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ENERGY CONSUMPTION ESTIMATION OF NON-PNEUMATIC TIRE AND PNEUMATIC TIRE DURING ROLLING

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Abstract

The characteristics of the car tire, and especially its deformation and interaction road, are mainly factors affected the energy consumption of the vehicle and consequently the amount of fuel consumption and emissions to the environment the harmful exhaust gas components. It is estimated that approximately 80-90% of the total energy losses (rolling resistance) are due to internal tire friction, which occurs during its deformation, the remaining 10-20% are ventilation losses, tread face interaction with the road surface and cyclical compression and expansion of air enclosed in the tire. Non-pneumatic tires (NPT) (as a direction of development) are the alternative solutions for conventional tires. Their advantages are as follows maintenance-free and the resistance to typical for pneumatic tires mechanical damages can be a major cause of their widespread use in future (and thus electric) cars. In the available publications, the results of the estimation of the features NPT based on numerical simulations are only presented. There is lack of experimental research results concerning real objects, which determine their driving properties.

Presented work is an attempt to check how the change in wheel structure affects the energy consumption of rolling wheels. Research objects (non-pneumatic tire and pneumatic tire) were selected for the size and destination compatibility. Experimental research were carried out at a universal quasi-static tire testing station, which is located at the Institute of Mechanical Vehicles and Transport at the Department of Mechanical at the Military University of Technology. According to the authors, the obtained results can be an interesting and unique supplement to the problem of assessing the properties of new and future (non-pneumatic tire) construction of vehicle wheels.

Keywords: *non-pneumatic tire (NPT), airless tire, resilient tire, pneumatic tire, special wheel, rolling resistance, energy consumption during rolling*

1. Introduction

One of the important factors affecting the fuel consumption of the vehicle is the rolling resistance of the tire. It is estimated that tire-rolling resistance is about 30% of vehicle motion resistance [10]. The value of the rolling resistance depends mainly on the energy losses associated with tire deformation (about 80-90%), which are show as the hysteresis loop in the load vs. deflection graph. The size of the hysteresis loop depends on the construction of the tire and the materials used to build it. The energy dissipation in the tire is not uniform throughout its volume. The literatures indicate that the most of energy dissipation to occurs in the tread, side, and tire foot (Fig. 1). Cyclical deformations of these areas of the tire are accompanied by internal friction and the resulting heat release (Fig. 2).

On the market in recent years, new construction of wheels have been shown, in which there is no compressed gas (enclosed in a sealed tire) as a factor resilient. They are called: non-pneumatic tire (NPT), airless tire, elastic wheel, structurally supported tire, resilient tire. The lack of compressed gas in the new wheel construction eliminates the typical pneumatic tires problems (e.g. unsealing) and related to this immobilisation of the vehicle. The resilient properties of the non-pneumatic tire are obtained by the appropriate construction and selection of the material of the support structure (Fig. 3) [7, 9, 11, 15]:

– rim – allows to connect NPT with vehicle hub,
– tread – provide e.g. appropriate traction properties,
– support structure, which includes:
  – flexible structure - built e.g. in the form of spokes or hexagonal shape (e.g. honeycomb, auxetic), whose task is to give appropriate directional stiffness (radial),
  – shear beam – composed of two membranes (e.g. steel, aluminum), inside which is a material of low shear modulus (polymer, for example polyurethane), is responsible for shaping the contact zone of the wheel with the ground (e.g. pressure in the contact zone of the road).

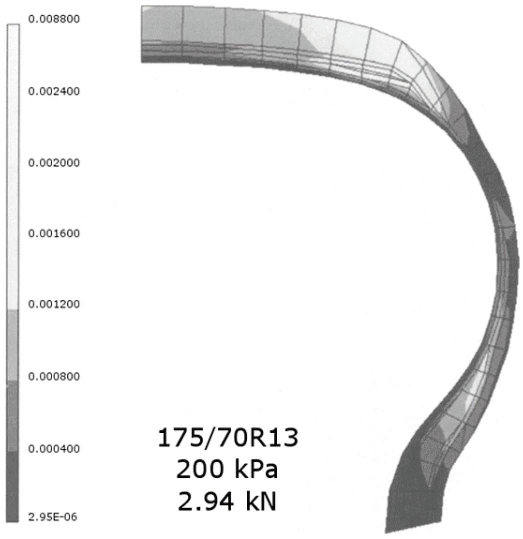

Fig. 1. Density of energy dissipation by individual parts of the tire [16]

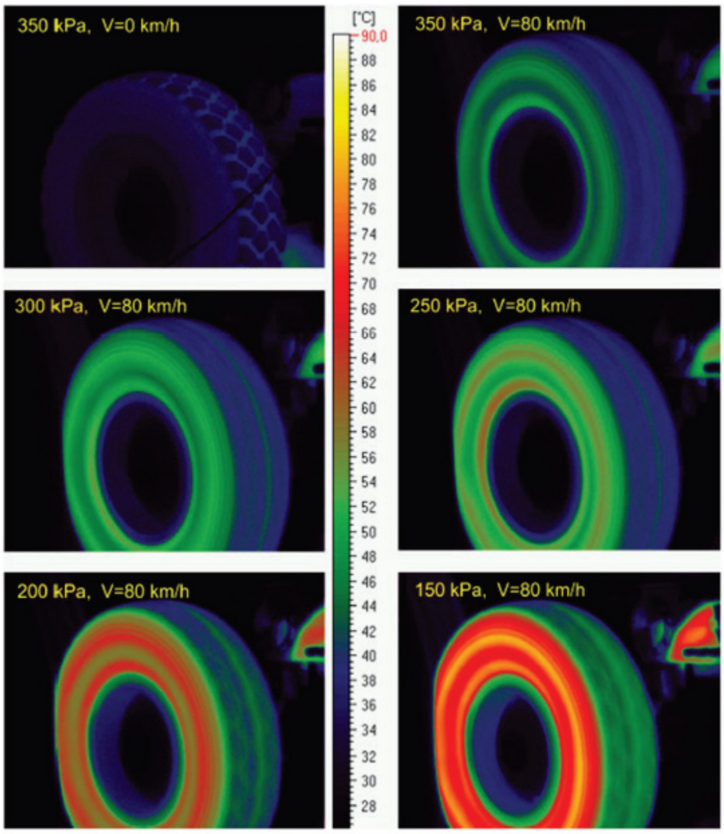

Fig. 2. Influence of pneumatic tire inflation pressure on the temperature distribution during rolling [4]

The level of energy consumed during rolling by the non-pneumatic tire and the pneumatic tire is due to the volume of the deformable material [6, 9, 11]. In articles [3, 8, 9] it has been reported that decreasing the volume of the shear beam results in a decrease in wheel rolling resistance (Fig. 4). However, in the article [11] presents the results of the optimization possibilities for the flexible structure construction in terms of reducing the rolling resistance (Fig. 5). The calculations were performed using FEM models.

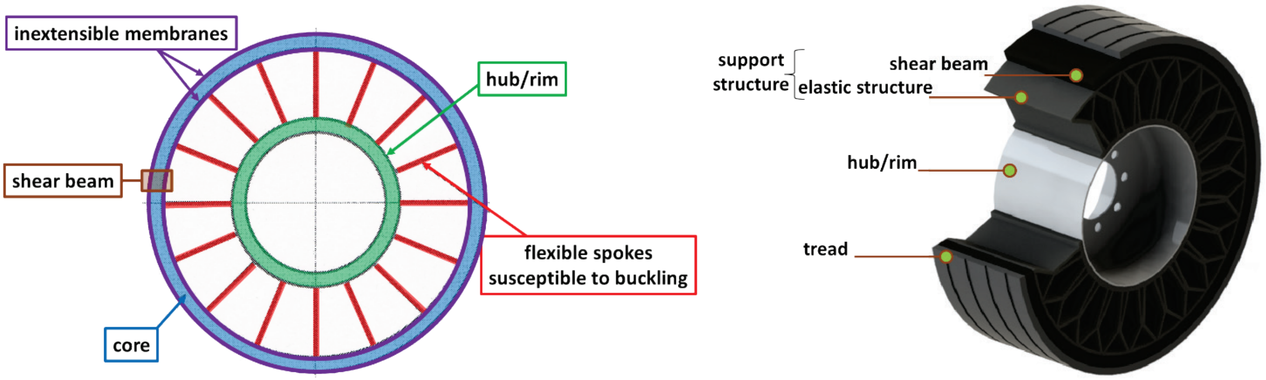

Fig. 3. General construction of non-pneumatic tires [7, 15]

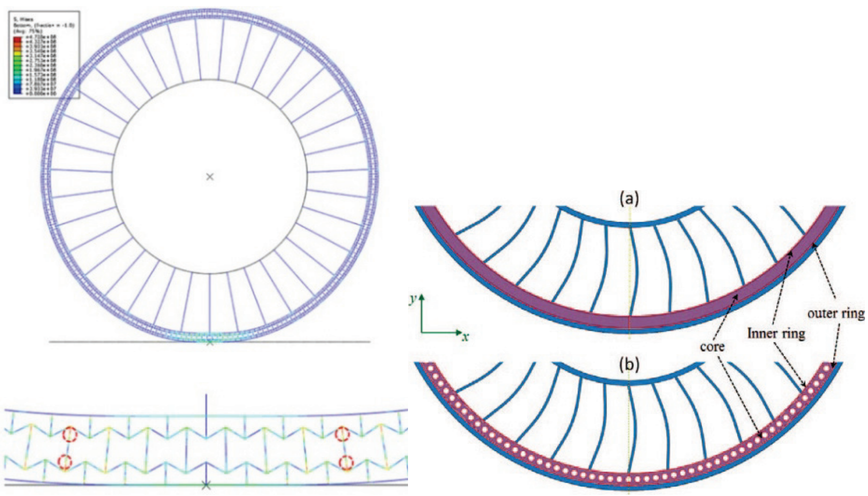

Fig. 4. Examples of shear beam optimization to reduce the NPT rolling resistance [8, 9]

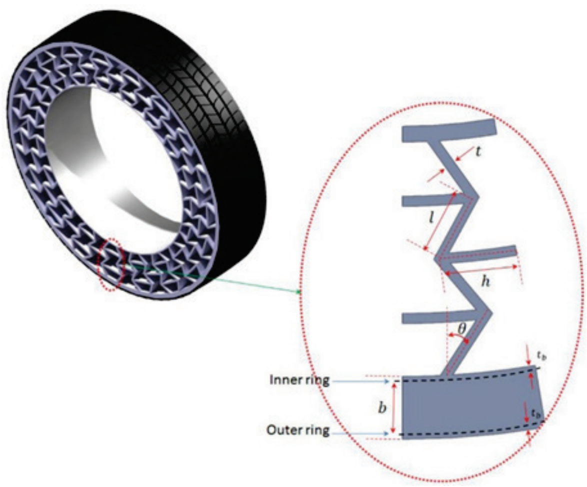

Fig. 5. The example of elastic structure geometry optimization to reduce the NPT rolling resistance [11]

Authors of this article have not found in the available literature the results of comparative studies of the properties of NPT and pneumatic tire conducted on real objects, therefore in this article an attempt was made to estimate and compare the energy consumption of rolling the NPT and pneumatic tire on the basis of experimental research.

2. Objects and test conditions

For testing 12 – 16.5 wheels were selected, which are alternately used in skid-steer loaders (Fig. 6, Tab. 1):

- non-pneumatic tire – in further parts of this article termed NPT,
- pneumatic radial tire – in further parts of this article termed PT.

Tab. 1. General characteristics of the research objects [2, 12]

Research object	External unloaded dimension [mm/inch]		Tread Depth [32nd/mm]	Weight [kg/lbs]	Inflation pressure [kPa]	Hardness of the tread rubber [Sh A]
	Overall Diameter	Section Width				
NPT	840 / 33.1	307 / 12.1	31 / 24	102.5 / 226	0	67
PT	832 / 32.8	311 / 12.2	29 / 23	63.5 / 140	150-500	68

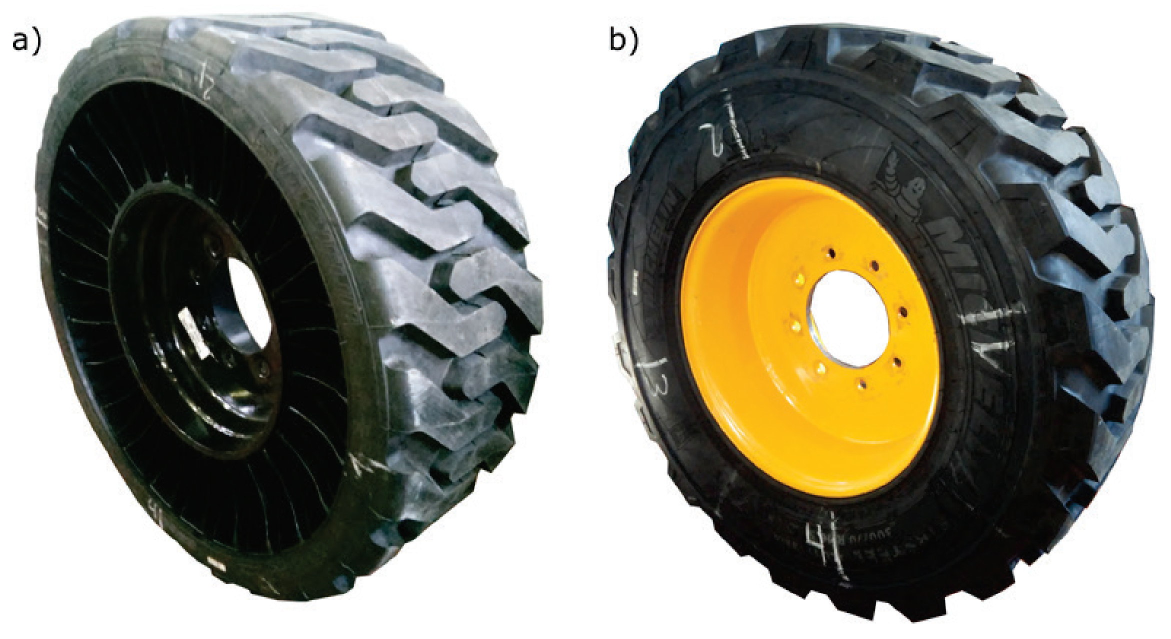

Fig. 6. Research objects: a) NPT, b) PT

The test conditions for research objects were selected taking into account the load conditions of the HSL850-7 HYUNDAI skid-steer loader. Operating weight of the skid-steer loader is 3290 kg and rated operating capacity is 840 kg [5]. The measurements show that approximately 73% of the total mass of the skid-steer loader is carried by the rear wheels.

In order to better understand the properties of the PT tires and their subsequent comparison to the NPT, the range of air inflation pressure was expanded (recommendations are 360-400 kPa).

Finally, taking into account the varying state of wheels loads and the inflation of PT, the test conditions were presented in Tab. 2.

Tab. 2. Test conditions

Research objects	Normal load [kN]	Inflation pressure [kPa]	Type of surface
NPT	4.0 12.0 20.0	-	asphalt – dry
PT		280 320 360 400 440	

3. The station for the tire static tests and methodology of the research

Research were made at the universal quasi-static indoor tire test facility (Fig. 7), which is located in the Institute of Vehicles and Transport at the Department of Mechanical at the Military University of Technology in Warsaw. Research included the determination of the radial static stiffness characteristics and parameters of the wheel contact with the ground. They were carried out in four different sections evenly distributed on NPT and PT circumference. Each of the tests was repeated four times under accepted test conditions.

Fig. 7. The universal quasi-static indoor tire test facility

Determination of radial static stiffness was based on a smooth wheel load of up to 125% of the normal load (Tab. 2), and then – on its unloading with the simultaneous recording of the tire's deflection.

The resulting hysteresis loop (Fig. 8), which shows differences between bending work L_U (during loading) and unbending work L_O (during unloading) research objects, has been used to determine the hysteresis coefficient W_H described by the formula [6]:

$$W_H = \frac{L_U - L_o}{L_U}. \tag{1}$$

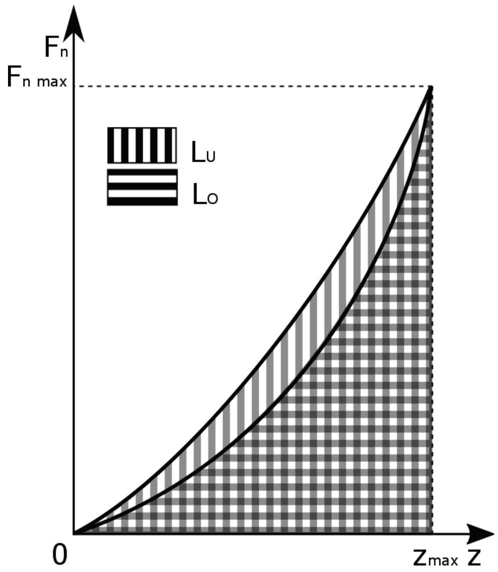

Fig. 8. Static radial stiffness characteristic of tire [6]

Moreover, the coefficient of static radial stiffness k_T is determined on the basis of the tangent to the centre line of the hysteresis loop (Fig. 9) [16]:

$$k_T = \frac{\Delta F}{\Delta z} \mid F \to F_{stat} = tg\alpha \ . \qquad (2)$$

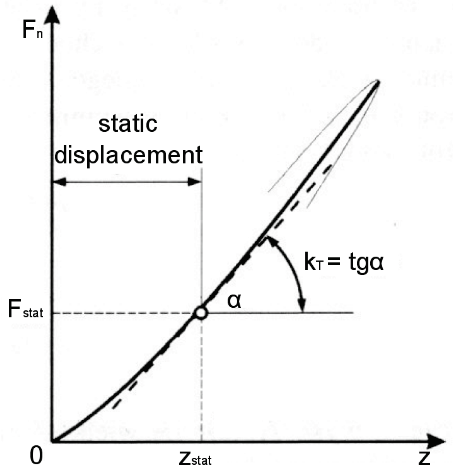

Fig. 9. Method of determining the static coefficient of radial stiffness [14]

Rolling resistance (constant component) was calculated according to the formula [6]:

$$F_T = \frac{W_H \cdot F_n \cdot z \cdot b}{A \cdot W_{GB}}, \qquad (3)$$

where:

F_n – normal load of tire (acting on the wheel axle),
z – static displacement of research object (tire),
b – width of the wheel contact with the ground,
W_{GB} – density of tread pattern coefficient [17]:

$$W_{GB} = \frac{A_W}{A}, \qquad (4)$$

A_W– contact area of tread blocks with the ground,
A – contact area of tire (total).

4. Laboratory results

Results of research (static radial stiffness test) (Fig. 10, Tab. 3) indicate that the NPT is characterized by a significantly higher static radial stiffness and a larger hysteresis loop (Fig. 11). This is mainly due to the NPT design. Elimination of compressed gas (e.g. air) required the use of components that took over its role. During NPT bending, greater volume of material is deformed (compared to the pneumatic tire). The research objects are characterized by a similar value of the tread rubber hardness and the height of the tread (Tab. 1). This allows saying that, the material volume and type of materials used under the tread and the value of pressured gas (in case of PT) will have a decisive influence on the energy consumption during their rolling. The results presented in [6, 9] confirmed that the volume of material deformed during the bending of the tire coating determines the value of energy losses. The results show that the NPT is characterized by a decrease in radial stiffness in the load function (Tab. 3). In the case of the tested pneumatic tire, the radial stiffness value increases with increasing load. The radial stiffness characteristics of analysed NPT are determined by the choice of material and the number of flexible spokes. During heavy loads (e.g. 20 kN), larger number of spokes is buckled causing a decrease in radial stiffness.

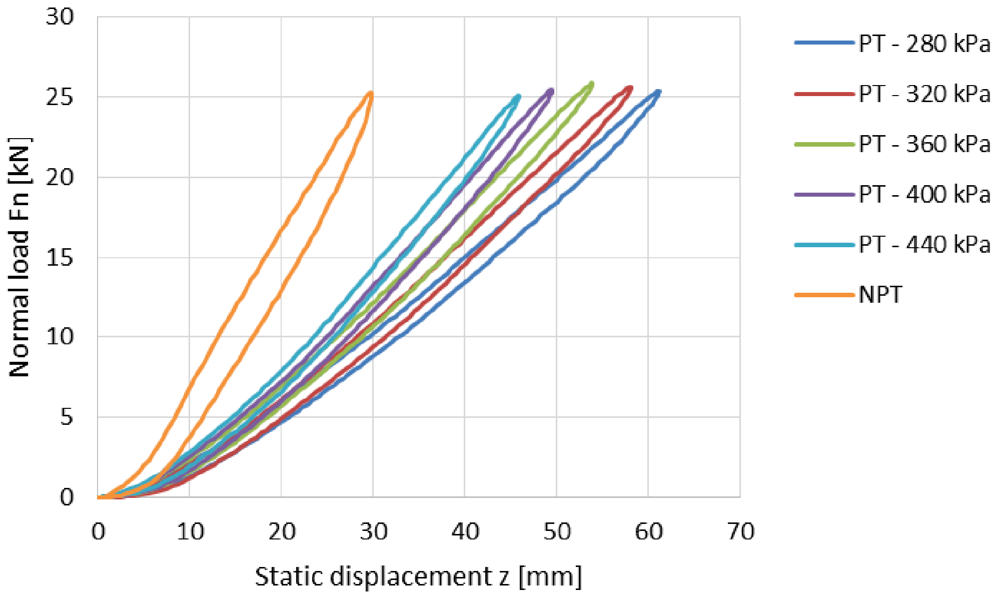

Fig. 10. Comparison of radial stiffness characteristics of NPT and PT (normal load 20 kN)

Tab. 3. Comparison of static radial stiffness coefficient NPT and PT

Inflation pressure [kPa]	Normal load [kN]		
	4	12	20
	Static radial stiffness coefficient k_T [kN/m]		
280	419 ± 15	494 ± 7	517 ± 4
320	448 ± 12	530 ± 8	566 ± 4
360	481 ± 10	568 ± 7	611 ± 2
400	485 ± 5	640 ± 9	670 ± 3
440	514 ± 5	684 ± 7	712 ± 7
NPT	1481 ± 59	1224 ± 31	1001 ± 20

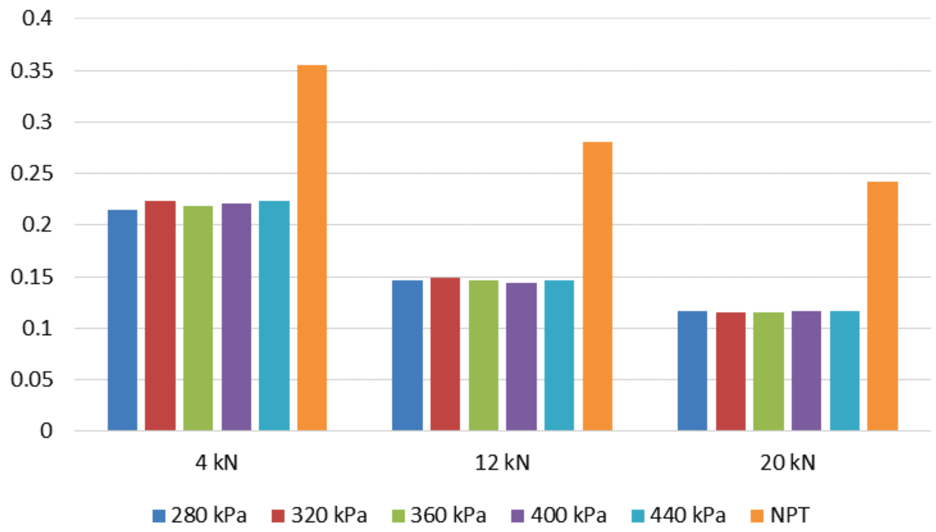

Fig. 11. Comparison of mean value of hysteresis coefficient NPT and PT

It has been noted that the value of the hysteresis coefficient (Fig. 11) for PT is almost 1.5 to 2 times lower than coefficient of NPT and practically does not depend on the inflation pressure. The lower value of the indicated range (1.5-2.0) refers to the lower wheel load (test conditions). This confirms that the values of the hysteresis coefficient are significantly related to the volume of material, which is bending. This influence was also noticed in model studies [9], where the hysteresis loop field and the rolling resistance of the NPTs were compared, the shear beam was made of full material and with circumferential holes (porous).

It was noticed that, the higher hysteresis coefficient value was recorded at lower load values; this may be related to the prevailing deformation of the tread blocks.

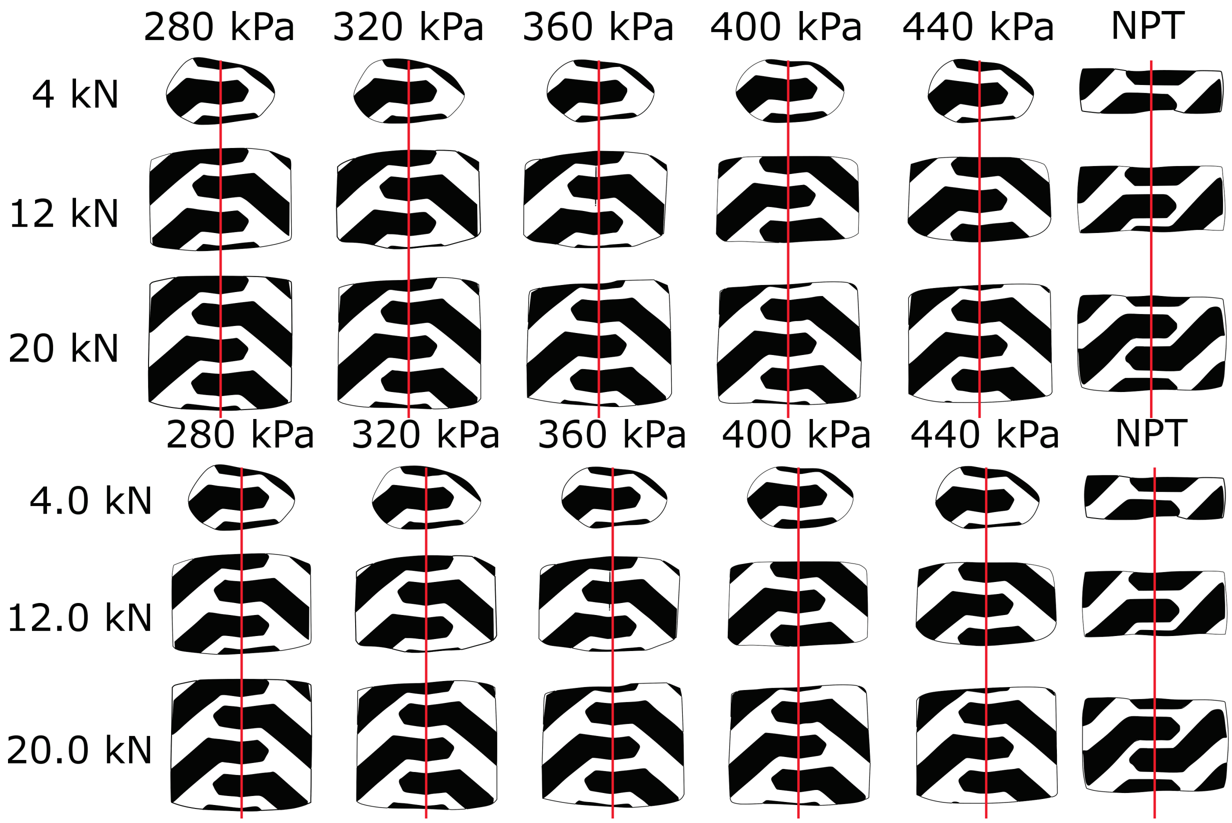

Fig. 12. Graphical comparison of NPT and PT footprints (load on rigid surface)

Fig. 12 shows footprints of NPT and PT during contact (load) on rigid surface. For NPT, the most (desirable) shape closest to the rectangle was recorded. As expected, increasing PT pressure decreases the value of the contact path, but even at the highest pressure, this value is greater than NPT.

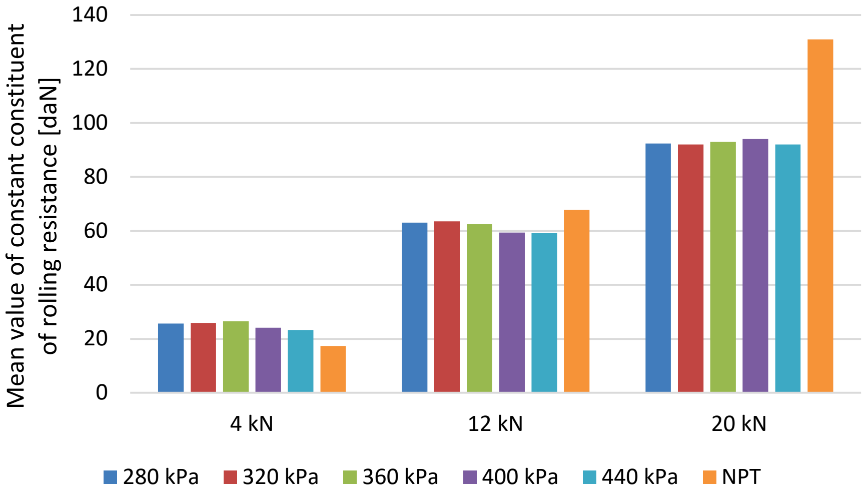

Fig. 13. Graphical comparison of mean values of the constant constituent of NPT and PT rolling resistance

Fig. 13 shows the results of the calculation (according to the formula 3) of the results of the rolling resistance constant constituent for NPT and PT. Rolling resistance of PT decreases with increasing inflation pressure. Value of the rolling resistance constant constituent mainly depends on hysteresis coefficient of research objects (direct influence of material volume and type of materials), parameters of contact area (footprint) and reaction of the research object to the applied load (see formula 3). PT loaded with a normal force of 4 kN is characterized by higher rolling resistance (despite the lower hysteresis coefficient) resulting mainly from the contact area parameters (width, contact area). It is also interesting to note that research objects loaded with normal force of 12 kN achieve similar values of the component of the rolling resistance constant constituent. The load of the research objects of normal force 20 kN increased the rolling resistance constant constituent value for NPT by about 40%.

Conclusions

Damage to the pneumatic tire results in immobilisation of the vehicle and, at the same time, turning off the ability to perform certain tasks. After using non-pneumatic tires in the vehicle, there is no such danger. The different design of the NPT (compared to pneumatic tires) results in other features of co-action with the ground. The results of the research indicate that the track of the NPT wheel with the ground is similar to the rectangle and its width is practically independent of the normal load. The analysed objects were characterized by similar values of the tread density coefficient, which allowed the authors to eliminate the influence of this parameter on the energy dissipation of the examined objects.

The non-pneumatic tire has a significantly (1.5-3 times) greater radial stiffness than the pneumatic tire. Lower values refer to lower static load on the wheel. What is more, the radial stiffness of NPT decreases as a function of the load (probably it is the effect of buckling of the flexible spokes of the support structure).

The non-pneumatic tire is also characterized by a higher value of hysteresis coefficient, which for NPT reaches 1.5 to 2 times higher than PT.

Carried out research shows that, NPT compared with PT for the highest load (20 kN) is characterised by higher rolling resistance values, but with a load of 12 kN and at 4 kN, the rolling resistance values are close to or even lower. Such relations were made using the formula 3, which is valid for a PT. It is also planned to conduct dynamic research to confirm the received relations.

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