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Evaluation of the changes in Bekker's parameters and their use in determining the rolling resistance

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A b s t r a c t. In order to determine the relationships between the soil stiffness constants of cohesive modulus of deformation, friction modulus of deformation and soil constant value and the rolling resistance, a series of tests was conducted using two types of loam and clay loam soil textures at four moisture contents of 10, 20, 30 and 40% and five loading speeds of 1, 2, 3, 4 and 5 mm s^{-1}. The results showed that all of the independent factors had a significant effect on the soil stiffness constants, so with increases in moisture content and loading speed, the soil stiffness constants of cohesive modulus of deformation, friction modulus of deformation and soil constant value varied significantly. The highest cohesive modulus of deformation and friction modulus of deformation values were obtained at a moisture content of 10% and loading speed of 5 mm s^{-1} in a clay loam soil. All parameters were significant in calculating the rolling resistance using Bekkers' relationship. With increases in soil moisture content, the rolling resistance increased, while increasing the loading speed reduced the rolling resistance significantly. In general, the highest rolling resistance value of 16887.1 N was obtained at a moisture content value of 40% and a loading speed of 1 mm s^{-1} in loam soil.

K e y w o r d s : rolling resistance, soil constant, moisture, loading speed

1. INTRODUCTION

At present, with recent population increases and the food needs of various societies, efficiency increases in agriculture and the research related to it are of particular importance. Due to the limited agricultural land available, researchers have made many efforts to increase yield and reduce energy consumption. Mechanization and the application of appropriate management regimes in different stages of agricultural operations have been effective in this matter to some extent. The relationship between the utilization of agricultural machinery and the condition of agricultural land represents one of the most contemporary and significant studies in the field of agricultural science, it has led to optimization in the design of tillage tools and mobile implements that are in contact with the soil. On the other hand, soil is a natural environment for growing crops, therefore, soil has an important role to play in human life, so it is essential to have a knowledge of and examine both the physical and mechanical properties of the soil.

Soil is the natural environment for growing crops, so its properties should always be examined so that crops can be grown in optimal conditions. The effects of agricultural machinery on agricultural soil, which is mostly due its traffic, should be considered when studying soil properties and its structure. Agricultural operations such as ploughing, which are carried out by these machines have beneficial effects but there are sometimes negative effects on the soil structure because of their wheel impact. The positive effects of ploughing include the dislodging of weeds and their

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control and also the return of surface residue and vegetation to the soil and the improvement of soil grain formation. However, on the other hand, the soil aggregates may collapse under the pressure of tractor wheels or other heavy equipment which have negative effects on the soil structure.

The wheel is one of the most important components of the machine which establishes a connection between the machine and the ground. Most of the forces acting on the machine and the soil are transmitted through the wheels, and this shows the importance of studying the forces acting between the wheels and the soil. One of these important forces is rolling resistance. The rolling resistance occurs as a result of soil and tire deformation in agricultural soils and in non-deformable soils it is the result of tire deformation (Zoz and Grisso, 2003). The wheel rolling resistance is one of the most important influential factors in energy consumption in field operations and its modelling in relation to other soil and machine parameters and has been taken into account by researchers for a considerable length of time. A knowledge of the behaviour of this component can be effective in controlling and adjusting the parameters of the tractor interactions with the soil and managing energy consumption, so the ability to compute the rolling resistance of the wheels mathematically can improve energy efficiency and eliminate the need for expensive field tests and reduce the time required for testing. Zeng *et al*. (2023) stated that the dynamic mechanical response of the tire-soil interaction cannot be predicted due to the time-dependent effects of the elastic-plastic behaviour of the soil terrain. However, numerical simulations that combine the applications of mathematics, numerical analysis, computational physics and even computer graphics have proved to be effective and efficient at reproducing physical phenomena and performing parametric studies, as a result they have attracted widespread attention to the targeted problem.

Soil deformation is one of the most important issues in soil mechanics and agricultural equipment design (Białczyk *et al*., 2015). Shafee and Khoshghalb (2022) developed a new numerical scheme for modelling large deformation problems in geomechanics. Their approach was based on the employment of node-based smoothed-point interpolation methods (NSPIMs) within the framework of the particle finite-element method (PFEM). The settlement of a soil layer may take place for the following reasons:

1. Due to static loads, these include the load imposed on the soil by the weight of a heavy vehicle such as a tractor or an implement.

2. As a result of dynamic loads, these include impact loads and the loads resulting from the movement of the wheels of off-road vehicles.

3. Due to changes in the amount of soil moisture.

Sufficient knowledge of the characteristics of soil in agriculture and construction is necessary in order to determine the reaction of the soil to frequent machine traffic, the rolling resistance and also the reaction of the soil to the construction of foundations. Becker's equation is one of the useful equations in determining these parameters (Bekker, 1956). In this equation, k_c, k_φ and n are soil pressure-displacement parameters. The soil pressure-displacement parameters are the soil stiffness constants, which can be used to calculate the tractor wheel rolling resistance. The soil resistance to the application of pressure is a mechanical property of the soil, which consists of the sinking or depression of the soil due to loading, such as the compression of the soil under the weight of a tractor. The conventional criterion for evaluating soil resistance is subsidence depth. For this purpose, special mathematical relationships have been formulated which determine the relationship between the applied load and the resulting subsidence. Bekker (1956) produced a model to analyse the mechanical properties of soil and developed a soil mechanical property measurement device called a bevameter. This device was designed to measure soil subsidence and shear forces in order to predict rolling resistance and draft forces in the driving wheels of agricultural vehicles such as tractors. The bevameter made by Becker is used as a reference for standard tests which in turn are used to model pressure-subsidence in off-road driving wheels.

In 1981, Stafford and de Carvalho Mattos investigated the degree of compaction created in the soil by pneumatic tires in a simulated laboratory environment (soil bin), by measuring the soil bulk density in different parts of the soil. They also took the soil moisture content into consideration and observed that with the reduction of the forward speed at relatively high moisture content levels, soil subsidence increased and compaction also increased.

In 2003, Zoz and Grisso investigated the effect of the forward speed of the tractor on the wheel rolling resistance and concluded that the effect of the forward speed on wheel rolling resistance was low at normal speeds in the field. In 2006, Yu invented a mobile device that, in addition to performing the loading- subsidence test and the soil shear test, also had the ability to install a cone penetrometer and measure the cone index value. The device has two horizontal and vertical jacks to apply a certain load on the loading plate and a horizontal hydraulic jack was used to ensure the horizontal movement of the cutting plate. The forward speed of the wheel affected the rolling resistance.

Kurjenluomar *et al*. (2009), investigated the rolling resistance and rutting produced by the tires of a towed implement on a clay soil with three soil strength levels. Wheel rolling resistance was evaluated using the coefficient of rolling resistance (CRR), rut depth (RD) and driving speed. In soft conditions (CI $\leqslant$0.48 MPa), the radial tires produced 15% shallower ruts than the bias ply tires. When the tire moved on a hard surface, the rolling resistance was due to tire flexibility, but under agricultural land, the rolling resistance was increased because of the vertical compaction of the soil and also the vertical and horizontal movement of the soil. Part of the resistance force was due to soil movement, which increased soil settlement.

Van *et al*. (2008) built a device to test soil pressure-subsidence in a laboratory. The device included a soil tank with dimensions of 400×700×390 mm, where the plates were compressed into the soil by means of mechanical rods moved by an electric motor. The soil subsidence tests were conducted by means of electrically driven loading equipment at a quasi-static speed of 13.3 mm s^{-1} to a depth of 120 mm. The vertical plate subsidence and the applied load on the plate were measured. The subsidence parameters of k_c, k_φ and n in the Bekker pressure – subsidence equation were extracted using experimental data. It was found that the values of k_c, k_φ and n were significantly different between rectangular plates with a low aspect ratio (length/width ratio) and circular plates, but the difference was negligible for high aspect ratio plates and circular plates having radii equal to the width of rectangular plates. Rashidi *et al*. (2008) compared two experimental and theoretical methods for determining soil mechanical parameters using Bekker's equation. In order to determine soil hardness constants and the reaction of rectangular plates in the soil, they conducted compression tests using three rectangular plates with different length to width ratios in soil with a relatively low density. They built a device which included a small tank and carefully chosen weights were used to create vertical tension on the plates. After placing each weight on the plate, the subsidence value was recorded using a ruler placed on the device. In another method circular plates were used to prove Bekker's equation. The regression results showed that the determination of the relevant parameters through the application of these two methods using different plates were similar with correlation values of 95 and 99%, respectively.

It was found that there is a need for more research information concerning the effect of moisture content, loading speed and the soil type effect on the soil modules used in Bekker's formula. The aim of the research was to study the effect of soil moisture, soil type and loading speed as a representative of tire travel speed on the soil modules and compute the rolling resistance exerted by those modules.

2. MATERIALS AND METHODS

Tests were conducted in a soil tank since the soil tank is a common device for conducting different types of research on soils. The size of most of the parts depends on the size of the soil tank. Its size is important for minimizing the effects of the walls on the experimental data, the tank wall should also be sufficiently resistant. The tank is made from a 5 mm thick steel sheet with a depth, width and length of 580×650×770 cm (Fig. 1). A 1.5 kW electromotor with a speed of 1 400 rpm which included a gearbox with a reduction ratio of 1 to 17.5 was used to create a vertical motion of the pressure plate. The speed of the electromotor must be variable in order to alter the speed of plate penetration within a certain range. For this purpose, an RS-485 three-phase inverter made by Hyundai Korea was used. The

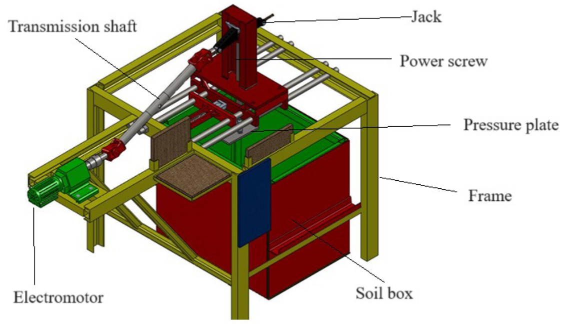

Fig. 1. System overview of the apparatus used for the soil subsidence test.

Fig. 2. Pressure plate and load cell installed on a rod.

inverter changes the speed of the electromotor based on the frequency change. For calibration purposes, the inverter was used under different frequencies and different speeds were applied and based on these variations the velocity-frequency diagram was extracted. Then for each velocity the required frequency was determined.

An S-shaped Loadcell with a capacity of 5 kN was used to measure the vertical load during the subsidence tests. A 10 kN mechanical jack was used to transform and create vertical movement and this was connected to a pressure plate by a power screw which caused the vertical movement of the pressure plate (Fig. 2). The rotary motion of the electromotor is transferred by the power screw and drive shaft to the jack and thereby converted into linear motion (Fig. 1).

A linear potentiometer with a 0.001 mm accuracy was used to measure soil subsidence. The potentiometer was mounted between the pressure plate arm and the main plate on the rails (Fig. 3). As the pressure plate went down the potentiometer rod compressed and measured the displacement or the soil subsidence. Two pressure plates with dimensions of 20×20 cm and 17.5×20 cm with a thickness of 2 mm were used for soil subsidence.

A multi-purpose data logger (capable of recording a variety of output data) classified as a DT800 model was developed by the Australian Data Taker company and used to collect and record soil displacement and load cell transducer data. This data logger has 12 analogue and 16 digital channels and is powered by a DC current of 12-24 volts.

Fig. 3. Potentiometer mounted between the pressure plate arm and main plate on the rails.

Two soil textures were used to conduct the test. The first soil texture was classified as clay loam. This was determined by a hydrometer test based on the percentages of sand (20%), silt (30%) and clay (50%). The second soil type was loam with sand, silt and clay percentages of 46, 30 and 24%, respectively. The soil bulk density was 1 200 kg m^{-3}, and the soil box was filled up to a height of 60 cm, hence its volume was 0.3 m^3 and the required soil mass for creating the aforementioned bulk density was 360 kg which was determined by applying the soil density formula. For the purposes of creating homogenous bulk density, the height of the soil box was divided into 12 sections of 5 cm and also the required soil mass was divided by 12 and each portion of the soil (30 kg) was filled to a predetermined volume. The tests were conducted in two types of loam and clay loam soil textures at four moisture content levels of 10, 20, 30 and 40% and five loading speeds of 1, 2, 3, 4 and 5 mm s^{-1}.

An experiment was conducted to determine the moisture content of the soil samples under various conditions. Hence, after weighing the wet soil, the specimen was placed in an oven for 24 h at 105°C. The dry specimen weight was determined and then the moisture content based on the dry base was also determined (ASTM D 7263-21, 2021). The soil moisture content should be increased to the desired values determined for the tests. On the basis of Eq. (1) the required amount of water was calculated and sprayed on the soil during the mix operation. After the test was conducted, the tested soil was unloaded from the soil box and then prepared for another test with a predetermined moisture value:

$$\Delta W = \frac{G(W_f - W_i)}{(100 - W_f)} \quad . \tag{1}$$

In which: W_f – final desired moisture content (g); W_i – initial moisture content of the mixture (g); G – weight of soil-organic matter mixture (g); ΔW – amount of required water that must be added to the mixture (g).

The tests were conducted in a factorial format as a completely randomized design and analysed using Minitab 21 software.

One of the methods used to determine the subsidence parameters was defined by Bekker (1956) using Eq. (2):

$$p = \left(\frac{k_c}{b} + k_\varphi\right) z^n \ , \tag{2}$$

where: p – pressure on the pressure plate (kPa); z – subsidence value (m); b – smaller dimension of the rectangle plate (m); k_c – cohesive modulus of deformation (kPa) (m^{n-1})$^{-1}$; k_φ – friction modulus of deformation (kPa) (m^n)$^{-1}$; n – soil constant value.

The basis of the Bekker model are the soil deformation equations, by generalizing and assigning this model to wheel and soil conditions, relationships are obtained which have the potential to predict wheel rolling resistance (Fakhri *et al*., 2012). In the Bekker test, two rectangle shaped plates of equal length but with different widths of b_1 and b_2 were compressed into the soil, while the required pressure and soil subsidence were measured simultaneously in order to compute Bekkers' equation parameters (Massah and Noorolahi, 2010).

For the purposes of obtaining an optimal level of accuracy, a pressure-displacement graph was drawn based on measured data (Fig. 4).

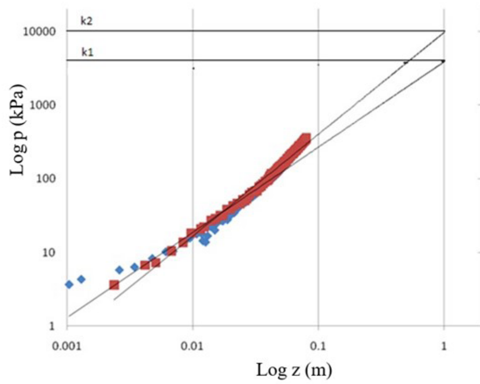

Fig. 4. Potentiometer mounted between the pressure plate arm and main plate on the rails.

According to the formula $p = kz^n$, z is the soil subsidence and p is the pressure. By using the following equations, when z =1 the value of p is equal to k. Then the n value can be calculated:

$$\begin{gathered} p = kz^n \\ \log(p) = \log(k) + n\log(z) \, . \end{gathered} \tag{3}$$

While conducting a test with two plates which width were b_1 and b_2 the different values of k_1 and k_2 were computed. Then k_φ and k_c were calculated using Eqs (4) and (5) below. k_c is a subsidence modulus influenced by soil cohesion, k_φ is a subsidence modulus which is affected by the soil friction angle. Bekker separated the subsidence modulus of the Bernstein model into two parts, one represents the effect of soil cohesion, the other represents the effect of the angle of internal shearing resistance. Also, the geometry of the contact patch was taken into account by the Bekker model (He *et al*., 2019):

$$k_c = \frac{b_1 b_2 (k_1 - k_2)}{b_2 - b_1} \quad , \tag{4}$$

$$k_\varphi = \frac{b_2 k_2 - b_1 k_1}{b_2 - b_1} \quad . \tag{5}$$

In the case where a pneumatic wheel moves on a soft surface like soil, the energy required to change the soil shape is considered to be an important factor in generating wheel rolling resistance (Becker, 1960). In other cases where the wheel contact length and width are equal to l and b the energy required to move the wheel in these circumstances is equal to the energy required to compress a plate with the same dimensions of l and b in the soil. The rolling resistance can be computed using Eq. (6):

$$R = \frac{b}{(n+1)\left(\frac{k_c}{b} + k_\varphi\right)} \quad . \tag{6}$$

3. RESULTS AND DISCUSSION

The analysis of variance results of the effect of soil parameters on n, k_c and k_φ value are presented in Table 1. A data analysis was conducted in the form of a factorial format as a completely randomized design using Minitab 21 software. The results indicated that all of the main effects and the two-way interaction effects of the experimental factors were significant at a probability level of 1%, except for the mutual effect of soil texture and the loading speed on k_φ was not significant. Also, the three-way interaction effects of soil texture×loading speed×moisture did not have a significant effect on the k_φ value at 1%.

Figure 5 shows that the soil constants at different loading velocities decrease significantly with increasing soil moisture. Hajiahmad *et al*. (2018) found that at a constant soil bulk density the n value decreased with increasing soil moisture. Also, Chancellor (1994) reported a rapid decrease in the n value with moisture increase.

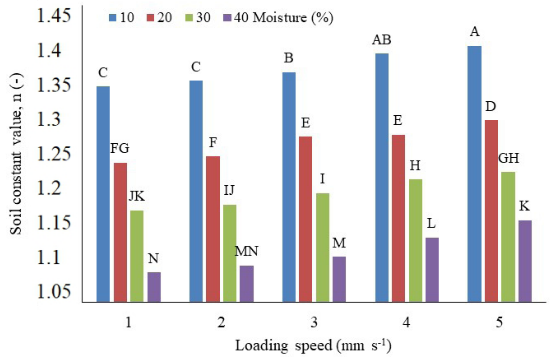

Fig. 5. Effect of the loading speed and soil moisture content on soil constants.

Table 2 shows the effects of the coefficient values of the soil type, loading speed and soil moisture content on the n values at a significance level of 0.00001. The soil type used was the factor which had the most pronounced effect on the n value. This parameter had a value of 1.3 for clay loam soil, while its value was 1 in loam soil. There was a direct relationship between the loading speed increase and the n value increase. Table 2 shows that soil type, loading speed and soil moisture content all had a significant effect on n value change, respectively.

The two-way effect of the loading rate and the soil texture on the k_c value is presented in Fig. 6, it may be observed that with increasing loading velocity in two different soil texture types, the k_c value increased significantly. At all speeds the k_c value for the clay loam soil was higher than that of the loam soil. The highest k_c value of 811.4 was observed at a loading velocity of 5 mm s^{-1} in clay loam soil and this decreased to 493.4 at a velocity of 1 mm s^{-1} in loam soil. It should be noted

Table 1. Analysis of variance the effective factors on rolling resistance

Factor	DOF	Factors effect on n value		k_φ value		k_c value		Rolling resistance	
		MSE	F	MSE	F	MSE	F	MSE	F
Soil texture	1	1.058	11004.8**	2399925	286.6**	526314	108407.3**	2326286409	3535.4**
Loadin speed	4	0.018	193.5**	104932	125.4**	222093	46363.5**	115714450	175.8**
Moisture	3	0.046	4859.5**	5693921	6806.1**	6588865	1357140**	617372374	938.2**
Soil texture×loading speed	4	0.0016	16.64**	539	0.64ns	1156	238.6**	47933408	72.8**
Soil texture×moisture	3	0.0076	79.27**	14822	169.52	99373	20468.2**	380105312	577.7**
Loading speed×moisture	12	0.0009	9.56**	3340	3.99	34137	7031.3**	237`2451	360.1**
Soil texture×loading speed×moisture	12	0.00084	8.76**	497	0.59ns	602	123.94**	14504022	22.1**
Error	120	0.000096		837		5		658000	
Total	159								

** and * – means significant, ns – means not significant, DOF – gegrees of freedom, MSE – mean square error, F – Fisher test value.

Table 2. Statistical characteristics of the stepwise regression model for *n* based on soil, speed, moisture

Term	Unstandardized coefficients B	Standard coefficients	T-value	Level of significance (Sig)
Constant	1.64757	0.00797	206.82	0.000001
Soil type	–0.16264	0.00361	–45.08	0.000001
Loading speed	0.01483	0.00128	11.63	0.000001
Soil moisture	–0.008326	0.000161	–51.60	0.000001

B – linear regression equation constants coefficient.

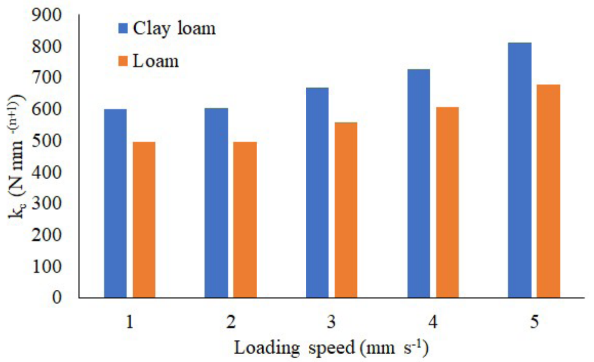

Fig. 6. Effect of the loading velocity on the k_c value for the two soil texture types.

that the high value of k_c in clay loam soil is due to its adhesion properties owing to its high clay content. Mason *et al*. (2020) carried out a series of tests in different soil textures in order to find methods of converting the cone index to bevameter parameters. They reported that the k_c value in heavy clay and loam clay was higher than that found in sandy loam soil.

The two-way interaction effect of soil moisture on soil texture showed that the k_c value decreased significantly with increasing moisture content in two soil texture types (Fig. 7). The slope of the increase was very high which shows the substantial influence of moisture on the increase in k_c values. At all moisture levels, the k_c value was higher for the clay loam soil and the highest value of 1 130.4 was found in the clay loam soil at a moisture content of 10%. It is noteworthy that the minimum value for k_c was 94.4 and this occurred at a level of 40% moisture and it was 84.4 for loam soil at a moisture content of 40%. Chancellor (1994) reported that both k_c and k_φ increased rapidly when the moisture content of the loam soil decreased. Similar results were found for the silty clay soil. A decreasing k_c value with moisture increase shows that moisture has a significant effect in decreasing the degree of soil cohesion. Based on the soil shear strength of unsaturated soil, the cohesion values are determined by both primary cohesion and curing cohesion. Primary cohesion is a result of the long-term pressure of geological formation, it is relatively stable. Curing cohesion results from matrix suction and negative pore pressure. When the soil moisture content increases, the matrix suction decreases, and the curing cohesion consistency of the soil decreases accordingly. Therefore, as the soil moisture level increases, the curing cohesion value decreases and, the total cohesion decreases accordingly (Zhao *et al*., 2018).

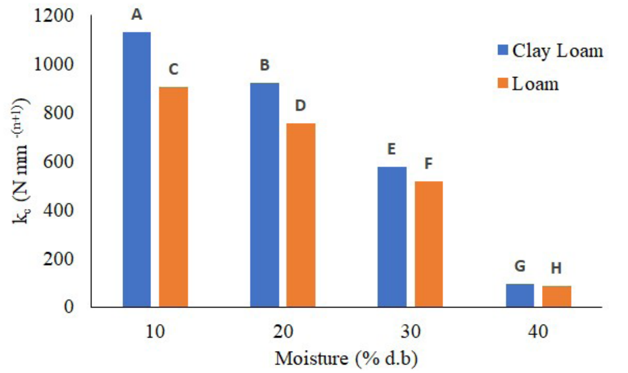

Fig. 7. Effect of the soil moisture content on the k_c value for different soil texture types.

The two-way interaction effects of the loading speed and moisture content showed that k_c changes were not significant at a 10% moisture content with the velocity increasing from 1 to 2 mm s^{-1} but in other cases with increasing loading speeds and a moisture content reduction the k_c value increase was significant (Fig. 8). The highest k_c value of 1 260.1 was obtained at a moisture content of 10% and a loading velocity 5 mm s^{-1} and the lowest k_c value of

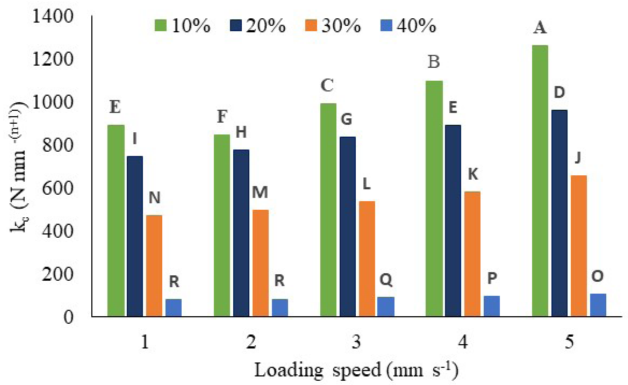

Fig. 8. Two-way interaction effect of the loading speed and moisture content on the k_c value.

Table 3. Statistical characteristics of the stepwise regression model for k_c based on soil type, loading speed, soil moisture

Term	Unstandardized coefficients B	Standard coefficients	T-value	Level of significance (Sig)
Constant	–128.9	35.0	–3.68	0.000001
Soil type	–114.7	15.9	–7.23	0.000001
Loading speed	51.36	5.61	9.16	0.000001
Soil moisture	30.801	0.709	43.43	0.000001

B – linear regression equation constants coefficient.

78.3 occurred at a moisture content of 40% and a loading velocity of 1 mm s^{-1}. At all speeds k_c reached its maximum value at a moisture content of 10%.

The coefficient of a stepwise regression model for the k_c prediction showed that a soil type with the standard coefficient of 15.9 was the most important factor for the determination of the k_c value (Table 3). This indicates the substantial effect of clay concentration on the k_c value. The k_c value was found to be 680.5 and 565.7 for clay loam and loam soil, respectively. Both the soil moisture content and loading speed increase were found to influence kc value increases.

3.1. Effect of various parameters on the k_φ value

A comparison of the mutual effects of the loading speed on soil texture in Fig. 9 shows that with increasing speed the k_φ value increased linearly. At all speeds, the k_φ value was higher in the loam soil. The lowest k_φ value of 1 418.2 occurred at a loading speed of 1 mm s^{-1} while the highest value of 1 808.3 occurred at a loading speed of 5 mm s^{-1}. Asadollahi *et al*. (2023) conducted subsidence tests at three loads of 2, 2.5 and 3 kN and three loading speeds of 0.5, 1, 1.5 km h^{-1} in the soil bin. They found that the k_φ value increased linearly with increases in loading speed at all vertical loads on the wheel. Fig. 10 shows the mutual effects of moisture and soil texture in the k_φ value. The k_φ value decreased linearly with moisture increase in the two types of soil texture examined. In general, the k_φ value was higher in the loam soil. The lowest value of k_φ was 1 083.3 with

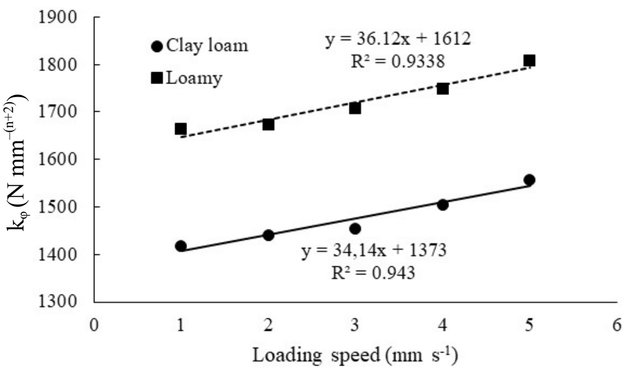

Fig. 9. Effect of the loading speed and soil texture on the value of k_φ.

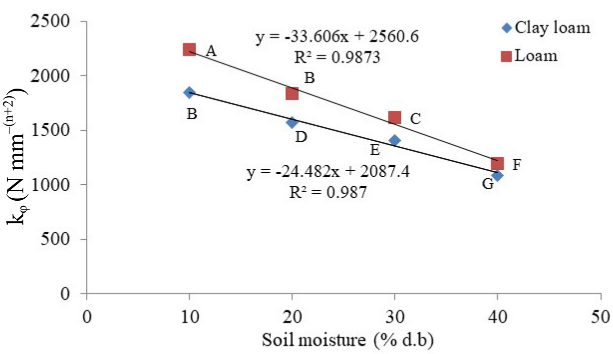

Fig. 10. Mutual effect of soil moisture content and texture on the value of k_φ.

a moisture content of 40% and the highest value of 2 237 was found in the soil with a 10% moisture content. When the soil moisture content increased to a certain extent, which amounted to more than the thickness of the water film around the soil particles, the bonding force of the water film on the soil particles decreased and the soil particles move easily, hence the friction force has decreased (Zhao *et al*., 2018). As the soil moisture content increases, the water will enforce a wedging effect on the cementing material, this results in smoother sliding dynamics between the soil particles, in this case the soil was vulnerable to an increased amount of damage. The soil internal friction angle was formed by the interaction of two parameters (Eq. (7)):

$$\varphi = \varphi_0 + \Delta\varphi \, , \tag{7}$$

where: φ is the friction angle of the soil, φ_0 is the basic friction angle, $\Delta\varphi$ is the difference between the actual internal friction angle and the basic internal friction angle. The basic friction angle is only dependent on the soil particle size and gradation; $\Delta\varphi$ depends on the change in soil moisture, and as the water content increases, together with the thickness of the water film between the soil particles, the aqueous electrolyte concentration decreases. With increasing distance between the colloidal particles, the soil particle joint strength decreased, the friction strength of the soil particles was reduced, and the soil internal friction angle decreased accordingly.

The mutual effects of the loading speed and moisture content shown in Fig. 11 demonstrate that a 10% moisture content with an increase in speed from 1 to 3 mm s^{-1} and a 40% moisture content with an increase in the loading speed from 2 to 3 mm s^{-1} and finally, with a 30% moisture content with the speed increasing from 1 to 2 mm s^{-1}, the changes in k_φ weren't significant, but in the other cases examined, with increasing loading speed and moisture content, the increase in k_φ value was significant. The highest value of k_φ obtained was 2 156 with a moisture content of 10% and a speed of 5 mm s^{-1} and the lowest k_φ value of 1 103 was obtained with a moisture content of 40% and a speed of 1 mm s^{-1}. It should be noted that according to the results for soil hardness constants, the results of this research are consistent with the results of Gharibkhani *et al*. (2012).

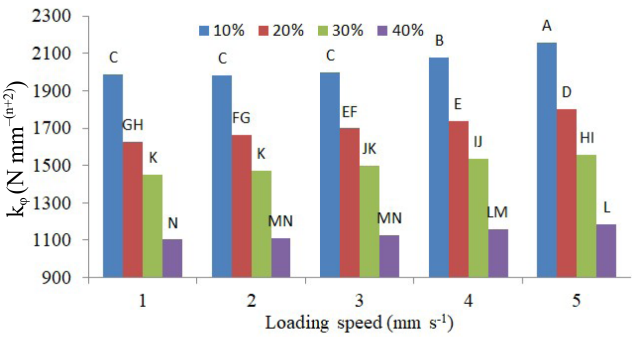

Fig. 11. Interactive effect of loading speed and moisture content on the value of k_φ (different letters on the bars show the significant difference between treatments).

Table 4. Statistical characteristics of the stepwise regression model for k_φ based on soil type, loading speed and soil moisture

Term	Unstandardized coefficients B	Std. coefficients	T-value	Level of significance (Sig)
Constant	1851.1	25.2	73.47	0.000001
Soil type	244.9	11.4	21.46	0.000001
Loading speed	35.15	4.03	8.71	0.000001
Soil moisture	–29.041	0.510	–56.90	0.000001

B – linear regression equation constants coefficient.

According to the standard coefficients listed in Table 4, the soil type, loading speed and soil moisture content had the greatest influence on the soil friction modulus, respectively.

3.2. Effect of parameter on the soil rolling resistance

Figure 12 shows the mutual effect of loading speed and soil texture on rolling resistance. Due to the increase in loading speed in the loamy soil texture, rolling resistance (R) decreased significantly, while in the clay loam soil, from 4 to 5 mm s^{-1} the change in the R value was not significant, but in other cases, R changed significantly. The highest value of R in the loam soil was 13 823.8 at a speed of 1 mm s^{-1} and the lowest R value of 1 830.7 was obtained in a clay loam soil at a speed of 5 mm s^{-1}. The loading speed is a representation of the wheel speed. Most research has shown that the rolling resistance decreased with wheel speed. Pope (1971) conducted an experimental and theoretical investigation of the effect of wheel speed on rolling resistance. A decrease from 106.75 to 89 N in the velocity range of 0.011-0.082 m s^{-1} and a wheel load of 551.5 N was reported.

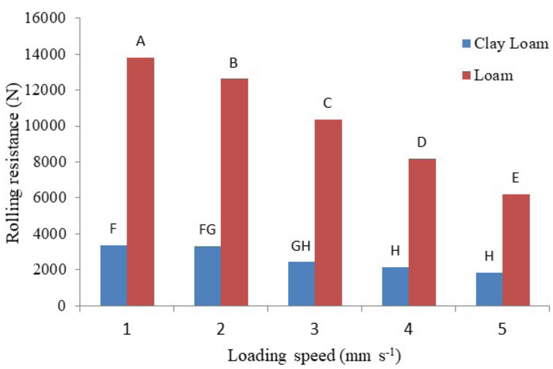

Fig. 12. Effects of soil texture and loading speed on rolling resistance (different letters on the bars show significant difference between treatments).

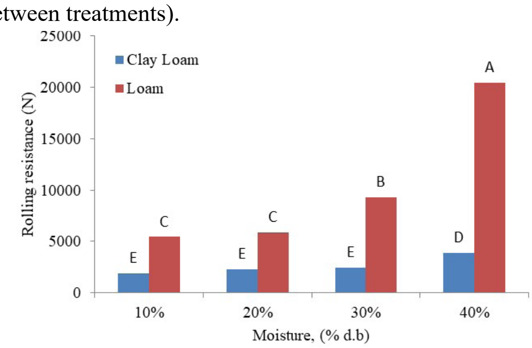

Fig. 13. Mutual effect of the soil moisture content and soil texture on the R value (different letters on the bars show the significant difference between treatments).

Fig. 13 shows that with an increase in the moisture content of the loam soil from 10 to 20%, the changes in the R value were not significant, but in the other cases, with an increase in the moisture content, the R value increased significantly. In a clay loam soil with moisture content values ranging from 10 to 30%, the changes in R were not significant, but at a value of 40% moisture, the increase in the R value was significant. Also, the maximum rolling resistance value was found at a moisture content of 40% in loamy soil which was 20 438.7 N. In general, the rolling resistance value has a direct relationship with the soil moisture content.

The effect of the soil moisture content (Fig. 14), loading speed and soil texture on the R value resulted in a maximum value of 16 887.1 occurring with a moisture content of 40% and a loading speed of 1 mm s^{-1} in loam soil. At a moisture content of 40%, with loading speeds ranging from 1 to 3 mm s^{-1}, the changes in R were not significant, but at speeds ranging from 3 to 5 mm s^{-1} with an increasing moisture content the changes in R were significant. Also, given the mutual effects of speed and moisture content, the highest value of

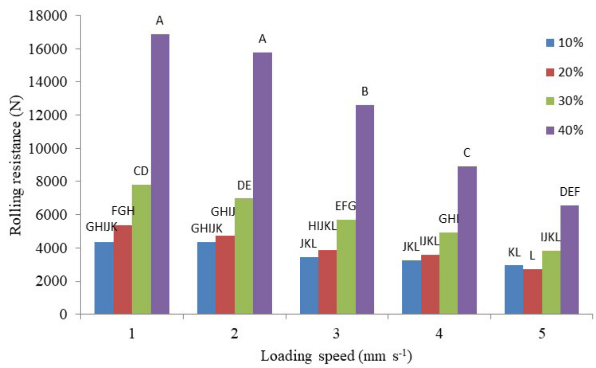

Fig. 14. Effect of the soil moisture content, loading speed and soil texture on the rolling resistance (different letters on the bars show significant difference between treatments).

Table 5. Statistical characteristics of the stepwise regression model for R based on soil, speed, moisture

Term	Unstandardized coefficients B	Standard coefficients	T-value	Level of significance (Sig)
Constant	–8 222	1 325	–6.21	0.000001
Soil type	7 626	600	12.71	0.000001
Loading speed	–1 196	212	–5.64	0.000001
Soil moisture	272.1	26.8	10.14	0.000001

B – Linear regression equation constants coefficient.

16 886.1 was recorded at a speed of 1 mm s^{-1} and a moisture content of 40%. In other words, with increasing moisture content values and a decrease in loading speed, the rolling resistance increased. The results obtained in this research are consistent with the results of Gharibkhani *et al*. (2012).

According to the standard coefficients listed in Table 5, the soil type, loading speed and soil moisture content values had the greatest effect on the rolling resistance, respectively.

4. CONCLUSIONS

It was found that loading speed acts like wheel speed, and with increases in loading speed there is less time for soil loading. Hence the soil subsidence value will be reduced at low speed. Based on the pressure-subsidence equation, at the same pressure but with decreasing subsidence values, the soil subsidence modules of cohesive modulus of deformation and friction modulus of deformation increased significantly. The mutual effect of the moisture and loading speed showed that at all moisture content values, the cohesive modulus of deformation value was higher in the clay loam soil than in the loam soil which was due to a high percentage of clay.

The soil moisture content increase reduced both the modules of cohesive modulus of deformation and friction modulus of deformation. Based on Bekker's formula, in order to compensate for the subsidence increase, the soil modules decreased. The decrease rate in loam soil was greater than that in the clay loam.

According to the values obtained for cohesive modulus of deformation, friction modulus of deformation and soil constant value the rolling resistance value was calculated according to Becker's relationship, and the effects of soil texture, loading speed and moisture content were also determined. As the load speed increased, the rolling resistance decreased in clay loam and loam soil, with the decrease being greater in clay soil. Also, with the increase in moisture content the rolling resistance increased. The mutual effects of the moisture content and loading speed on rolling resistance showed that the higher the moisture content up to a value of 40%, the lower the loading speed up to a value of 1 mm, also the higher the rolling resistance and, as a result, the traction efficiency of the vehicle decreases and the fuel consumption increases.

Conflicts of Interest: The authors declare no conflict of interest.

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