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Traction properties of the wheel-turfy soil system

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A b s t r a c t. An analysis of the traction properties of tyre size 9.5-24, with non-skid chains and without, on turfy ground of various levels of compaction are shown. The authors present the effect of packing on changes in the physical, mechanical and traction properties of the analyzed subsoils and determine the effect of loading of the wheel system and of installing anti-skid chains on the tyres on the traction properties under analysis. It was found that increase in the level of soil packing or compaction causes an increase in the traction value of a turfy soil. Increased level of soil compaction was conducive to the obtainment of higher values of traction forces and efficiency at lower levels of wheel skid. The values of traction force generated by the studied wheels on soil with the highest level of compaction (4 PU) were even 75% higher with relation to those obtained on non-compacted soil. The authors demonstrated that the application of chains on the tyres is an effective method of improving the traction properties of the wheel system as it contributes to an increase in the values of traction forces and efficiency and to improved grip.

K e y w o r d s: traction force, traction efficiency, index of grip, compaction, total porosity

INTRODUCTION

A moving vehicle transmits onto the ground, via its wheel system, loads that cause the appearance of stress and strain in the soil. Every soil structure is characterized by a certain stability with relation to mechanical load. If the load is small, the soil responds in a flexible manner. If, however, the load is greater than the stability of the soil structure, irreversible deformation of the soil takes place. Vertical deformation is the result of the vehicle mass, and it causes soil compaction or packing (Ademiluyi *et al*., 2009; Błaszkiewicz, 2007). Horizontal deformation appears as a result of the effect of tangent forces and it causes displacement of soil particles and leads to the skidding of the wheel system of vehicles. Soil compaction leads to changes in the physical, chemical and biological conditions in the soil, with resultant numerous negative phenomena (Keller *et al*., 2002; Głąb, 2009). Soil compaction contributes to increase in its density and a decrease in its total and air porosity, the consequence of which are changes in the water-air relations. Excessive compaction of soil inhibits root growth, with the resultant oxygen deficit and reduced yields of crops (Czyż and Tomaszewska, 1998). The most frequent response of roots to soil compaction is a reduction of their length, concentration in the surface horizon of the soil, and reduced depth of rooting (Lipiec *et al*., 1991; 2003). Compacted soil has reduced capacity for infiltration and retention of precipitation water, which causes surface runoff and soil erosion. The results of numerous studies demonstrate also that soil compaction not always results in reduced yields of perennial crops; sometimes such crops yield much better on strongly compacted soil (Dwyer and Studie, 1989; Frost, 1988). The reasons and mechanisms of that phenomenon have not been fully researched yet, and most often it is attributed to higher levels of water and minerals in compacted soil.

The effect of soil compaction by tractor wheels depends on the design and operation parameters of the tractor, such as the width and diameter of tyres, tyre pressure, unit load, speed, wheel skid, or the number of passes (Canillas and Salokhe, 2002; Stenitzer and Murer, 2003; Simanov, 2008). The kind and extent of effects of agricultural vehicle traffic over the ground depends on the properties of the soil, among which we should enumerate the soil type, its grain size composition and structure, organic matter content, and moisture (Defossez and Richard, 2002; Lipiec and Hatano, 2003; Niemczyk 2004; Raper, 2005). A few publications dealing with the problems of changes in soil structure under the

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effect of compaction on grasslands indicate increased strength of soil aggregates and lower susceptibility of such soils to compaction (Głąb and Ciarkowska, 2006). Moreover, on grasslands, where there is a dense mass of roots in the surface horizon, one can observe the phenomenon of attenuation of the loads exerted by the wheels of agricultural vehicles and machinery, which causes reduced density of the soil compared to arable soils (Douglas and Crawford, 1993).

Farming on soils requires the achievement of a balance between two opposing requirements – that of creating proper conditions for the growth and development of crop plants, and that of ensuring adequate conditions for vehicle and machinery traffic.

The problem of identification of the conditions of generation of traction forces on non-typical surfaces has recently acquired increased importance. This is due to the fact that increasingly heavy vehicles, equipped with engines with very high power ratings (200-300 kW), move over such soils (Rastogi *et al.*, 2002). Such vehicles generate very high vertical loads in the ground and also high tangent forces, necessary to achieve required traction forces or pulling power. That situation causes that the problem of energy losses involved in the traffic of such vehicles, and the related damage to the soil structure, becomes more and more important. Conclusions from the above considerations indicate that there exists a need for the search of solutions aimed at minimisation of energy losses involved in vehicle traffic over deformable surfaces. Limitation of such losses will result in reduced degradation of soil structure on the one hand, and on the other – in financial savings due to reduced fuel consumption.

The primary objective of the study reported herein was qualitative assessment of changes in selected mechanical and physical properties of soil resulting from varied compaction of turfy soil, and demonstration how the changes in those parameter would affect the basic traction properties *ie* traction force, traction efficiency, and values of the index of grip, determined for two different loads applied to a 9.5-24 tyre. Moreover, the study was aimed at demonstrating whether, and to what extent, the use of anti-skid chains on the tested tyre would contribute to changes in the traction properties under evaluation.

MATERIAL AND METHODS

The study was conducted on an experimental plot located between the embankments of the river Odra in Wrocław. An experimental object was established in an area with natural grass cover by sowing a grass mix (Super Sport), with the following species composition: 60% red fescue, 30% permanent darnel, 10% meadow-grass in 2006. The substrate for the created turf was acid brown soil, gleyed in places, developed from light silty loam over common silt. The particle size distribution was fairly uniform within the whole profile. Horizons A, A-Bbr and Bbr contained the light silty loam, while in the deeper horizons, Bbr-Cgg and Cgg, the common silt. The solid phase density of the soil was 2.48 Mg m^{-3}. Humus content in the layer of 0-0.18 m was 2.2%.

Five different levels of turf compactness (0-4 PU), simulating varied use of the turf, were obtained by compacting with a specially designed roller with 0.4 m in diameter and width of 1 m. The design of the roller permitted the reproduction of turf compaction and of the effect of tangent forces occurring in normal use of turf. The desired effect was obtained through the application, on the surface of the roller, of studs, identical to those on the soles of football shoes. The roller was loaded so that the unit pressure on the ground was equivalent to that exerted by a football player with average mass of 70 kg and shoe size 42.

To achieve total destruction of the aboveground parts of the plants, 140 passes of a tractor with the roller were made, thus obtaining the fourth, highest level of turf compactness (4 PU). Intact turf was such that was not compacted at all (0 PU). Intermediate levels of compactness were obtained by making 35 passes of the tractor with the roller (1 PU), 70 passes (2 PU) and 105 passes (3 PU), respectively.

Determinations of the selected physical properties of the soil were made by standard methods. Soil moisture was determined as the ratio of water contained in the soil to the mass of solid phase of the soil after drying at 105°C (ISO 11461/2). Density of the soil was determined by means of a pycnometer. Specific density of the soil solid phase was tested by ISO 11272. Total porosity was determined on the basis of the results of determinations of soil density and of the density of the solid phase. Soil samples were taken from the layers of 0-0.05 and 0.05-0.1 m in three replications.

Measurements of soil compaction, or of penetration resistance, were made with a cone penetrometer with electronic recording of the force and depth of penetration. The cone applied for the measurements had an apex angle of 60° and base surface area of 0.0001 m^2. The instrument had a drive system that permitted the setting of a constant speed of penetration, maintained at the level of 0.03 m s^{-1}. The measurements were made in five replications, in the layer of 0-0.1 m.

Measurements of the traction forces were made using a universal device for traction testing of tyres under field conditions, designed at the Institute of Agricultural Engineering, University of Environmental and Life Sciences in Wrocław. A schematic of the testing device is presented in Fig. 1.

Using this test device, it is possible to conduct similtaneous measurement and recording of the traction force generated by the tested drive tyre, the torque applied to the tested wheel, and the theoretical and actual distance covered by the tested wheel. The measurements were realized for two levels of vertical load applied on the wheel (3 300 and 4 300 N). The measurements of the traction force were made in five replications for each level of spoil compaction, each tyre, and the different levels of wheel loading.

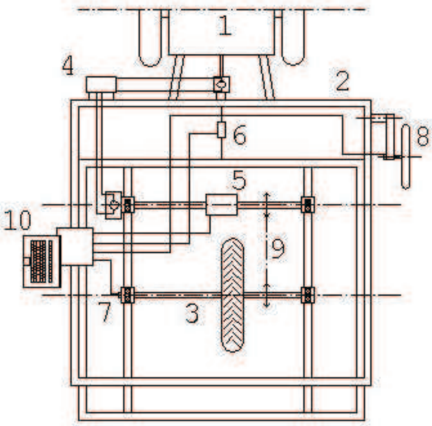


Fig. 1. Device for traction tests: 1 – tractor, 2 – frame, 3 – shaft with tested wheel, 4 – hydraulic system supplied from the external hydraulic system of the tractor, 5 – torque sensor, 6 – force sensor, 7 – sensor measuring the angle of wheel rotation, 8 – fifth wheel with sensor measuring the actual distance covered, 9 – chain transmission, 10 – electronic recording system coupled with a computer.

The available software and instrumentation of the testing device permit immediate graphic presentation of the results of tests, which is an important factor when experiments are conducted under field conditions. Wheel slip (δ) was calculated from relation (1), where (s_{rz}) is the actual distance covered by the wheel, and (s_t) is the theoretical distance by the wheel tested, while the traction efficiency was calculated using relation (2) (Jakliński, 2006):

$$\delta = 1 - \frac{s_{rz}}{s_t} (\%) , \quad (1)$$

$$\eta = \frac{P_T}{M} r_d (1 - \delta) (\%) . \quad (2)$$

Values of the dynamic radius (r_d) of the tested wheels were determined individually for each load level, on the basis of measurement of the actual distance covered for five full revolutions of the wheel. The index of grip (μ), according to the standard PN-ISO 8855 referred to as the index of longitudinal force, defining the ratio of the longitudinal force on the wheel (P_T) to the vertical load on the wheel (G), was calculated from the formula (3):

$$\mu = \frac{P_T}{G} . \quad (3)$$

All the sensors recorded the measured values with an accuracy of 0.001 (N, Nm, angle of wheel rotation). The measurements were made in five replications for each value of wheel loading. Determinations of the traction properties were made for an agricultural driven tyre, size 9.5-24, at tyre pressure recommended by the tyre manufacturer *ie* 0.21 MPa. The experiment included also determinations made for the same size of tyre, 9.5-24, equipped with anti-skid chains with spurs.

RESULTS AND DISCUSSION

The mean values of soil compaction within the layer of 0-0.1 m determined at the particular levels of turf compactness, are shown in Fig. 2. Analyzing the diagram one can observe that the compactness of the turf oscillated around the level of 0.8 MPa. At soil compaction level equivalent to the destruction of the aboveground parts of the turf vegetation (4 PU) the compactness of the turf was higher by 107% and amounted to 1.7 MPa. The greatest differences in the compactness of the turf were recorded between the soil compaction levels 2 and 3-35%. The results of measurements of compactness suggested that soil compaction may also lead to changes in the physical properties of the soil. Figure 3 presents the results of measurements of total porosity of turfy soil for various levels of compaction, determined at 2 depths: 0-0.05 and 0.05-0.1 m. On the undisturbed turf (0 PU) the total porosity in the surface horizon of the soil was 44%, and in the layer of 0.05-0.1 m it was 41%. As a result of soil compaction with the roller (1 PU, 2 PU and 3 PU), the values of porosity in both studied soil layers equalized and oscillated around the level of 40-41%. Only at soil compaction level corresponding to the destruction of the plant cover did total porosity differentiation reappear in the soil horizons studied. The values of total porosity determined in that treatment were 40% in the layer of 0-0.05 m and 38% in the layer of 0.05-0.1 m.

To determine the significance of differences in the values of total porosity determined at the various levels of compaction of the turfy soil, the significance t test was performed for independent groups. The test revealed a lack of significant differences among the soil porosity values at the studied levels of compaction, at significance level of α=0.05. Statistically significant differences were noted only between compaction levels 0 PU and 4 PU in the profile of 0-0.05 m. The very low differentiation in total porosity among the various levels of soil compaction was due to varied soil moisture, falling within the range of 15.1-17.8%. The obtained results concerning changes in the mechanical and physical properties of turfy soil under the effect of

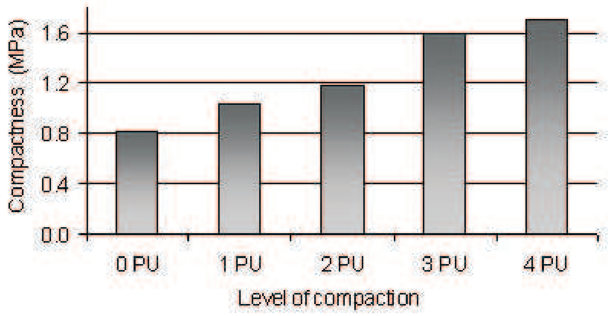


Fig. 2. Turf compactness in the layer of 0-0.1 m for various levels of soil compaction.

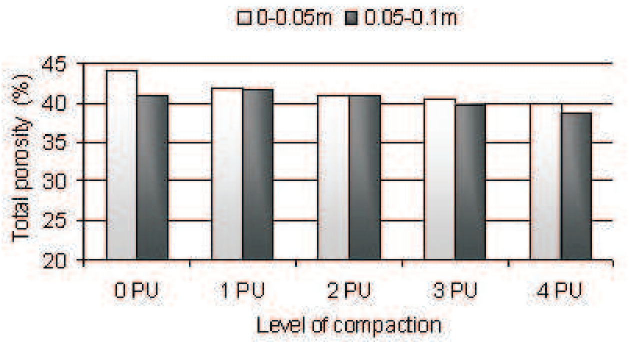


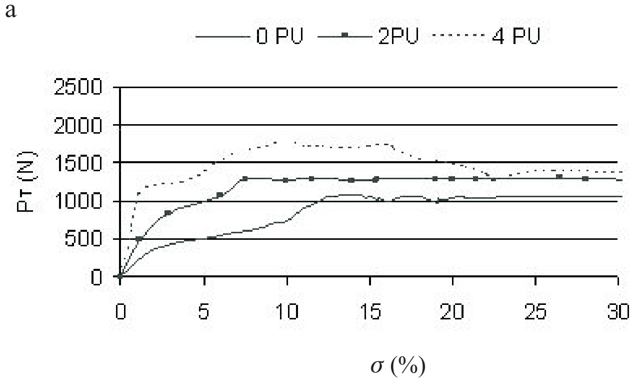
Fig. 3. Total porosity of soil determined for various levels of turfy soil compaction.

compaction permit the assumption that they may cause a deterioration in the conditions for plant growth and development, whereas they should prove favourable from the viewpoint of the traction properties of the tested tyre.

The traction forces of the tyre size 9.5-24 and the 9.5-24 tyre with the chain as a function of wheel skid at the selected levels of compaction of turfy soil are shown in Fig. 4. Analyzing the diagrams one can note that the more compacted the soil the higher the traction force values generated by the wheel systems tested. A characteristic feature is that with increasing level of soil compaction the maximum values of traction force are achieved at lower values of wheel skid. In the case of the 9.5-24 tyre, differentiation in the values of the traction force obtained at various levels of soil compaction is observed at skid values within the range of 0-20%. At higher skid values, the traction forces – irrespective of the level of compaction – oscillated around a fairly constant level of 1 200-1 300 N. Traction forces achieved by the 9.5-24 tyre with the anti-skid chains display a variation related with the level of soil compaction, throughout the skid range under analysis. One can observe that wheel skid above 22% results in a decrease in the value of the parameter analyzed at all levels of compaction of the turfy soil. The most dynamic increase in the traction force was noted at wheel skid within the range of 0-15%. Similar results were obtained by Shmulevich *et al.* (1996) who measured the traction force of an agricultural tyre, size 18.4-34, generated on loamy sand with moisture of 11%.

The maximum values of traction forces generated by the 9.5-24 tyre and by the 9.5-24 tyre with anti-skid chains for two different values of perpendicular loading of the wheel are shown in Fig. 5. Increase in the degree of compaction of the soil resulted in the achievement of higher and higher values of traction force by the tyres tested. For example, for the tyre with no chains the traction force increase was 17% for compaction level 2 PU, 50% for level 3 PU, and as much as 64% for compaction level 4 PU, compared to the values obtained on the non-compacted soil, on which the value of traction force generated at a load of 3 300 N was 1 090 N. The situation is similar in the case of the tyre with chains, where also large increases in traction force values were observed with increase in the level of soil compaction. The value of traction force measured on the soil with the highest level of compaction was 2 062 N and it was 75% higher than the value measured on the non-compacted soil. Analyzing the diagrams below one can observe that the effect of loading on the traction force values obtained is not uniform for the two wheel systems under analysis. Load application on the tyre with no chain causes non-uniform increments of traction force on plots with various levels of compaction, amounting to several percent. The highest increase in traction force was obtained on the plot with the highest level of compaction, by 23% in comparison with the value measured at wheel load of 3 300 N. Loading of a wheel with chain is an effective way of improving its traction properties under the ground conditions analyzed, as it caused an increase in the generated traction forces by as much as 15-20%.

a



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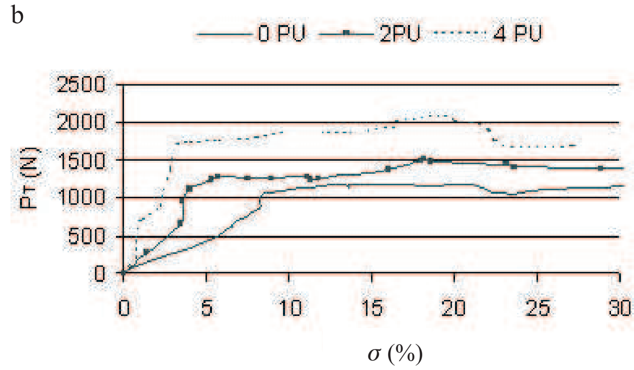


Fig. 4. Variation of traction force of: a – 9.5-24 tyre, b – 9.5-24 tyre with chains as a function of wheel skid, for selected levels of soil compaction, at wheel load of 3 300 N.

The determine the advantages resulting from the application of the wheel system modification (installation of anti-skid chains), a comparison was made of the traction forces measured for the tyre without and with the chain, at all the levels of soil compaction analyzed, at a wheel load of 4 300 N (Fig. 6). The installation of the chain on the wheel tested caused an increase in the value of the traction parameter under analysis on each of the studied plots. The highest effectiveness of the modification applied was noted for the compaction levels 2 and 3 – the traction force increased by as much as 30%. At those levels of compaction, the aboveground parts of the plants were already partially destroyed, but the soil was still not too hard. Under such conditions the spurs of the chains penetrated the soil to the greatest extent.

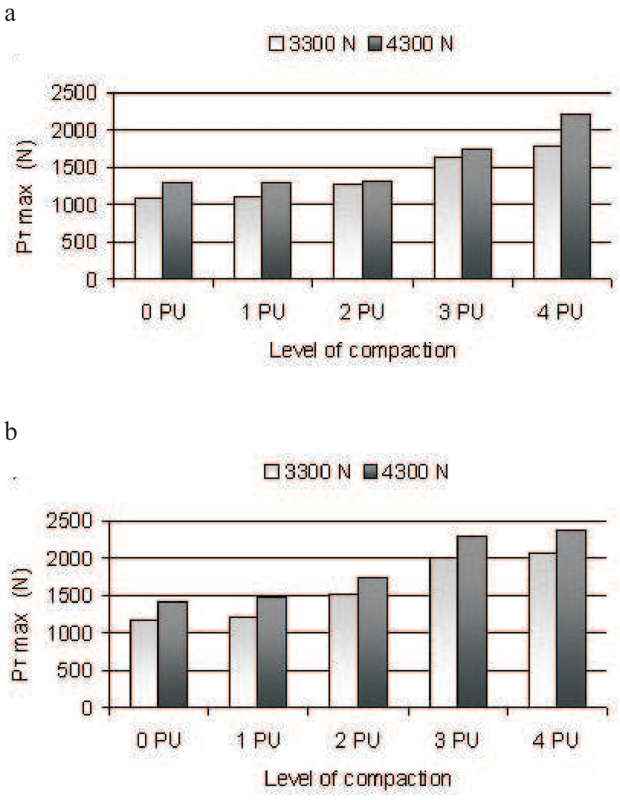


Fig. 5. Maximum values of traction force of the: a – 9.5-24 tyre, b – 9.5-24 tyre with chains measured on turf with various levels of compaction, for two values of vertical load.

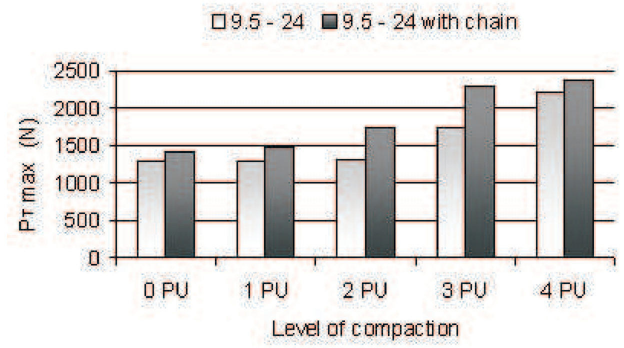


Fig. 6. Maximum values of traction force of the 9.5-24 tyre and the 9.5-24 tyre with chains measured on turf with various levels of compaction, at vertical load of 4 300 N applied to the wheel.

To determine the effect of the level of compaction, wheel loading and use of anti-skid chains on the values *f* traction forces, the results obtained were subjected to multi-factorial analysis of variance. The analysis demonstrated that the values of the traction force were significantly affected by all of the factors studied, at significance level of α=0.05.

Estimation of the traction properties of the driven tyre on turfy soil was performed also on the basis of the traction efficiency that, in its essence, indicates what percentage of the energy supplied is irretrievably lost. Figure 7 presents examples of the results of calculations of the traction efficiency of the tyres on turf with the various levels of compaction, at varied slip values of the tested wheel. Analysis of the presented diagrams permits the conclusion that irrespective of the degree of compaction of the turfy soil the highest increments of traction efficiency are obtained at the lowest wheel slip values, below 5%. In the case of the tyre without chains (Fig. 7a), the extreme values of the parameter under analysis were obtained at wheel slip values within the range of 15-20%, while further increase in wheel slip was conducive to increased energy losses and, consequently, reduced traction efficiency. Increase in the degree of soil compaction caused an increase in traction efficiency, from 64% on soil with 0 PU to 77% on 4 PU. Application of anti-skid chains

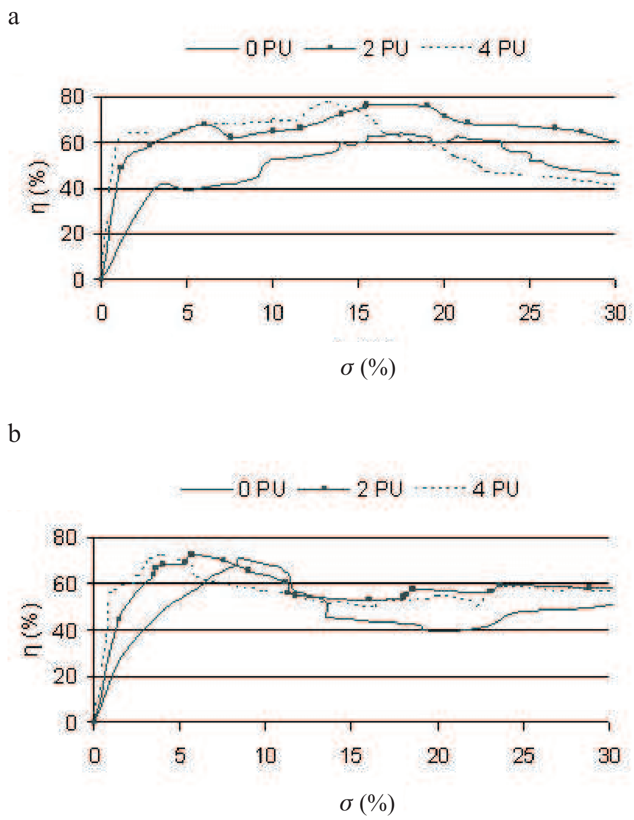


Fig. 7. Variation of traction efficiency calculated for the: a – 9.5-24 tyre, b – 9.5-24 tyre with chains as a function of wheel skid, for selected levels of soil compaction, at wheel load of 3 300 N.

on the tested tyre not always led to a significant increase in the value of the parameter under analysis. Noteworthy is the fact that the tyre with the chain achieved the highest values of traction efficiency at skid values below 15%, and on turf with the highest level of compaction (4 PU) – at wheel skid of *ca*. 4%. The passage of a vehicle with chains on the tyres is accompanied by lesser horizontal deformation of the ground. Upadhyaya *et al*. (1997), in a study on the traction properties of a 18.4-38 tyre on a loamy soil with moisture of 11.5%, obtained the maximum traction efficiency of 75% at wheel skid values of 8-10%. Further increase in wheel skid resulted in significantly reduced traction efficiency on the soil studied.

Comparing the maximum values of traction efficiency determined for the tyres without chains and with chains (Fig. 8) one can observe that the application of that modification results in an increase in traction efficiency, especially on turfy soil with lower levels of compaction. On the non-compacted soil that increase was as much as 32%, and of turfs with compaction levels 1 and 2-16%. At soil compaction level corresponding to the destruction of vegetation (4 PU), the traction efficiency values calculated for the two wheel systems under analysis were identical at 76%.

Figure 9 presents the maximum values of traction efficiency calculated for the tested tyre for all the levels of soil compaction and for both wheel loads applied. As follows from the diagram, loading of the wheel tested had a negative effect on traction efficiency, irrespective of the level of soil compaction. At the higher wheel load level, on the non-compacted soil (0 PU) and on the soil with the lowest level of compaction (1 PU) a 5-8% drop of traction efficiency was observed compared to the values obtained at wheel load of 3 300 N. Increased wheel load on soil with compaction levels 2 PU and 3 PU caused a 15% drop in traction efficiency. In the case of the highest level of soil compaction, equivalent to the destruction of vegetation (4 PU), no significant differences were observed between the traction efficiency values calculated for the two levels of wheel loading. The decrease of traction efficiency caused by the higher wheel load was due to increased vertical deformation, especially observable at soil compaction levels 2 and 3, as the vegetation cover at those levels of compaction was already largely destroyed and had lost its shock absorption and strength properties, while the soil itself was not yet compacted enough to prevent the tyre tread from penetrating into it.

The multi-factor analysis of variance revealed a significant effect (at significance level of α=0.05) of the level of soil compaction, change in the load level of the tested wheel, and of the application of anti-skid chains on the traction efficiency values obtained.

To determine the significance of differences in traction efficiency of the tyre with and without chains for the particular levels of soil compaction and for the two adopted levels of vertical load, significance tests t for independent groups were performed. The tests revealed statistically significant differences, at significance level of α=0.05, for the soil compaction levels 0 PU, 1 PU and 2 PU. For the highest level of soil compaction (4 PU) no statistically significant differences in traction efficiency values were noted relative to the wheel load value or to the application of anti-skid chains on the wheel tested.

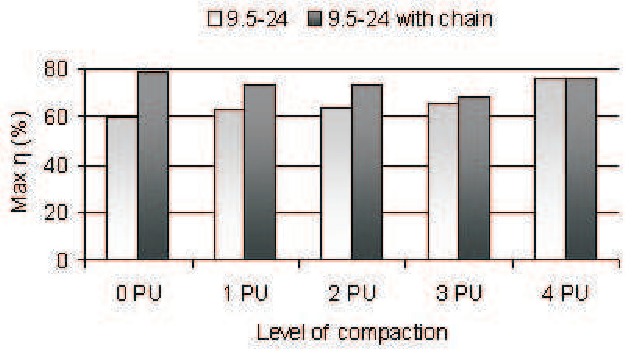


Fig. 8. Maximum values of traction efficiency calculated for the 9.5-24 tyre without anti-skid chains and with the chains for the analyzed levels of soil compaction, at wheel load of 4 300 N.

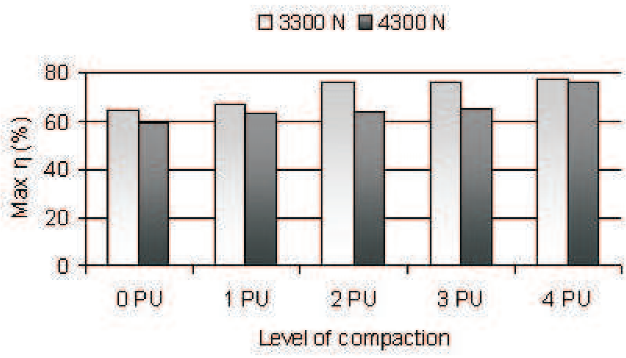
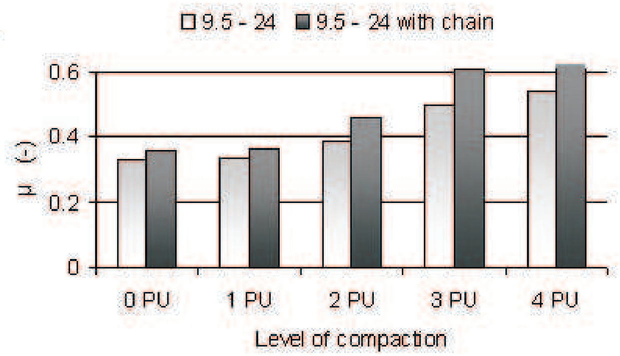


Fig. 9. Maximum values of traction efficiency calculated for the 9.5-24 tyre for the analyzed levels of soil compaction, at two levels of wheel load – 3 300 N and 4 300 N.

Wheel grip of a vehicle depends on the surface over which it is moving, type of wheels, tyre tread, and on the load on each wheel. Next to the engine power, it is the second factor limiting the traction force that can be generated by a vehicle (Kubiak and Matusiak, 1972). To perform a comprehensive analysis of the traction properties of tyres on turfy soil with various levels of compaction, calculation was made of the values of the index of grip (longitudinal force) for the maximum traction force values achieved by the 9.5-24 tyre and the 9.5-24 tyre with anti-skid chain at two different levels of wheel load, of 3 300 N and 4 300 N (Fig. 10). The use of anti-skid chains on the tested tyre caused an increase in the index of grip, especially on soils with high a



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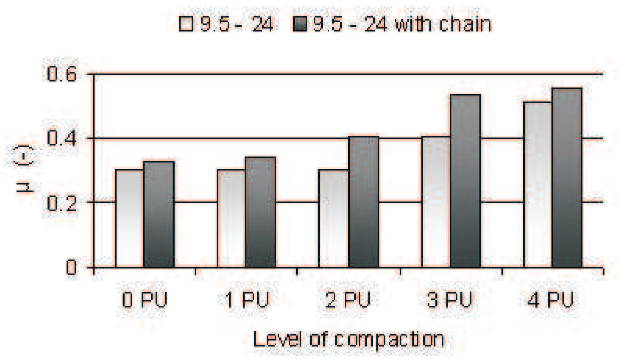

Fig. 10. Values of the index of grip calculated for the maximum values of traction force at wheel loads of: a – 3300 N, b – 4300 N.

levels of compaction (from 2 PU to 4 PU), contributing to an increase in the values of the index calculated, even by more than 30%. As follows from the presented diagrams, however, increased wheel loading on the soils analyzed does not lead to improved wheel grip, as the increase in traction force is lower than the extra loading applied. As a rule, increase in the level of soil compaction resulted in an increase in the values of the index of grip, both for the tyre without chains and for the tyre without chains. It was observed that, at the wheel load of 3 300 N, for the tyre without chains higher values of the parameter under analysis were obtained on non-compacted turfy soil than on plots with soil compaction levels 1 PU and 2 PU.

CONCLUSIONS

1. The compactness of the soil with the highest level of compaction (4 PU) was over 100% greater than that of the non-compacted turf. No statistically significant differences in the total porosity of soil were observed between the particular levels of soil compaction. Only between the soil with no compaction applied (0 PU) and the soil with the highest level of compaction (4 PU) a 10% drop of porosity was noted (from 44 to 40%).

2. Increase in soil compaction caused that the tyres tested achieved higher traction forces at decreasing values of wheel skid. The values of traction forces generated by the tested wheels on the soil with the highest level of compaction (4 PU) were higher by as much as 75% compared with the values obtained on the non-compacted soil. The use of anti-skid chains on the tested tyre caused an increase of traction force value by as much as 30%. Increased load applied on the wheel systems tested resulted in an increase in the traction force values obtained, even by 20%.

3. The wheel systems under analysis achieved their maximum values of traction efficiency at wheel skid lower than 20%. Increase in the level of soil compaction caused an increase in the traction efficiency of the 9.5-24 tyre from 64% on the soil with compaction level 0 PU to 77% on the most compacted soil (4 PU). The application of anti-skid chains resulted in an increase in traction efficiency, compared to the tyre without the chain, especially on turfy soils with lower levels of compaction: 0 PU – 32%, 1 and 2 PU – 16%. The application of increased load on the wheels caused a decrease in traction efficiency, the level of the decrease being related to the level of soil compaction and amounting to 1-15% compared to values obtained at wheel load of 3 300 N.

4. Increase in the level of compaction of the turfy soil caused an increase in the values of the index of grip. The application of anti-skid chains on the tested tyre contributed to an improvement of wheel grip, especially on soils with high levels of compaction (from 2 PU to 4 PU), causing an increase in the value of the index by as much as over 30%.

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