

EXPERIMENTAL INVESTIGATION OF BIONIC SOIL-ENGAGING BLADES FOR SOIL ADHESION REDUCTION BY SIMULATING ARMADILLIDIUM VULGARE BODY SURFACE

بررسی تجربی تیغه‌های خاک‌ورز بایونیک به منظور کاهش چسبندگی خاک با شبیه‌سازی سطح بدن ARMADILLIDIUM VULGARE

Jafar Massah ^{*1)}, Fatemeh Hassanpour Roubeneh ²⁾, Zeinab Hassanpour Roubeneh ³⁾, Keyvan Asefpour Vakilian ¹⁾ ¹

¹⁾ Department of Agrotechnology, College of Abouraihan, University of Tehran, Tehran, Iran

²⁾ Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran

³⁾ National Institute of Genetic Engineering and Biotechnology (NIGEB), Tehran, Iran

Tel: +982 136041058; E-mail: jmassah@ut.ac.ir

DOI: <https://doi.org/10.35633/inmateh-60-11>

Keywords: soil adhesion, bionic blades, energy consumption, drag force

ABSTRACT

Soil adhesion is a physical phenomenon which results in undesirable effects including increment in drag force and energy consumption of cutting or tillage tools. One method to reduce the soil adhesion is biomimetics, i.e., focusing on the technique soil-burrowing animals' benefit. In this study, three types of blade were designed and built: flat blade, corrugated blade and a combination of flat and corrugated blades. The corrugated blade was simulated from *Armadillidium vulgare* body surface geometrical shape. Experimental results showed that in dry soil, flat and corrugated blades required similar drag force while the combined blade showed higher drag force requirements. In wet soil, the corrugated blade resulted in the lowest drag force, which was due to faster movement of soil layer on the blade surface. Drag force of the corrugated blade was lower than the half of the drag force of two other blades at travel speed of 0.04 m/s. Besides, the drag force of corrugated blade decreased by increasing the blade travel speed. Furthermore, in wet soil, the energy consumption of the corrugated blade at the travel speeds of 0.02 and 0.04 m/s was 66% and 83% lower than the flat blade, respectively.

ABSTRACT

چسبندگی خاک یک پدیده فیزیکی است که منجر به اثرات نامطلوب از جمله افزایش نیروی کششی و مصرف انرژی ابزار برش یا خاک‌ورز می‌شود. یکی از روش‌های کاهش چسبندگی خاک، بایومیمتیک است، یعنی تمرکز بر روی تکنیکی که حیوانات حرکت‌کننده در خاک از آن بهره می‌گیرند. در این مطالعه سه نوع تیغه طراحی و ساخته شد: تیغه مسطح، تیغه کنگره‌ای و ترکیبی از این دو تیغه. تیغه کنگره‌ای از شکل هندسی سطح بدن *Armadillidium vulgare* شبیه‌سازی شد. نتایج آزمایشات تجربی نشان داد که در خاک خشک، تیغه‌های مسطح و کنگره‌ای نیاز به نیروی کششی مشابه دارند، در حالی که تیغه ترکیبی نیروی کشش مورد نیاز بیشتری را نشان داد. در خاک مرطوب، تیغه کنگره‌ای منجر به کمترین نیروی کششی شد که دلیل آن، حرکت سریع‌تر لایه خاک بر روی سطح تیغه بود. نیروی کشش تیغه کنگره‌ای کمتر از نیمی از نیروی کششی دو تیغه دیگر در سرعت پیشروی 0/04 متر بر ثانیه بود. علاوه بر این، با افزایش سرعت پیشروی تیغه، نیروی کششی تیغه کنگره‌ای کاهش یافت. همچنین، در خاک مرطوب، مصرف انرژی تیغه کنگره‌ای در سرعت‌های پیشروی 0/02 و 0/04 متر در ثانیه به ترتیب 66٪ و 83٪ کمتر از تیغه مسطح بود.

INTRODUCTION

The phenomenon of soil adhesion takes place frequently when soil cutting or tillage machines interact with soil. Soil adhesion increases the working resistance and energy consumption of cutting or tillage tools and often reduces the working quality (Soni and Salokhe, 2016). Soil adhesion, working resistance and abrasive wear are the three major problems of soil-engaging tools. Wang et al. (1998) found that soil adhesion can be reduced using vibration of the machines' parts contacted with soil. Furthermore, Tong et al. (2005) described that soil adhesion can be decreased using methods such as lubrication, electro-osmosis and vibration.

¹ Massah J., Prof.; Hassanpour Roubeneh F., Ms.; Hassanpour Roubeneh Z., Ms.; Asefpour Vakilian K., Dr. Eng.

They also found that phosphorus has the ability of decreasing adhesion between two surfaces. *Zhang (1985)* analyzed the influence of moisture contents and soil bulk density on adhesive properties. The moist compressed soils are more adhesive than loose dry soils. Results demonstrated that the undisturbed soils are 2 to 3 times more adhesive than disturbed soils.

Many approaches, such as surface coating, surface shape modification, materials modification, lubrication, heating, vibration, a flexible structure, electro-osmosis and magnetization have been considered in order to decrease soil adhesion forces between soil and tool surfaces (*Ren et al., 2006; Soni et al., 2007; Saha and Celata, 2011; Sun et al., 2018*).

The problem of soil adhesion has been resolved by some soil-burrowing animals, such as the dung beetle, ant, and pangolin which make a hole or tunnel in soil (*Sun et al., 2008*).

Studies have shown that some external parts of soil-burrowing animals have geometrical rough structures, which is one of the causes why soil-burrowing animals do not stick to the soil (*Ren et al., 2002; Ren, 2009; Zhang et al., 2016*). These structures have corrugated, concave, wavy and scaly shapes etc. The size of structural parts on these rough surfaces differs from 0.075 to 0.20 mm, and they are useful for the reduction of adhesion and surface frictional shear resistance against soil. The rough shapes on soil-burrowing animals' body surfaces were analyzed by scanning electron-microscopy and visual stereomicroscopy (*Qian et al., 1999; Cheng et al., 2002*).

As a pioneering research, *Qian and Zhang (1984)* reported that the energy consumed by adhesion and friction between soil and tillage implements is 30-50% of the gross energy required for the tillage procedure. The surface structures of the soil-engaging implements play an important role in decreasing soil adhesion and friction (*Zhu et al., 1992*). *Salokhe and Gee-Clough (1989)* studied decreasing adhesion by coating lug surfaces with different materials containing silicon lubricant oil, lead oxide paint, gloss paint and varnish, chromium painting, Teflon tape, Teflon sheet, ceramic tile and enamel coating. They showed that lug coating can reduce soil adhesion noticeably. However, there were practical problems such as cost and low durability in using silicon lubricant oil, Teflon tape, ceramic tile and enamel coating.

Chen et al. (1990) reported that soil animals prevent adhesion of soil to their bodies because of their exterior structure, presence of anti-adhesive parts and biological electrical system in their body surfaces, and secretion of some special substances. *Ren et al. (2001)* demonstrated that bodies of soil animals have low soil adhesion resistance because of the evolution of their biological systems.

Zu et al. (2006) showed that earthworms decrease adhesion of soil to their bodies due to electro-osmotic flow of lubricating fluid at the body and soil interface. *Gao et al. (2010)* reviewed some of these methods useful in adhesion preventing mechanism related to soil animals on the surfaces of soil engaging parts of various devices.

In this paper, several blades for use in soil tillage implements were made by modeling the body surface of a soil-animal called *Armadillidium vulgare* (the common pill bug). Then, the effects of these blades on drag force of simulated surfaces were investigated. The objective of this research is to reduce soil adhesion of soil tillage implements such as ditcher machines and bulldozers using the simulation of geometric shape of organism body, which can result in a reduction in energy consumption.

SOIL-BURROWING ANIMALS AND BIONIC TILLAGE TOOLS

Human being has benefited the nature not only as the source of life but also as a model to improve living conditions. This improvement was done by paying attention to surrounding living world consisting of plants and animals. A group of animals which can be considered as living models to improve lifestyle are soil-burrowing animals. These animals prepare the soil for plant growth by their movements (*Wang et al., 2018*).

These characteristics of soil organisms make them a suitable pattern for designing and manufacturing soil preparation tools in agriculture and industry.

The simulation of the pattern of soil organisms' geometrics would result in tremendous innovation in the field of soil preparation tool (*Zhang et al., 2017; Li et al., 2019*).

During the evolution, the body surface structure of soil-burrowing animals has been mutated to adapt to their environment.

The surface morphology features related to a kind of *Armadillidiidae* family called *Armadillidium vulgare* – the common pill bug is investigated in this study as a method to reduce soil adhesion (Fig. 1).

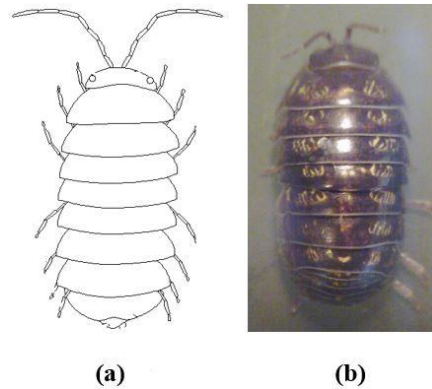


Fig. 1 - The *Armadillidium vulgare* body surface, (a) schematic image, (b) real image

Armadillidiidae is a family of woodlice, also known by many common names is an isopod crustacean. *Armadillidium vulgare* may reach a length of 18 mm and is capable of rolling into a ball when disturbed; this ability, along with its general appearance, gives it the name pill bug. Fig. 1 depicts a schematic of this organism's body surface. As seen in Fig. 1, pill bug has a laminated body which help it to burrow in soil. The laminated body of pill bug was simulated to construct soil preparation tool.

MATERIAL AND METHODS

Construction of the simulated blades

After studying the shape of soil-burrowing bodies and their ability of soil tunnelling, the pill bug *Armadillidium vulgare* was selected for simulation and construction of an efficient tillage blade. To study the shape of the soil-engaging blades, three types of blade were designed and built namely flat blade, corrugated blade and a combination of flat and corrugated blades (Fig. 2). The corrugated blade was simulated from *Armadillidium vulgare* body surface geometrical shape. All the three blades had a dimension of 100×308 mm² and the corrugated and combined blades had bumps with a diameter of 22 mm and a length of 100 mm. The number of these bumps was 7 and 14 in combined and corrugated blades, respectively. The weight of corrugated blade was 24% and 48% more than that of combined and flat blades, respectively.

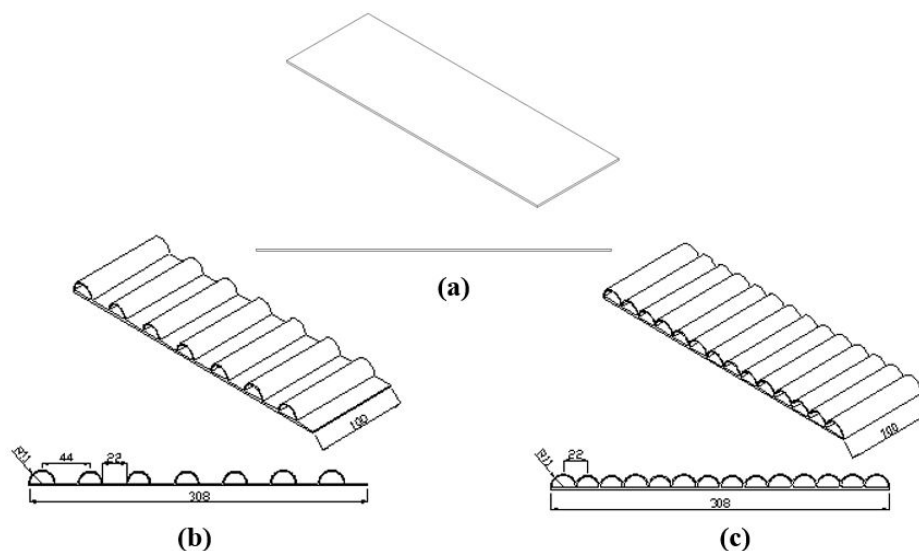


Fig. 2 - The designed blades, (a) flat blade, (b) combined blade and (c) corrugated blade

After the blade modeling by SolidWorks software, distributed force was applied by soil to the blades (Fig. 3). The amount of distributed loading was considered as 15 N/cm². The bending resistance of the corrugated and combined blades under distributed loading were equal and 25% more than the flat blade, respectively.

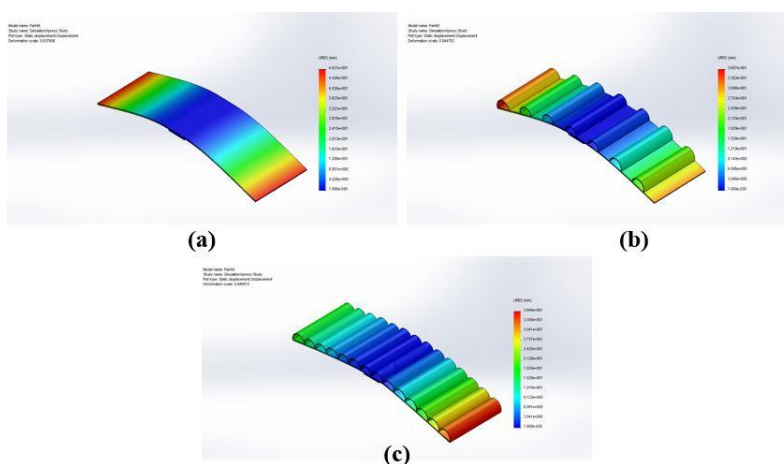


Fig. 3 - Stress distribution in the blades obtained by SolidWorks software, (a) flat blade, (b) combined blade, and (c) corrugated blade

Experiment equipment

Experiments were conducted at the Laboratory of Soil Dynamics, College of Abouraihan, University of Tehran using a soil bin (Fig. 4). As seen in this figure, the soil bin contained five main parts: bin, carriage, power transmission unit, soil processing unit and control unit.

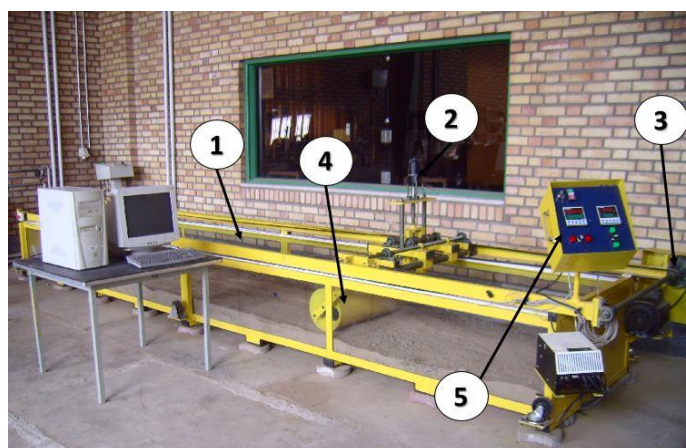


Fig. 4 - The soil bin used in this study

Part 1: The soil bin operative dimensions were: length - 6 m, width - 1 m and height - 0.5 m and filled up by soil to a depth of 0.3 m.

Part 2: The moving carriage had an overall dimension of 0.9 m wide and 0.5 m in high, with total weight of 50 kgf. The rails supported the carriage by four rigid wheels installed at four corners of the carriage.

Part 3: The power transmission unit consisted of two electromotors. A 2 kW 380V- AC electromotor moved the carriage along with the tool-tester through the length of soil bin using chain system, and a 1.5 kW 24V- DC electromotor moved an inner frame of carriage at vertical direction.

Part 4: The soil processing unit included one roller to compact the soil. The soil in the tank was manually prepared for each experiment.

Part 5: A control unit was used to control the direction and travel speed of carriage movement as well as the soil processing roller.

Experiment conditions

Two types of soil were used in the experiments, dry soil and wet soil with 34.3g (100g)^{-1} moisture content (Fig. 5). The soil was classified as a loam, with a texture analysis of 24.6% clay, 40.8% silt and 34.6% sand. After filling the soil tank by dry soil and carrying out the required experiments on dry soil, the wet soil was prepared by adding water to obtain desirable wet soil. Then, the wet soil surface was coated by a nylon cover for 24 h to homogenize the soil moisture.



Fig. 5 - Two types of soil; (a) dry soil, and (b) wet soil.

To conduct the experiments, the blades traversed a distance of 1.5 meters in each soil type with a minimum depth of 150 mm at three speed levels (0.01, 0.02 and 0.04 m/s) similar to the travel speed of a soil-burrowing animal in soil. The experiments were carried out with three replications.

Throughout the procedure, the interface received the analog signals from the S-shape load cell. Then, the signals were transferred to the monitoring software in a computer to record the force–time graph for each experiment. The control software was developed using a graphical user interface (GUI) in Microsoft Visual C. The control system software acquired the output data from the interface and produced a force-displacement graph based on the data for further analysis.

RESULTS AND DISCUSSION

Performance of the simulated surfaces in dry soil

Comparison of Fig. 6 and Fig. 7 shows the flat surface in wet soil required more drag force than dry soil. To reduce the surface drag force in wet soil, the body surface of *Armadillidium vulgare* was modeled as two types of blade: corrugated and combined blades.

The force-time curves at three travel speeds of 0.01, 0.02 and 0.04 m/s are drawn for each type of the blades in Fig. 6. As seen in the figure, flat and corrugated blades had almost the same performance in drag force, but the curves belonging to combined blade showed an irregularity in drag force. The reason of this irregularity may be the soil pass from non-uniform surface.

As shown in Fig. 6, in dry soil, the drag force of combined blade was higher than that of the other blades by increasing the travel speed which could result from its uneven surface. The combined blade consisted of semi-circular bumps and smooth surfaces among them (Fig. 2) and this alternative surface geometry shape caused the non-monotonic movement of soil layer on blade surface.

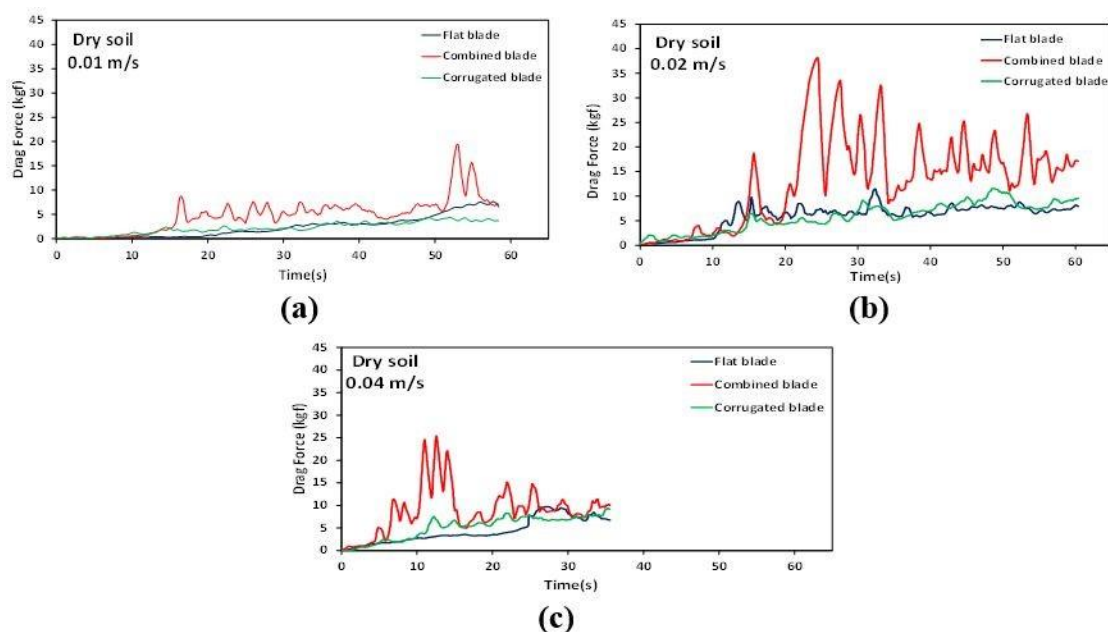


Fig. 6 - The drag force-time curves of the blades in dry soil at three travel speed of (a) 0.01, (b) 0.02, and (c) 0.04 m/s

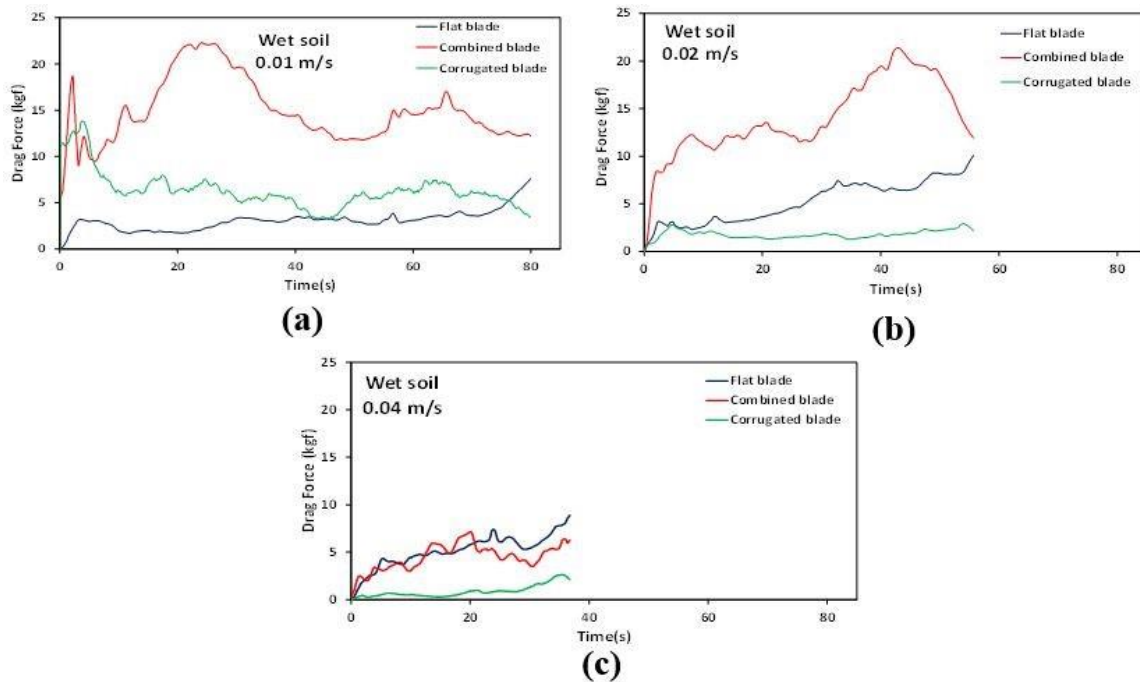


Fig. 7 - The drag force-time curves of the blades in wet soil at three travel speed of (a) 0.01, (b) 0.02, and (c) 0.04 m/s

Performance of the simulated surfaces in wet soil

As can be seen in Fig. 7(a), drag force belonging to the combined, corrugated and flat blades had decreasing trend, respectively. As shown in Figs. 7(b) and 7(c), the corrugated blade had the lowest drag force, which was due to faster movement of soil layer on corrugated blade surface. So, the soil layer could not be inserted into the grooves between the bumps, and it was only in contact with the outer surface of bumps. This event reduced the contact surface of soil layer with the metal surface and therefore decreased the soil adhesion to metal. This finding can be used in construction of the off-road vehicles side surfaces.

As illustrated in Fig. 7, in wet soil, the combined blade had the most drag force at travel speeds of 0.01 and 0.02 m/s, which resulted from the non-uniform surface shape of this blade. However, at travel speed of 0.04 m/s, the drag force of combined blade was similar to flat blade. It was found from Fig. 7 that the drag force of corrugated blade decreased by increasing the travel speed, for example; the drag force of corrugated blade was lower than those of the two other blades at travel speed of 0.04 m/s (1/3 less than others). These findings about reducing the drag force are in good agreement with the results of *Ren et al. (2006)* who investigated soil adhesion on a soil-burrowing animal.

Energy consumption of the simulated surfaces in dry and wet soils

The energy consumption for the blades was calculated using the area below the drag force-time curve at three constant travel speeds (0.01, 0.02 and 0.04 m/s) which is shown in Figs. 8 and 9 for dry and wet soils, respectively.

As shown in Fig. 8, the corrugated blade had a proper performance compared to other blades at the travel speed of 0.01 m/s. However, at the travel speed of 0.02 m/s, the corrugated blade performance was similar to the flat blade, and at the travel speed of 0.04 m/s it had a poor performance compared to the flat blade. The combined blade had a poorer performance than the others at all three travel speeds, which can be due to non-uniform motion of the soil on this blade.

Fig. 9 shows the energy consumption of blades in wet soil. Obviously, the corrugated blade had a favourable performance in reducing the energy consumption compared to the flat and combined blades. It is notable that the energy consumption of corrugated blade decreases in wet soil. The energy consumption ratio of this blade at 0.04 m/s was about a quarter lower than its rate at 0.01 m/s, which could be attributed to a more fluid motion of the soil at higher travel speeds on the corrugated blade. This indicates that the outer surface of *Armadillidium vulgare* is compatible with its living environment, which is mostly wet soil.

Therefore, using the corrugated blade in cutting or tillage tools in contact with wet soil will not only increase their strength, but also significantly reduce energy consumption.

Although the combined blade had a poor performance compared to the other blades at the travel speed of 0.01 and 0.02 m/s; it had a good performance in reducing the energy consumption compared to the flat blade at the travel speed of 0.04 m/s. The poor performance of the combined blade may be due to non-uniform motion of the soil on this blade causing the soil to move with more resistance.

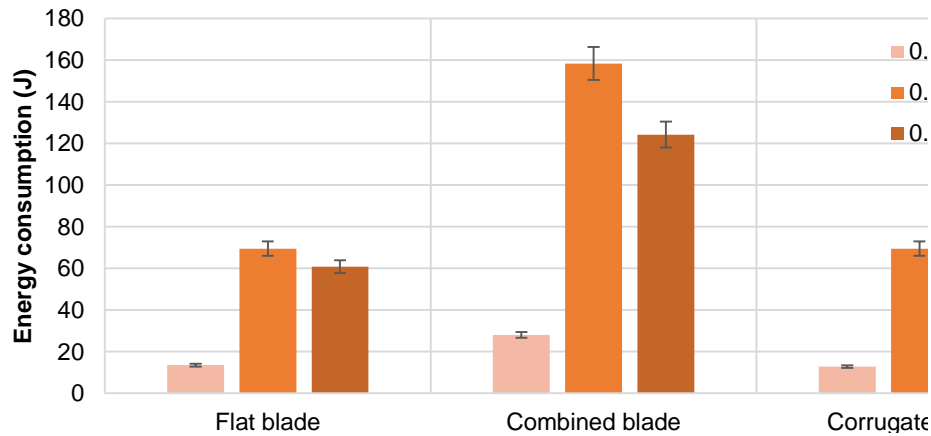


Fig. 8 - The energy consumption of the blades in dry soil.

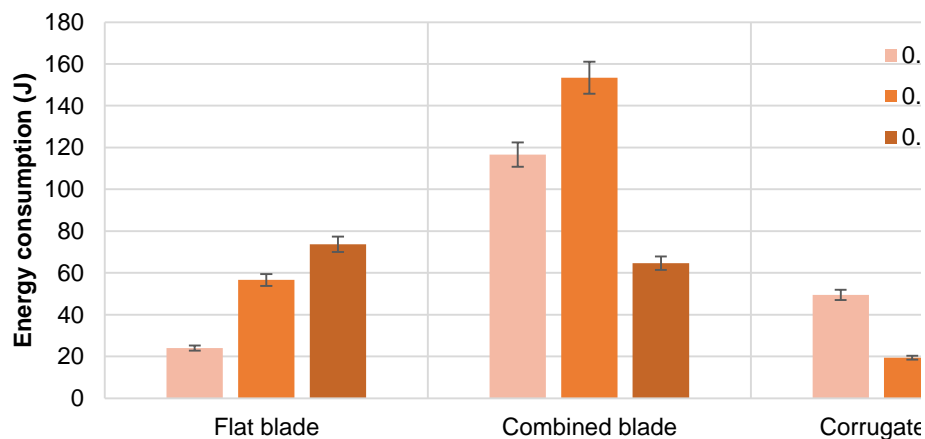


Fig. 9 - The energy consumption of the blades in wet soil

CONCLUSIONS

In this research, it has been tried to design and construct a blade for utilizing in soil tillage implements such as the ditcher machine and bulldozer using the simulation of geometric shape of *Armadillidium vulgare* surface body (corrugated blade). The drag force of this blade was compared with the flat and combined blades. Results showed that the corrugated blade had better performance in wet soil and its drag force was lower than two other blades' drag force. The energy consumption of the corrugated blade at the travel speed of 0.02 and 0.04 m/s in wet soil was 66% and 83% lower than the flat blade, respectively. This simulated blade with such desirable characteristics can be used in agricultural machines and construction equipment, which can result in a decrease in drag force and energy consumption.

REFERENCES

- [1] Chen B.C., Ren L.Q., Cui X.X., Wang Y.M., (1990). Preliminary research on reducing soil adhesion and resistance of claw shapes of typical soil animals. *Proceedings of the international agricultural engineering conference and exhibition*, Bangkok, Thailand. pp. 309-315.
- [2] Cheng H., Sun J., Li J., Ren L., (2002). Structure of the integumentary surface of the dung beetle *Copris ochus* Motschulsky and its relation to non-adherence of substrate particles. *Kun chong xue bao. Acta Entomologica Sinica*, Vol.45, Issue 2, pp. 175-181.

- [3] Gao F., Baraka-Kamali E., Shirtcliffe N., Terrell-Nield C., (2010). A preliminary study of the surface properties of earthworms and their relations to non-stain behaviour. *Journal of Bionic Engineering*, Vol.7, Issue 1, pp. 13-18.
- [4] Li B., Wang X., Xia R., Yang Z., Liu Y., Li T., (2019). Research on the bionic design of the middle trough of a scraper conveyor based on the finite element method. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol.233, Issue 9, pp. 3286-3301.
- [5] Qian C., Luquan R., Bingcong C., Beizhan Y., (1999). Using characteristics of burrowing animals to reduce soil-tool adhesion. *Transactions of the ASAE*, Vol.42, Issue 6, pp. 1549.
- [6] Qian D.H., Zhang J.X., (1984). Research on adhesion and friction of soil against metallic materials. *Acta Agromecanica*, Vol.15, Issue 1, pp. 70-78.
- [7] Ren L., (2009). Progress in the bionic study on anti-adhesion and resistance reduction of terrain machines. *Science in China Series E-Technological Sciences*, Vol.52, Issue 2, pp. 273-284.
- [8] Ren L.Q., Tong J., Li J.Q., Chen, B.C., (2001). SW—soil and water: soil adhesion and biomimetics of soil-engaging components: a review. *Journal of Agricultural Engineering Research*, Vol.79, Issue 3, pp. 239-263.
- [9] Ren L., Han Z., Li J., Tong J., (2002). Effects of non-smooth characteristics on bionic bulldozer blades in resistance reduction against soil. *Journal of Terramechanics*, Vol.39, Issue 4, pp. 221-230.
- [10] Ren L.Q., Han Z.W., Li J.Q., Tong J., (2006). Experimental investigation of bionic rough curved soil cutting blade surface to reduce soil adhesion and friction. *Soil and Tillage Research*, Vol.85, Issue 1-2, pp. 1-12.
- [11] Saha S.K., Celata, G.P., (2011). Advances in modelling of biomimetic fluid flow at different scales. *Nanoscale Research Letters*, Vol.6, Issue 1, pp. 344.
- [12] Salokhe, V.M., Gee-Clough, D., (1989). Technology showcase applications of enamel coating in agriculture. *Journal of Terramechanics*, Vol.26, Issue 3-4, pp. 275-286.
- [13] Soni, P., Salokhe V.M., (2016). Bio-Inspired Macro-Morphologic Surface Modifications to Reduce Soil–Tool Adhesion. In: Yuehao L., Yin-kwee N.E. (eds.). *Bio-Inspired Surfaces and Applications*. UK: World Scientific Publishing. pp. 421-484.
- [14] Soni P., Salokhe V.M., Nakashima H. (2007). Modification of a mouldboard plough surface using arrays of polyethylene protuberances. *Journal of Terramechanics*, Vol.44, Issue 6, pp. 411-422.
- [15] Sun J.Y., Tong J., Ma Y.H., (2008). Nanomechanical behaviours of cuticle of three kinds of beetle. *Journal of Bionic Engineering*, Vol.5, pp. 152–157.
- [16] Sun J., Wang Y., Ma Y., Tong J., Zhang Z., (2018). DEM simulation of bionic subsoilers (tillage depth > 40 cm) with drag reduction and lower soil disturbance characteristics. *Advances in Engineering Software*, Vol.119, pp. 30-37.
- [17] Tong J., Sun J., Chen D., Zhang S., (2005). Geometrical features and wettability of dung beetles and potential biomimetic engineering applications in tillage implements. *Soil and Tillage Research*, Vol.80, Issue 1-2, pp. 1-12.
- [18] Wang X.L., Ito N., Kito K., Garcia P.P., (1998). Study on use of vibration to reduce soil adhesion1. *Journal of Terramechanics*, Vol.35, Issue 2, pp. 87-101.
- [19] Wang P., Ni H., Wang R., (2018). A new drilling method—Earthworm-like vibration drilling. *PLoS one*, Vol.13, Issue 4, e0194582.
- [20] Zhang J.G., (1985). Studies on the adhesion and friction of soil to solid materials, Doctoral dissertation, Ph.D. Dissertation, Jiangsu Technical College, China.
- [21] Zhang D., Chen Y., Ma Y., Guo L., Sun J., Tong J., (2016). Earthworm epidermal mucus: Rheological behaviour reveals drag-reducing characteristics in soil. *Soil and Tillage Research*, Vol.158, pp. 57–66.
- [22] Zhang Z., Shao F., Liang Y., Lin P., Tong X., Ren L., (2017). Wear Behaviour of Medium Carbon Steel with Biomimetic Surface Under Starved Lubricated Conditions. *Journal of Materials Engineering and Performance*, Vol. 26, Issue 7, pp. 3420-3430.
- [23] Zhu H., Tan L., Wu S., (1992). An experimental study on the “comet-type passage-holes” plough of reducing resistance. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.23, Issue 4, pp. 20.
- [24] Zu Y.Q., Yan Y.Y., (2006). Numerical simulation of electro-osmotic flow near earthworm surface. *Journal of Bionic Engineering*, Vol.3, pp. 179–186.