Original Research Article

DEVELOPMENT OF A SINGLE WHEEL TEST RIG FOR MEASURING MOTION RESISTANCE

ABSTRACT

Research on soil-wheel interaction is essential in studies of motion resistance of narrow wheels of agricultural machines. The aim of this research was 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. It consists of a soil bin, carriage, single narrow wheel tester, trolley and drive system. An existing 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 high. The single-wheel test facility was utilized to investigate the effect of tyre inflation pressure and vertical load on motion resistance of wheel. Two narrow wheels of 90/10-10 in width, IRC MB90 tyre were used as the test wheels on clay soil and were separately installed on a carriage that traversed 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) were examined at two different soil moisture conditions (bulk density of 1.58 g/cm^3 and 1.55 g/cm^3, soil moisture content of 8% and 10% dry basis and soil penetration resistance of 1.02 MPa and 1.5 MPa). 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. 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%). 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 The research provides data that are relevant in the study of soil-wheel interaction.

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

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 of wheels used on our farms makes 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 (Zoz and Grisso, 2003). 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 x 1.98 m width x 0.92 m. 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 which is a cylindrical drum loaded with weights about 100 kg as shown in Figure 1, which was passed on the soil three to four time to achieve the bulk density of 1.58 g/cm^3 and 1.55 g/cm^3, soil moisture content of 8% and 10% dry basis and soil penetration resistance of 1.02 MPa and 1.5 MPa which was guided by the use of recording soil penetrometer.

Figure 1. Soil penetrometer and Compaction roller

2.7 Design Considerations

Design considerations for the single wheel test rig include;

Power requirement: Two electric motors will be used for the test rig; one to move the carriage and the other to rotate the wheel.

Sizes of wheels to be tested: tyre sizes ranges from 5.0 x 12 and 5.5 x 13 of rim sizes which are used for the calculation of the minimum and maximum width of the wheel.

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.

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.

Soil processing device: Soil Processing device include frame and weigh pan.

Safety: The machine was design by avoiding sharp edges which was fillet to prevent injuries.

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 tyre; 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 wire cable, thus towing the cart as shown in Figure 1. 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 tyre 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 tyre wheel as shown in Figure 2.

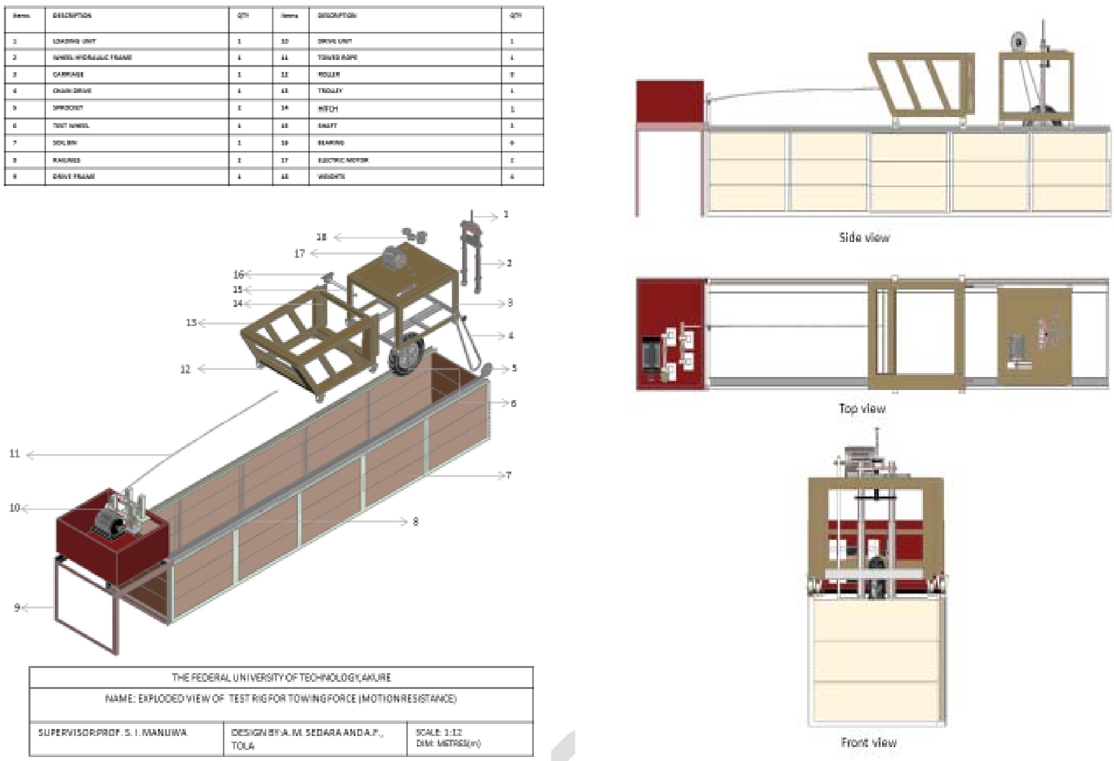

Figure 1. Exploded and Orthographic view of Test Rig for motion studies (CAD Design)

Figure 2: Drive unit view showing the towing cable, coupling of trolley to the carriage and wheel tester

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 meters above the mean sea level and means annual rainfall between 1300 mm to 1500 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.

Characteristics of the wheels to be studied

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

Tyre 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 by loading the drum with weights of 100 kg and passed on the soil bin three to four times to achieve the desired soil condition of soil moisture content of 8% and 10%, and bulk density of before it is processed by the active body or performing various experiments with the tyre test wheel. When the carriage is towed by the means of a wire cable connected to the drive system, the wheel rotates due to the force/pull 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 tyre 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 tyre 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 narrow wheels of 90/90-10; Bias/Radial with different threading as shown in Figure 3

Figure 3. Test wheel one (1) and test wheel two (2) showing different thread design

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 as shown Figures 5-6.

Figure 4. Testing of the Test Rig to get the effect of load on the Motion resistance and contact area with soil.

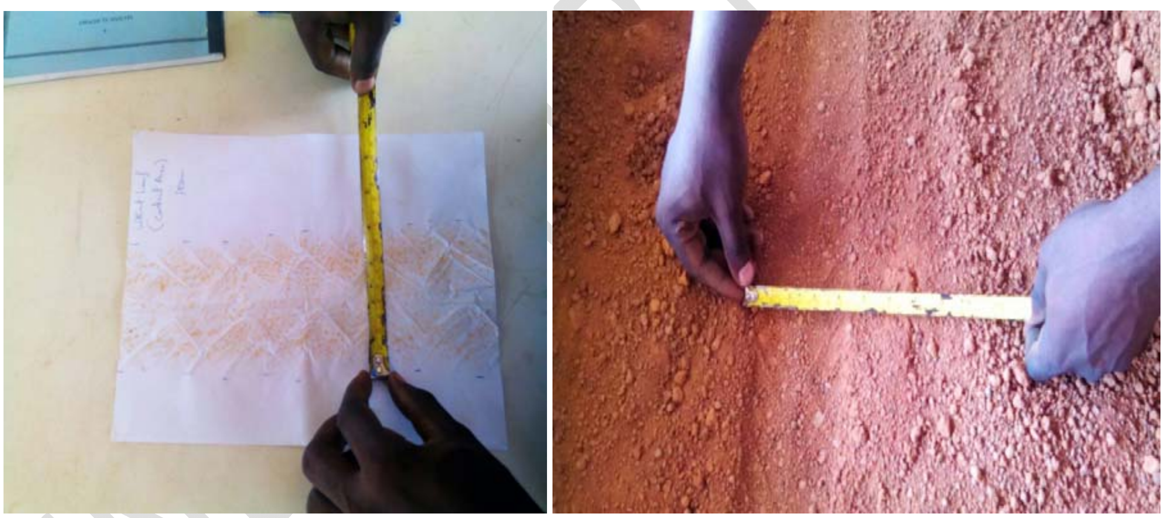

Figure 5. Measuring the Effect of load and inflation pressure on the contact area with soil.

Data Analysis

The data obtained will be analysed 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.

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 dimension was 9.76 m length x 1.98 m width x 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 densities of 1.58 g/cm^3 and 1.55 g/cm^3. The data obtained was presented as shown in Tables 1-3.

Table 1. Towing force acting on the Test Wheel 1 with inflation pressure of 274 kPa (soil condition bulk density, moisture content and soil penetration resistance of 1.58 g/cm^3, 8%, and 1.02 MPa)

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 with inflation pressure of 380 kPa (soil condition bulk density, moisture content and soil penetration resistance of 1.55 g/cm^3, 10%, and 1.5 MPa)

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 with inflation pressure 274 kPa (soil condition bulk density, moisture content and soil penetration resistance of 1.58 g/cm^3, 8%, and 1.02 MPa)

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 with inflation pressure 380 kPa (soil condition bulk density, moisture content and soil penetration resistance of 1.55 g/cm^3, 10%, and 1.5 MPa)

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

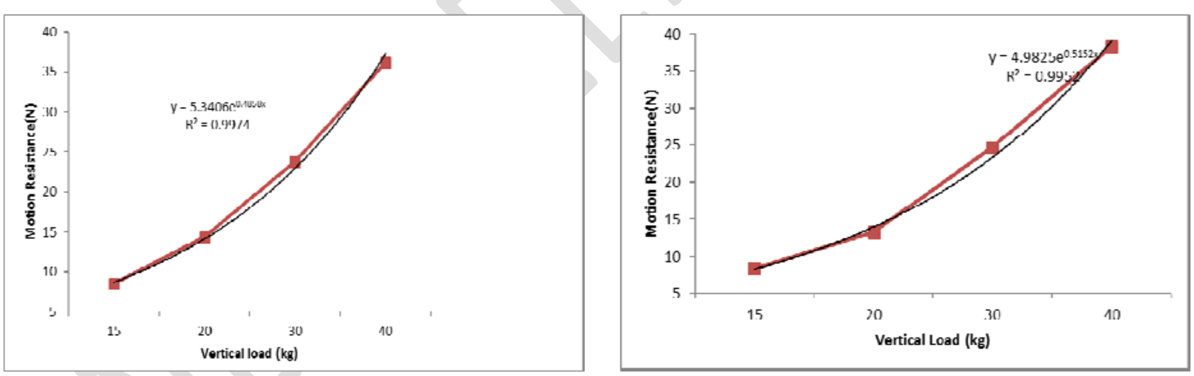

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Figure 6: (a)Effect of Vertical Load and Inflation Pressure (274 kPa) on Motion Resistance Test Wheel 1 8% moisture content; (b) Effect of Vertical Load and Inflation Pressure (380 kPa) on Motion Resistance for Test Wheel 1 at 10% moisture content

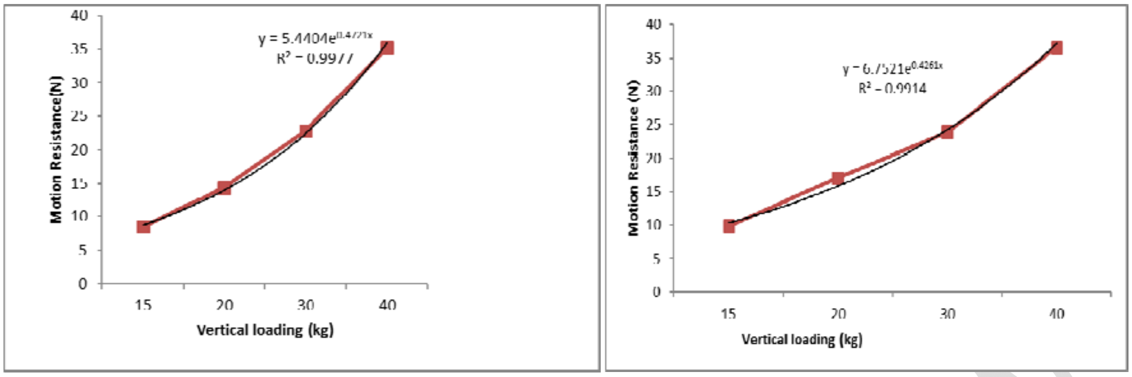

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Figure 7: (a) Effect of Vertical Load and Inflation Pressure (274 kPa) on Motion Resistance Test Wheel 2 at 8% moisture content; (b) Effect of Vertical Load and Inflation Pressure (380 kPa) on Motion Resistance Test Wheel 2 at 10% moisture content

Table 5. Analysis of variance (ANOVA), for the effect of tyre 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			

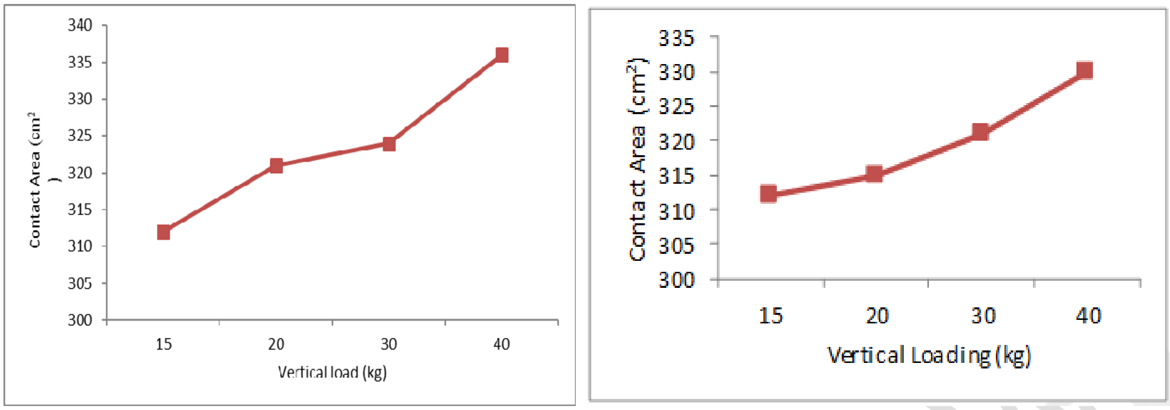

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Figure 8: (a) Effect of Vertical Load and Inflation Pressure (270 kPa) on Contact Area, Test Wheel 1; (b) Effect of Vertical Load and Inflation Pressure (380 kPa) on Contact Area, Test Wheel 1

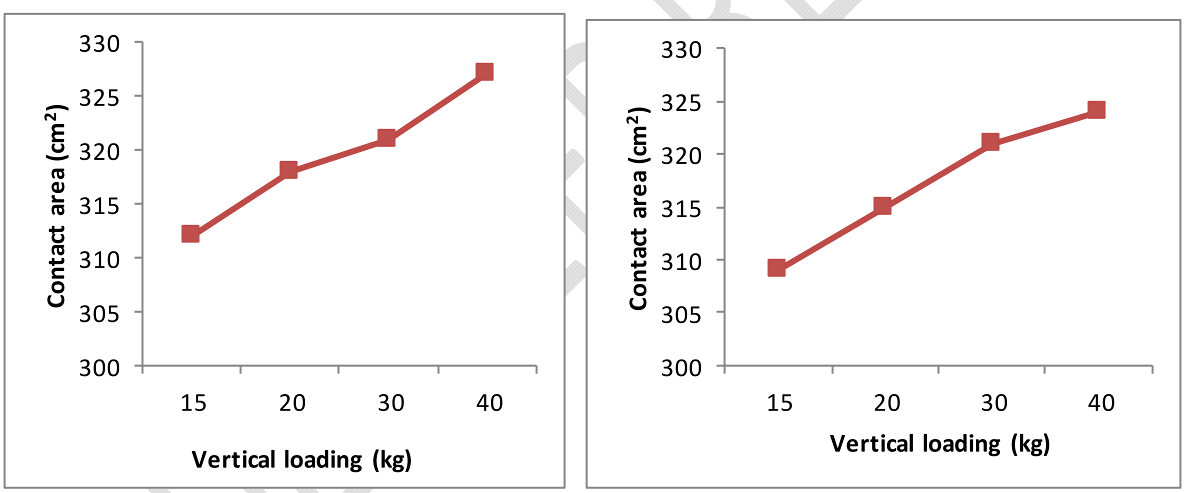

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Figure 9: Effect of Vertical Load and Inflation Pressure (270 kPa) on Contact Area, Test Wheel 2; (b) Effect of Vertical Load and Inflation Pressure (380 kPa) on Contact Area, Test Wheel 2

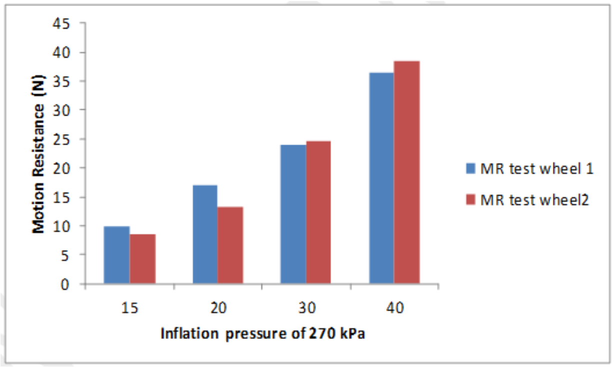

Figure 10. Motion resistance of pneumatic wheels at 270 kPa inflation pressure and at different weight on clay soil surface at 8% moisture content

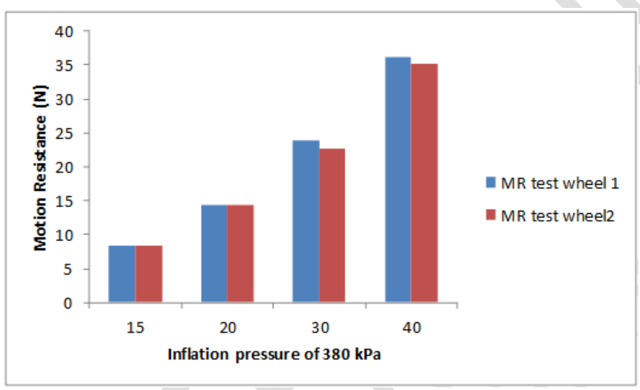

Figure 11. Motion resistance of pneumatic wheels at 380 kPa inflation pressure and at different weight on clay soil surface at 10% moisture content.

Discussions

Effect of soil moisture content and inflation pressure on motion resistance of wheel one (1) and wheel two (2)

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. Table 5 shows the analysis of variance (ANOVA), for the effect of tyre 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 with significant value of 0.017(<0.05) and 0.48 (<0.05) respectively. Moreover, 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 Figures 6-7.

The R^2 value shows exponential fits that best describe the relationship between tyre inflation pressure (P), vertical load (W) and the interaction of them on wheel Motion Resistance. Exponential regression was obtained for the two wheels as shown in Equations 1-4 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.

Predictive models (exponential fit)

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

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

$y = 5.4404e^{0.4721x}$ $R^2 = 0.9977$ Wheel 2, inflation pressure (274 kPa) (3)

$y = 6.7521e^{0.4261x}$ $R^2=0.9914$ Wheel 2, inflation pressure (380 kPa) (4)

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

Effect of vertical weight and inflation pressure on contact area of Wheel one (1) and wheel two (2)

Figures 8-9 showed the relation of tyre contact area pressure with vertical load and tyre inflation pressure. The tyre 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. Average contact pressure increased nearly linearly with increase in vertical load and increase in inflation pressure. Comparing the results of contact area of narrow wheels with the results of Masoud *et al.* (2012) whose research on wheel-soil rolling resistance of narrow wheel with contact area of range of 60-490 cm^2 and Cesbron *et al.* (2008) research on estimate of average ground pressure whose narrow tyre contact area showed that there is not much difference between tyre contact areas in static and dynamic conditions of about 20%

conforms that we can generalize the results of tire contact area in static mod for dynamic mode.

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Comparism between motion resistance of wheel one (1) and wheel two (2) at different loads

Figure 11-12 showed the comparism 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 which ranges from 0.57-0.99 for the two wheels. Kurjenluomar *et al*. (2009) reported "reduction of tyre 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 this experiments were conducted in clay, the results conforms the result of their research, and shows that reduction in inflation pressure increases the MR of tyre. Also Elwaleed *et al.* (2006) reported that reduction in tyre inflation pressure by 171.8 kPa from the recommended value resulted in decrease of tyre motion resistance ratio by 5.01%. However, further reduction by 380 kPa resulted in an increase in tyre motion resistance ratio by 9.96%, but their experiments were conducted on loosened soil condition which was different from this test condition.

Conclusion

A research was carried out to study the effects of different inflation pressures 274 kPa and 280 kPa and vertical loads of 15 kg, 20 kg, 30 kg and 40 kg on the motion resistance of two narrow wheels (90/90-10; Bias/Radial) under two different soil conditions of bulk density of 1.58 g/cm^3 and 1.55 g/cm^3, soil moisture content of 8% and 10% dry basis and soil penetration resistance of 1.02 MPa and 1.5 MPa. It was found that motion resistance ratio increases with increase in vertical load and also with inflation pressure with ANOVA analysis showing significant value of 0.017(<0.05) and 0.48 (<0.05) respectively. Best predictive models established to describe the relationship between motion resistance, tyre inflation pressure and vertical loads were those of exponential fit with 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. Data obtained are relevant in the studies of soil/machine interaction studies such as obtain in soil dynamics in tillage and traction.

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