Original Research Article

DEVELOPMENT OF A SINGLE WHEEL TEST RIG FOR MEASURING MOTION RESISTANCE

ABSTRACT

Research on soil-wheel interaction is *sine qua non* in studies of motion resistance. This however requires test rig facility for controlled experiment. However, such facility is non-existent presently in Nigeria. A single wheel Test Rig facility was developed at FUTA. It consists of a soil bin, tool carriage, single wheel tester, trolley and drive system. The indoor soil bin facility was equipped with a soil bin which dimension was 9.76 m length x 1.98 m width x 0.92 m height. The wall of the soil bin was constructed with wood. The wood walls are clad with bin wall (angle iron) for better reinforcement, rigidity and effective behavior of bin walls in service

A single-wheel tester facility was utilized to investigate the effect of tire inflation pressure and vertical load on the wheel motion resistance. Two narrow wheels of 90/10-10 in width with IRC MB90 tires which are used as the tester wheel on clay soil and installed on a carriage traversing the length of soil bin. Two inflation pressures of 274 kPa and 380 kPa and four levels of vertical load applied on wheel (i.e. 15, 20, 30, and 40 kg) was examined at two different soil conditions (8% and 10% moisture content). The soil leveling 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 data obtained will be analyzed using graphical method and statistical inherent analysis to get the significant effect of the factors with the response using ANOVA using statistical package for social sciences (SPSS 16). Exponential regression was obtained for the two wheels to check for linearity at different 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, this shows for 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 for test wheel 2 with inflation pressure of 270 kPa 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.

Figures 5 and 6 show comparisons between Motion resistance (MR) for the two-test wheel as both the vertical load and the inflation pressure increase. Design Expert software was used to establish and validate a model based on how the experiment was designed, the model established shows the coefficient determination (R^2) of 0.9822 and the validation shows R^2

value of 0.9727. The contact area for all tests was in the range of 309-330 cm^2, average contact pressure increased nearly linearly with increase in vertical load and increase in inflation pressure. A single wheel test rig has been developed to study motion resistance of narrow wheels. The effect of different inflation pressures and vertical loads on the motion resistance of the narrow wheels has been investigated under different moisture content (8% and 10%). Data to assist in the development of simple, low cost and easy to maintain agricultural machines with narrow pneumatic wheel as traction members have been provided in terms of motion resistance and motion resistance ratios.

Keywords: Single wheel, test rig, Soil bin, motion resistance, vertical load, inflation pressure and moisture content**.**

1. INTRODUCTION

Field machines contribute a major portion of the total cost of crop production. The proper operation is essential for any system to be reasonably profitable. 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.
Zoz and Grisso (2003) 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 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 mechanisation development in developing countries is a key solution to increased agricultural productivity and economic survival (Akande *et al.*, 2008). The specific objectives of these research is to design and fabricate a single wheel test rig to measure motion resistance of towed wheels in an indoor soil bin; evaluate the performance of the test rig under different soil moisture content; and establish and validate models to predict motion resistance for single towed wheels. The soil bin designed by Siemens and Weber (1964), Stafford (1979), Durant *et al.* (1980), 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 (2002) studied the effect of steering forces on a driven tractor wheel in a soil bin. Canillas and Salokhe (2002) developed a decision support system to predict soil compaction based on a soil bin research. Carmen (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.

2. Test Rig Facility

The study is located in the soil Dynamics laboratory of the Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure. A soil bin is required for this study, an existing soil bin was extended from its initial dimensions of 5.49 m length x 1.98 m width x 0.92 m height; and after extension it was 9.76 m length by 1.98 m width and 0.92 m height. Other features of the equipment are: 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 measure using weighing balance to get the vertical loading on the wheel. 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).

2.7 Design Considerations

Design considerations for the single wheel test rig include;

i. Power requirement: Two electric motors will be used for the test rig; one to move the carriage and the other to rotate the wheel.
ii. Sizes of wheels to be tested: tire sizes range from 5.0x12 and 5.5x13 of rim sizes which are used for the calculation of the minimum and maximum width of the wheel.
iii. Location of the test rig facility: the test rig facility will be located in the Soil Tillage dynamics Research Laboratory of the Department of Agricultural Engineering of the Federal University of Technology, Akure.
iv. Type of soil: the soil was gotten from Federal university of Technology, Akure, STEP-B site and analyzed to get the class of soil; the soil was clay soil.
v. Soil processing device: Soil Processing device include frame and weigh pan.
vi. Control measurement
vii. Safety: The machine was design to be safe to man and its environment by avoiding sharp edges.

2.2 Test rig development

The test rig consists of a rigid frame, the soil bin, the carriage, on which the active part for soil working is mounted, 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.

Characteristics of the Soil to be studied

Sample Location

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) for soil-analyses. The area has a general elevation of between 300 and 700 m above the mean sea level and means annual rainfall between 1,300 to 1,500 mm.

Sampling Method

The sampling method used in collecting the sample is the pit sampling. It is done by using farm tools (which 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 5cm) was removed. Then, the soil is dug in profiles such that five profiles of soil were collected. The depth of each profile is 10cm as shown in table 1 below.

Characteristics of the wheels to be studied

Brand - IRC (INOUE RUBBER COMPANY); Front/Rear - Front, rear

Tire size - 90/90-10; Bias/Radial - Bias Ply; Rim size - 10

Tube/Tubeless - Tubeless

Experimental setup

The soil leveling 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 obtained experimentally, the inflation pressure was achieved using pressure gauge, vertical loading with the weighing scale, the rolling resistance (towing force) and torque were calculated.

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 tire inflation pressures at 274 kPa (40 psi) and 380 kPa (55 psi) and at two different soil conditions (8% and 10% moisture content).

Dynamic loads

The dynamic loads which is synonymous to the axle or vertical loads are first measured in the laboratory comprise the weight of the test rig and the test wheel. Four levels of added dynamic loads (dead weights) of 98.1 N (10 kg), 147.15 196.2 N (20 kg), 294.3 N (30 kg) and 392.4 N (40 kg).

Effect of Vertical Load and Inflation Pressure on Motion Resistance of the Wheels

The vertical loading and wheel inflation pressure was varied to evaluate its effect on the motion resistance of the wheel.

Effect of Vertical Load and Inflation Pressure on Contact Area

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

Data Analysis

The data obtained will be analyzed using graphical method and statistical inherent analysis to get the significant effect of the factors with the response using ANOVA using statistical package for social sciences (SPSS 16) to test whether there is significant difference between the means of the measured motion resistance on the test surfaces and the two pneumatic wheels of the same sizes. Design expert 9 would be used to establish a two-level factorial model and validated using Excel 10.

3. Results and Discussion

Component Design and Features of the Single Wheel Test Rig

The soil bin facility consists of (i) The bin (ii) tool carriage (iii) Single wheel tester (iv) Trolley (v) drive. The bin is a soil box with rails on the top on which the carriage rides. The indoor soil bin facility was equipped with a soil bin which dimensions 9.76 m length by 1.98 m width and 0.92 m height, respectively. The walls of the soil bin were constructed with wood. The woods are clad with bin wall (angle iron) for better reinforcement, rigidity and effective behavior of bin walls in service. Soil fitting refers to the process used to prepare the bin soils to provide desired soil conditions. The soil fitting sequence usually begins with the leveling of the soil surface to refill irregularities, pits and furrows and to make sure there is an even distribution of soil side to side and end to end of the bin, also the roller for compacting the soil to have different bulk density.

Table 1. Towing force acting on the Test Wheel 1(soil condition: moisture content: 8%, inflation pressure: 274 kPa)

Actual Velocity Va (m/s)	Theoretical velocity Vt (m/s)	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 the Test Wheel 1 (soil condition: moisture content: 10%, inflation pressure: 380 kPa)

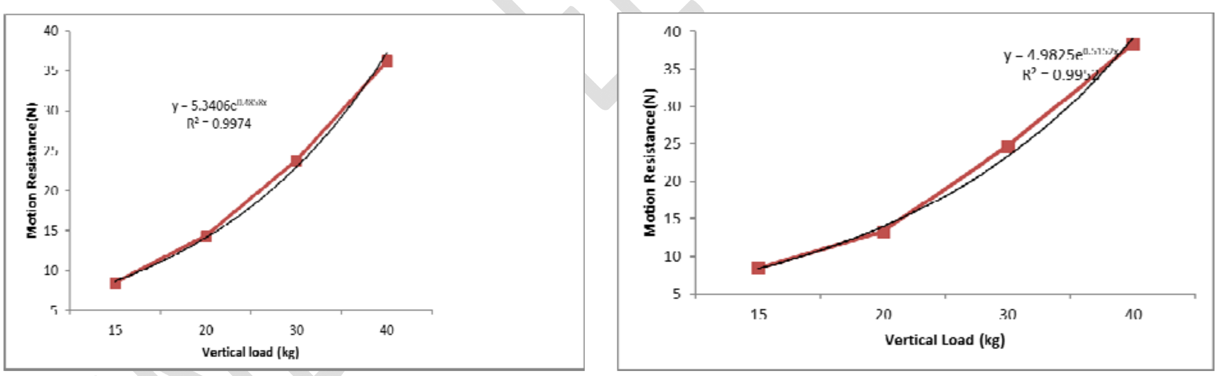
Actual Velocity Va (m/s)	Theoretical velocity Vt (m/s)	Wheel Radius r (m)	Weight (kg)	Torque T(N)	Draw bar pull P(N)	Wheel slip (S)	Motion Resistance (MR) (N)	Contact Area (cm^2)	Motion Resistance ratio (MRR)
0.34	0.46	0.4	15	5073	7176	0.35	8.48	312	0.64
0.28	0.43	0.4	20	4612	8351	0.36	13.25	315	0.82
0.25	0.4	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 the Test Wheel 2(soil condition: moisture content: 8%, inflation pressure: 274 kPa)

Actual Velocity Va (m/s)	Theoretical velocity Vt (m/s)	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

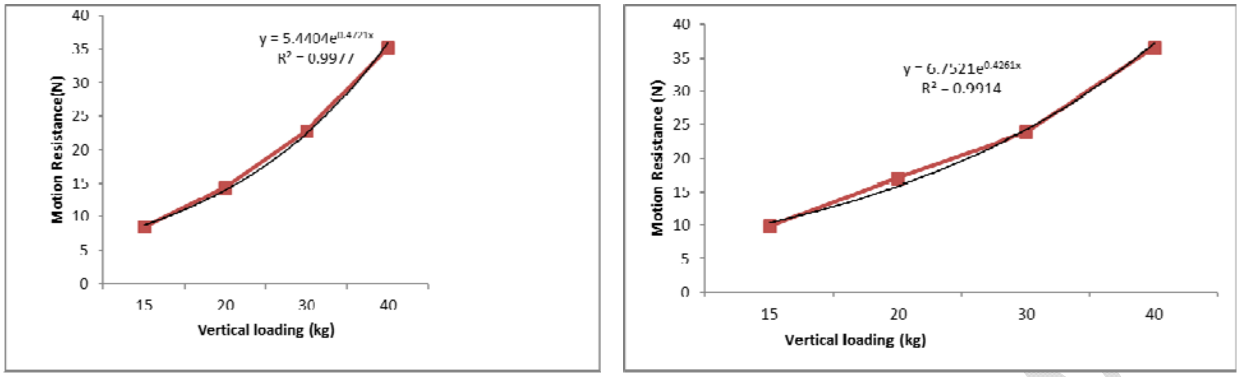
Table 4. Towing force acting on the Test Wheel 2(soil condition: moisture content: 10%, inflation pressure: 380 kPa)

Actual Velocity Va (m/s)	Theoretical velocity Vt (m/s)	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



(a) (b)

Figure 1: (a)Effect of Vertical Load and Inflation Pressure (274 kPa) on Motion Resistance Test Wheel 1 8% moisture content; (b) Effect of Vertical Load and Inflation Pressure (380 kPa) on Motion Resistance for Test Wheel 1 at 10% moisture content



(a) (b)

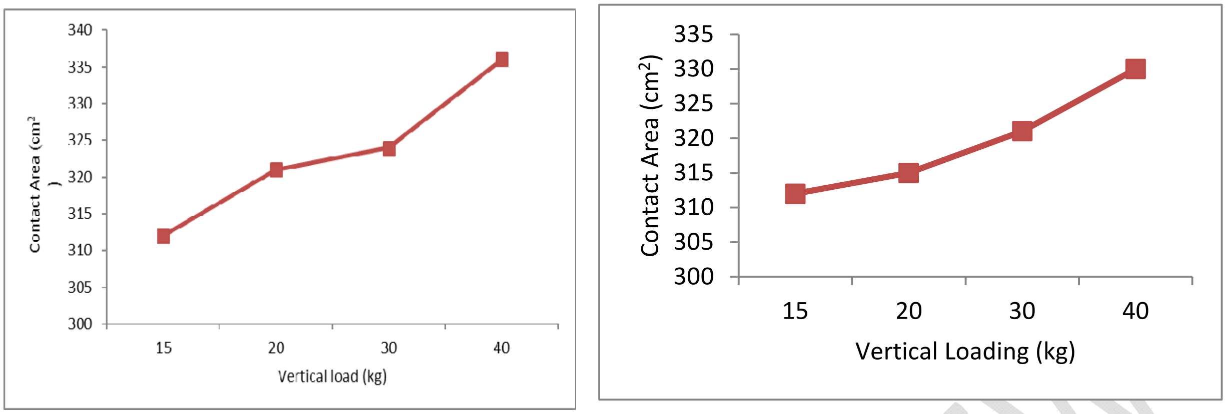
Figure 2: (a) Effect of Vertical Load and Inflation Pressure (274 kPa) on Motion Resistance Test Wheel 2 at 8% moisture content; (b) Effect of Vertical Load and Inflation Pressure (380 kPa) on Motion Resistance Test Wheel 2 at 10% moisture content

Table 5. Analysis of variance (ANOVA), for the effect of tire inflation pressure (P) and vertical load (W) on wheel Motion Resistance (MR).

ANOVA

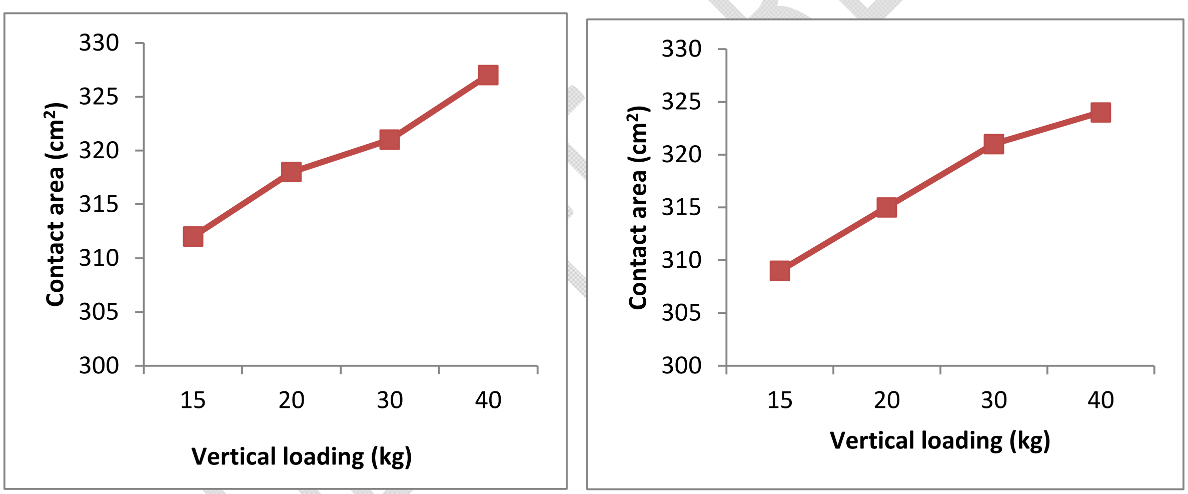
	Motion resistance on Test wheel 1				
	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	.500	1	.500	.003	.017
Within Groups	971.163	6	161.860		
Total	971.663	7			

	Motion resistance on Test wheel 2				
	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	5.265	1	5.265	.040	.048
Within Groups	788.807	6	131.468		
Total	794.072	7			



(a) (b)

Figure 3: (a) Effect of Vertical Load and Inflation Pressure (270 kPa) on Contact Area, Test Wheel 1; (b) Effect of Vertical Load and Inflation Pressure (380 kPa) on Contact Area, Test Wheel 1



(a) (b)

Figure 4: Effect of Vertical Load and Inflation Pressure (270 kPa) on Contact Area, Test Wheel 2; (b) Effect of Vertical Load and Inflation Pressure (380 kPa) on Contact Area, Test Wheel 2

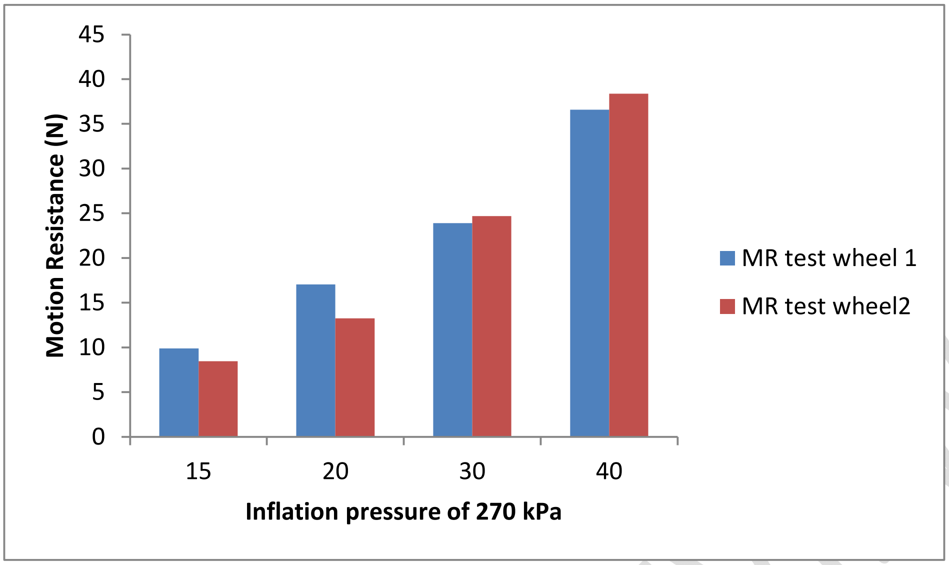


Figure 5. Motion resistance of pneumatic wheels at 270 kPa pressure and 4 added loads on clay soil surface at 8% moisture content

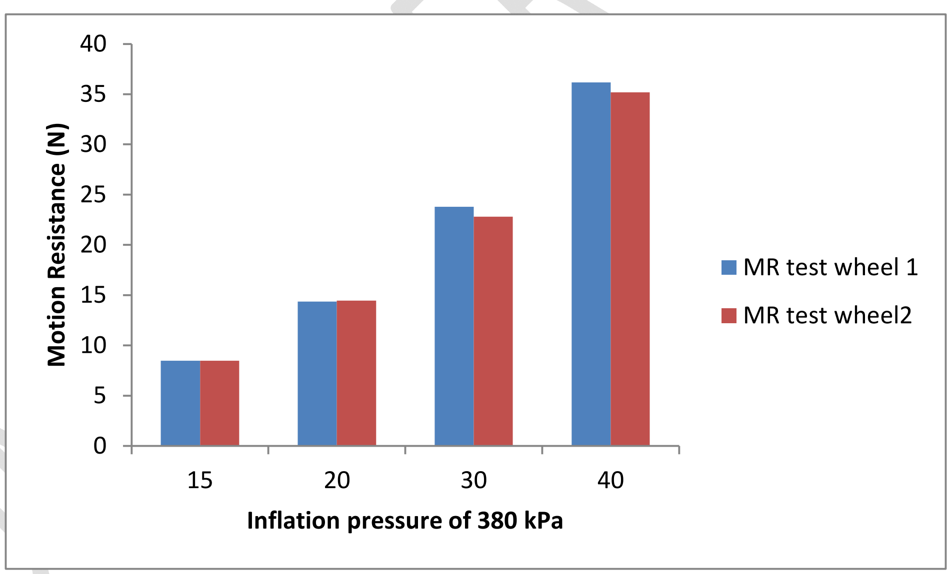


Figure 6. Motion resistance of pneumatic wheels at 380 kPa pressure and 4 added loads on clay soil surface at 10% moisture content.

Development of a Model for measuring Motion Resistance at 8% Moisture Content

The data gotten from the experiment carried where separated into two; and this was done in the ratio of 80% of the data to establish the model while 20% to validate the model. In this study, BBD was used for response surface optimization with three process variables (inflation pressure, vertical load, and wheel speed) at three levels. The design points fall within a safe operating limit, within the nominal high and low levels, as BBD does not contain any points 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.

Predictive model for motion resistance:

$$\boldsymbol{MR} = -0.011302 - 0.082711\boldsymbol{IP} - 0.10229\boldsymbol{VL} + 93.45734\boldsymbol{WS} \qquad R^2=0.9822 \qquad (1)$$

Where *IP* is inflation pressure

VL is vertical load

WS is wheel speed

MR is motion resistance

Validation of model

$$\boldsymbol{MR} = +22.51389 - 0.086379\boldsymbol{IP} - 0.023379\boldsymbol{VL} + 5.44293\boldsymbol{WS} \qquad R^2=0.97274 \qquad (2)$$

Where *IP* is inflation pressure

VL is vertical load

WS is wheel speed

MR is motion resistance

4. Discussion

Table 1-4 contain the actual velocity of the carriage, theoretical velocity, wheel radius, load (weight), 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. Figure 5 and Figure 6 showed the relation of tire contact area pressure with vertical load and tire inflation pressure. The tire contact pressure has a direct relation with vertical load and inflation pressure of the wheels. The contact area for all tests was in the range of 309-330 cm^2 as shown in Figures 3 and 4. Average contact pressure increased nearly linearly with increase in vertical load and increase in inflation pressure. Comparing 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 different between tire contact areas in static and dynamic conditions (about 20%). Table 5 shows the analysis of variance (ANOVA), for the effect of tire inflation pressure (P) and vertical load (W) and the interaction of them on wheel Motion Resistance (MR). This table shows that both of these two parameters have significant effect on MR changes. More ever the interaction of independent variables (P, W) on dependent variable (MR) was significant with the probability rate of 95%. A typical plot of vertical load versus MR as 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 were obtained for the two wheels to check for linearity at different 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, this shows for 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 for test wheel 2 with inflation pressure of 270 kPa 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. Figure 6 shows comparisons between Motion Resistance (MR) for the two test wheel 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 conforms the result of their research, and shows 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. The model established shows the coefficient determination (R^2) of 0.9822 and the validation shows R^2 value of 0.9727

Predictive models (exponential fit)

$y = 5.3406e^{0.4858x}$ $R^2 = 0.9974$ Wheel 1, inflation pressure (274 kPa) (4.8)

$y = 4.9825e^{0.5152x}$ $R^2 = 0.9952$ Wheel 1, inflation pressure (380 kPa) (4.9)

$y = 5.4404e^{0.4721x}$ $R^2 = 0.9977$ Wheel 2, inflation pressure (274 kPa (5.0)

$y = 6.7521e^{0.4261x}$ $R^2=0.9914$ Wheel 2, inflation pressure (380 kPa) (5.1)

Other fits tested :Linear fits ; $R^2=0.9757$, Logarithm fit; $R^2=0.8792$, Power fit; $R^2=0.9761$

Plate 1. Test-Rig facility

5. Conclusion

1. A single wheel test rig has been developed to study motion resistance of narrow wheels.
2. The effect of different inflation pressures and vertical loads on the motion resistance of the narrow wheels have been investigated under different moisture content (8% and 10%)
3. Data to assist in the development of simple, low cost and easy to maintain agricultural machines with narrow pneumatic wheel as traction members have been provided in terms of motion resistance and motion resistance ratios.
4. The motion resistance ratio increases with increase in vertical load.

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