Effects of soil mechanical properties on the height and tractive performance of rubber grouser at different moisture contents

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Abstract: Rubber tracked vehicles are commonly used on agricultural machinery that perform agricultural operations such as rice harvesting in soft paddy fields with low bearing capacity. Research was carried out to assess the influence of soil moisture content and mechanical properties on the tractive performance of a rubber grouser with three heights (45 mm, 55 mm, 60 mm). The direct shear test and penetration test were used in this study, which was based on a semi-empirical approach of determining tractive parameters. Direct shear tests were used to measure soil shear strength parameters such as cohesion, adhesion, internal and exterior friction angles. The results of the penetration test were used to determine tractive parameters such as soil thrust, running resistance, and traction, for the penetration test, a device was designed and developed. The experimental results revealed that soil cohesion and adhesion increased linearly with increasing soil moisture content, however adhesion dropped after 30.7%. Similarly, the soil thrust initially increased till 21.5% then decreased. Furthermore, running resistance had a decreasing trend over soil moisture content whereas maximum traction achieved for 45 mm grouser height at 21.5% moisture content. It was concluded that a rubber grouser with 45 mm height had better traction rather than 55 mm and 60 mm, it can be suitably used for designing a track system for a crawler vehicle (e.g., harvester) leading to its greater adoption among the farmers.

Keywords: soil moisture content, traction, rubber grouser, soil mechanical properties, tracked vehicle
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1 Introduction

The track system of a vehicle relies on soil characteristics to provide traction[1]. The term “mobility” refers to the connection that exists between the soil and the vehicle. In order to assess vehicle mobility and traction it is necessary to identify the mechanical properties of soil, which are thought to be connected to vehicle mobility[2]. The accuracy of off-road vehicle predictions is determined by an accurate assessment of the soil’s mechanical properties. Aside from the essential vehicle qualities, terrain topography and soil conditions have an impact on vehicle performance. To effectively analyze the mechanical properties of soil in terms of mobility of tracked vehicles, measurements under load conditions alike to those imposed by tracked vehicles are required[1,3,4].

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Tracked vehicles are typically employed in agriculture or construction because the speed of vehicles is slow to work[1,5]. Recently, rubber tracked vehicles are commonly used on agricultural machinery that perform agricultural operations on soft soil with low bearing capacity, in agricultural operations such as rice harvesting in paddy fields, the movability of the vehicle plays an important role due to its need for frequent changes in working directions[6]. To avoid losing traction when driving off the pavement, heavier off-road vehicles must have a low ground contact pressure and keep their mobility system on the ground surface, because a track system has a larger ground contact area than a wheel system so it can accomplish this, the track system is generally ideal for off-road conditions[7,8]. Moreover, the traction force developed by the track system is usually higher than that of wheel system. For these reasons, the track system is preferable for mobility system of the heavy off-road vehicle for greater mobility over a wide range of terrains. When a tracked vehicle travels in a straight line, a terrain piece beneath the track is repeatedly loaded by successive roadwheels. The terrain's response to repeated loading should thus be taken into account when calculating normal pressure and shear stress distributions[9].

Traction is defined in the literatures by many researchers[1,8,10] as the ability to prevent two contacting surfaces from shear failure. Alternatively, traction is the ability of the tractive element (track etc.) to generate enough forces to overcome all types of vehicle resisting forces[8]. It plays a dominant role in trafficability of the vehicle moving over an interacting surface such as sand or soil. If sufficient traction is not created, it may lead to shear failure along the contact planes, such as in the case of soft soils, digging the interaction element into the surface resulting in sinkage. This develops an agglomeration of soil in front of the tractive element leading to the phenomenon referred to as the bulldozing effect[8]. In order to prevent the bulldozing effect, sinkage, and other factors such as shear failure that leads to loss of traction, a proper tread system needs to be developed. An efficient tread system needs lower effort in generating trafficability leading to improved fuel efficiency.

Off-road tracked vehicle performance has been evaluated using a range of methodologies (empirical, semi-empirical, and numerical methods). The empirical methods are based on the findings of a number of representatives tracked vehicles in a variety of terrains, during the Second World War, Waterways Experiment Station (WES) of the U.S. Army Corps of Engineers developed a standardized cone penetrometer, and the cone resistance was empirically correlated with the 'go' and 'no go' performance of the vehicle. For an accurate solution to soil-track interaction problems, numerical approaches such as the Finite Element Method (FEM) and the Discrete Element Method (DEM) have been applied. In the numerical approach, complicated soil-track systems are numerically simulated, and off-road tracked vehicle performance is evaluated using computer-aided programs (codes). In the Terramechanics field, the DEM has been mainly applied to the investigations of soil-wheel/track interaction problems[11-14].

To overcome the weaknesses of empirical method and numerical method, semi empirical method has been evolved firstly by Bekker[1]. In this method, mathematical models, which can take into consideration influence factors on off-road tracked vehicle performances, are established on the basis of traction mechanisms of off-road tracked vehicle. Considering the fact that off-road tracked vehicle performances can be determined by its ability to develop traction which is defined as the difference between soil thrust and motion resistances, each mathematical model for both soils thrust, and motion resistances is expressed as a function of the influence factors (shear properties of the soil, track system configurations, and normal contact pressure). Because the soil mechanics are quite complex and direct measurement of the force of wheel/track-soil interaction is difficult, most of the equations for estimating traction performance have been empirically established[15]. Wong et al.[9] also evaluated the tractive capability of off-road vehicles' wheels and tracks. However, it was more concerned with the design of the running gear than with the impact of soil moisture content.

The rubber tracks are currently mainly used on agricultural tractors and combines, thus, to predict the off-road tracked vehicle performance, it is imperative that the soil thrust, and motion resistance need to be approached based on soil-tack interaction theory. Between these two basic features of soil track interface behavior can be predicted. In this work, particular attention was focused on the tractive performance of rubber grouser with different grouser heights under the 13 moisture contents.

2 Material and methods

2.1 Soil preparation

The soil for the experiment was collected from the school's experimental location and sun dried before being layered into the soil bin until it reached a height of 400 mm. The calculated amount of water was added, properly mixed, and allowed for 24 h to achieve homogeneity and a greater moisture content[16]. Soil samples were obtained from the soil bin at three different locations, and the soil moisture content was measured using the oven dried method[17]. 13 moisture contents were used for the research as: 7.5%, 10.0%, 12.0%, 15.0%, 16.7%, 20.0%, 21.5%, 25.0%, 26.2%, 30.0%, 30.7%, 35.8% and 38.0%. Soil bulk density was measured for every moisture content. The experimental work for this study was separated into two parts: direct shear test and penetration test.

2.2 Direct Shear Test

A strain-controlled direct shear test equipment (ZJ Nanjing Soil Instrument Factory Co., Ltd. Nanjing, China. Figure 1) was used to measure the shear strength parameters of soil for each moisture content. Shear box, digital display, proved ring, and various weights were all part of this device. The soil sample was put into the upper part and the circular rubber plate was put in bottom of shear box to measure the soil adhesion with rubber and external frictional angle. The shear strength of soil and soil adhesion were calculated by following equations[18]:

$$\tau = C + \sigma\tan\varphi \tag{1}$$

$$\tau = C_a + \sigma\tan\delta \tag{2}$$

where, τ is shearing stress, kPa; σ is normal stress, kPa; C is soil cohesion, kPa; φ is internal friction angle. Furthermore, when the rubber plate was at the bottom of shear box then, C_a is soil adhesion and δ is external friction angle.

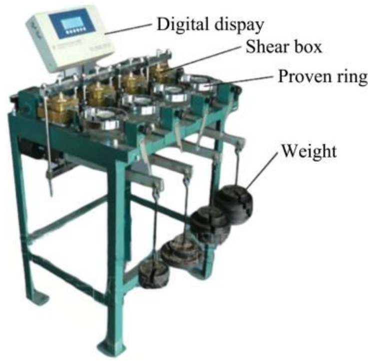

Figure 1 Direct shear test device

2.3 Test device and penetration test

The typical pressure-sinkage relationship is measured by the penetration test. If test soil is assumed homogeneous within the depth of interest, Bekker's sinkage model (Equation (3)) can be used to evaluate the pressure-sinkage relationship of experimental soil[1]:

$$p = (k_c/b + k_\phi)z^n \tag{3}$$

where, p is normal pressure, kPa; b is the width of rubber plate, cm; k_c is soil cohesive modulus; k_ϕ is soil friction modulus; and n is sinkage exponent. The values of k_c, k_ϕ and n are derived from the results of rubber plates according to Bekker's method and reported in Table 1. There were two rubber plates with dimensions of 40 mm×30 mm and 40 mm×25 mm used for the experiment.

Table 1 Soil cohesive (k_c), friction (k_ϕ) and sinkage modulus (n)

Soil Moisture content/%	k_c/kN $(m^{n+1})^{-1}$	k_ϕ/kN $(m^{n+2})^{-1}$	n
7.5	0.162	1.354	1.231
10	0.181	1.201	1.159
12.0	0.195	1.102	1.021
15	0.209	0.926	1.011
16.7	0.221	0.887	0.983
20	0.256	0.689	0.919
21.5	0.258	0.621	0.875
25	0.346	0.512	0.789
26.2	0.415	0.478	0.727
30	0.593	0.273	0.632
30.7	0.618	0.342	0.716
35.8	0.525	0.558	0.863
38.0	0.329	0.685	0.982

A penetration device was designed and constructed for the penetration test (Figure 2). The penetration test device consisted of soil bin (1500×500×500 mm), an AC motor assembled with spur rod and a load cell (ATO-LCS-DYLY-106), and a displacement sensor (ATO-LDSR, 400 mm) was used to penetrate the plates into soil. A load cell and displacement sensor were used to detect the pressure acting on the test plate as well as the displacement. For each moisture content, the penetration test was carried out in triplicate. The data acquisition was performed by a DAQ device (Ni-6009) with the interface of LabView software.

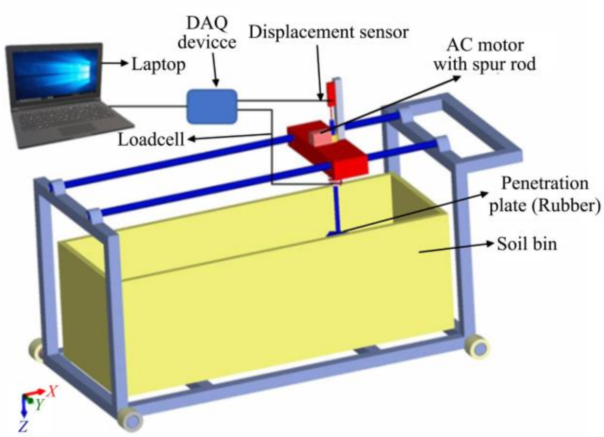

Figure 2 Designed device for the Penetration test

2.4 Proposed single grouser shoe details

The table below shows the specifications of a single grouser shoe model with 3 different grouser heights.

Table 2 Dimensional parameters of a single grouser shoe model

Grouser shoe parameters	Symbol	Dimensions/mm
Height of grouser shoe	h	45, 55, 60
Length	L	100
Width	B	150
Grouser thickness ratio	λ	0.45, 0.55, 0.60
Thickness of shoe plate	t	40

2.5 Tractive performance parameters

To determine the tractive performance of a rubber grouser shoe (Figure 3) at various soil moisture contents, the thrust created by a single grouser shoe must be predicted, and the shearing condition beneath the grouser shoe must be determined. Soil thrust was calculated from the results of shear and penetration test parameters with help of Equations (4)-(11). The thrust exerted at the grouser's tip surface denoted by F_1 was calculated by Equation (4).

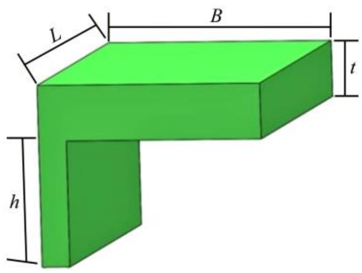

Figure 3 Model of the grouser shoe

$$F_1=\lambda LB(C_a+q_1\tan\delta) \tag{4}$$

where, λ is grouser plate thickness; L is grouser shoe length; B is width of grouser shoe; C_a is soil adhesion, q_1 is contact pressure on top of the grouser; δ is external frictional angle of soil with rubber grouser. Moreover, the thrust on sides (lateral) of grouser shoe (F_2) was obtained by Equations (5)-(8).

$$F_2=2(F_{sg1}+F_{sg2}+F_{ss}) \tag{5}$$

$$F_{sg1}=\lambda hL\left[C_a+q_1\tan\delta\tan\varphi\left(45-\frac{\varphi}{2}\right)\left\{\frac{\gamma_t(2Z_0+h)}{2}\tan\left(45-\frac{\varphi}{2}\right)-2C\right\}\right] \tag{6}$$

$$F_{sg2}=Z_0L\left[C_a+q_1\tan\delta\tan\varphi\left(45-\frac{\varphi}{2}\right)\left\{\frac{\gamma_tZ_0}{2}\tan\left(45-\frac{\varphi}{2}\right)-2C\right\}\right] \tag{7}$$

$$F_{ss}=(1-\lambda)hL\left[C+\left\{q_2+\frac{\gamma_t(h+2Z_0)}{2}\right\}\tan^2\left(45-\frac{\varphi}{2}\right)\tan\varphi-2C\tan\left(45-\frac{\varphi}{2}\right)\tan\varphi\right] \tag{8}$$

where, F_{sg1} denotes the shearing force on sides of grouser shoe, N; h is grouser height, m; φ is internal frictional angle, rad; γ_t is soil bulk density, kg/m^3; Z_0 is soil sinkage, m; F_{sg2} denotes the shearing force generated on spacing of lateral sides, N; q_2 denotes the pressure on spacing surface of grouser shoe, Pa; and F_{ss} is force generated below the lateral sides of grouser shoe, N. The shearing force beneath the spacing surface of grouser shoe (F_3) was obtained by Equation (9).

$$F_3=(1-\lambda)LB(C+q_3\tan\varphi) \tag{9}$$

where, q_3 is the stress on the soil failure plane, and it was calculated by Equation (10).

$$q_3=q_2+\gamma_t h \tag{10}$$

The total soil thrust was calculated by Equation (11).

$$F=F_1+F_2+F_3 \tag{11}$$

The running resistance of grouser shoe (R) with interaction of soil was determined by Equation (12).

$$R=\frac{k_c+Bk_\phi}{n+1}\{(h+Z_0)^{(n+1)}\lambda+Z_0^{(n+1)}(1-\lambda)\} \tag{12}$$

The total traction of a single grouser shoe was determined by Equation (13).

$$T=F-R \tag{13}$$

3 Results and discussion

3.1 Soil bulk density

The bulk density of soil at different moisture contents is shown in Figure 4. The results showed an increasing trend between bulk density and soil moisture content. The bulk density was increased with increase in moisture content, the maximum was at 38.0% and minimum was at 7.5%. Soil moisture content had a significant effect on bulk density, the coefficient of correlation was 0.9102. If soils are wetter than field capacity, bulk density may increase[19,20].

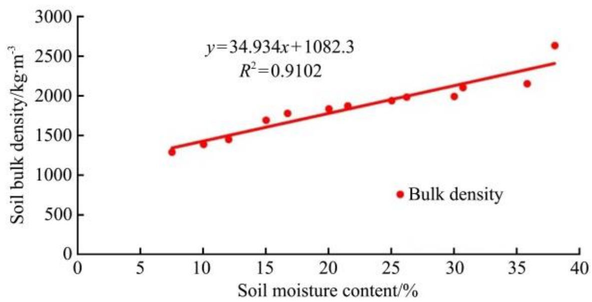

Figure 4 Soil bulk density at different soil moisture contents

3.2 Soil cohesion and adhesion with rubber grouser

The results of soil cohesion and soil adhesion with rubber at different soil moisture contents are presented in Figure 5. According to the graph, soil cohesion and adhesion have similar increasing trend over soil moisture content, the coefficient of correlation were 0.9564 and 0.8186 obtained for cohesion and adhesion with rubber, respectively. Soil cohesion and rubber adhesion were all low when the soil moisture content was low, but as the moisture content increased, they increased until they reached their respective peak values. Then soil adhesion with rubber proceeded to drop as soil moisture content increased, eventually reaching a low value when soil moisture content was high because when the soil moisture content was at 30.7% it had reached the threshold that caused soil lubrication, and the friction coefficient in this case dropped as the amount of water increased. When wetted, soil cohesion was found to be significantly higher, and adhesion increased to the highest value at a moisture content of 27%, but gradually decreased at higher moisture contents[21]. Adhesion increases as the moisture content of the soil increases; by adding water, moisture films were formed between the soil and the rubber, resulting in an increase in adhesion to a specific limit[22,23]. The adhesion between rubber and soil is less than the internal cohesion of the soil[24]. When the soil moisture content was between the plastic and liquid limits, soil adhesion increased and was at its peak[20,25].

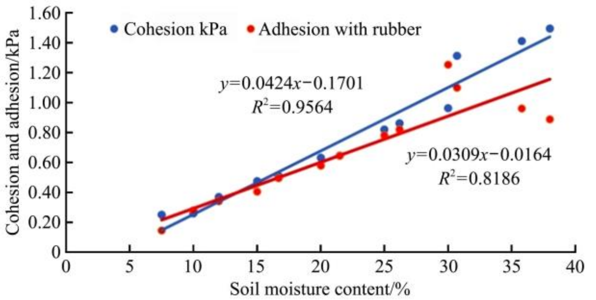

Figure 5 Soil cohesion and adhesion with rubber grouser at different soil moisture contents

3.3 Internal frictional and external frictional angle for rubber grouser

Figure 6 shows the results of a direct shear test which was used to determine the internal and external friction angles at 13 levels of soil moisture contents. Throughout the experiment, the notable effect of soil moisture content on both angles was found, both angles linearly decreased as the moisture content increased, with coefficients of correlation of 0.9774 and 0.988 for the internal and external friction angles, respectively. The graph showed a similar decreasing trend of both angles toward the soil moisture content. The lack of a sufficient water film to produce a suitable lubricating effect is the reason for these reductions in both internal and external friction (soil-rubber). The major and minor decrease was at 38.0% and 7.5% moisture content respectively. With increasing moisture content, the angle of shearing resistance decreased[26]. The results are similar to those reported by a number of authors, for example[27,28].

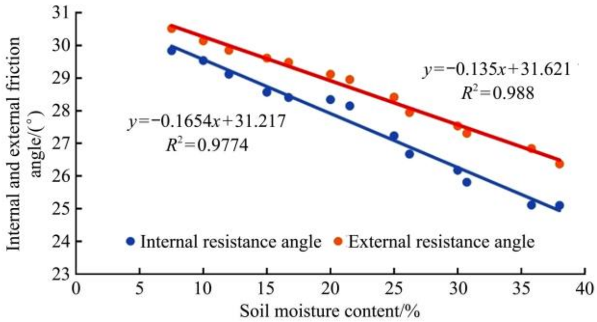

Figure 6 Soil internal and external friction angle with rubber grouser at 13 different moisture contents

3.4 Pressure and sinkage of soil with rubber plate

The pressure and sinkage data were determined by newly designed penetration device based on bavemeter technique developed by Bekker. Figure 7 presents the results of pressure and sinkage of soil at 7.5%-15.0% moisture content for penetration rubber plate 1 and 2, Figure 8 show the results of 16.7%-25.0%, and Figure 9 report the results of 26.2%-38.0%. These all results had a similar increasing trend over sinkage, as pressure increases the sinkage of soil also increased. The maximum value of pressure and sinkage was observed at 38.0% moisture content for plates 1 and 2, accordingly. It is evident from graphs that the maximum sinkage was at high level (38.0%) moisture content, maybe the reason is when soil becomes softer the penetration plates will enter in soil deeply, and the result will be more sinkage. All results have linear trend with considerable values of coefficient of correlation. The research results are consistent with past researches[29-34].

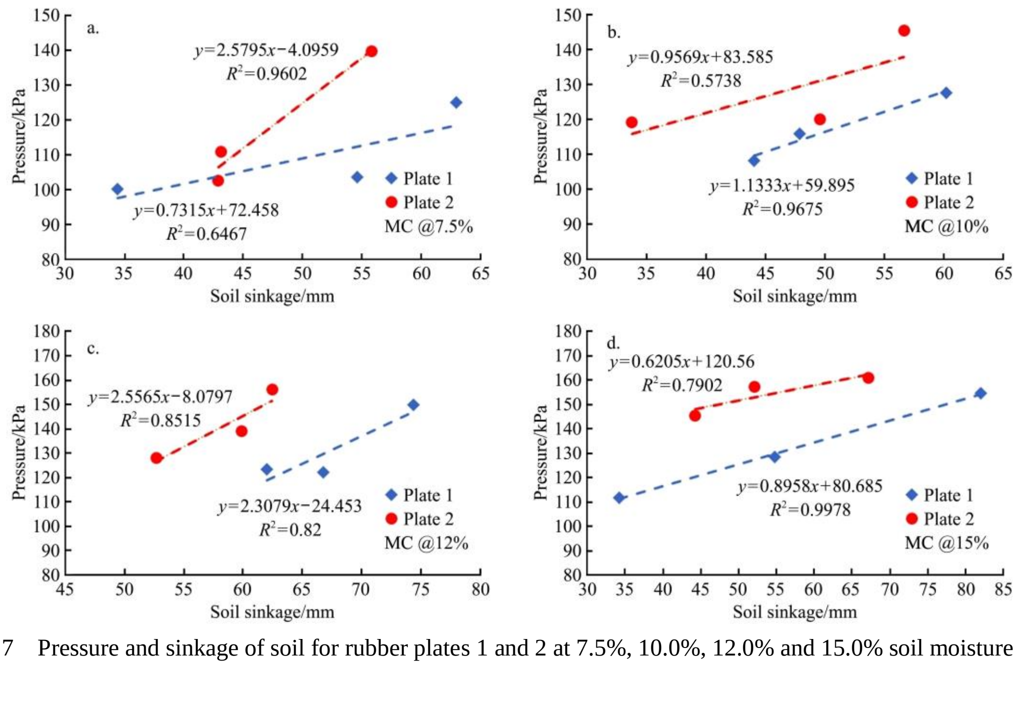

Figure 7 Pressure and sinkage of soil for rubber plates 1 and 2 at 7.5%, 10.0%, 12.0% and 15.0% soil moisture content

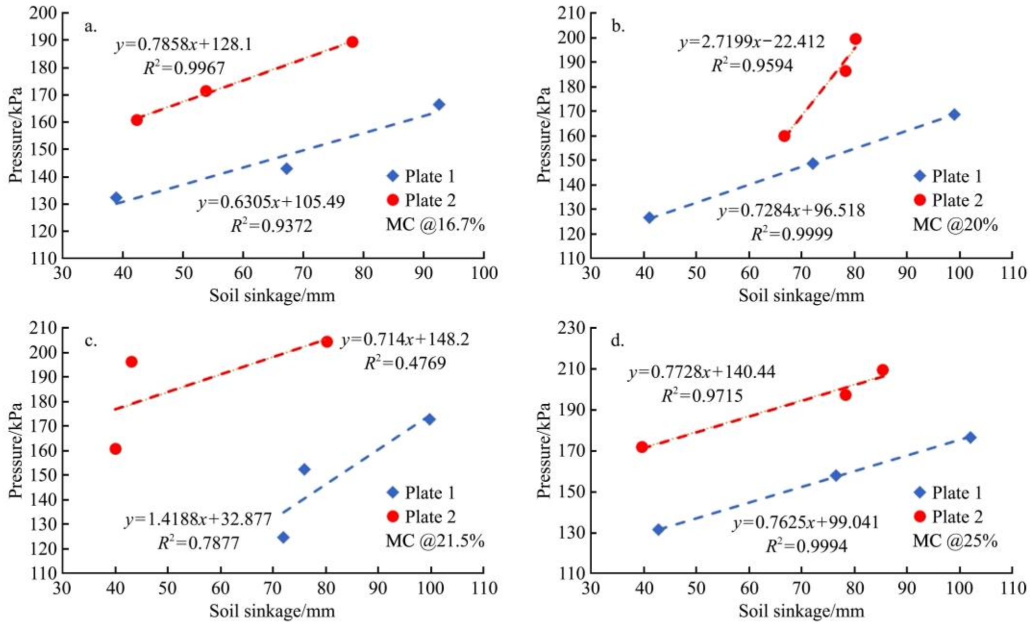

Figure 8 Pressure and sinkage of soil for rubber plates 1 and 2 at 16.7%, 20.0%, 21.5% and 25.0% soil moisture content

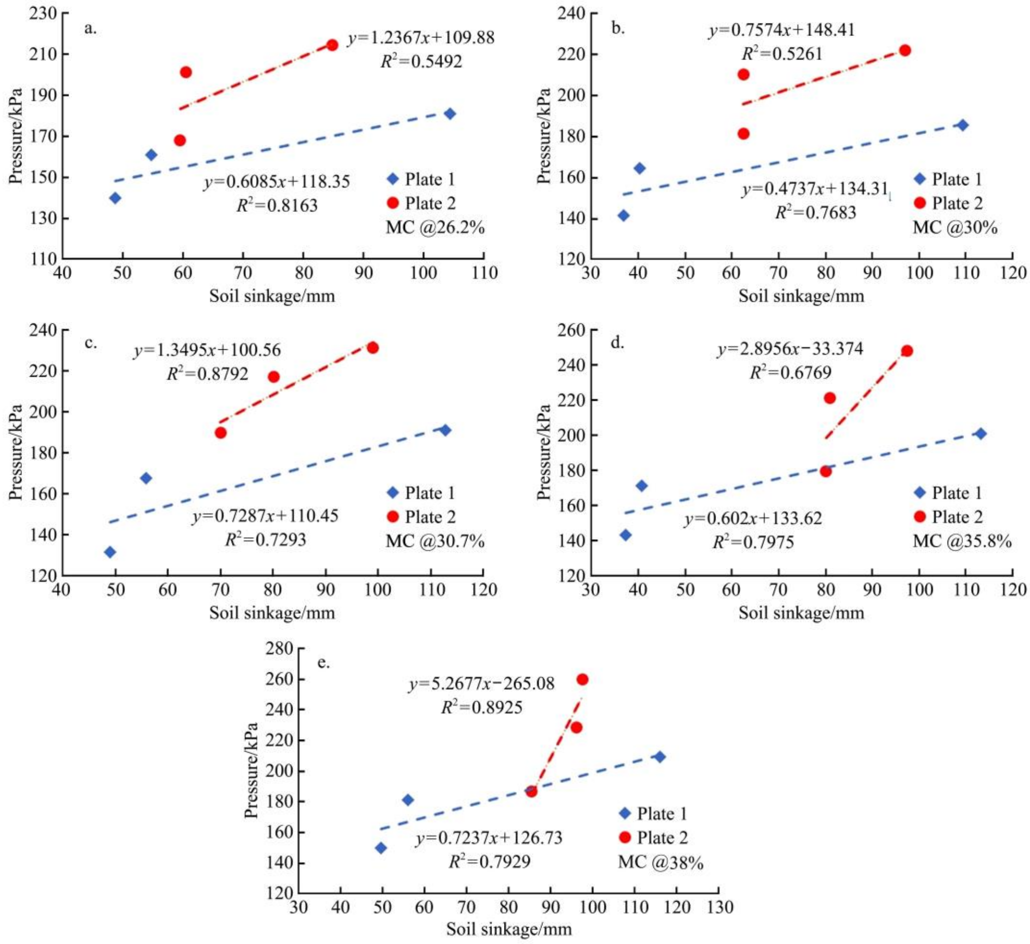

Figure 9 Pressure and sinkage of soil for rubber plates 1 and 2 at 26.2%, 30.0%, 30.7%, 35.8% and 38.0% soil moisture content

3.5 Total thrust of rubber grouser at various soil moisture contents

The resistance to soil deformation secured between each grouser shoe on the underside of the track, as well as on the sides and bottom of the grouser shoe, is the thrust of a tracked vehicle. It is represented by the sum of soil and mechanical (metal or rubber) shear resistance. The thrust generated at various interfaces of a single grouser shoe with three grouser heights (60, 55, and 45 mm) at 13 moisture contents of soil varying from 7.5% to 38.0% is shown in Figures 10a-10c; a is the thrust at the grouser's tip (F_1), b is the spacing between the lateral sides of the grouser (F_2), and c is the grouser's bottom surface (F_3). For all three grouser heights, the maximum thrust for F_1 and F_3 was 6.76456 kN and 7.93816 kN at 45 mm height, respectively, whereas F_2 was 7.03282 kN at 60 mm height for 30% moisture content, while the minimum thrust for F_1 and F_2 was 0.31887 kN and 1.13924 kN at 55 mm height, respectively. Furthermore, at 60 mm height, F_3 had a minimum thrust of 1.09487 kN. The best fit line and coefficient of correlation were obtained using the Gauss method of nonlinear curve fitting.

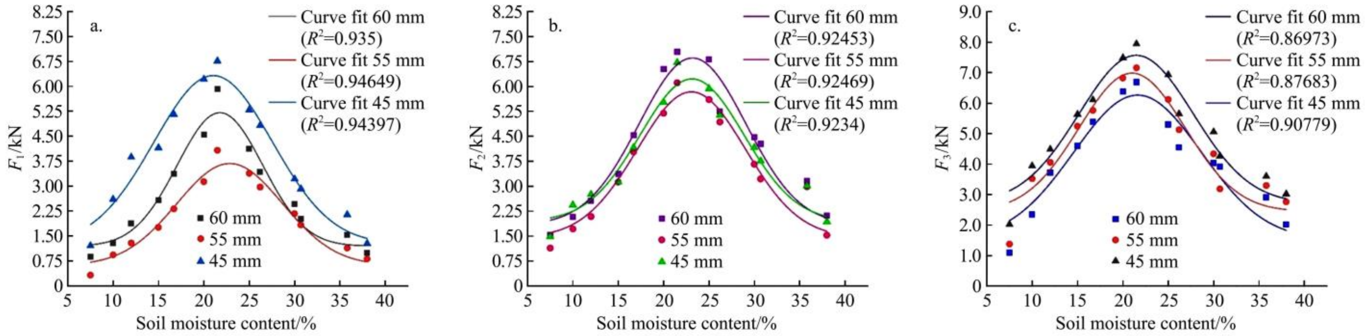

Figure 10 Soil thrust at grouser tip surface, lateral side spacing, and grouser surface and bottom surface spacing with three grouser heights at 13 moisture contents

The total thrust of a single grouser shoe is the sum of all thrust found at different interfaces and sides. Total thrust of rubber grouser is shown in Figure 11. The result indicated that when moisture content rises to a particular level (21.5%), overall thrust increases, and then decreases for 60 mm, 55 mm, and 45 mm grouser heights, respectively. The maximum rise in thrust was recorded for 45 mm grouser height at 21.5% soil moisture content. For 60, 55, and 45 mm grouser heights, the coefficients of correlation were 0.93715, 0.92828, and 0.93613, respectively. The results agree with that of the references [20] and [35]. The increase of thrust for the multiple grouser system is a useful indicator of track efficiency[36].

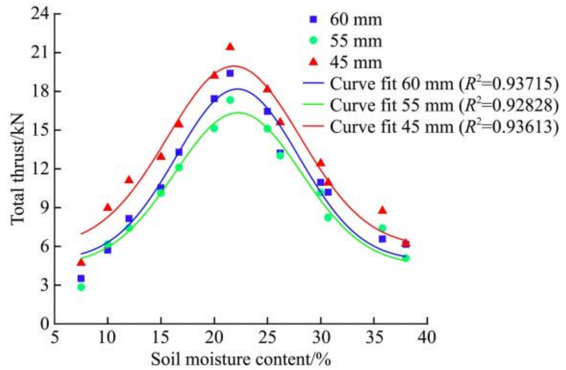

Figure 11 Total soil thrust generated at rubber grouser with three heights at 13 moisture contents

3.6 Running resistance of rubber grouser at different moisture contents

The results of running resistance of rubber grouser shoe with three grouser heights at 13 levels of soil moisture contents are shown in Figure 12. The results showed an increasing trend, implying that as soil moisture content increased, thus increased running resistance. The major rise was recorded for 45 mm grouser height as compared to 60 mm and 55 mm height at 38.0% moisture content. Running resistance decreased as grouser height was increased; this could be due to minimal sinkage. R-square 0.98917, 0.99046 and 0.98821 were calculated for 60 mm, 55 mm and 45 mm grouser height, respectively. It was found that the running/motion resistance of tracks is highly influenced by the strength of the soil, and therefore it is higher for soft soils than that for hard soils[37]. The results showed good relation with the previous research such as; The influence of grouser height on rubber grouser running resistance has been evident as a result of increased passive earth pressure on contact area between soil and grouser because of changes in grouser height[20,38-40].

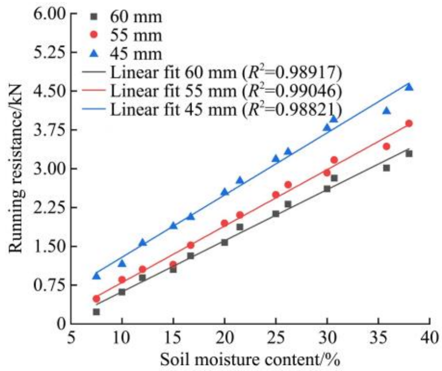

Figure 12 Running resistance of rubber grouser with three heights at 13 moisture contents

3.7 Traction

Figure 13 shows the experimental results of traction/tractive force generated on a rubber grouser with three grouser heights at 13 different soil moisture contents ranging from 7.5% to 38.0%. The traction results revealed that at 7.5% moisture content, the traction began to rise until it reached 26.2%, and that when soil moisture content increased further, the traction dropped significantly at all three grouser heights. The 45mm grouser height had the highest traction (18.65 kN) at 21.5% soil moisture content, while the 55 mm height had the lowest (1.22 kN) at 38.0% soil moisture level. The findings reveal that when the grouser's height is kept to a minimum, traction is maximized. On the other hand, long grousers may cause rapid wear if the vehicle is to be operated on frictional soils, they might substantially reduce the vehicle's tractive performance on wet clay soils. In harder soil conditions, higher tractive efficiencies could be attained, and when the moisture content increased to a certain limit, the tractive efficiency dropped[37].

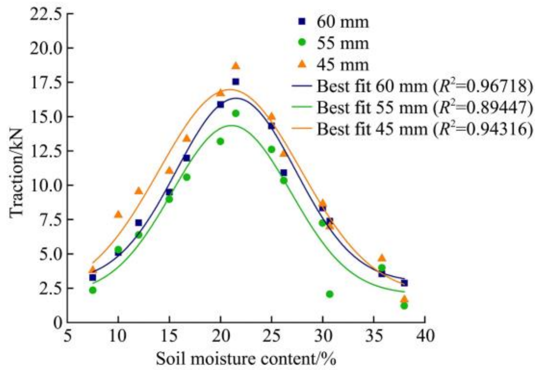

Figure 13 Traction generated on rubber grouser with three heights at 13 moisture contents

4 Conclusions

The rubber grouser of proposed dimensions was tested for tractive performance at 13 levels of soil moisture contents under controlled conditions in a soil bin. The study used a semi-empirical approach and included two components: direct shear testing and penetration tests. Two penetration plates of rubber were used for penetration test. The main findings were that the density of soil was increased by the increase in moisture, soil cohesion and adhesion were linearly increased with moisture content, but adhesion was decreased after 30.7% moisture content, for both plates, the pressure and sinkage of every moisture content increased linearly. The maximum soil thrust, running resistance and traction was 21.418 kN, 4.561 kN and 18.65 kN for 45 mm grouser height at 21.5%, 38.0% and 21.5% soil moisture content, respectively. it is concluded that the rubber grouser with 45 mm height achieved major traction at 21.5% soil moisture content, it can be suitably used for designing a track system for a crawler vehicle (e.g., harvester) leading to its greater adoption among the farmers.

Acknowledgements

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