SELECTED TIRE CHARACTERISTICS AND THEIR RELATION TO ITS RADIAL STIFFNESS

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DOI: 10.17973/MMSJ.2016_12_201687
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The article deals with the description of the experimental results of static radial deformation characteristics measurement for the selected tire and its impact on the size of the contact area, contact pressure and rolling resistance on a solid support. The measurement was carried out on the diagonal tire Mitas TS05 10.0/75-15.3 PR10 in the area of the test soil channel. The radial deformation characteristics of the tire in question were determined for inflation pressures of 300 kPa, 220 kPa, 160 kPa, and 100 kPa, with a radial load of the tire varying in the range from 567.9 kg to 1025.09 kg. At the same time, the treadmarks of the tire contact area were made for the corresponding inflation pressure and the corresponding radial load. The size of these treadmarks was subsequently measured using the digital Koizumi KP-90N polar planimeter. The mean contact pressure values on a solid support were subsequently calculated from the values of the tire radial load and the obtained contact surfaces. The calculated static radial stiffness value was obtained through the linearization of the measured deformation characteristics according to Jante. Rolling tire resistances on a solid support were verified by pulling the test wheel using the auxiliary winding system of the test equipment, the soil channel, along the concrete surface after removing the container with soil.

KEY WORDS
terramechanics, mobile machinery, wheeled chassis, soil bin, rolling resistance, tire stiffness

1. INTRODUCTION

The radial stiffness of the tires (whether static or dynamic) not only affects the cushioning of the energy means in the terrain, but it also affects other tire features relating to its contact with the surface of the terrain it is moving on. It affects the size of the tire contact area, the size of the contact pressure, the size of the internal as well as external component, rolling resistance and thus also affects the energy losses of the total power applied to the wheels of mobile equipment [Antille et al. 2013; Abrahám et al. 2014]. The radial tire deformation characteristics of mobile technology used in forestry and agriculture are therefore an important attribute for solving contact issues between the tire and the underlying surface. The size of the contact pressure is influenced mainly by the size of the tire contact area and the normal load. The size and course of the tire contact pressure affects to a large extent how the tire will behave, for example, on soil, how it will get damaged (e.g. press or excessive slip) and what driving and operating properties will the mobile vehicle reach under the given soil conditions [Braunack 2004; Cedik 2015]. In the past, several authors, for example, Zhang et al. [2002], Krmela [2008] and Koutny [2009] have dealt with the research of tire deformation properties, also highlighting the impact of tire deformation properties on their driving and contact features in their work. Progressive methods of research using different physical principles of tactile sensing elements were also used in the research of mutual ties between the deformation characteristics of tire wheels and the contact variables, especially the size of the contact area and contact pressure distribution on a solid support. This allows the precise determination of the distribution of contact pressure in the tire contact area with the support and accurately determine the size of this contact area. Thus-ranging work is indicated by authors such as De Beer and Fisher [1997], who applied tactile matrix consisting of tensiometric sensor elements to map the contact area and the contact pressure.

Rolling resistance is also an important tire characteristic. This clearly relates to the tire stiffness and is also affected by its structure. The more pliable the tire is, the more it leads to its deformation and, under certain conditions, increased rolling resistance. This model applies well on hard unyielding surfaces. On flexible and plastic surfaces, the said situation is not so clear. Here, under certain conditions, the tire may reach the optimal (minimum) value of the rolling resistance under a certain load and inflation pressure. The cause is smaller tire frame deformation and greater deformation of the plastic substrate.

As can be seen from the above brief overview, the topic is still relevant and currently addressed through advanced technologies brought by microelectronics. In this article, we will also attempt to indicate the relationship between the radial deformation characteristics of the selected tire and the size of the contact area, contact pressure and rolling resistance.

2. MATERIAL AND METHODS

We investigated the radial deformation characteristics of the selected tire for various values of inflation pressure and various values of the vertical load in the test soil channel (Figure 1). The vertical load on the tire was inferred through steel weights from 567.90 kg. to 1,025.09 kg. We selected the tire load so as not to exceed the maximum load indicated by the manufacturer at the given tire pressure. The structure of the wheel's supporting frame (Note 3, Figure 1) does not allow achieving a tire load of less than 480 kg. It is due to the fact that the entire drive mechanism of the test wheel is mounted on the said component, which is used during the tire traction test. Diagonal tire with arrow tread Mitas TS05 10.0/75-15.3 PR10 was selected as test tire. Its basic technical parameters are shown in the following Table No.1.

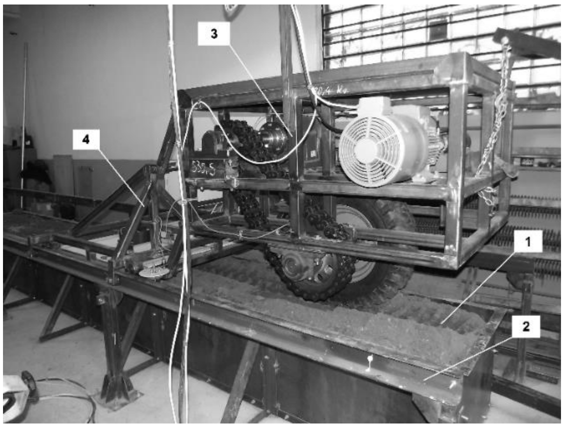

Figure 1: Test soil channel
1. The body of the test soil channel with soil, 2. Side routing, 3. Tire support frame, 4. Guide frame

We realized the actual measurement of radial deformation characteristics by lifting the supporting frame with the mounted tire using a workshop crane with a load capacity of 5,000 kg, and placed a steel plate with the thickness of 15 mm under the wheel on a flat soil surface. We investigated the actual tire compression using an altimeter with a nominal size of 1,000 mm. In addition to these measurements we investigated the required parameters of the tire's contact area with the surface. The contact area of the tire was imprinted on thick drawing paper after coating the tire in ink. For the given tire load and inflation pressure, we always took a print of the tire contact area, which is closer to the contact surface on the soil surface. We subsequently determined the size of the tire contact area by means of a digital Koizumi KP-90N polar planimeter. The resulting radial tire deformation characteristics were determined for the following inflation pressures: 300 kPa, 220 kPa, 160 kPa and 100 kPa.

From the obtained deformation characteristics, we then calculated the static radial stiffness of the observed tire. The course of the dependence of the vertical load on the tire and its deformation is represented by a second degree polynomial in the form:

$$Q = A.y + B.y^2 \text{ [N]} \quad (1)$$

where: Q – vertical load on the tire, [N]
A, B – constant factors of functional dependence Q (y), [-]
y – vertical tire deformation, [m]

We performed the linearization of the dependence according to Jante [Cvekl1976] based on the statement that the work expended to deform the tire, expressed by the formula:

$$E_p = \int_0^{y_{max}} (A.y + B.y^2) dy \text{ [J]} \quad (2)$$

is as great as the work expended to deform the tire in linearized form. The sought constant of the linearized loading process stiffness is then based on the formula:

$$E_p = \int_0^{y_{max}} c.y dy = \frac{1}{2}.c.y_{max}^2 \text{ [J]} \quad (3)$$

where: E_p – work expended to deform the tire, [J]
c – radial static stiffness of the tire, [$N.m^{-1}$]
y_{max} – maximum vertical tire deflection at a given load and corresponding inflation pressure, [m]

We then calculated the values of the mean contact pressures from measurements of the contact area and vertical load.

We investigated the rolling resistance of the tire in question at selected vertical load intervals and selected tire inflation pressure by dragging the test wheel on laboratory concrete surface after removing the container with soil, which forms the basis of the test soil channel. For pulling, we used the auxiliary winding mechanism, which is part of the test soil channel. Because of the free rolling of the tire wheel we removed the drive chain from the drive. Other parts of the drive wheel on the support frame remained in their original location and were used as load for the tested tire wheel.

A resistance force when pulling was measured by means of the HBM S9 force transducer with a nominal size of 10 kN. The sensor signal record was recorded using HBM a Quantum X MX 840A measuring recording device. The signal was subsequently converted to MS Excel where it was then processed. We determined the resulting rolling resistance value as a difference between the measured total resistance force and the resistance forces in the longitudinal guide of the wheel frame and the resistance created in the wheel bearings.

3. RESULTS

The results of the measurements and calculation of the work expended for the tire deflection and static radial stiffness of the tire are shown in the following Table 2. All the calculations and the functional dependence of the work were developed in the environment of the MS Excel spreadsheet. Measured tire deformation characteristics for each inflation pressure are graphically illustrated in Figure 2. The given functional dependencies of the tire load depending on the vertical deformation can be approximated by a polynomial of the second degree. The resulting functional dependencies indicating the correlation coefficient are given in Table 3.

Tire type	Dimension	PR	Tread	Wheel rim	Width (mm)	Diameter (mm)	Radius (mm)	Rolling circumferences (mm)
Mitas	TS05 10.0/75-15.3 PR10	10	TS05	9.00x15.3	264	790	395	2,295

Table 1: Basic technical parameters of the observed tire

We then used the values of coefficients for these obtained approximation functional dependencies (Table 3) to calculate the potential energy (deformation performance) according to Formula 2 and to calculate the radial static stiffness of the tire according to Formula 3.

The results of measuring the size of the tire contact patch observed for each load and tire pressure are shown in Table 4. This table shows the calculation of the mean contact pressure for each load and the tire print area, as well as the values of the measured rolling resistances.

4. DISCUSSION

Dependence on the tire deflection load (Figure 2) is a nonlinear second degree describable polynomial (quadratic function). Reported static radial stiffness values were obtained through the linearization of these functions according to Jante [Cvekl 1976], Table 3.

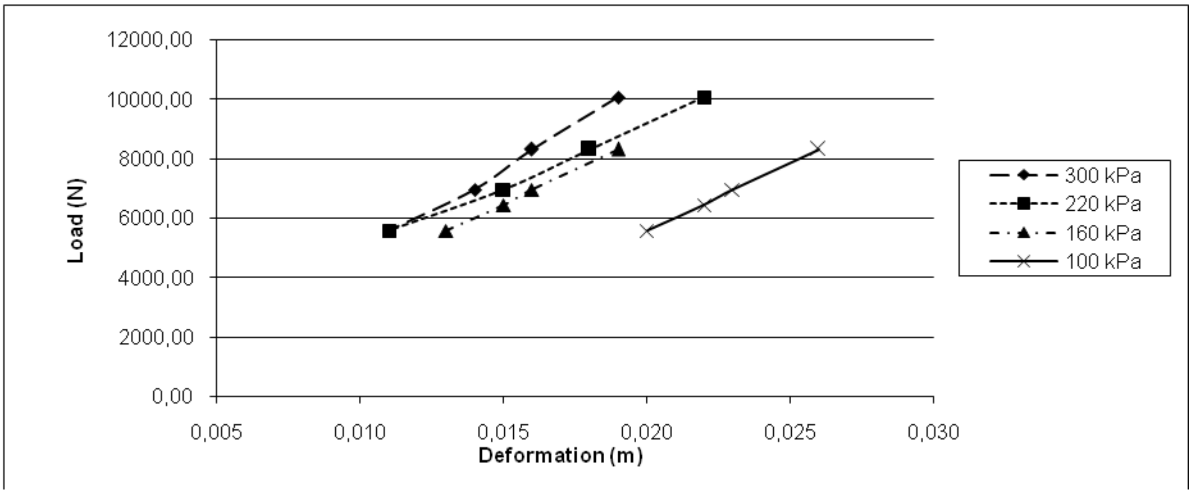

Figure 2. Radial deformation characteristic of the Mitas TS05 10.0/75-15.3 PR10 tire

Load (kg.)	Load (N)	Pressure (kPa)	Tire rolling radius (mm)	Tire deformation (mm)	Deformation performance (J)	Stiffness ($N.m^{-1}$)
1,025.09	10,056.13	300.00	376.00	19.00	94.77	525,000
847.14	8,310.44	300.00	379.00	16.00	69.19	
709.30	6,958.23	300.00	381.00	14.00	54.82	
567.90	5,571.10	300.00	384.00	11.00	36.88	
1,025.09	10,056.13	220.00	373.00	22.00	126.46	522,500
847.14	8,310.44	220.00	377.00	18.00	90.53	
709.30	6,958.23	220.00	380.00	15.00	67.98	
567.90	5,571.10	220.00	384.00	11.00	43.18	
847.14	8,310.44	160.00	376.00	19.00	76.39	423,200
709.30	6,958.23	160.00	379.00	1600	53.57	
656.48	6,440.07	160.00	380.00	15.00	46.88	
567.90	5,571.10	160.00	382.00	13.00	34.86	
847.14	8,310.44	100.00	369.00	26.00	64.99	192,300
709.30	6,958.23	100.00	372.00	23.00	42.20	
656.48	6,440.07	100.00	373.00	22.00	35.52	
567.90	5,571.10	100.00	375.00	20.00	23.53	

Table 2. Measured and calculated results, tire Mitas TS05 10.0/75-15.3 PR10

Tire inflation pressure	Operation	R^2
300 kPa	$y=1E+07.x^2+208,866.x+1,800.2$	0.9977
220 kPa	$y=6E+06.x^2+199,416.x+2,586.4$	0.9993
160 kPa	$y=1E+06.x^2+424,967.x-136.92$	0.9995
100 kPa	$y=1E+06.x^2+410,363.x+3,060.6$	0.9995

Note: y – vertical tire load, [N] x – tire deformation, [m]

Table 3. Dependencies of deformation characteristics for Mitas TS05 10.0/75-15.3 PR10

The dependence of the tire print area on the load and inflation pressure (Figure 3) shows that the print area clearly grows with the increasing radial load and decreasing tire inflation pressure. It reaches its maximum at 100 kPa inflation pressure and a maximum load of 847.14 kg. In this dependence, however, we may discern some variations consisting in a significant drop in the print area of the tire depending on the load and inflation pressure during inflation to a pressure of 160 kPa. This jump is probably due to the fact that at an inflation pressure of 160 kPa and less the tire manufacturer does not recommended burdening it with the weight of 1,025.09 kg anymore. This value is missing in the chart and the graph starts from the value of 847.14 kg.

In the dependence of the mean tire contact pressure on the load and inflation pressure (Figure 4) we can observe that the mean contact pressure of the tire increases not only due to increasing vertical load but also due to the rising inflation pressure of the tire. It reaches its peak at an inflation pressure of 300 kPa and a vertical load of 1,025.09 kg.

Several authors suggest in their work that the value of mean contact pressure is approximately equal to the tire inflation pressure [Faria 1992; Grecenko 1995; Noor 1995]. However, this ideal situation would be valid if the tire was perfectly elastic. In fact it is not. Our results showed the following. At the tire pressure of 100 kPa, the mean value of the contact pressure stood at 138 kPa to 149 kPa when considering the print area, which is consistent with the theory that the real value of mean contact pressure is always greater than the tire pressure in a real tire. At the tire pressure of 160 kPa, the values of mean contact pressure are approximately equal to the inflation pressure of the tire. At the inflation pressure of 220 kPa, the contact pressure was slightly lower, moving at 168 kPa to 193 kPa.

From the measured values on rolling resistance (Figure 5) it is clear that the rolling resistance on a hard – concrete surface clearly grows with the increasing vertical load and decreasing tire inflation pressure. In terms of static stiffness, the more inflated the tire is, the less pliable on a hard surface, thus showing a smaller deformation of the frame and also the lower value of the internal rolling resistance. It would seem that the more we inflate the tire, the smaller the rolling resistance. But the reality is that in a tire that is inflated too much there is a significant reduction of the contact area, which may be manifested in the deterioration of the vehicle's driving performance under certain conditions. But there is also another side to the problem related to the mechanical stress of the casing's frame due to excessive internal pressure, as well as uneven tire wear manifested in the reduction of its life.

The course of deformation characteristics and calculation of static radial stiffness (Figure 2, Table 2) shows that this is heavily dependent on tire inflation pressure. The lower the tire inflation pressure, the more pliable the tire (smaller radial stiffness). At the inflation pressure of 100 kPa it is nearly 2 times lower than 300 kPa. The radial static stiffness and thus tire flexibility are affected not only by the inflation pressure in the tire but also the very structure of the tire. It depends on whether the tire structure is radial or diagonal, the number of cord layers and the material of cord layers.

More pliable tire structure at lower inflation pressure allows reaching higher contact surface values (for the given load) and lower contact pressure values [Schreiber 2008; Barosa 2015].

Load (kg.)	**Load (N)**	**Inflation pressure (kPa)**	**Track width (mm)**	**Track length (mm)**	**Compression (deformation) (mm)**	**Print area (mm²)**	**Mean contact pressure (print) (Pa)**	**Rolling resistance (N)**
1,025.09	10,056.13	300.00	230.00	245.00	19.00	45,561.19	220,717.08	100.56
847.14	8,310.44	300.00	220.00	220.00	16.00	40,820.27	203,586.19	83.10
709.30	6,958.23	300.00	212.00	205.00	14.00	35,475.40	196,142.48	69.58
567.90	5,571.10	300.00	200.00	190.00	11.00	30,260.13	184,106.91	55.71
1,025.09	10,056.13	220.00	228.00	260.00	22.00	52,120.40	192,940.44	181.01
847.14	8,310.44	220.00	222.00	229.00	18.00	46,196.07	179,895.03	149.59
709.30	6,958.23	220.00	221.00	223.00	15.00	41,888.78	166,112.09	125.25
567.90	5,571.10	220.00	210.00	188.00	13.00	33,182.52	167,892.58	100.28
847.14	8,310.44	160.00	221.00	243.00	19.00	47,674.24	174,317.27	166.21
709.30	6,958.23	160.00	220.00	225.00	16.00	44,865.21	155,091.95	139.17
656.48	6,440.07	160.00	219.00	222.00	15.00	41,385.37	155,612.24	124.30
567.90	5,571.10	160.00	218.00	200.00	13.00	35,905.52	155,159.96	111.42
847.14	8,310.44	100.00	220.00	285.00	26.00	55,756.47	149,048.95	207.76
709.30	6,958.23	100.00	218.00	256.00	23.00	51,681.50	134,636.82	173.96
656.48	6,440.07	100.00	219.00	234.00	22.00	48,005.95	134,151.50	156.62
567.90	5,571.10	100.00	220.00	210.00	20.00	40,330.40	138,136.47	139.28

Table 4: The results of measurements regarding the size of the contact area and contact area of the monitored tire

At the tire pressure of 300 kPa we had resulting values of mean contact pressure of 184 kPa to 221 kPa.

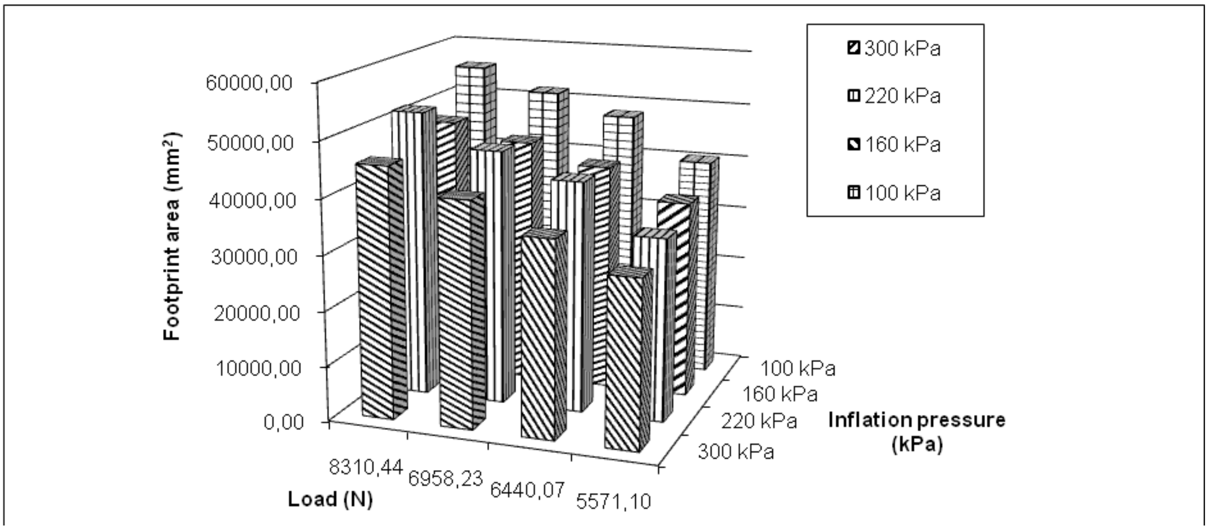

Figure 3. Dependence of the tire print area on the vertical load and inflation pressure

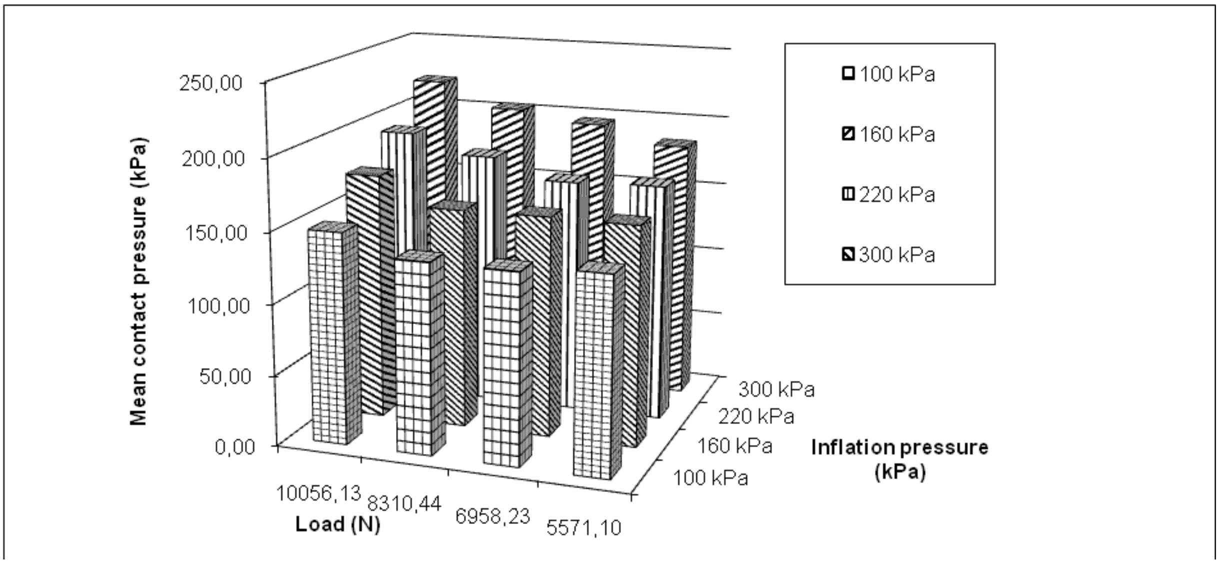

Figure 4. Dependence of the mean tire contact pressure on the load and inflation pressure

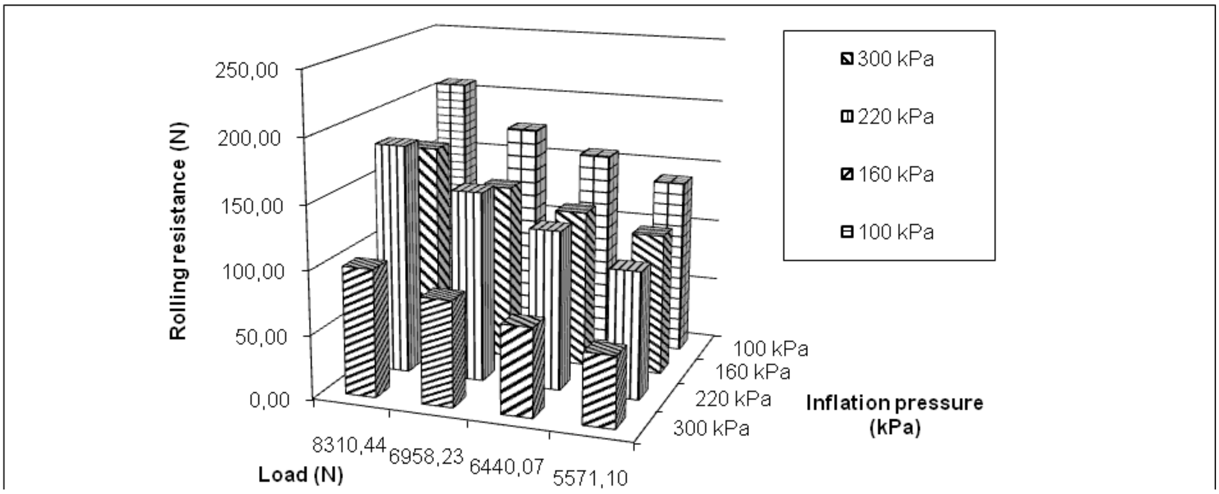

Figure 5. Dependence of tire rolling resistance on the load and inflation pressure

This feature can be used in selecting an appropriate tire inflation pressure when driving off-road on a pliable substrate to reduce damage to the soil and reduce tire rolling resistance. On a solid surface, however, a reduction in tire inflation pressure for the given load clearly leads to the increased internal component of tire rolling resistance. Here, therefore, we strive to achieve that the tire is reasonably solid (inflated to the highest pressure proportionate to its maximum load), which will ensure the acceptable value of the rolling resistance when reaching optimum life.

5. CONCLUSION

Finally, we would like to mention that the very test soil channel on which we conducted the measurements of the tire's deformation characteristics in question is not fully fit for the given purpose. The main limiting parameter here is the fact that it does not allow us to ensure a tire load of less than 480 kg without having to uninstall the wheel drive mechanism. As mentioned above, the vertical load on the tire was inferred by means of mechanical weights, their manual handling cumbersome, time-consuming and arduous for equipment operators. A device called the static adhesive is more suitable for verifying the deformation characteristics of the tire wheels, allowing the accurate measurement of individual deformation characteristics (not only in the radial direction) of the tires. However, our workplaces currently do not have the given equipment. In the future, we would like to continue in the research of deformation characteristics and specify the measures at the desired level.

The measurement of rolling resistance in test soil channels also has its drawbacks. These are mainly due to the uneven resistance in the conduct of wheel frame with a tire that varies not only with the tires load, but its size also depends on the accuracy of the assembly of longitudinal guiding. The size and course of this resistance can be measured and taken into account in the calculations. However, it is worse when determining the resistance of the wheel bearings. The size of the resistance force is clearly changing with the tire load value and is further influenced by the overall structural design of the wheel placement. We are not realistically able to measure this constant, and so when determining it we follow the empirical calculation, taking into account the wheel load and type of used bearings.

The measurements performed by us do not provide any fundamentally new results, but they confirm the opinions that the tire inflation pressure, as well as the choice of an appropriate tire size for a specific vehicle, play an important role in the energy efficiency of these machines. We think that we have managed to suggest a link between radial tire stiffness, the size of the contact surface and the rolling resistance on a hard surface. These tire properties must be reviewed even before the tire is fitted to specific mechanization equipment. Based on the results of this verification it is then possible to determine a tire's suitability for particular mechanization equipment so that its performance off-road or on a paved road can be as efficient as possible.

ACKNOWLEDGMENT

The article was prepared with the support of the VEGA grant program by the Ministry of Education, Science, Research and Sports of the Slovak Republic No. 1/0676/14.

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