Effects of Tire Inflation Pressure on Soil Contact Pressure and Rolling Resistance of Farm Tractors

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Summary

The benefits of low inflation pressure of farm tractor tires may include decreased soil-tire interface pressures, increased tire performance, and decreased soil compaction. Measurements of soil contact pressures were made at the centerline of the front tire and the lug tip of the rear tire of a 2 WD farm tractor operated on sandy soil at four combinations of wheel load and inflation pressure. The rolling resistance of the tractor was also measured simultaneously. These measurements showed that as tire inflation pressure was reduced, soil-tire interface stresses decreased 19% and 17% for front and rear tires, respectively, while the rolling resistance of the tractor decreased 25%.

Key words: Rolling resistance, Soil contact pressure, Tire inflation pressure Soil, Tractor, Soil

I. Introduction

Inflation pressure determines tire stiffness, which has a significant influence on the ground contact area of the tire and the pressure distribution over the contact surface. Adjusting tire inflation pressure has been used as a means of reducing soil compaction and improving the tractive performance of agricultural tractors. Effects of inflation pressure on ground contact pressure, pressure beneath the tire as well tractive efficiency, particularly for radial tires, have recently been considered by many researchers (Raper, 1995; Bailey, 1996; Way, 1996; Ryol, 1997; Jun, 2004; Adams, 2004; Pytka, 2005). It is known that optimum tractive performance of a driving tire can be obtained by adjusting the inflation pressure of the tire according to the soil conditions over which it moves. The benefits of lower inflation pressures might include decreased soil-tire interface pressures, increased tire performance, decreased soil compaction, and a smoother ride. Accordingly, inflation pressure has been set at the manufacturer’s recommendation for the actual load on the tire, which is the minimum acceptable inflation pressure for that load. This will minimize soil stresses and compaction, and maximize tractive efficiency.

The tractor is an important component of any farming system, and an understanding of its performance is essential for engineers involved in agriculture to develop the knowledge and skills necessary to analyze and predict tractor performance, and to advise and assist farmers in the choice and efficient operation of a wide range of tractors. Tractive characteristics and soil pressure beneath the tires of tractors are usually determined by conducting either filed experiments or
controlled laboratory soil bin experiments. These tests are useful in selecting tire geometry (width, overall diameter, section height), tire type (radial versus bias), lug design, inflation pressure, and dynamic load on axles for various field operations in different field conditions. Moreover, these test data help design engineers to develop tires that perform better under a given set of operating conditions (Upadhyaya, 1988). Although controlled laboratory soil bin tests are useful for obtaining insights into traction mechanics, the tests are always conducted in remolded soils, which do not behave like natural soils. Field tests with full-scale tractors yield more valuable traction related data.

In this study, the soil contact pressure and rolling resistance of farm tractor were measured at various tire inflation pressures by using spot pressure sensors and a load cell in order to investigate the effects of tire inflation pressure on the change of the soil vertical stress state and rolling resistance caused by the operation of the tractor.

II. Materials and Methods

1. Tractor instrumentation

The tractor used in this study is a 2WD farm tractor (Kubota L200) mounted with a rotary tiller (Fig. 1). The specifications of the test tractor are shown in Table 1.

![Fig. 1 The test tractor](image)

**Table 1 Dimensions of the test tractor**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>1092 kg</td>
</tr>
<tr>
<td>Front axle weight</td>
<td>380 kg</td>
</tr>
<tr>
<td>Rear axle weight</td>
<td>712 kg</td>
</tr>
<tr>
<td>Overall width</td>
<td>120 cm</td>
</tr>
<tr>
<td>Overall length</td>
<td>360 cm</td>
</tr>
<tr>
<td>Wheel base</td>
<td>150 cm</td>
</tr>
<tr>
<td>Front tire</td>
<td>Bridgestone 4.00-R15 4ply rating</td>
</tr>
<tr>
<td>Rear tire</td>
<td>Bridgestone 8.3/8-R24 4ply rating</td>
</tr>
<tr>
<td>Engine</td>
<td>Z 1100 1070 cc 2700 rpm 20 PS</td>
</tr>
</tbody>
</table>
In order to measure the ground contact pressure, the left front and rear tires of the 2WD tractor were instrumented with Kyowa spot pressure sensors (PS-5KC) of 500 kPa capacity on the centerline of front tire and on the lug of the rear tire (Fig. 2 a, b). These sensors are 6 mm in diameter and 0.6 mm in thickness, and respond only to normal pressures against sensor diaphragm.

The internal rolling resistance \((R_i)\) of a tractor, which is generated within the vehicle itself due to friction, vibrations, hysteresis, and the ventilating effect of the tires, is the force necessary to draw the tractor on an asphalt road. Meanwhile, the external rolling resistance \((R_e)\) of the tractor, which is created by soil deformation and does not produce thrust, is a subtraction of the force necessary to draw the tractor on tilled sandy clay soil \((R_t)\) and \(R_i\). A load cell (KT/2T, Keisoku) with capacity of 2kN was mounted on the front drawbar of 2WD tractor (Fig. 2c) for measuring \(R_i\) and \(R_o\) during tests on an asphalt road and sandy clay soil, respectively. Two slip rings (SR/4B, Shinkoh) were mounted on the central parts of the front and rear wheels for making the interface between the rotating parts (tires) and the stationary part (data acquisition system).

2. Test site

Tests were carried out on tilled sandy clay soil in covered site of 20 m in length and 6 m in width. The soil was thoroughly tilled to 250 mm depth by a rotary tiller attached to the 4WD tractor making the soil in two-layer configuration, i.e. the soft tilth on the hardpan. Table 2 gives the initial conditions of the test soil. Moreover, some tests were conducted on a dry asphalt road to measure the internal rolling resistance of the 2WD tractor.

3. Data acquisition

A NR-500 series data acquisition system (Keyence, Japan) and a portable computer were fixed to the 2WD tractor to collect the data from two pressure sensors, the KT/2T load cell. The measurements were recorded on the portable computer at sampling rate of 100 Hz.

4. Experimental procedure

The experiments were conducted by pulling the 2WD tractor forward at a constant speed of approximately 0.3 km/h at various tire inflation pressures \((p_i)\) of 60 kPa, 100 kPa, 160 kPa, and 200 kPa on sandy loam soil and an asphalt road. A 4WD tractor was used to supply drawbar pull.

| Table 2 The physical properties and conditions of the test soil |
|-----------------|------------------|
| Classification  | Top soil  | Subsoil   |
| Depth           | Sandy clay soil | Heavy clay soil |
| Water content   | 0~250 mm       | 250 mm~   |
| Bulk density    | 11 kPa/m       | 18.7 kPa/m |
All tires of the 2WD tractor were first normally inflated up to 200 kPa. After the test at 200 kPa inflation pressure was performed, tire inflation pressure was reduced to 160 kPa, 100 kPa, and 60 kPa and the tests were repeated. Each test was replicated three times in order to minimize the effect of soil non-homogeneity in the test site. After each test, the soil was re-tilled and the soil condition was assumed to be the same for all tests.

In order to calculate the angle velocity of front and rear tires from the velocity of the 2WD tractor, the rolling radii of the tires at different inflation pressure were measured. Table 3 shows the result of measurements.

### Table 3  Rolling radii of front and rear tires at various inflation pressures

<table>
<thead>
<tr>
<th>Inflation pressure (kPa)</th>
<th>Front tire (mm)</th>
<th>Rear tire (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>280</td>
<td>458</td>
</tr>
<tr>
<td>100</td>
<td>283</td>
<td>468</td>
</tr>
<tr>
<td>160</td>
<td>288</td>
<td>470</td>
</tr>
<tr>
<td>200</td>
<td>290</td>
<td>477</td>
</tr>
</tbody>
</table>

In order to calculate the angle velocity of front and rear tires from the velocity of the 2WD tractor, the rolling radii of the tires at different inflation pressure were measured. Table 3 shows the result of measurements.

### 5. Data processing

Since the 2WD tractor was pulled by a 4WD tractor, the maximum contact pressure is assumed to have occurred at the bottom dead center of the tires directly below the axles. The center angle of the tire contact patch was adjusted so that the value of zero on the abscissa represents the bottom center position for the pressure sensors. Each test resulted in three rotations for the front tire and two rotations for the rear tire. That means the number of replications for contact pressure measurement was nine times for front tire and six times for rear tire. The average obtained data were used to plot graphs showing the distribution of the ground contact pressure along the soil-tire contact patch and the peak contact pressures at different tire inflation pressures.

### III. Results and Discussion

#### 1. Soil contact pressure

It can be seen from Fig. 3 that the curves of ground contact pressure for the center angle at different inflation pressures have the same form during the loading and unloading processes of the tires. After the pressure sensor lost contact with the soil, the contact pressure for the front tire still remains, while the contact pressure for the rear tire becomes negative due to the deformation and hysteresis of the front tire tread and the rear tire lug. However, this residual pressure becomes all most zero before the sensor fist contacts the soil in the next rotation.

At any level of tire inflation pressure, the maximum contact pressure of the front tire is lower than that of the rear tire whilst the contact angle of the front tire is much higher than that of the rear tire. When the inflation pressure decreases from 200 kPa to 60 kPa, the ground contact angle increases from 68° to 81° for the front tire, and from 30° to 40.5° for the rear tire (Fig. 4 a), increasing the ground contact area of the tires. Consequently, the maximum ground contact pressure decreases from 118 kPa to 96 kPa, and from 133 kPa to 111 kPa for the front and the rear tires, respectively.
When inflation pressure is reduced from 200 kPa to 160 kPa, the contact angle and peak contact pressure change insignificantly for both front and rear tires. Therefore, the critical tire inflation pressure, at which the front and rear tires of a 2WD tractor perform as a rigid tire, seems to be around 160 kPa. At inflation pressure lower than 160 kPa, the tires will perform as an elastic tire.

2. Rolling resistances

Figure 5 shows the results of internal rolling resistance tests and total rolling resistance tests. The general shape of the obtained curves of rolling resistance with respect to tractor displacement is identical whatever the test condition. The values of the $R_i$ and $R_o$ rolling resistances were calculated from the average of the forces when the velocity of the 2WD tractor was relatively stable.

Figure 6a show the results of internal and total rolling resistance tests, respectively. If we neglected the external component in the rolling resistance tests on the asphalt road, the internal rolling resistance is thus 0.39 kN, 0.26 kN, 0.25 kN, and 0.22 kN for 60 kPa, 100 kPa, 160 kPa, and 200 kPa, respectively, approximately equal to 2% ~ 3.6% of the 2WD tractor’s weight. The $R_o$ rolling resistance consists of the external component $R_e$, which is dependent on the soil-tire interaction, and the internal component $R_i$, which is dependent on friction within the running gear.
The rolling resistance ratio calculated by dividing $R_o$ by the tractor weight is shown in Fig. 6 b. It is pointed out that the increase of tire inflation pressure brought about the increase of the external rolling resistance as well as the increase of the rolling resistance ratio. This is obvious because lower inflation pressure allows a larger footprint of tire, reducing the soil compaction and rolling resistance. Consequently, for regular tillage, the tires should be inflated to the lowest pressure recommended for the load. However, users should not underinflate the tires though, because tires with too little pressure can become unstable, resulting in poor handling and tire damage.

**Fig. 5** Measured external and total rolling resistances at different tire inflation pressures

**Fig. 6** Average internal and external rolling resistances at different tire inflation pressures

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IV. Conclusions

In this study, the laboratory trials for measuring the ground contact pressures and rolling resistances of a 2WD farm tractor at different tire inflation pressures operating on tilled sandy clay soil were conducted. Based on the experimental results, some conclusions can be drawn as the follows.

- Tire inflation pressure greatly affected the soil-tire interface pressures across the surface of the tire. Increased inflation pressure caused soil contact pressures of the front and the rear tires increasing.
- The shape of the tire-soil contact contour changed with inflation pressure. The contact angle between the soil and the tire was increased as inflation pressure decreased.
- Tire inflation pressure had significant effects on rolling resistance of the 2WD tractor. Low inflated tires can reduce the external rolling resistance; hence increase the tractive performance of the tractor.

References

トラクタの接地圧及び走行抵抗における
農用タイヤの空気圧効果

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摘 要

空気圧の低い農用タイヤの利点は，農耕車両の接地圧を減少させ，車両の走行性を向上させる．また，土の圧縮を減少させている．本実験では砂質粘土での走行時に，前，後輪に付けて
いる小型圧力センサーによって，2WD 農業トラクタの接地圧をタイヤ空気圧と荷重の四つの
組み合わせで測定した．更に同時にトラクタの走行抵抗も測定した．実験結果より，タイヤ
空気圧が低い時に前輪と後輪の接地圧がそれぞれ19％と17％減少した．またトラクタの走行抵抗が25％減少した．