

MOISTURE-DEPENDENT TRACTIVE PERFORMANCE OF SINGLE GROUSER SHOE IN PADDY SOIL: A MECHANICAL PROPERTIES ANALYSIS

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Abstract

The mechanical properties of soil are most pertinent to the tractive performance of an off-road tracked vehicle. The purpose of this study was to determine the effect of soil mechanical properties on the tractive performance of a single grouser shoe. Under controlled paddy soil conditions, the experiments comprised five soil moisture contents (10, 15, 20, 25, and 30%) and a single grouser shoe. Soil (soil reaction force, sinkage, cohesion, adhesion, internal and external friction angle) and tractive performance parameters (thrust, running resistance, and traction) were obtained by direct shear and penetration tests. A sensor-based soil bin was designed and constructed for the penetration test. The results revealed that the highest cohesion and adhesion were found for 10%, whereas the lowest were at 30% moisture content. Similarly, the maximum internal and external friction angles were obtained for 10% and 15%, while the minimum was at 20% and 25%, respectively. Furthermore, the maximum running resistance and soil sinkage were obtained for 30% and minimum at 10%. Moreover, soil thrust and traction had a linear decreasing trend towards soil moisture content. It was concluded that a tracked vehicle with the proposed dimensions of the track shoe could be operated under moderate moisture content under paddy soil for achieving better traction.

1. Introduction

Soil conditions significantly affect the traction performance of off-road or tracked/wheeled vehicles. Soil properties are important for generating traction for soil track systems (Shaikh et al., 2022). The key to off-road vehicle performance prediction lies in the proper evaluation of the mechanical properties of the field (Abubakar et al., 2010; Yokoyama et al.,

2020). To determine the soil at a certain time, it is necessary to determine the soil parameters in a mathematical model related to mobility, efficiency, cost, and other operational requirements. The mechanical properties of the soil play a very important role in the traction characteristics of a tracked vehicle; for the same soil with different soil water contents (MC), the

traction characteristics of a tracked vehicle will be different (Mari et al., 2015, 2024).

Tracked vehicles have attracted the attention of many researchers because of their larger contact area with the ground, which leads to better float and traction than wheeled vehicles, making them suitable for rough terrain. Tracked vehicles are used in various fields, such as mining, forestry, agriculture, planetary exploration, the army, and construction (Wong, 2001). The tractive performance of tracked vehicles, including propulsion and resistance, is very important for terrain trafficability and is influenced by vehicle and soil factors. Grousers are devices intended to increase the traction of continuous tracked vehicles on deformable terrain by enhancing the interaction between the track and the ground surface (Yokoyama et al., 2020; Nakashima et al., 2013). This is achieved by teeth equipped on the crawler tracks, which function similarly to conventional tire treads and are commonly manufactured from hardened forged steel.

The tractive performance of off-road vehicle prediction depends on the appropriate assessment of mechanical properties (soil cohesion, soil adhesion, and angle of internal and external friction, etc.) of the soil. Mobility is a relationship between soil and the vehicle. To assess the mobility and traction of vehicles, it is important to determine the mechanical properties of the soil, which are believed to be related to the mobility of vehicles. To correctly determine the mechanical properties of in terms of the mobility of off-road vehicles, it is necessary to carry out measurements under load conditions similar to those imposed by vehicles. The vertical load applied by the off-road vehicle to the soil causes sinkage, while the horizontal load created by the track/wheels on the soil surface causes the development of shear strength and the associated slip (Fu et al., 2019). Determining the mobility and traction of off-road vehicles requires a thorough understanding of soil mechanics, since it is necessary to use a track / wheel to determine power transfer between the vehicle and the soil (Shaikh, Li, Zheng, et al., 2021).

Traction is a force derived from the interaction between the track and soil. It can be affected by two types of factors: soil conditions and shoe

dimensions (Ge et al., 2019). The effects of the soil on tractive performance were obtained under soft conditions over 50% (Shaikh, Li, Zheng, et al., 2021). The methods developed for the study of the traction of the track-soil interaction are empirical, semi-empirical, and computer methods (Li et al., 2022). The empirical model was originally developed by the U.S. Army Waterway Experimental Station (WES) to meet military needs in predicting the performance of land-based off-road vehicles, including concepts of “go / no go” and mobility index (Baek & Chung, 2018). A semi-empirical approach named the bevameter technique for prediction of traction of a tracked vehicle was developed by Bekker (Rashidi et al., 2012). Hiroshi made a computer approach by using “The Discrete Element Method (DEM)” program for specific ability to assess total traction potential based on interaction studies of computing reactions and soil behaviors. Regardless of the type of method chosen for predicting traction, soil parameters should be known at first (Nakashima et al., 2015).

Sinkage occurs when a known load is applied to the surface of the soil, and the area under the load sinks in the soil at a certain depth until the resistance of the soil is balanced with the applied force. Soil pressure resistance uses two parameters for characterization: soil cohesion and internal friction angle (Shaikh, Li, Ma, et al., 2021). The tractive performance of the single-track shoe (grouser) can be predicted by considering the normal stress distribution and shear at the front of the soil path and 3D geometry of the contact surface. In the past several decades, numerous studies have examined the traction performance of tracked components, including the effects of grouser geometry and soil conditions on single grouser shoes (Ge et al., 2019; Shaikh et al., 2021). Nevertheless, there is still limited work that systematically links measured soil mechanical properties (such as cohesion, adhesion, and friction angles) with the tractive performance of a single grouser shoe in paddy soils.

The present study addresses this gap by using the semi-empirical method developed by Bekker to predict the traction performance of a single shoe in certain soil conditions and evaluate the

mechanical properties of soil under the sensor-based soil bin.

2. Materials and Methods

2.1. Theoretical approach

Accordingly, when a vertical load was applied to a single grouser shoe, the vertical load was shared

between the grouser and the support plate. The proposed model and schematic depiction of the forces acting on a single-track shoe are shown in Fig.

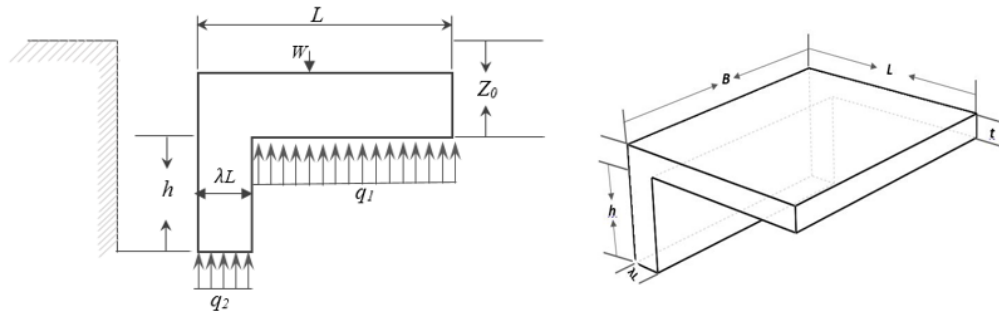


Fig. 12 Forces acting on single track shoe

Single-track shoe parameters: the track shoe vertical load W , L track shoe pitch (cm), track shoe width B (cm), grouser height h (cm), and the ratio of grouser plate thickness and SGS length λ . Thus, the vertical load on the top

$$W = q_1 \lambda L B + q_2 (1 - \lambda) L B \quad (1)$$

Although both q_1 and q_2 track soil stress, because the grouser of the track shoe and the soil at different compression, so q_1 and q_2 are not as

$$q_1 = K(h + Z_0)^n$$

$$q_2 = K Z_0^n \quad (2)$$

where K is the soil deformation modulus, n is the soil deformation index, and Z_0 is the soil

$$K = \frac{k_c}{B} + k_\phi$$

where k_c is the soil cohesion within the deformation modulus (kN/m^{n+1}) and k_ϕ is the

$$W = \left(\frac{k_c}{B} + k_\phi \right) L B \{ (h + Z_0)^n \lambda + Z_0^n (1 - \lambda) \} \quad (3)$$

The sinkage of a single grouser shoe can be measured according to Bekker's pressure-sinkage relationship as follows:

$$p = \left(\frac{K_c}{b} + K_\phi \right) Z^n \quad (4)$$

where p is the pressure (N), b is the width of the penetration plate (cm), and k_c , k_ϕ , and n can be obtained from the results of at least two tests on plates of two sizes with different widths. The tests produce two curves:

$$P_1 = \left(\frac{K_c}{b_1} + K_\phi \right) Z^n \quad (5)$$

$$P_2 = \left(\frac{K_c}{b_2} + K_\phi \right) Z^n \quad (6)$$

Sinkage gives rise to running resistance. Therefore, the running resistance of a single-track shoe can be calculated using eq 9:

surface of the contact pressure grouser q_1 (Kpa) and the bottom surface of the track shoe pressure q_2 (Kpa) have the following relationship:

uniform load distribution as load size by track, so they are described as equation (2) and (3) as follows:

sinkage (cm). The value of K can be determined using equation (4):

friction modulus of soil (kN/m^{n+2}). Therefore, equation (1) yields the following relationship:

$$R = \frac{k_c + Bk_0}{n+1} \{ (h + Z_0)^{(n+1)}\lambda + Z_0^{(n+1)}(1 - \lambda) \} \quad (9)$$

Soil thrust is the most vital parameter for traction of the single-track shoe. The thrust is the resultant of the shearing force on the tip surface of the grouser (F_1), the shearing force of the

$$F_1 = \lambda LB(C_a + q_1 \tan \delta)$$

where C_a is soil adhesion and δ is the external friction angle of the soil. Furthermore, the shearing force of grouser's lateral sides is divided

$$F_2 = 2(F_{sg1} + F_{sg2} + F_{ss}) \quad (10)$$

$$F_{sg1} = \lambda hL[C_a + q_1 \tan \delta \tan \varphi \left(45 - \frac{\varphi}{2}\right) \left\{ \frac{\gamma_t(2Z_0 + h)}{2} \tan \left(45 - \frac{\varphi}{2}\right) - 2C \right\}] \quad (12)$$

where F_{sg1} is the shearing force at grouser's lateral side, φ is the internal friction angle of soil, γ_t is the soil density and C is the soil

grouser shoe's lateral sides (F_2), and the shearing force on the bottom surface of the soil beneath the spacing surface (F_3). F_1 was determined using Equation (10):

(10)

into 3 parts as F_{sg1} , F_{sg2} , and F_{ss} . Moreover, they could be shown by the following relationships:

$$F_{sg2} = tL[C_a + q_1 \tan \delta \tan \varphi \left(45 - \frac{\varphi}{2}\right) \left\{ \frac{\gamma_t(2Z_0 - t)}{2} \tan \left(45 - \frac{\varphi}{2}\right) - 2C \right\}] \quad (13)$$

where t is the thickness of the shoe spacing. Finally, the shearing force of the lateral side of the soil below the spacing surface (F_{ss}) was measured using Equation (14):

$$F_{ss} = (1 - \lambda)hL[C + \{q_2 + \frac{\gamma_t(h + 2Z_0)}{2}\} \tan^2 \left(45 - \frac{\varphi}{2}\right) \tan \varphi - 2C \tan \left(45 - \frac{\varphi}{2}\right) \tan \varphi] \quad (14)$$

Furthermore, the shearing force on the bottom surface of the soil beneath the spacing surface (F_3) was calculated as follows:

$$F_3 = (1 - \lambda)LB(C + q_3 \tan \varphi) \quad (15)$$

The total soil thrust is the addition of all thrusts, including F_1 , F_2 , and F_3 , as follows:

$$F = F_1 + F_2 + F_3 \quad (16)$$

The subtraction of total soil thrust from running resistance is the traction T , it can be expressed as equation 17:

$$T = F - R \quad (17)$$

2.2. Experimental procedure

Soil bin experiment was executed at the key laboratory of modern agricultural equipment and technology, school of agricultural equipment engineering, Jiangsu University, Zhenjiang, P.R China. A 500 mm wide, 1500 mm long, and 500 mm deep soil bin was used for the mechanical properties of soil. The five levels of moisture content (10, 15, 20, 25, and 30%) were kept constant throughout the experiments, the range of moisture content was selected on basis of liquid limit of experimental soil.

The soil was collected from the experimental site of the School of Agricultural Equipment Engineering and then dried using the open sun method. The type of soil was clay loam. The dried soil was hammered and passed through the sieve analysis method for fine soil particles [17]. The soil was filled in soil bin layer by layer, when the soil reached a height of 100 mm, a small

wooden roller was used to roll it back and forth twice. The process of placing the soil was repeated until the height of the soil bin reached 400 mm (Shaikh, Li, Zheng, et al., 2021). To ensure uniformity of soil moisture content, the moisture content of the soil in the soil bin was increased to a higher level by adding a calculated amount of water and mixing it thoroughly, and leaving it for 24 h. The soil bin was covered with a plastic sheet (polyethylene) to reduce moisture loss by evaporation. Soil samples were taken from three different random locations in the soil bin. The moisture content of each test was recorded by averaging the moisture contents of the three samples. Furthermore, the soil moisture content was assessed using the oven-drying method.

2.3. Development of soil bin device for Penetration test

The proposed device was designed and constructed for the penetration test; the penetration device comprised a soil bin, frame, and penetration system (Fig. 3). The soil bin dimensions were 500 x 500 x 1500 mm, which was connected to one AC gear motor with a spur rack (ASLONG-5F4, 120 W) to push the plates

into the soil. Two penetration plates (1 × 3 × 4 and 1 × 2.5 × 4 cm) were used for the experiments; the penetration test was performed five times for each plate at five moisture contents. The soil reaction force (N) and sinkage (cm) were measured by a penetration test, while other parameters related to pressure sinkage were determined by deriving the equations (3-6 to 3-14). Table 3.1 presents the details of the penetration test parameters.

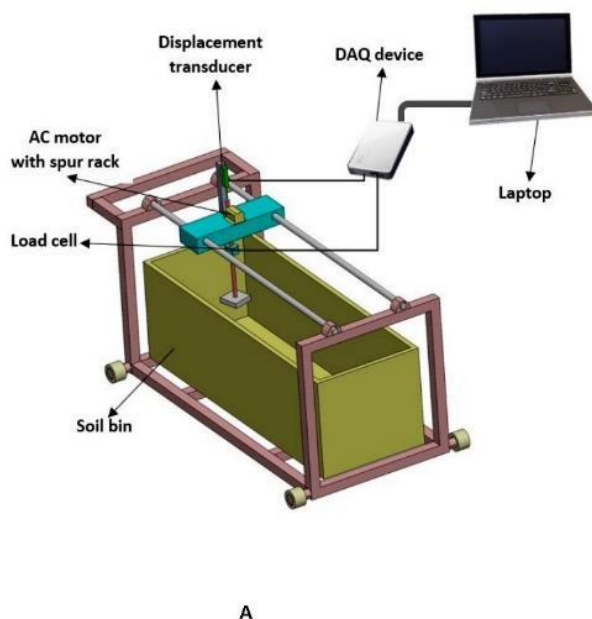


Fig. 3 Designed (A) and original (B) picture of Penetration test device [18]

2.4. Direct shear test

The strength properties of the soil were determined using a strain-controlled direct shear test apparatus (ZJ type Nanjing Soil Instrument Factory Co., Ltd, Nanjing, China Fig 4) after each experimental run at 10, 15, 20, 25, and 30%. The core component of this device is a shearing box, comprising an upper and lower section. The soil sample was usually filled in the upper box, and the lower box contained soil or

a steel circular plate to measure the adhesion/cohesion and friction angle. The horizontal shear force was applied to the shear, and the shear stress during the soil sample failure was obtained under pressure. Additionally, according to Coulomb's law, the cohesion of soil (C) was measured using equation 18, and soil adhesion (C_a) was determined using equation 19 (Abbaspour-Gilandeh et al., 2020):

$$\tau = C + \sigma \tan \phi \quad (18)$$

$$\tau = C_a + \sigma \tan \phi \quad (19)$$



Fig. 4 Strain controlled direct shear test apparatus ZJ type

Table 1. Soil cohesive modulus, soil friction modulus and soil sinkage exponent at different soil moisture contents

Soil Moisture content (%)	k_c kN/m^{n+1}	$k\phi$ kN/m^{n+2}	n
10	0.81395195	1.10815145	0.59
15	0.5099458	1.4121576	0.88
20	0.63743225	1.6671305	0.80
25	0.5099458	1.55925735	0.52
30	0.95124505	2.01036325	0.43

2.5. Parameters of single-track shoe

The details of the single-track shoe used in the research-based study are shown in Table 2.

Table 2. Dimension details of the proposed single-track shoe

Parameter of single-track shoe	Dimensions (cm)
Length, L	10
Width, B	15
Height of grouser, h	6
Grouser thickness ratio, λL	0.6
Thickness of shoe plate, t	4

2.6. Data acquisition system

The data acquisition system comprised of a load cell (ATO-LCS-DYLY-106, capacity 50 kg), linear displacement transducer (ATO-LDSR, capacity 400 mm), DAQ device (Ni-6009) with sampling rate of 2 Analog Output (150 Hz), and LabVIEW software. Data acquisition was made by DAQ device with help of LabVIEW.

3. Results and discussion

3.1. Pressure and sinkage of soil at different Moisture contents

The penetration test results at different moisture contents (%) with two penetration plate sizes are shown in Figs 5-8. The mean maximum soil reaction pressure and sinkage were varied from 120.14 to 239.98, 148.09 to 205.95, 148.09 to 205.95, 110.82 to 147.11, 117.68 to 215.75 and 147.11 to 220.66 N whereas, 103.95 to 149.07, 189.28 to 248.12, 129.45 to 225.56,

156.91 to 284.40 and 215.75 to 295.98 N for plate 1 and 2 towards 10, 15, 20, 25 and 30% soil moisture content, respectively. Moreover, the largest sinkage of soil for plates 1 and 2 was 20.15 and 20.19 cm at 30%, and the smallest was 5.02 and 3.70 cm at 10% moisture contents, respectively. The plotted results of soil reaction pressure and sinkage of soil had highly significant ($P < 0.05$) at plate 1 than plate 2. The major effect of moisture content on soil sinkage was observed at 30%, due to higher moisture content the soil becomes more softer resulted in higher sinkage values. Thus, increasing the soil

moisture content allowed plates for penetration into the soil than the lower moisture content with the lowest soil reaction pressure. Similar results have occurred with the previously reported results that, the variation in results for both plates is due to change in dimension of plates [23]. The plate sinkage recorded the highest value at the moisture content of 25% (Bahnasy, 2012). Sinkage test results show that plate sinkage increases with increasing pushing load penetration force increases with penetration depth (Baek et al., 2020; Mari et al., 2014; Shaikh et al., 2022).

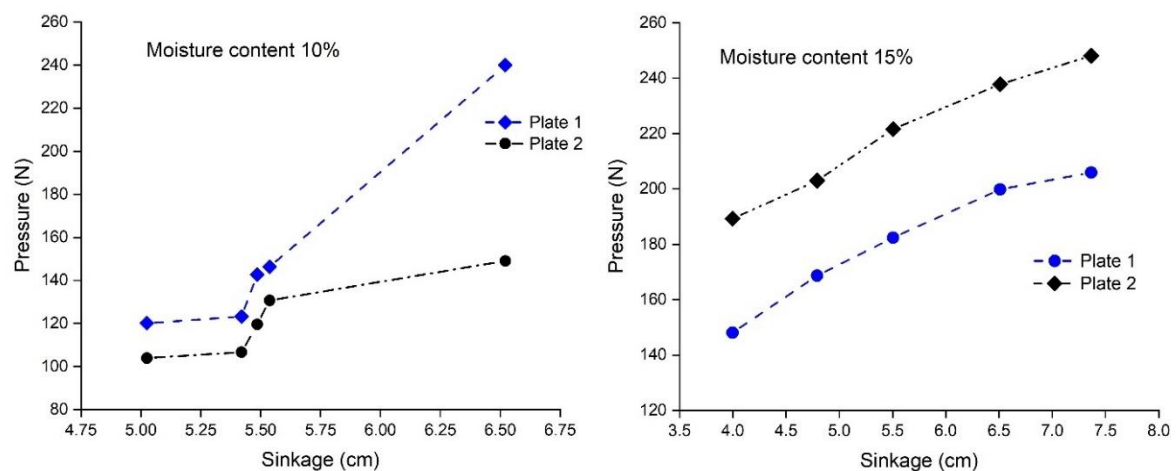


Fig 5 Soil reaction pressure and sinkage at 10% and 15% for plates 1 and 2

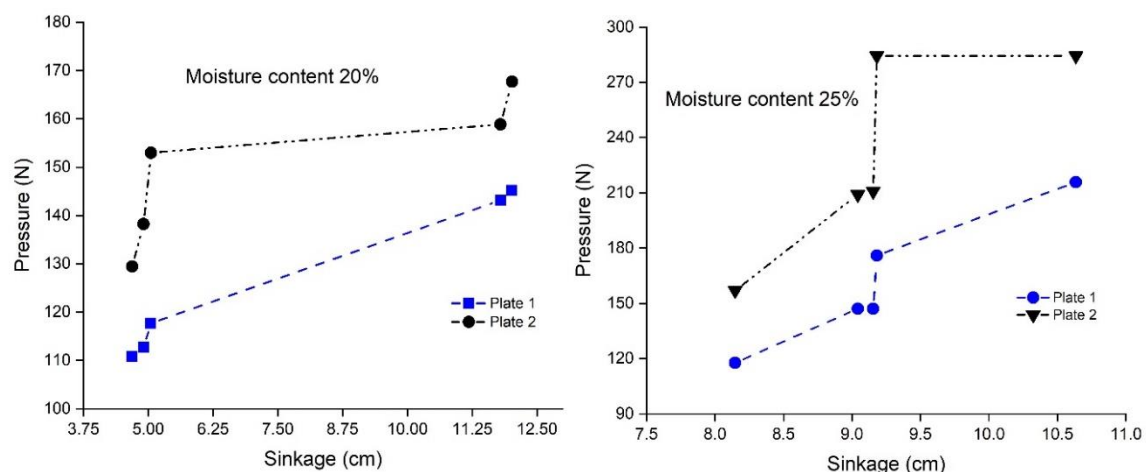


Fig. 6 Soil reaction pressure and sinkage at 25 and 20 % for plates 1 and 2.

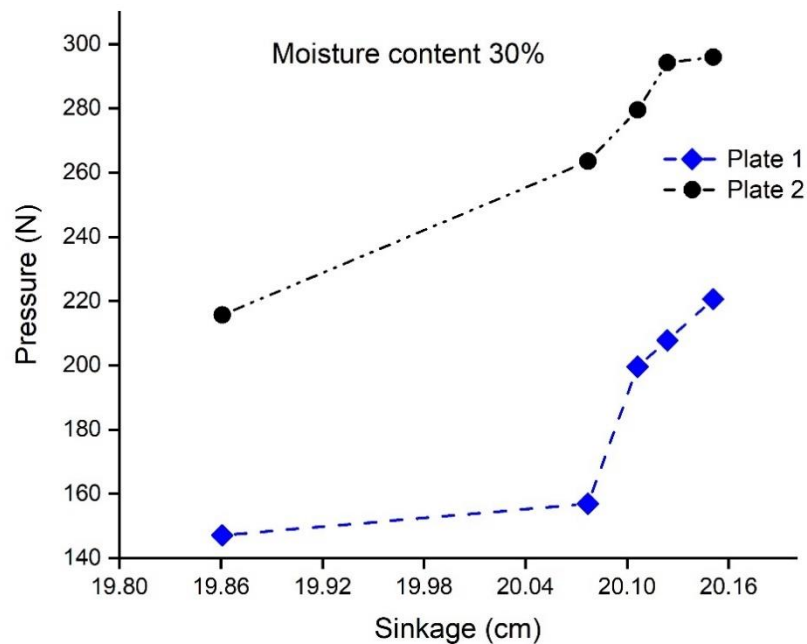


Fig. 7 Soil reaction pressure and sinkage at 30% for plates 1 and 2

3.2. Soil cohesion

Soil cohesion at five levels of moisture content is shown in Fig 8. The results were 0.28, 0.77, 0.362, 0.171, and 0.15 kPa obtained for 10, 15, 20, 25, and 30 % moisture content, respectively. It is evident from graphs results that soil cohesion was significantly ($P < 0.05$) increased with soil moisture content linearly to 15 % then cohesion decreased at the moisture content (30%) headed towards the liquid limit of soil. To obtain the best fit, non-linear curve fitting was used, the adjusted value of R^2 (0.9994), and the

best fitting line was determined by non-linear curve fitting. Previous studies have shown that when the water content in the soil is low, soil adhesion is very small and then increases with increasing water content to a corresponding peak value (Bláhová et al., 2013; Jun et al., 2016). Soil cohesion and soil adhesion have a strong dependence on water content, and the cohesion values on the soil-metal interface decrease. Mechanical properties vary linearly with soil moisture content (Bravo et al., 2012; Mari et al., 2023).

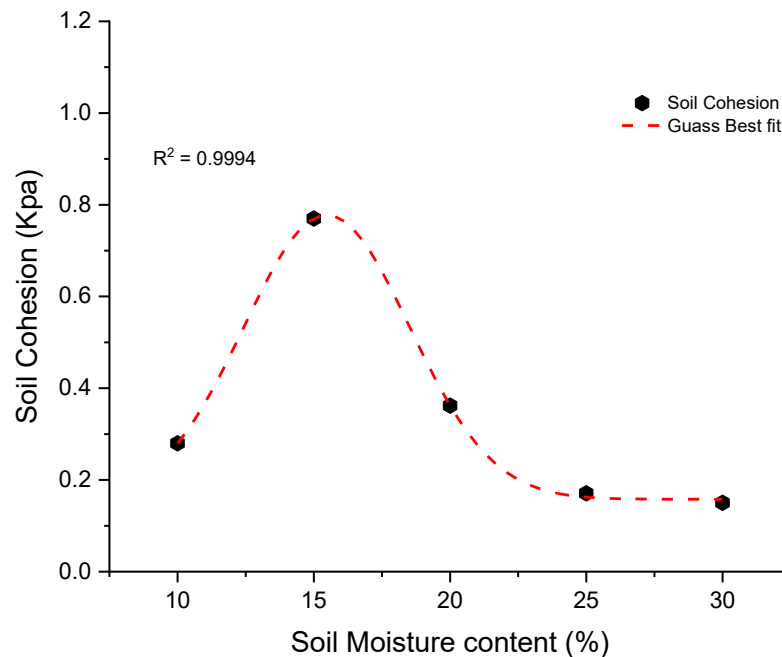


Fig. 8 Soil cohesion at different soil moisture contents

3.3. Soil adhesion

Adhesion of soil at different soil moisture contents is shown in Fig 9, where the adhesion values were 0.11, 0.23, 0.644, 0.942, and 0.787 kPa at 10, 15, 20, 25, and 30 % soil moisture content, respectively. The results showed that the adhesion significantly increased ($P < 0.05$) with increasing moisture content up to a certain limit, after which a decreasing trend was observed. Nonlinear curve fitting was applied to obtain the best fit, and the adjusted R^2 value was

0.99982. These results are in agreement with those reported by (Bravo et al., 2012; Jun et al., 2016; Lyasko, 2010), who reported that soil moisture content significantly influences the physical and mechanical properties of any type of soil, and high moisture content weakens the molecular bonds of the soil, thereby reducing the adhesion of soil particles (Shaikh et al., 2020). Soil cohesion and friction are influenced by the soil resistance to tool movement with variations in moisture content (Abbaspour-Gilandeh et al., 2020).

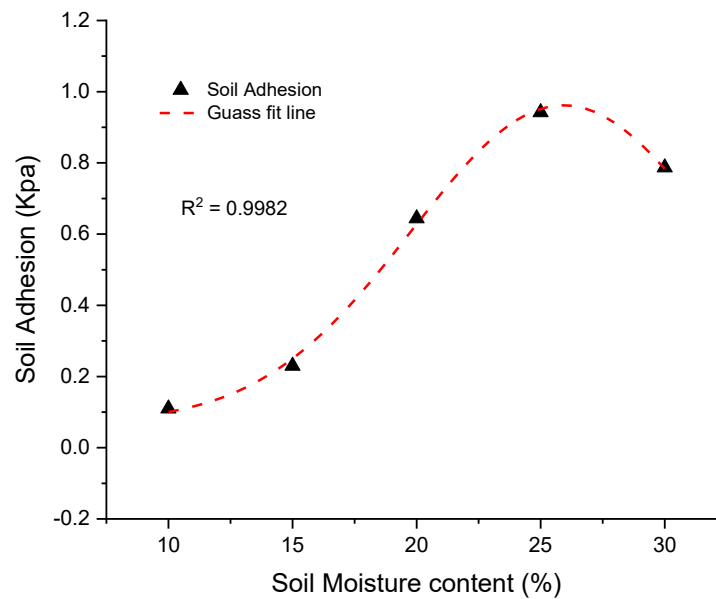


Fig. 9 Soil Adhesion at different soil moisture contents

3.4. Internal friction angle and external friction angle of soil at different moisture contents

Internal and external friction angles for 10, 15, 20, 25, and 30 % shown in Fig 10 and 11. Results of internal (23.95, 22.86, 20.92, 18.43, and 28.52) and external friction angle (25.93, 24.21, 22.25, 19.77, and 25.07) of soil were obtained at 10, 15, 20, 25, and 30 % levels,

respectively. Moreover, the highest internal and external angles were occurred at 30%, whereas the lowest were at 10% moisture content. Similarly, a linearly decreasing trend was observed for both angles. Increasing soil moisture content causes a decrease in the internal friction of the soil (Han et al., 2020). Furthermore, increasing the soil moisture content decreases the internal and external friction angles (Shaikh et al., 2022).

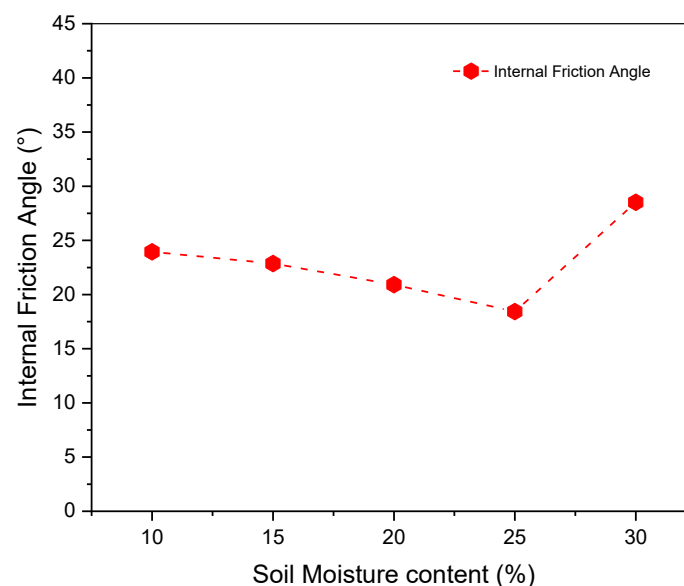


Fig. 310 Internal friction angle of soil at different soil moisture contents

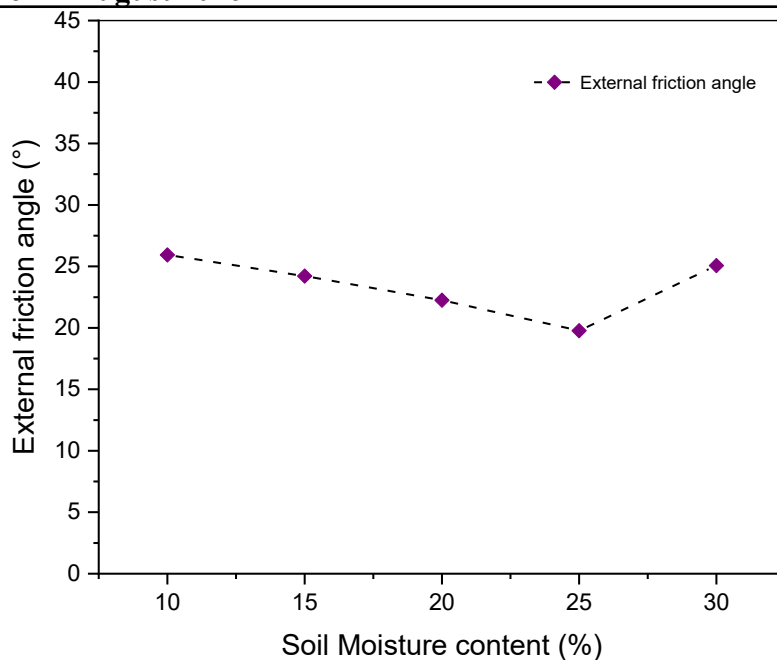


Fig. 11 External friction angle of soil at different soil moisture contents

3.5. Soil thrust at different sides of single grouser shoe

Fig 12 presents the results of thrust generated at different sides of single grouser shoe. F1 indicates the thrust at the tip of grouser, F2 represents lateral sides of grouser and F3 is bottom surface of grouser. Results showed that maximum thrust (8.218 kN) was generated on F2, whereas minimum (1.0421 kN) was for F1. The Fig shows that the thrust was increased with increase in soil moisture content till 15% then started decreasing till 30%. Similarly, the F1, F2 and F3 has the same trend at all moisture contents. The coefficient of determination for different thrusts were 0.7354, 0.9989, and

0.95673 observed for F1, F2 and F3, respectively. Fig 13 shows the results total thrust of single grouser shoe. The total thrust is the sum of all thrusts (F1, F2 and F3). The gauss model was used for non-linear curve fitting to obtain best fit line and coefficient of determination. The results are in line with (Ge et al., 2019), who concluded that soil thrust decreased with an increase in moisture content, due to a decrease of internal friction angle (ϕ), cohesive (K_c), friction modulus (K_ϕ) and sinkage exponent (n) decreased with increase in moisture content. The results are in agreement with (Jun et al., 2024) increase in soil moisture content causes a decrease in the peak values of the thrust.

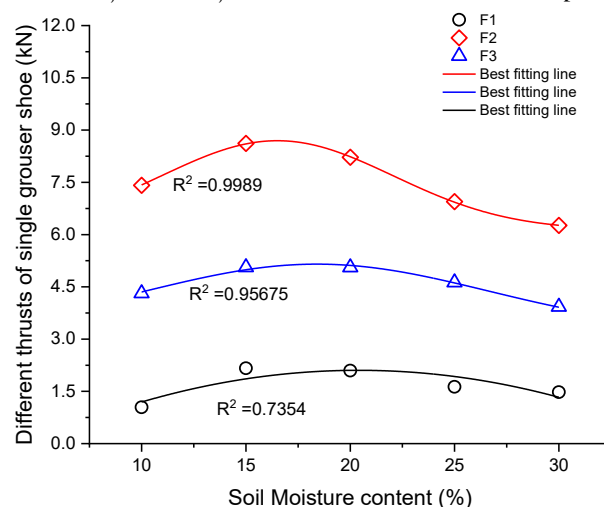


Fig. 12 Thrust generated at different sides of single grouser shoe with different moisture contents

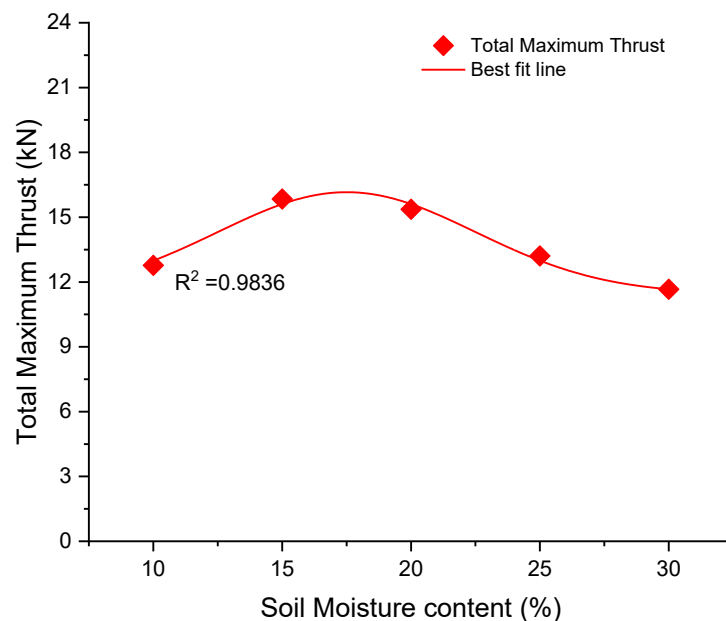


Fig. 13 Total soil thrust at different moisture contents of soil

3.6. Running resistance

The running resistance of the single-track shoe is shown in Fig. 14. The mean running resistance results were 2.1240, 2.5645, 2.8784, 3.1209, and 3.5419 kN at 10, 15, 20, 25, and 30% soil moisture contents, respectively. The results showed a direct relationship between running resistance and moisture content of paddy soil as

one increases the other one also increases. Mostly running resistance depends on the sinkage of the single-track shoe and sinkage depends on soil moisture content. Present results are in agreement with (Shaikh et al., 2022), who observed a rapid increase of running resistance with the increase of moisture content. The running resistance of soil was increased with increasing the moisture content.

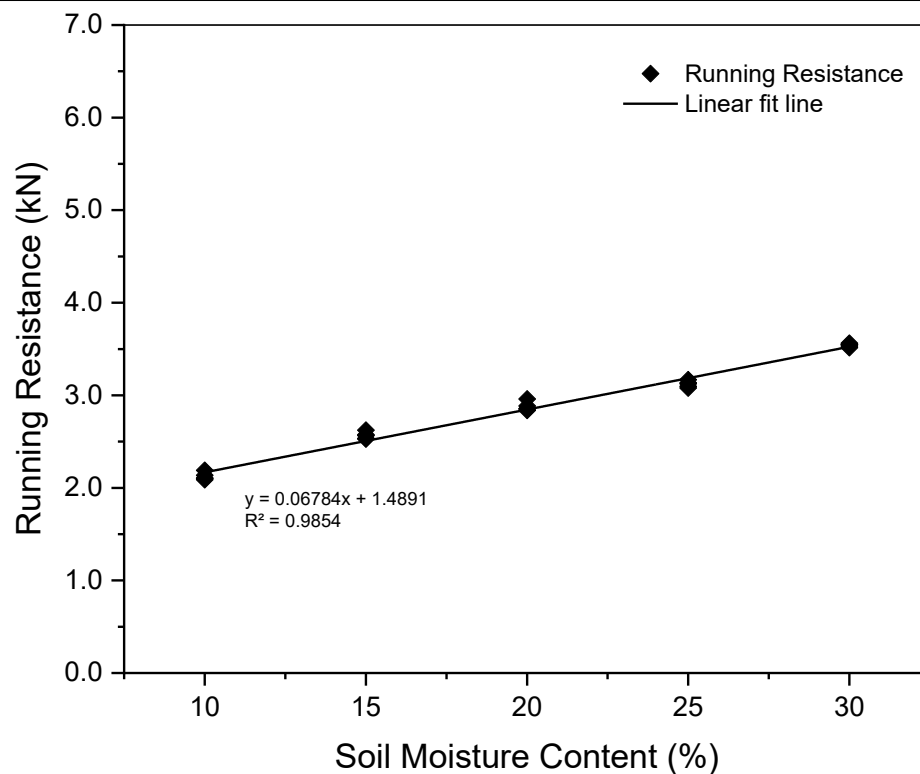


Fig. 14 Running resistance of the single-track shoe

3.7. Traction of single-track shoe

The traction of single-track shoe at the moisture content (10, 15, 20, 25, and 30%) is shown in Fig 15. The mean traction was varied from 13.2797 to 8.12523 kN at 10 to 30%. It was revealed from the results that the traction values slightly increased with moisture content to 15%, then a decrease trend was observed towards higher moisture content, this is due to the vertical component of the high internal friction forces between stagnant soil. Additionally, a

correlation of traction was 0.99602. furthermore, Previous results (Jun et al., 2016; Shaikh, Li, Zheng, et al., 2021) showed the correlation value values of tractive efficiency as 0.997. Similar research reported that traction efficiency of two-wheel agricultural tractor reduced in soft soil as compared to concrete and other soils (Chandio et al., 2021; Shaikh, Li, Zheng, et al., 2021), peak tractive efficiency was decreased as the soil became softer (Rasool & Raheman, 2016), soft soil can drastically reduce the traction performance.

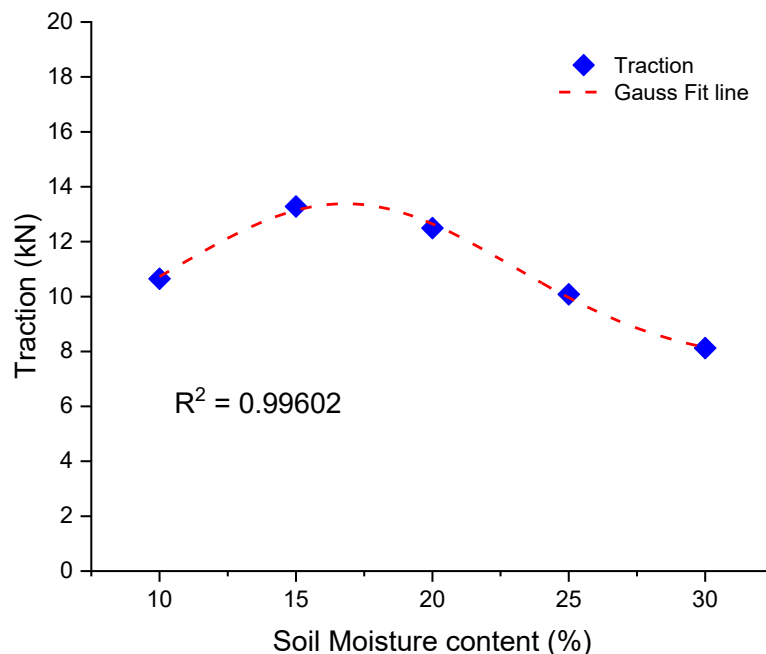


Fig. 16 Traction of single-track shoe with the different moisture content of soil

4. Conclusion

In this study, the influence of mechanical properties with different moisture contents on the tractive performance of a single grouser shoe was evaluated in controlled (soil bin) conditions. The proposed semi-empirical method is suitable to estimate the soil mechanical properties as well as tractive parameters of a single grouser shoe. The highest cohesion and adhesion were found at 10%, whereas the lowest was at 30% moisture content. Similarly, the maximum internal and external friction angle was at 10%, while the minimum was 25%. The extreme running resistance (3.5419 kN) was observed at 30% while lowest (2.124 kN) was obtained at 10%. The highest soil thrust, and traction were achieved at 10%, whereas the lowest was found at 30%. The data collected in this study could be used for the design of traction systems, the performance assessment of off-road vehicles, and the study of natural terrain mobility.

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