Effects of soil moisture content and tyre inflation pressure on motion resistance of a single narrow wheel

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Abstract: Interaction between wheels and soil need to be studied to help in productivity of machine**.** The research aim is to study the effects of soil moisture content and tyre inflation pressure on motion resistance of narrow wheels using a locally developed single wheel test rig. A single wheel test rig facility was developed at Federal University of Technology, Akure, Nigeria. Two narrow wheels of 90 mm in width 10-10 in diameter, IRC MB90 (INOUE RUBBER COMPANY motorcycle/bikes) tire were used as the test wheels on clay soil. Two inflation pressures of 274 kPa and 380 kPa and 15, 20, 30, and 40 kg load were examined at two different soil moisture conditions (8% and 10% moisture content). R^2 value for test wheel 1 with inflation pressure of 270 kPa at 8% moisture content was 0.9974 while that of inflation pressure of 380 kPa at 10% moisture content was 0.9952. Also for test wheel two (2) R^2 value was 0.9977 and 0.9914 at moisture content of 8% and 10% respectively, which exhibits that test wheel 1 with inflation pressure of 270 kPa at 8% moisture content showed more motion resistance compared to motion resistance of test wheel 1 at inflation pressure of 380 kPa and 10% moisture content, while test wheel 2 with inflation pressure of 270 kPa showed low motion resistance at 8% motion content.

Keywords: motion resistance, vertical load, inflation pressure, moisture content, wheel, test rig, soil bin

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1 Introduction

Soil-wheel interaction has been one of the fundamental research subjects in the terramechanics field. Research on soil/wheel interaction provides understanding of the dynamics of the soil-press-wheel interaction and provides useful information for machine design (Acquah and Chen, 2021). This knowledge of soil/machine interaction is essential for sustainable productivity in agriculture as inadequate knowledge and misunderstanding can lead to mismatch of agricultural implements and sources of power, soil compaction and so on. The machines and equipment used for operations make use of wheels and they are used on our farms. They make impact on the soil; then there is the need to measure motion resistance and its effect on soil is essential (Sedara, 2019).

Zoz and Grisso (2012) reported that tractive ability of tractor is normally affected by soil reactions against the front and rear wheels. In the tractive performance of off-road vehicles, rolling resistance is a major factor in the determination of the drawbar pull of agricultural vehicles. Motion resistance is defined as the force opposing the motion of a free rolling wheel in contact with a surface. Motion resistance also refers to the resistance to motion of a wheel caused by the absorption of energy in the

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contacting surfaces of the wheel and the soil upon which the wheel rolls (Plackett, 1985; Macmillan, 2002). Therefore, simple and low-cost appropriate machines will help to increase the agricultural productivity of the agricultural mechanization development in developing countries which is a key solution to increased agricultural productivity and economic survival (Akande et al., 2008). The soil bins designed by Siemens and Weber (1964), Stafford (1979), Durant et al. (1981), Godwin et al. (1980), and Onwualu and Watts (1989) are some examples of small-scale soil bin. Researchers have been using soil bins to investigate the phenomena of soil-traction and soil compaction. Raheman and Singh (2003) and studied the effect of steering forces on a driven tractor wheel in a soil bin. Cannillas and Salokhe (2002) developed a decision support system to predict soil compaction based on a soil bin research. Carman (2002) evaluated the degree of compaction caused by a towed wheel in a soil bin. Others (Watyotha et al., 200l; Hendriadi and Salokhe, (2002) utilized a soil bin to gain a better understanding in Cage wheel design to improve the traction of the cage wheel. The objective of these research is to evaluate the effects of soil moisture content and tyre inflation pressure on motion resistance of a single narrow wheel.

2 Materials and methods

This research was carried out at the Soil Dynamics Laboratory of the Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure located at 7.307°N latitude and 5.1398° E longitude. The area has a general elevation of between 300 and 700 metres above the mean sea level and mean annual rainfall between 1300 mm and 1500 mm.

The study period was from 12th January, 2018 to 30th January, 2019. An existing soil bin was extended from its initial dimensions of 5.49 m length × 1.98 m width × 0.92 m height, and after extension it was 9.76 m length × 1.98 m width × 0.92 m height. Other features of the equipment include an electric drive system, trolley, carriage which houses the test rig, a selected soil type and narrow wheels of different sizes and torque meters for the measurement of drought force and torques. The load shall be measured using weighing balance to get the vertical loading on the wheel. The soil bin was filled with sandy loam soil (20% sand, 10% silt and 70% clay). Clay loam soil was chosen due to its extensive use for growing crops and its availability across the Nigeria. Preparation of soil was done by soil processing roller guided by the use of recording soil penetrometer to get the soil condition (moisture content and bulk density).

2.1 Some considerations for design of test rig

The following factors have been considered in the development of the single wheel test rig:

(1) Power requirements: Two electric motors were used for the test rig; the first motor rated 0.75 kW was used to move the carriage and the other rated 1.12 kW was used to rotate the wheel.

(2) Sizes of wheels to be tested: tyre sizes range from 5.0 cm × 12 cm to 5.5 cm × 13 cm of rim sizes which are used for the calculation of the minimum and maximum width of the wheel.

(3) Type of soil: the soil was got from Federal University of Technology, Akure, STEP-B site and analyzed to get the class of soil; the soil was clay soil.

(4) Control measurement: K19500 penetrometer model was used to obtain bulk density.

(5) Safety: The machine was designed to be safe to man and its environment by avoiding sharp edges.

2.2 Description of the test rig

The test rig consists of a rigid frame, the soil bin, the carriage, on which the active part for soil working is mounted, and the wheel with tire. At the end of laboratory test rig a winch is fixed, which is for trolley carriage with the cable. An electric motor, pulley, shaft, bearing and belt are used for transmission of motion to drive the trolley. The trolley was driven by the cable, thus towing the cart. The ends of the drive are attached to the carriage by the means of the hitches. The carriage is also fitted with an electric motor and a gear transmission in order to drive the tire wheel. The working depth of the wheel can be adjusted by the means of the hydraulic fork, dependent on the vertical load and it is used to adjust the vertical position of the tire wheel.

2.3 Characteristics of the soil to be studied

The sample of soil used in the indoor soil bin facility for testing was taken at the Teaching and Research Farm of the Agricultural and Environmental Engineering (AGE), Federal University of Technology, Akure (FUTA), Nigeria for soil-analyses.

2.3.1 Sampling method

The sampling method used in collecting the sample is the pit sampling. It is done by using farm tools that include digger, spade, cutlass and hand trowel to collect the soil sample through the soil profile. During the collection of this sample, the outermost layer of the soil (about depth of five cm) was removed. Then, the soil is dug in profiles so that five profiles of soil were collected and depth of each profile is 10 cm.

2.4 Characteristics of the experimental wheels

The brand of wheel used was IRC (INOUE RUBBER COMPANY), having front/rear tire size of 90/90-10 with bias/radial-bias ply, with rim size-10 and tubeless.

2.5 Experimental setup

The soil levelling and compaction roller mounted on the carriage was used to achieve a certain soil compaction, before it is processed by the active body or performing various experiments with the tire test wheel. When the carriage is towed by the means of the cable, the wheel rotates due to the force on the cable. Towing cable is connected to the carriage by the means of a hitch hook, allowing the measurement of the towing force needed to displace the carriage. A control panel is used for the power supply of the two electric reducing motors. The dynamic braking principle is used in order to stop the carriage at the end of travel with the use of a forward contactor. Switches on the control panel allow the selection of the electric motor (the carriage towing motor or the tire wheel driving motor), as well as its forward or reverse motion.

The soil moisture content was determined using gravimetric method, according to the American standard test method ASTM D2216 (1980) (Arsoy, 2008). In this method, the loss in weight after oven-drying at 105^0C for 24 hours expressed as a fraction of the oven-dried soil represents the moisture content. A cylindrical soil sampling was weighed on sensitive electronic scale and recorded as W_1. The required quantity of the soil was taken into the moisture can and the weight was recorded as W_2. The can with soil was oven-dried at 105^0C for 24 hours to a constant weight as W_3. The percentage of soil moisture content was obtained using Equation 1;

$$\% \text{ soil moisture}(M_w) = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \qquad (1)$$

where: Mw is soil moisture wet basis (%), W_1 is weight of empty can (kg), W_2 is weight of can and wet soil (kg), W_3 is weight of can and dried soil (kg).

Inflation pressure was achieved using AstroAI digital tire inflator with pressure gauge of 1723.69 kPa, and vertical loading with the weighing scale, the rolling resistance (towing force) and torque were calculated.

2.6 Test variables

For this study on the motion resistance (towing force) of pneumatic wheels, two wheels were used of the same overall wheel diameter 510 mm but different design at four levels of added loads, two levels of tyre inflation pressures at 274 kPa (40 psi) and 380 kPa (55 psi) and at two different soil conditions (8% and 10% moisture content).

2.7 Dynamic loads

The dynamic loads which is synonymous to the axle or vertical loads are first measured in the laboratory comprising the mass of the test rig and the test wheel. Four levels of added dynamic loads (dead mass) of 98.1 N (10 kg), 196.2 N (20 kg), 294.3 N (30 kg) and 392.4 N (40 kg).

2.8 Experimental setup

The vertical loading and wheel inflation pressure was varied to evaluate its effect on the motion resistance of the wheel. The vertical loading of 150 N, 200N, 300 N, 400 N and wheel inflation pressure of 274 kPa and 380 kPa was varied for every experiment to evaluate its effect on the contact area. The contact area was measured by the use of

A4 paper placed on the path of the wheel to calculate the contact area of the wheel with the soil.

2.9 Data analysis

The data obtained was analyzed using graphical method and statistical regression analysis to get interaction between inflation pressure, vertical load, and wheel speed on the measured motion resistance on the test surfaces and the two pneumatic wheels of the same sizes.

3 Results and discussion

Table 1－Table 4 contain the actual velocity of the carriage, theoretical velocity, wheel radius, load (mass), torque, drawbar wheel slip motion resistance, contact area and motion resistance ratio (8% and 10%) and inflation pressure of 274 kPa and 380 kPa respectively.

Table 1 Towing force acting on test wheel 1 at MC 8% and inflation pressure 274 kPa

Actual velocity *V*a, m s^{-1}	Theoretical velocity *V*t, m s^{-1}	Wheel radius *r*, m	Weight, kg	Torque *T*, N	Draw bar pull *P*, N	Wheel slip, S	Motion resistance (MR), N	Contact area, cm^2	Motion resistance ratio (MRR)
0.31	0.47	0.4	15	5060	7150	0.34	8.48	312	0.57
0.27	0.42	0.4	20	4598	8250	0.36	14.35	321	0.72
0.25	0.4	0.4	30	4378	8800	0.37	23.79	324	0.79
0.22	0.4	0.4	40	4378	9900	0.45	36.18	336	0.90

Table 2 Towing force acting on wheel 1 at MC 10% and inflation pressure 380 kPa

Actual velocity *V*a, m s^{-1}	Theoretical velocity *V*t, m s^{-1}	Wheel radius *r*, m	Weight, kg	Torque *T*, N	Draw bar pull *P*, N	Wheel slip, S	Motion resistance (MR), N	Contact area, cm^2	Motion resistance ratio (MRR)
0.34	0.46	0.4	15	5073	7176	0.35	8.48	312	0.64
0.28	0.43	0.4	20	4612	8351	0.36	13.25	315	0.82
0.25	0.40	0.4	30	4423	8785	0.38	24.69	321	0.69
0.23	0.38	0.4	40	4388	9971	0.44	38.38	330	0.86

Table 3 Towing force acting on test wheel 2 at MC 8% and inflation pressure 274 kPa

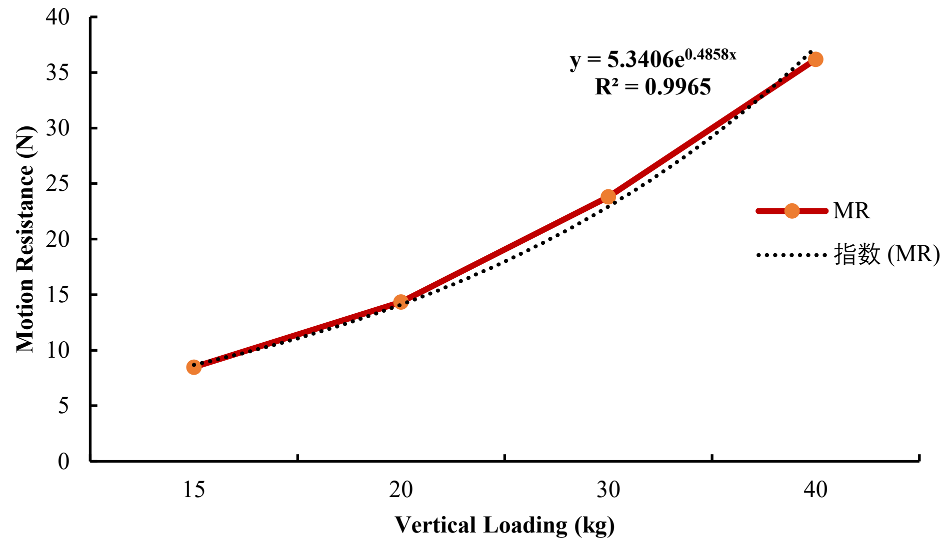
Actual velocity *V*a, m s^{-1}	Theoretical velocity *V*t, m s^{-1}	Wheel radius *r*, m	Weight, kg	Torque *T*, N	Draw bar pull *P*, N	Wheel slip, S	Motion resistance (MR), N	Contact area, cm^2	Motion resistance ratio (MRR)
0.34	0.47	0.4	15	5074	7177	0.33	8.49	309	0.67
0.29	0.46	0.4	20	4622	8352	0.36	14.45	315	0.84
0.24	0.43	0.4	30	4424	8786	0.38	22.79	321	0.87
0.23	0.38	0.4	40	4398	9973	0.46	35.19	324	0.98

Table 4 Towing force acting on test wheel 2 at MC 10% and inflation pressure 380 kPa

Actual velocity *V*a, m s^{-1}	Theoretical velocity *V*t, m s^{-1}	Wheel radius *r*, m	Weight, kg	Torque *T*, N	Draw bar pull *P*, N	Wheel slip, S	Motion resistance (MR), N	Contact area, cm^2	Motion resistance ratio (MRR)
0.34	0.46	0.4	15	5074	7176	0.35	9.89	312	0.79
0.27	0.42	0.4	20	4632	8351	0.37	17.05	318	0.82
0.25	0.41	0.4	30	4422	8795	0.38	23.89	321	0.89
0.22	0.38	0.4	40	4398	9976	0.45	36.58	327	0.99

3.1 Effect of vertical load and inflation pressure on motion resistance of wheel 1 and wheel 2

A typical plot of vertical load versus MR is shown in Figure 1 － Figure 2. The R^2 value shows exponential fits that best describe the relationship between tire inflation pressure (*P*), vertical load (*W*) and the interaction of them on wheel Motion Resistance. Exponential regression was obtained for the two wheels to check for linearity at different moisture content, and R^2 value for test wheel 1 with inflation pressure of 270 kPa at 8% moisture content was 0.9974 while that of inflation pressure of 380 kPa at 10% moisture content was 0.9952. Also, for test wheel two (2) R^2 value was 0.9977 and 0.9914 at moisture content of 8% and 10% respectively, for test wheel 1 with inflation pressure of 270 kPa at 8% moisture content, which showed more motion resistance compared to motion resistance of test wheel 1 at inflation pressure of 380 kPa and 10% moisture content, while for test wheel 2 with inflation pressure of 270 kPa it showed low motion resistance at 8% motion content. In general, at constant level of soil compaction, the MR was found to increase within the increase in vertical load, and in all inflation pressures, the effect of vertical load seems to be similar. Equation 1 — Equation 4 shows the exponential regression fit for wheel 1 and 2 compared to other fits.



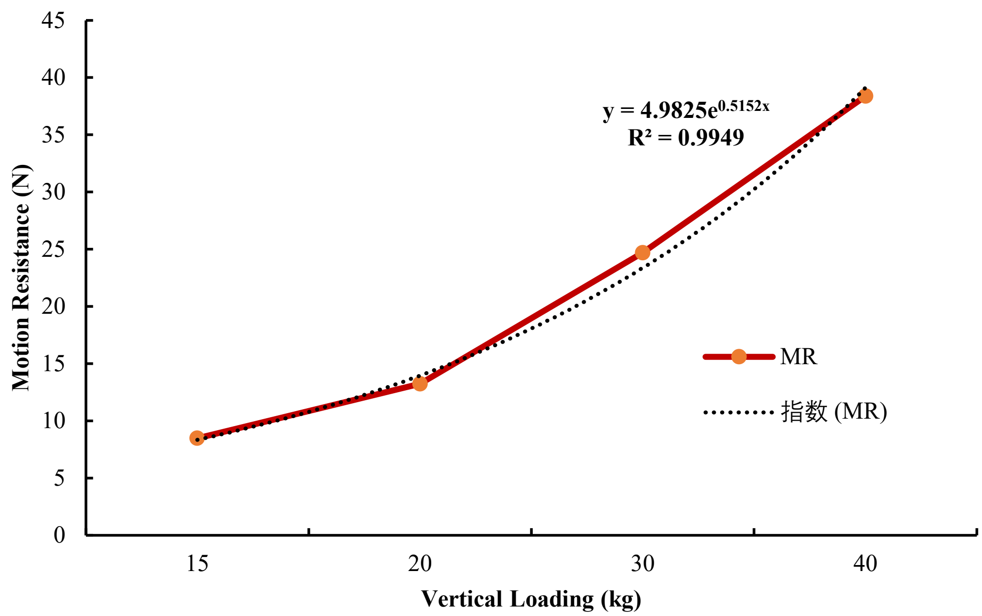


Figure 1 Effect of vertical load on motion resistance (test wheel 1) at inflation pressure (274 kPa, 380 kPa) and moisture content (8% and 10%)

Motion resistance predictive models

(a) Exponential models

$y = 5.3406e^{0.4858x}$ $R^2 = 0.9974$ wheel 1, inflation pressure (274 kPa) (2)

$y = 4.9825e^{0.5152x}$ $R^2 = 0.9952$ wheel 1, inflation pressure (380 kPa) (3)

$y = 5.4404e^{0.4721x}$ $R^2 = 0.9977$ wheel 2, inflation pressure (274 kPa) (4)

$y = 6.7521e^{0.4261x}$ $R^2 = 0.9914$ wheel 2,

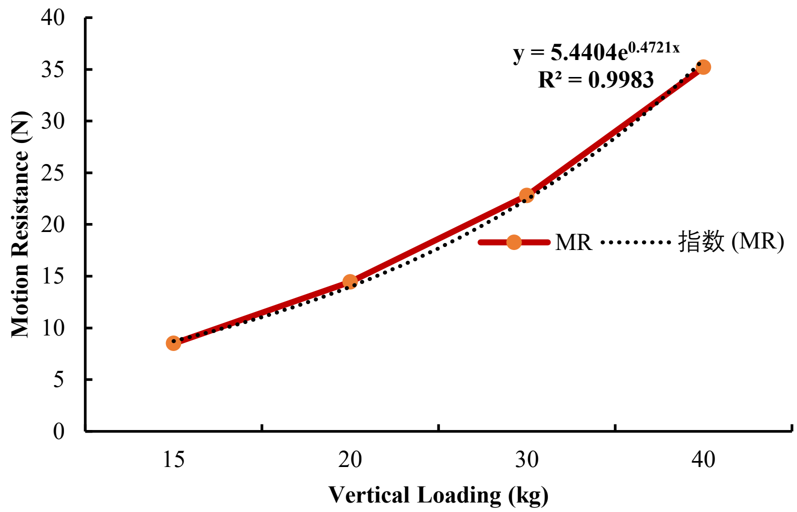
inflation pressure (380 kPa) (5)

where, y is motion resistance and x is vertical load, while R^2 is coefficient of determination

(b) Other models

Other fits have their coefficient of determination as listed below:

Linear fits; $R^2 = 0.9757$, Logarithm fit; $R^2 = 0.8792$, Power fit; $R^2 = 0.9761$.



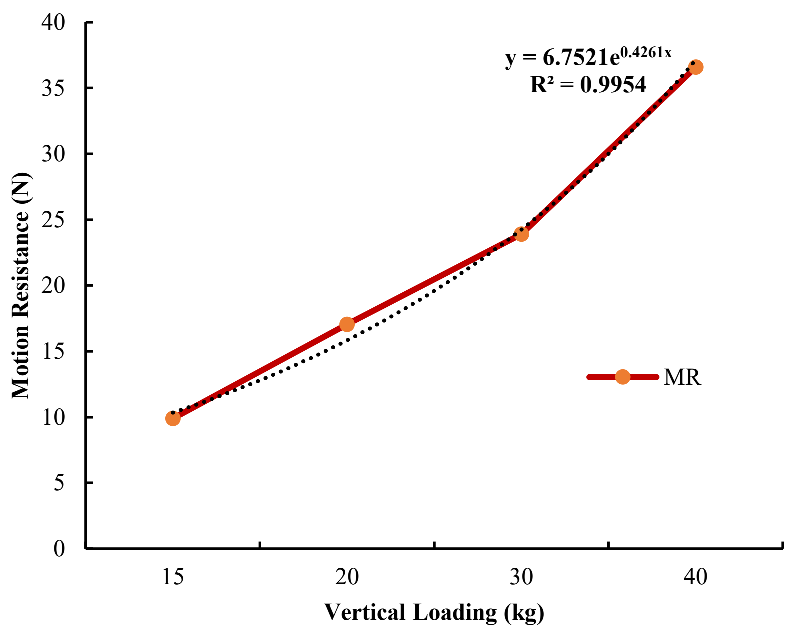
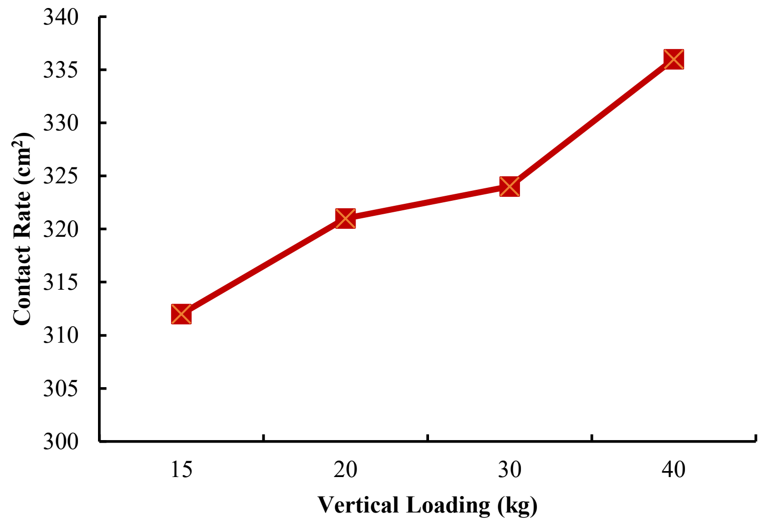


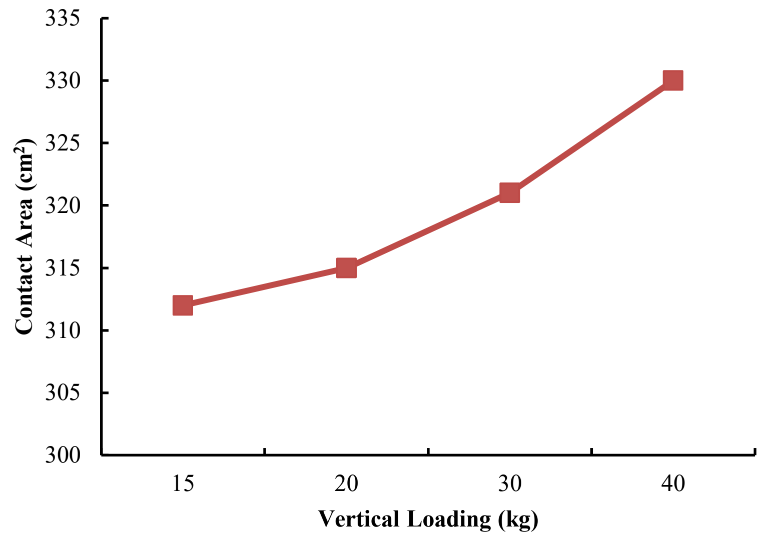
Figure 2 Effect of vertical load on motion resistance (test wheel 2) at inflation pressure (274 kPa, 380 kPa) and moisture content (8% and 10%)

3.2 Effect of vertical load on tyre contact area

The contact area for all tests was in the range of 309 — 330 cm^2 as shown in Figure 3 — Figure 4. Average contact pressure increased nearly linearly with increase in vertical load and increase in inflation pressure. Compare the results of contact area of tire-land with the results of Cesbron et al. (2008) whose research about tire contact area showed that there is not much difference between tire contact areas in static and dynamic conditions (about 20%).

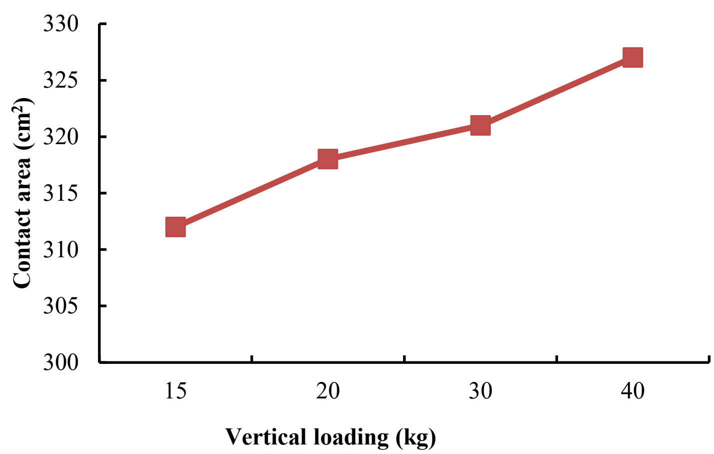


(a)

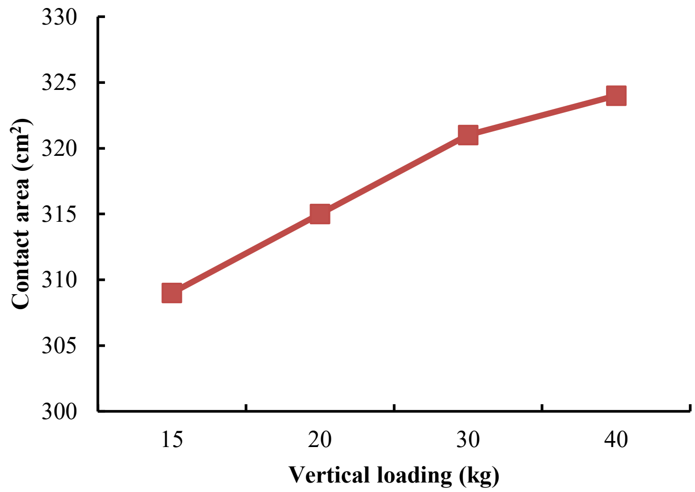


(b)

Figure 3 Effect of vertical load on contact area (test wheel 1) at inflation pressure of 270 kPa and 380 kPa



(a)



(b)

Figure 4 Effect of vertical load on contact area (test wheel 2) at inflation pressure of 270 kPa and 380 kPa

3.3 Comparison between motion resistance (MR) for the two test wheel

Figures 5-6 showed the comparison between motion resistance (MR) for the two test wheels as the vertical load and inflation pressure increases. The increase in inflation pressure caused MR to decrease at some point, but this effect was not significant at low levels of vertical load. Kurjenluomar et al. (2009) reported "reduction of tire inflation pressure reduced MR and rut depth only on soft soil, when the soil strength was low, and in hard soil conditions the effect was opposite on MR" and these experiments were conducted in clay. The results conform the result of their research and show that reduction in inflation pressure increases the MR of tire. Also Elwaleed et al. (2006) reported that reduction in tire inflation pressure by 171.8 kPa from the recommended value resulted in decrease of tire motion resistance ratio by 5.01%. However, further reduction by 380 kPa resulted in an increase in tire motion resistance ratio by 9.96%, but their experiments were conducted on loosened soil condition which was different from this test condition.

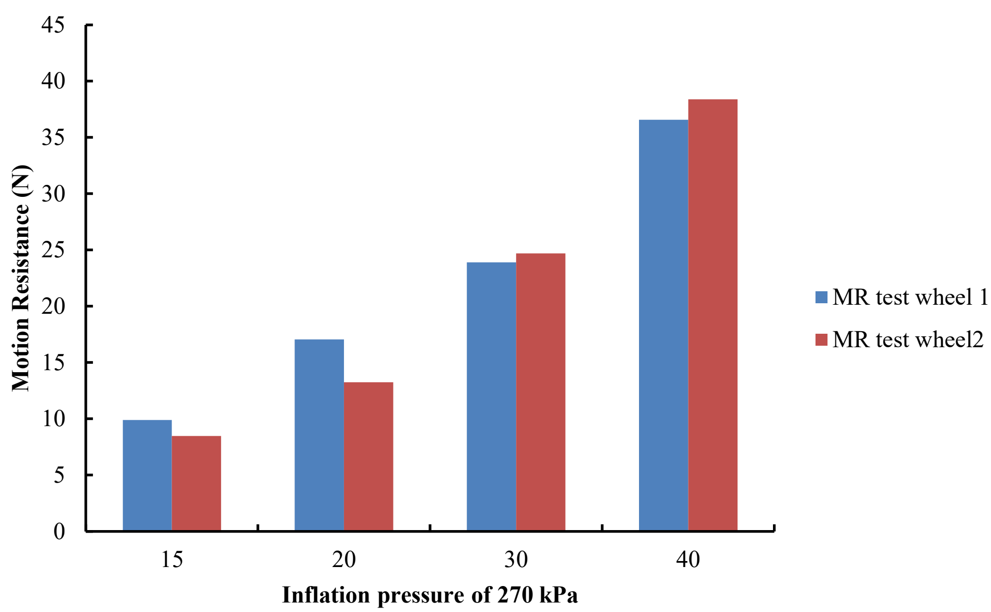


Figure 5 Motion resistance of pneumatic wheels at 270 kPa pressure and four added loads on clay soil surface at 8% moisture content

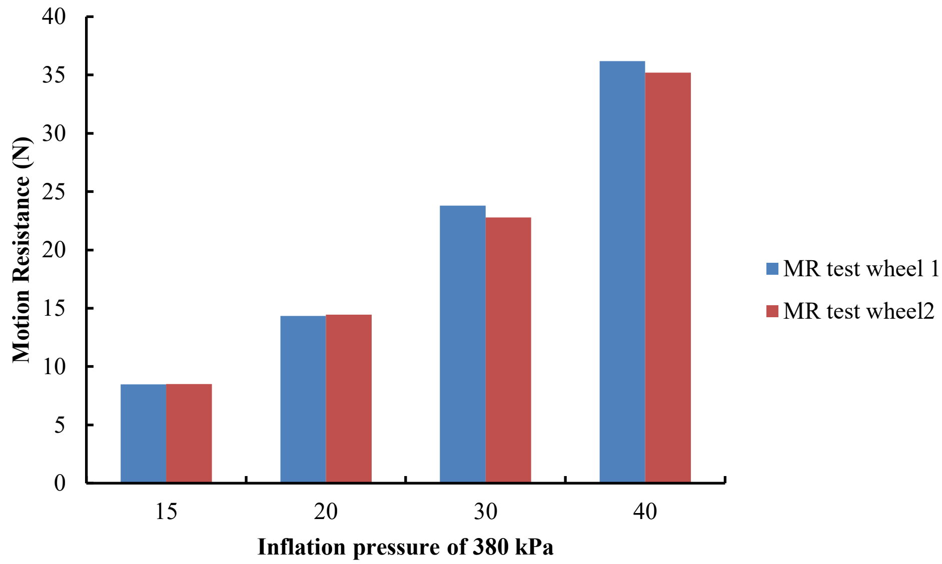


Figure 6 Motion resistance of pneumatic wheels at 380 kPa pressure and four added loads on clay soil surface at 10% moisture content

3.4 Model development for measuring motion resistance at 8% moisture content

The design points fall within a safe operating limit, within the nominal high and low levels, as BBD does not contain any point at the vertices of the cubic region. Two different tests, namely, sequential model sum of squares and model summary statistic were performed to check the adequacy of the models generated from the obtained data. Equation 5 showed the relationship of tire contact area pressure with vertical load and tire inflation pressure. The tire contact pressure has a direct relationship with vertical load and inflation pressure of the wheels. The model established shows the coefficient determination (R^2) of 0.9822 as shown in Equation 5 and the validation shows R^2 value of 0.9727 shown in Equation 6.

Predictive model for motion resistance:

$$MR = -0.011302 - 0.082711IP - 0.10229VL + 93.45734WS \quad (R^2 = 0.9822) \quad (6)$$

Where *IP* is inflation pressure; *VL* is vertical load; *WS* is wheel speed; *MR* is motion resistance.

Validation of model

$$MR = +22.51389 - 0.086379IP - 0.023379VL + 5.44293WS \quad (R^2 = 0.97274) \quad (7)$$

Where *IP* is inflation pressure; *VL* is vertical load; *WS* is wheel speed; *MR* is motion resistance.

4 Conclusions

A research was carried out to study the effects of different inflation pressures and vertical loads on the motion resistance of two narrow wheels under different moisture contents (8% and 10%). It was found that motion resistance ratio increases with increase in vertical load and also with inflation pressure. Best predictive models established to describe the relationship between motion resistance, tyre inflation pressure and vertical loads were those of exponential fit, followed by power, and linear fit in that order. Data obtained are relevant in the studies of soil/machine interaction studies such as obtainment in soil dynamics in tillage and traction.

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Plate 1 Single wheel test rig facility