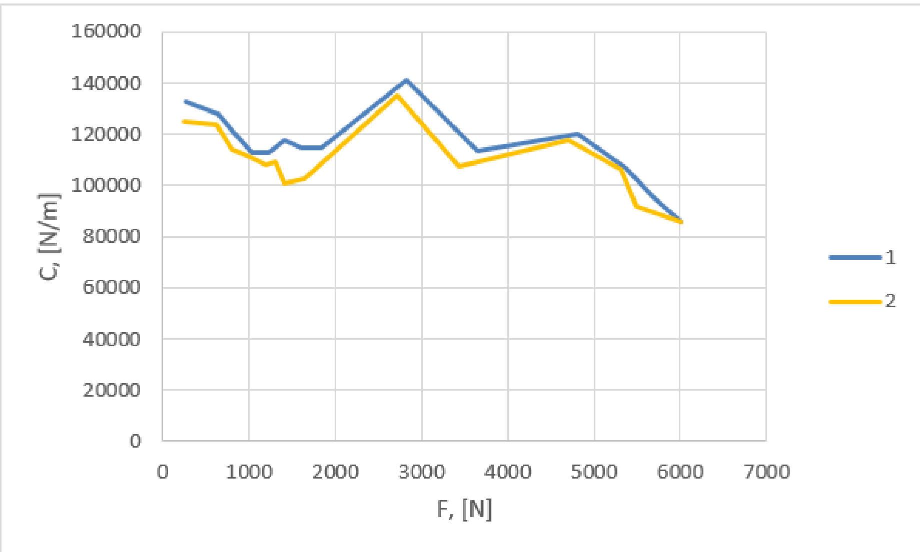


Fig.10. Modification of the elastic constant of a tire, size 205/55R16.
1 - depreciated tire; 2- new tire.

The shown graphic dependence obtained during the measurement of the elastic constant of car tires allows the analysis and comparison of the parameters of different types of tires.

Determining the real elastic constants of different tire types allows modelling automobile motion taking into account real traffic conditions (Kolev and Kadirova, [11]; Lyubenov *et al.*[12]).

3. Numerical study of rubber elasticity

3.1. Pneumatic tire model

The pneumatic tire model was created using SolidWorks software. A prototype radial tire structure is depicted in Fig.11 (Moisescu and Frăţilă, [13]; Korunovic *et al.*[14]). To create the geometric model of a radial tire, tire construction data was used, which fully corresponds to the modern tire.

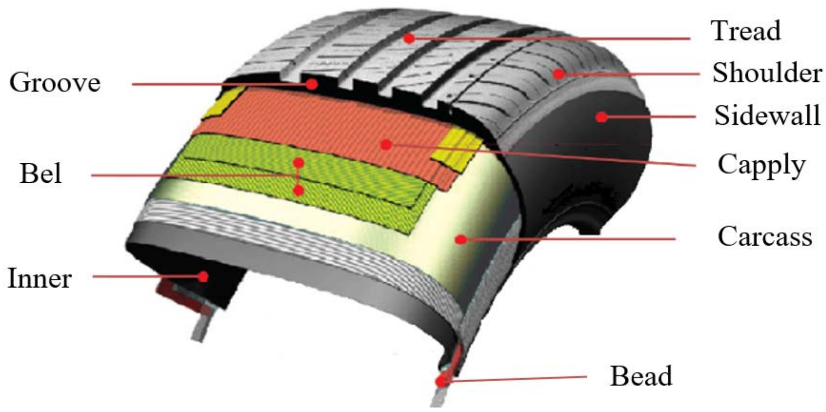


Fig.11. Structure of a radial car tire.

Geometric modelling was done in SolidWorks. The model of the investigated car tire presented in Fig.12 was assembled from separate parts. The corresponding movable and immovable connections between them were defined. For each detail, in addition to its geometric dimensions, the characteristics of the materials from which they had been made were defined.

Fig.12. 3D model of a radial tire created using SolidWorks software.
a) radial tire; b) rim.

The created model in SolidWorks is imported into the Abaqus/Explicit dynamic analysis software system. The Abaqus/CAE system exports a sketch in standard STEP file format, recording all the geometric data of a layer of the model (Yang [15]; Kolev and Kadirova [16]; Lyubenov *et al.*[17]).
A three-dimensional FEM model of a pneumatic tire was created using Abaqus software (Fig.13).

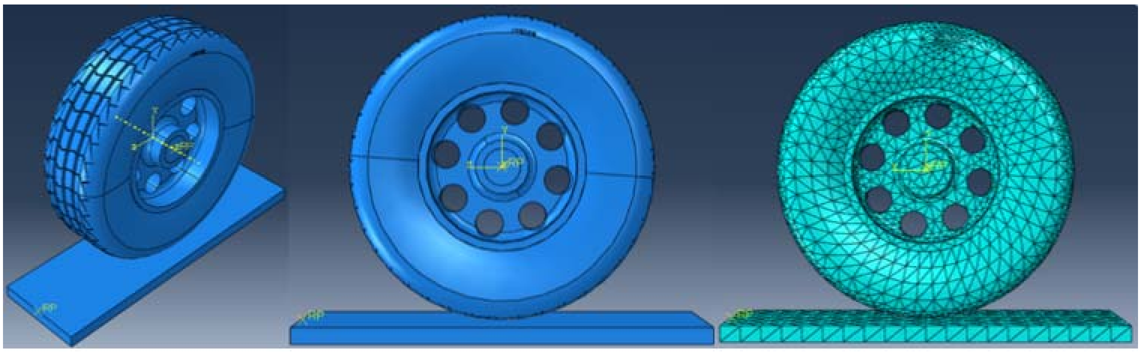


Fig.13. Three-dimensional FEM model of tire in Abaqus environment.

The pneumatic tire model is for a 205/55R16 automobile. The wheel rim is modelled as a rigid body with standard body elements (Abaqus elements S3R and S4R). The materials of the wheel rim rings and metal threads are considered linear.

Materials and their characteristics have been selected from the Abaqus database. The specified material properties, such as density, Young modulus and Poinson's ratio, are shown in Tab.2.

Table 2. Wheel rim material.

Material	Density, kg/m^3	Young Modulus MPa	Poisson ratio	Yield Strength MPa
Stainless Steel 304L	*8000*	*193000*	*0.25*	*172*

The Mooney-Rivlin model is used for nonlinear elastomeric material. The potential strain energy for the Mooney-Rivlin reference model (Pranoto *et al.* [18]; Sreeraj *et al.* [19]; Korolev *et al.* [20]) values C_{10}, C_{01} and D are shown in Tab.3.

Table 3. Rubber tire material.

Material	$C_{10}\ N/m^2$	$C_{01}\ N/m^2$	$D_1 N/m^2$	Density kg/m^3
Rubber	*0.8061*	*0.805*	*0.01*	*1400*

The layer between the housing and the outermost layer of the tire is modelled as an elastic-plastic material using the constant shown in Tab.4. It is assumed that nylon polymers have perfect plastic properties, according to the constant which is also included in Tab.4. Strengthening the properties of the material is considered homogeneous and orthropic.

Table 4. Properties of the material.

Material	Elastic (Modulus elasticity) N/m^2	Poisson ratio	Density kg/m^3
Tire housing	*500*	*0.3*	*1200*
Layer between the body and the outermost layer of the tire	*172200*	*0.3*	*5900*

The depreciation of the tire is according to the year of its manufacture and mileage covered under normal technical operation. The mileage for the tire is in accordance with the mileage of the vehicle of its class for a specific purpose. The research was done over a long period with specific observations of the depreciation mileage of a car with a specific brand of car tires. Normal technical operation includes movement on flat terrain and the influence of micro-uniformities of the asphalt coating.

The next step was to simulate a pneumatic tire under dynamic loading. The pneumatic tire was loaded with a concentrated force of magnitude $F = 5000N$, which is concentrated centrally (Fig.14). Figure 15 shows the deformation for a depreciated and new tire.

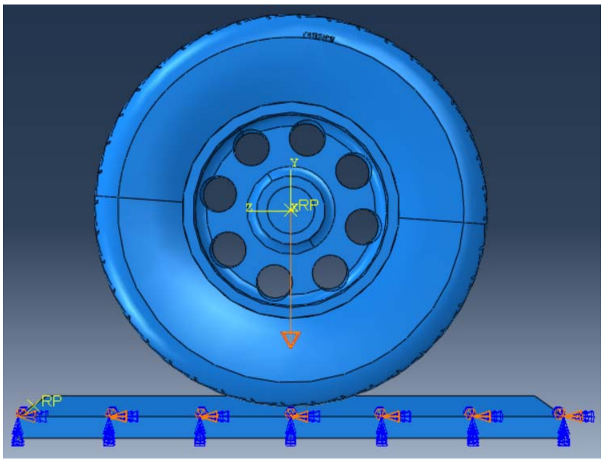
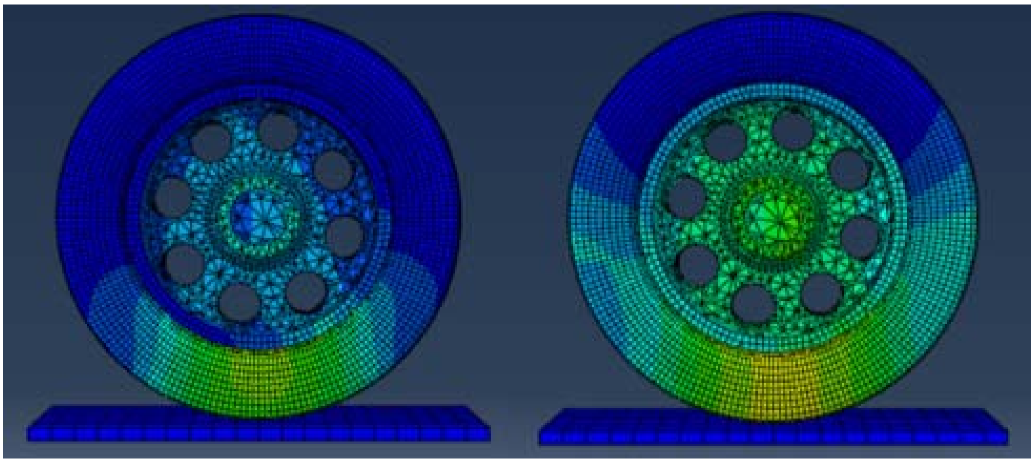


Fig.14. Application of external loads.



a) depreciated tire b) new tire

Fig.15. Deformation of a pneumatic tire.

3.2. Results of the numerical experiment of measuring and determining the elasticity of a new and depreciated tire

The graphical dependence of the deformation on the force causing it $(\Delta = f(F))$ is drawn in relation to the reported force F in [N] and shown in Fig.16.

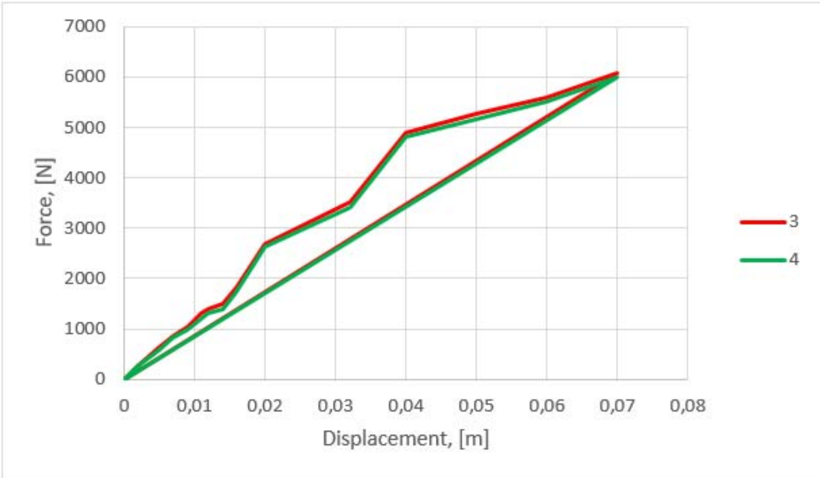


Fig.16. Modification of the deformation of a tire, size 205/55R16: 3 - tire depreciation; 4 - new tire.

Table 5. Data from the experimental studies of the elastic constant of rubber under radial loading.

№	Depreciated tire			New tire		
	$F[N]$	$\Delta[m]$	$C\ [N/m]$	$F[N]$	$\Delta[m]$	$C\ [N/m]$
1	*266*	*0.0020*	*133000*	*250*	*0.0020*	*125000*
2	*641*	*0.0050*	*128200*	*620*	*0.0050*	*124000*
3	*840*	*0.0070*	*120000*	*800*	*0.0070*	*114286*
4	*1030*	*0.0091*	*113187*	*1010*	*0.0091*	*110989*
5	*1240*	*0.0110*	*112727*	*1190*	*0.0110*	*108182*
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9	*2830*	*0.0200*	*141500*	*2710*	*0.0200*	*135500*
10	*3640*	*0.0320*	*113750*	*3440*	*0.0320*	*107500*
11	*4810*	*0.0400*	*120250*	*4710*	*0.0400*	*117750*
12	*5360*	*0.0500*	*107200*	*5310*	*0.0500*	*106200*
13	*5699*	*0.0600*	*94983*	*5499*	*0.0600*	*91650*
14	*6010*	*0.0700*	*85857*	*6010*	*0.0700*	*85857*

The elastic constant of the tire is determined according to the dependence (Tab.5).

$$c = \frac{F}{\Delta}\ \left[{}^{N}\!/_{m}\right] \tag{3.1}$$

where c is the elastic constant of the tire; F is the force, applied by the power hydraulic cylinder to the movable frame of the rig leading to axially symmetrical loading in the tire axle system; Δ is deformation, caused by the front two components of the rig and evident in linear movement of the axle together with the tire.

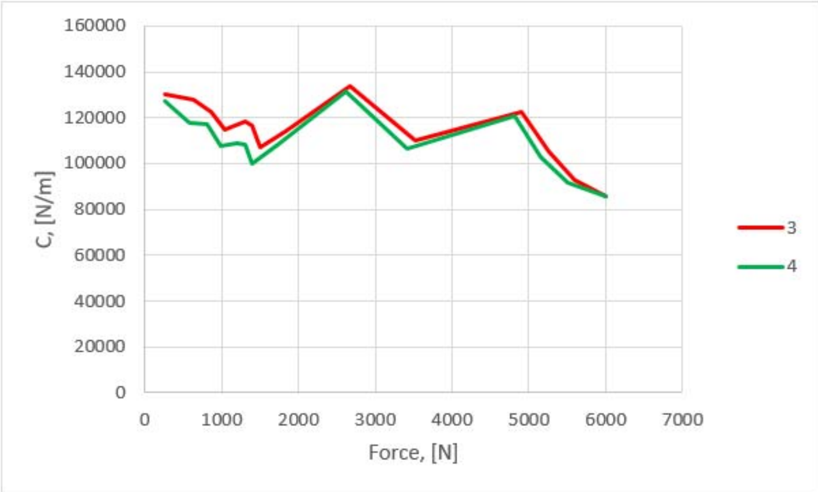

Fig.17. Modification of the deformation of a tire, size 205/55R16: 3 - tire depreciation; 4 - new tire.

4. Comparative analysis of the field and the numerical experiment of measuring and determining the elasticity of a new and depreciated tire

A comparative analysis of the results of the obtained values of the elastic constant in the performed field and numerical research was made. The obtained graphical dependences are close in values, which shows that both the performed analysis of the materials and the deformation state of the new and depreciated tire were precisely carried out. Thus, dynamic processes related to the deformation of the car tire during operation could be modelled with sufficient accuracy (Figs 18 and 19) and the influence of bumpy road surface on driving comfort could be taken into account.

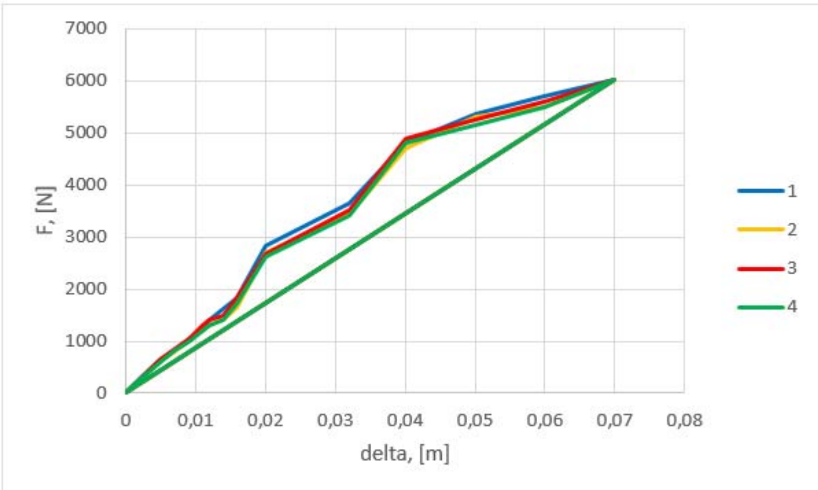

Fig.18. Modification of the deformation of a tire, size 205/55R16: 1 - tire depreciation of field experiment; 2 - new tire pattern of field experiments; 3 - tire depreciation of numerical experiment; 4 - new tire pattern of numerical experiment.

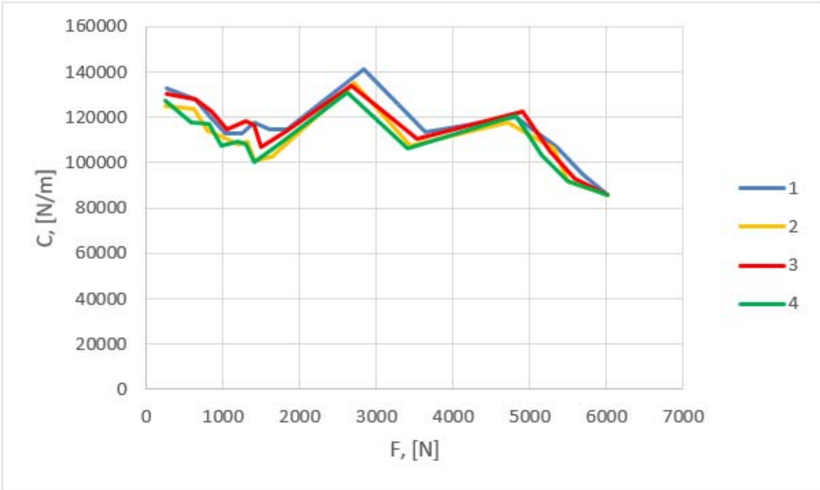

Fig.19. Modification of the elastic constant of a tire of size 205/55R16: 1 - tire depreciation of field experiment; 2 - new tire pattern of field experiments; 3 - tire depreciation of numerical experiment; 4 - new tire pattern of numerical experiment.

The created dynamic car model with 12 generalized coordinates (Karapetkov *et al.* [21, 22]; Uzunov *et al.* [23, 24]) takes into account the effect of the elasticity of suspension, including the tire. The model performs dynamic analyses of a car tire at a fixed value of the elastic constant. The research thus carried out allows the elastic constant to be used depending on the load and the dynamically changing characteristics.

5. Conclusion

1. An experimental study and comparison of the elastic characteristics of a new and depreciated tire were performed. The obtained close results from the field and numerical solution allow modelling and simulation of dynamic processes in the analysis of tire motion on road surface.
2. Change of the elastic characteristic property of the depreciated tire compared to the new one has been registered, which shows that the hardness of the tire increases. The average value of the change is about 5% higher than the value of the elastic constant.
3. The increase in the tire hardness is an approximately linear dependence over the years at an average milleage of about *25000-30000 km* on an annual basis. This means that the change in the elastic properties of the tire could be predicted with sufficient accuracy.
4. The change in the elastic characteristic of the tire by increasing its hardness leads to a decrease in the coefficient of friction, and it can be considered that the dependence of change is also a linear dependence. A similar conclusion can be drawn when the elastic characteristics of the tire change, the conditions of comfort when driving on a flat and rough road surface also change.
5. In dynamic models of cars after loss of transverse stability main components of the input quantities are the coefficients of friction. Knowledge of the tire, the effect of its elastic characteristics, and the mathematical prediction based on the created models, would lead to a significantly more accurate technical expert analysis of road accidents.
6. There are additional possibilities to study the lateral displacement of the tire and to create a model for the impact of the characteristics of the tire especially in a car taking a turn.

Acknowledgements

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Nomenclature

c – elastic constant of the tire
F – force, applied by the power hydraulic cylinder to the movable frame of the rig leading to axially symmetrical loading in the tire axle system
HS – hydraulic station
P – pressure exerted and applied fluid pressure from the hydro station in *MPa*, converted into load force, *N*, by the hydraulic cylinder
Δ – deformation, caused by the front two components of the rig and evident in linear movement of the axle together with the tire

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