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EXPERIMENTAL RESEARCH OF TIRES ROLLING RESISTANCE

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Abstract:
The paper presents the results of a laboratory measurement of rolling resistance of two different types of tires on a concrete surface. A soil test channel was used to realization of the measurements. The article presents the results of laboratory measurement of rolling resistance of two different types of tires on a concrete surface. A soil test channel was used to perform the measurements. The result of the measurements was the determination of the rolling resistance coefficient. Linear function approximation and statistical analysis were applied in the research. The conclusions of the analysis confirmed the fact that the values of the measured rolling resistance coefficients of both types of tires do not show a statistically significant difference. The obtained results confirmed the assumption that the values of the rolling resistances on a solid surface can be reduced by increasing the tire inflation pressure.

Key words:
rolling resistance, tyre, tyre testing

1 INTRODUCTION

The main component of the loss resistance of vehicles and mobile work machines with wheeled chassis in forestry is rolling resistance. At the same time, a significant part of their movement is often realized on public roads or on paved surfaces of forest roads. The flexibility of these surfaces is very small and therefore the deformation of the tires is mainly applied here. This significantly affects their final value of rolling resistance and the overall energy efficiency of driving on a paved unbending surface. Rolling resistance can be defined as the energy loss caused by the rolling of the tire caused by its imperfectly elastic deformation as well as the springing of the tire (Pouget, et al., 2012). During the driving, the tire deforms under vertical (radial), circumferential and lateral forces (Djordjevic, Jankovic and Jeremic, 2009). When the tire is loaded with a vertical force (the weight of the vehicle), the part of the curve of the running surface of the tire (tread) which comes into contact with the road surface must be compressed to a certain length. After turning the tire, this part of the running surface is relieved, so that the part of the rubber which was previously compressed will expand again. In a similar way, the running surface deforms in the transverse direction (Akutagawa, 2017). After unloading, the rubber particles expand again. In this way, the tire particles alternate in the circumferential and transverse directions and expand at a certain frequency, which depends on the speed of the wheel and thus also on the speed of the vehicle or machine (Faraji, 2010).

The deformation work, which forms by the effect of the mentioned vertical, circumferential and lateral forces, does not return completely after the tire is unloaded. Part of the work is used for repression of the hysteresis losses of the tire. According to Luchini and Popio (2009), the cause is the imperfect flexibility of the tire, which does not return completely to its initial state due to its own damping after unloading. The aforementioned work to repression the tire losses is just related to rolling resistance. Part of the rolling friction is also the partial slip of the tread figures in the contact surface and the losses associated with the adhesion and tearing of the tread figures from the road surface (Andersson et al., 2012). The roughness, resp. micro and macro-relief of the road surface on which the tire rolls have an important effect on the final value of the rolling resistance. This often complicates the correct determination of the final value of the rolling resistance of the monitored tire (Wang, 2019). The value of tire pressure affects a number of important vehicle features. Synak and Kalasova (2020) pay attention to assessing the impact of the change in the tire pressure on both the rolling resistance and fuel consumption. A novel evaluation method for the rolling resistance characteristics of truck tire is proposed by (Zhu, CW et al., 2020) , in which a simplified modal experiment is suggested through a single-point vibration sampling from the tire surface with a polyvinylidene fluoride (PVDF) piezoelectric film.

2 MATERIALS AND METHODS

The rolling resistance of a tire rolling on a resilient surface (soil) is formed from the internal part F_{ri} and external part F_{re}. The internal rolling resistance is caused by hysteresis losses during the deformation of the tire in the contact surface. The external rolling resistance of the tire is caused by the formation of a permanent track. The current experimental research confirms that when a wheel rolls on the ground, two different areas are formed in it, namely:

- front plastic, in which the soil is raking in front of the wheel,
- lower elastic, in which the soil is shifting by arc backwards.

These areas are based on a common point on the circumference of the wheel, in which the vector of absolute velocity v_a in the motion of the soil particles forms with the wheel radius an angle of $45° - \varphi/2$ (Fig. 1). This is in line with Mohr's theory of ultimate stresses for soils, according to which the slick surfaces form with the direction of the higher principal stress an angle $45° - \varphi/\mathbf{2}$. The φ is the internal friction angle of the soil (Bretšnajdr, 1984).

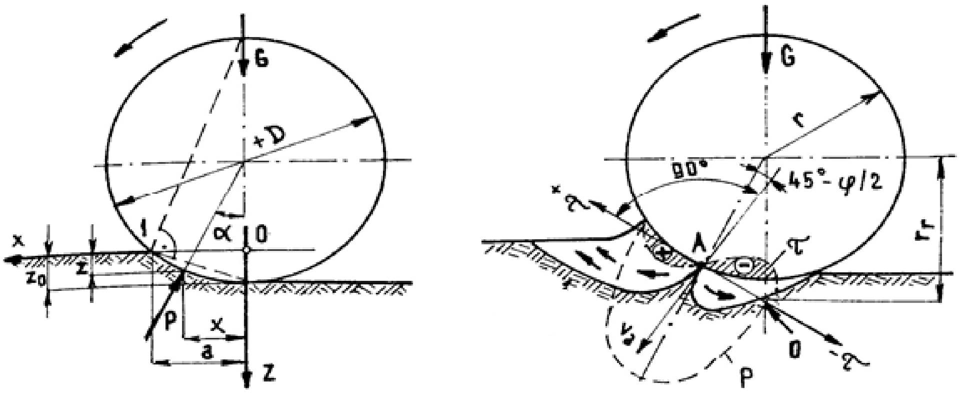

Fig. 1 *Scheme of the tire effect on the soil*

In the experimental part of the study we focused on the evaluation of rolling resistances of two diagonal agro-forestry tires Mitas rolling on a concrete surface (Fig. 2). As an example of the results we mention a part which was chosen for diagonal tires Mitas TS05 10,0/75-15,3 10PR and Mitas TS04 6,00-16 6PR. Their basic technical parameters according to the producer's data are presented in Table 1.

Tab.1 Basic technical paramters of the tested tires

Mitas TS05 10,0/75-15,3 10PR

Parameter	Value
Diameter of tire-casing	800 [mm]
Width of tire-casing	277 [mm]
Maximal load capacity of trailing tire	1 500 [kg]
Maximal load capacity of driven tire	1 090 [kg] at a rate of 10 [km.h^{-1}]
Maximal tire pressure	300 [kPa]
Weight of tire-casing with rim	38,30 [kg]

Mitas TS04 6,00-16 6PR

Parameter	Value
Diameter of tire-casing	750 [mm]
Width of tire-casing	177 [mm]
Maximal load capacity of trailing tire	710 [kg]
Maximal load capacity of driven tire	610 [kg] at a rate of 10 [km.h^{-1}]
Maximal tire pressure	300 [kPa]
Weight of tire-casing with rim	24,30 [kg]

(a) (b)

Fig. 2 *Tire (a)Mitas TS05 10,0/75-15,3 10PR, (b) Mitas TS04 6,00-16 6PR and experimental device for measurement of rolling resistance*

The schema of the experimental device is presented in (Fig. 3). We consider the determination of rolling resistance of tested tires as a key and at the same time as a starting point for further measurements in the field of energy evaluation of wheeled vehicles, whether on the selected soil or on a solid surface. We realized the rolling resistance measurements in on a concrete base in order to determine the rolling resistance of the monitored tires. The construction of the soil channel was dismantled in this case. The methodology of measuring the rolling resistance of the tires was simple and basically based on pulling the main frame with the tire using a braking and winding device (Fig. 3).

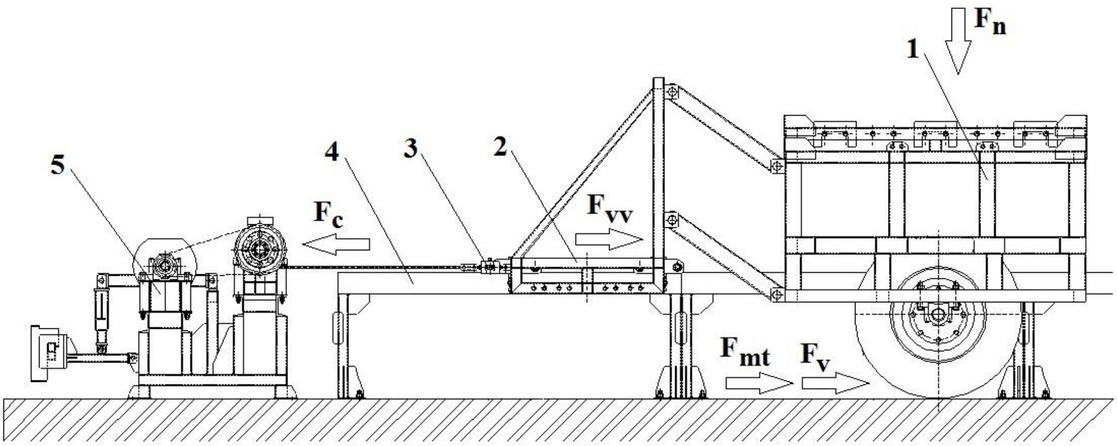

Fig.3 *Action of forces by pulling of tire wheel (measurement on the concrete surface)*
1. The main frame with wheel, 2. Guide frame, 3. Force scanner HBM S9M, 4. Side main 5. Braking and winding device, F_c *– Total resistance force by pulling,* F_n *– Normal force for tire,* F_v *– Rolling resistance,* F_{mt} *– Force of friction resistance in bearings,* F_{vv} *– Force of resistance in the guide frame*

The measurement was realized at tire inflation pressures of 100 kPa, 150 kPa, 200 kPa, 250 kPa and 300 kPa. The vertical loading of the tire was chosen in five levels, namely 222 kg (weight of the main frame without the wheel drive mechanism and without weights), 350 kg, 478 kg, 606 kg and 734 kg. For the tire Mitas TS04 6.0-16 6PR, we skipped a load level of 734 kg, as we would exceed the permissible tire load specified by the producer for the given inflation pressure levels. Mechanical weights made from steel plates with the weight 32 kg were used to load the tire. The tire inflation pressures and their vertical loads have been chosen to meet the technical requirements set by the tire manufacturer and to avoid unnecessary overloading, which reduces their service life.

In such a way of measuring the rolling resistances of tires, the total measured tensile force consists not only of the rolling resistance component but also of the components of other resistive forces, which we must take into account in the calculation itself.

3 RESULTS AND DISCUSSION

As we mentioned above, the methodology of measuring the rolling resistance of the researched sample of tire was simple and based on pulling of the main frame with the tire using a braking and winding device (Fig. 3). We obtained the values of the internal component of rolling resistance. We realized the measurement for five levels of tire inflation 100 kPa, 150 kPa, 200 kPa, 250 kPa and 300 kPa and five levels of vertical wheel loading (222 kg, 350 kg, 478 kg, 606 kg and 734 kg), for the tire Mitas TS04 6.00-16 6PR only at four load levels (222 kg, 350 kg, 478 kg and 606 kg).

During the measurement, we recorded the traction resistance of the towing wheel using a force sensor HBM S9M / 10kN with a sampling frequency of 5 Hz. We chose this value of the sampling frequency on the basis of the work of the authors Bauer and Sedlák (2003), they used the stated value of the sampling frequency for measuring the traction indicators of tractors. The measured data were transferred to a personal computer via the HBM Quantum X MX 840 A and by the measuring software HBM Catman Easy transferred to MS Excel files, in which they were also subsequently processed. The speed of movement of the trailing wheel was 0.1 $m.s^{-1}$. The sets of measured tensile resistances at individual values of vertical loading and corresponding values of inflation pressures of the monitored tires were subsequently statistically processed in the program Statistica 12 CZ.

There is an almost linear relation between the rolling resistance of tires and their loading (Berger et. al., 2016). The linear course of the equilibrium rolling resistance as a function of the tire load is probably random. However, it is very well known and has led to the introduction of the rolling resistance factor. The rolling resistance coefficient is a useful parameter because it allows you to compare different tires. Based on the calculations of the rolling resistance coefficients, we also compared the monitored tires. The following Figure 4 shows the dependences of the rolling resistance coefficients on the tire inflation pressure for a load level of 606 kg.

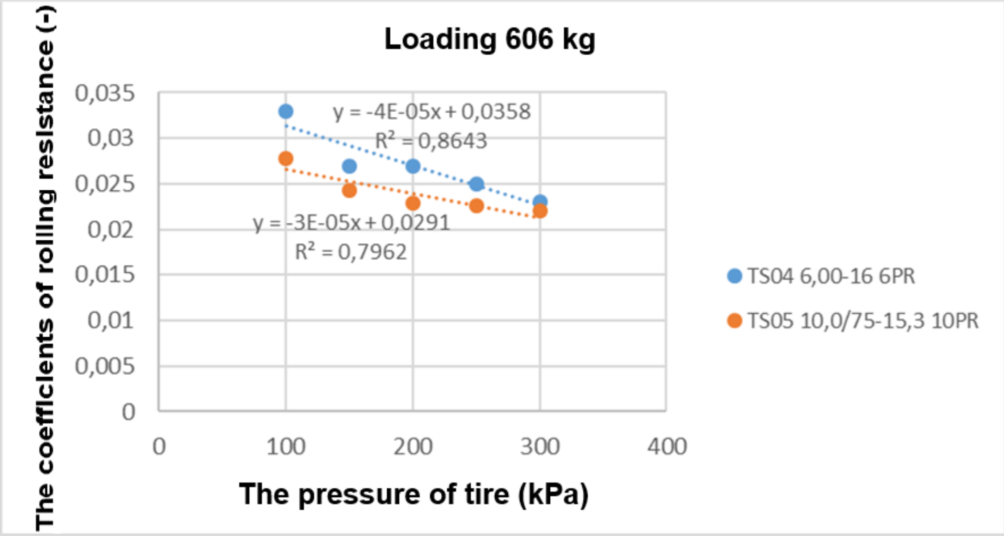

Fig. 4 *Dependence of the coefficients of rolling resistance on the pressure of tire pressure – loading 606 kg*

In the above-mentioned graphical dependence, a decrease in the values of the rolling resistance coefficients of the monitored tires with increasing inflation pressure is observable. The same was true for the other used loading levels. At first sight, it might seem that the tire Mitas TS05 10.0 / 75-15.3 10PR is slightly better than the tire Mitas TS04 6.00-16 6PR in terms of the values achieved in the rolling resistance coefficients. To confirm or negation this hypothesis, we used a conformance testing of the regression coefficients of linear functions by which we translated the measured points for individual tires in the above-mentioned graphical dependences of the rolling resistance coefficients on their inflation pressure. An example of the obtained results by of the used test method is presented in the table 2 for a tire load 606 kg.

Tab.2 *Example of the results of calculations of the conformance testing of regression coefficients of linear function for loading of tires 606 kg*

Regression function	**R^2**	**R**	**Residual dispersion**	**s_b^2**	**p - level**	**|t|**	**$t_{0,95}$**
y = -4.E-05.x + 0,0358 TS04 6,00-16 6PR	0,864	0,930	2,533333E-06	1,700000E-10	0,217	1,381	1,943
y = -3.E-0,5.x + 0,0291 TS0510,0/75-15,3 10PR	0,796	0,892	1,716667E-06				

This testing characteristics has with the accept of the null hypothesis the Student's probability distribution with the number of degrees of freedom 6. If the test characteristic is from the critical area $|t| > t_{0,95}$, so we reject the null hypothesis about the agreement of regression coefficients. In this case, we must consider the directives of the regression lines as different, and we cannot assume that a unit change in the explanatory variable will cause the same change in the explanatory variable in the first and second base sets.

When we look at the results of statistical analysis (Table 2), we see that the value of the test characteristic $|t|$ is less than the value of quantile of the Student's distribution $t_{0,95}$. The situation was similar at other **loading** levels in addition to the load value 350 kg, where the test characteristic exceeded the critical value of the test criterion $t_{0,95}$. Exceeding this value was caused by a significant decrease in the rolling resistance coefficient at inflation pressures of 250 kPa and 300 kPa for the tire Mitas TS05 10,0/75-15.3 10PR and a more significant decrease in the reversed function compared to the data for the tire Mitas TS04 6,00-16 6PR. Based on the above, we can state that there is no statistically significant difference in the achieved values of rolling resistance coefficients at inflation pressures of tested tires for individual levels of vertical load in addition to the load value of 350 kg.

Therefore we can state, that the tested tires are essentially equivalent in terms of the achieved values of rolling resistances and there is no statistically significant difference between them. Nevertheless, in individual courses we can monitor that the course of the rolling resistance coefficients of the tire Mitas TS04 6.00-16 6PR at the individual inflation pressures and at the individual used load values is slightly higher than with the tire Mitas TS05 10.0 / 75-15.3 10PR. However, based on the results of the statistical analysis, we can say that this difference is not statistically significant.

Based on research realized by Clark (Clark,1978), we can state that with the presented loading, rolling resistance decreases with increasing tire diameter and decreasing profile number (ratio of profile height to tire profile width). The author found that significant energy savings (fuels) on solid surfaces can be achieved for example by replacing the double mounting of tires with one wide-profile tire. In our case, the tire Mitas TS05 10.0 / 75-15.3 10PR is only 100 mm wider and has only 50 mm larger diameter than the tire Mitas TS04 6.00-16 6PR. The achieved values and courses of rolling resistance coefficients of tires could support the presented statement, but in regard to the results of the statistical analysis, we can consider them as equivalent and neglect the differences between them.

However, this increase of the tire inflation pressure cannot be spontaneous and reckless. It is always a matter of a compromise between the obtained rolling resistances, the appropriate mileage and, last but not least, the achievement of good tire performance. Therefore, when choosing the correct tire inflation pressure for the specific vehicle or work machine, it is necessary to follow the technical regulations of the tire producer as well as the vehicle or device producer.

4 CONCLUSION

Tire rolling resistance is also affected by the properties of the cord material, by the losses inside the cord due to hysteresis, and by the modulus of elasticity on the deformation of the rubber. Of course, the tire rolling resistance is also related to the viscoelastic properties of its rubber components. Viscoelastic losses in tires are most affected by the tread (Garcia, 2016). Its work cycle is a combination of radial compression, bending and friction. There is a strong interaction between these parts, and it can cause that the actual energy losses are greater than expected in the case, if different polymers are used in different parts of the tire.

Tire rolling resistance is in some measure affected by the operating time (driving) of the vehicle on which it is operated (Behnke and Kaliske, 2015). As the operating time increases, the tire gradually heats up and the rolling resistance decreases slightly. We did not solve this issue on our equipment, because we do not have an equipment on which we could run the tire to a certain operating temperature. In our experiment, the tire was warmed to the temperature of the environment of our laboratory, which ranged from 20 °C to 22 °C.

The question of the level of reduction of the tire rolling resistance on solid surfaces is primarily a question of the trade-off between the profit in energy savings and the loss in the lifetime of the tire. The adhesive properties of the tire should not be affected from the point of view of operational safety. Reduction of material hysteresis can be achieved by using more efficient rubber-cord composites and by using rubber compounds and cords with lower hysteresis.

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