The effect of TBM operational parameters on the wear of cutting tools using a tunnel boring machine laboratory simulator

A. H. Nickjou Tabrizi[1],H. Chakeri[1], M. Darbor[1]*, H. Shakeri[1]

1- Dept. of Mining Engineering, Sahand University of Technology, Tabriz, Iran

* Corresponding Author: *darbor@sut.ac.ir*

(Received: July 2022, Accepted: December 2022)

Keywords

TBM

Rotation speed

Penetration rate

Wear of cutting tools

Abstract

The performance of mechanized excavation depends on the soil abrasivity and the resistance of cutting tools against wear. The wear has a negative effect on excavation machine parameters, such as penetration rate, and reduces the machine's efficiency. Worn tools require replacement, which interrupts the project and incurs high maintenance costs. For this reason, many efforts have been made to understand the interaction between soil and cutting tools. Various wear-measuring devices have been designed and built to measure soil abrasivity and cutting tool wear. In this research, to study the mechanism of tunnel excavation in the laboratory, a tunnel boring machine laboratory simulator was designed and built, and the effect of the operating parameters of the excavation machine on the average wear of cutting tools was studied. The features of this machine are its horizontal excavation, the low rotation speed of the cutterhead, continuous contact of the cutters with fresh soil during the test, and continuous injection of materials with a specific injection pressure during the test. Using the granulation of soil prepared from Tabriz metro line 2 in three moisture content of zero, 7, and 13%, the effect of the rotation speed of the cutterhead, rotation time, and penetration rate on the wear of cutting tools was studied. The investigations showed that with the increase in the rotation speed of the cutterhead, the average wear increases. Also, the increasing rotation time has caused more friction between the cutting tools and the cutterhead with the soil, and the wear has increased. The wear decreased with the increase in the penetration rate, despite the increase in the intensity of the conflict between the soil particles and the cutting tools. The results obtained from this research by using a tunnel boring machine laboratory simulator are in good agreement with previous studies.

1. INTRODUCTION

One of the most common methods of tunnel excavation is the full-face mechanized excavation method. Usually, full-face tunnelling machines (TBM) are used to excavate tunnels of great length and varied geology. In the meantime, shielded TBMs are specially used on soft ground. Today, 60-80% of long tunnels in the world are excavated with TBMs [1]. Usually, the performance of full-face tunnelling machines is dependent on soil abrasivity as well as the wear of TBM components. The issue of wear in the mechanized excavation on soft ground is one of the fundamental problems that, if not paid enough attention to, causes long-term interruptions in the project and additional design and construction costs [2].

Abrasion is defined as the continuous loss of materials from the surface of a solid body due to mechanical actions between two bodies [4, 3]. In tunneling with full-face tunnelling machines, wear may occur in the cutting tool and the cutterhead [5]. The phenomenon of wear in the mechanized excavation of tunnels includes two types of primary and secondary wear. In the first type, which is known as primary wear or excavation wear, the cutting tools are worn due to direct contact with the soil. Among the parts of the excavation machine that are subjected to initial wear, we can mention the disks, buckets, and scrapers of the excavation machine. For this type of wear, the factor determining the wear is the contact force between the cutting tools and the soil grains in the tunnel face. The second type, known as secondary wear, includes the wear of cutting tools and parts that are indirectly involved with the ground [6, 7].

The problem of abrasion in tunneling projects is one of the fundamental problems that have a significant impact on the schedule and costs. As the cutting tool wears, the hyperbaric operation should replace the worn tools. Considering that the excavation machine chamber is under pressure, this operation will require a lot of time and cost. Therefore, control of wear in cutting tools is of particularly importance [8]. Several parameters affect the wear of cutting tools in tunnel excavation. The geology of the region, which includes equivalent quartz content, rock strength, grain size, grain roundness, etc., as an abrasive material, has a great influence on the wear rate [9]. On the other hand, operational factors (including excavation parameters and technical specifications of the excavation machine) also have a significant effect on wear. Penetration rate, the rotation speed of the cutterhead, ground stresses, torque of the cutterhead, soil conditioners, hardness, material, and arrangement of the cutting tool are among the factors that control the wear of the cutterhead [3, 10]. In Table 1, the classification of factors affecting soil abrasivity in mechanized excavation is explained.

Table 1. Factors affecting soil abrasivity in mechanized excavation [11].

Factors affecting soil abrasion	
Factors of excavation	Rotation speed of cutterhead, penetration rate, the torque of cutterhead, rotation time, the pressure of excavation chamber, compressive force, type of additives, and soil conditioners
Technical specifications of excavation machine	Type of excavation machine, arrangement of cutting tools, the diameter of the machine, opening of the cutterhead, number of cutting tools, material, and hardness of the tool
Geological characteristics	Soil size distribution, soil texture, mineralogy, soil density, grain shape, soil type, density, moisture, and angularity

Despite the widespread use of cutting tools in soil, there is no standard and comprehensive method for measuring soil abrasivity. For this reason, several researches and experiments have been conducted to measure the soil abrasivity [12]. Nilsen et al. (2006) divided wear into primary and secondary wear, and while reviewing existing wear tests, they introduced the SAT device to measure wear in soil [13, 14]. Thuro et al. (2007), evaluated wear by LCPC test [15, 16]. Thuro and Kasling (2009) studied and classified soil and rock wear by LCPC test [10]. Alavi Gharahbagh et al. (2011 and 2013) studied the problems caused by the wear of cutting tools in the mechanized excavation on soft ground. Also, while introducing parameters affecting wear, they introduced a new device of wear evaluation called PSAI [12, 17]. Rostami et al. (2012), by completing the PSAI wear measurement device, investigated and predicted the parameters affecting wear [18]. Jakobsen et al. (2012, 2013) investigated the methods of measuring the wear in soft ground and the existing challenges. They studied the soil abrasivity on the soft ground by constructing the SGAT device. They also investigated the effect of soil mineralogy, water content, pressure, compaction, and soil conditioning additives on the wear rate [19, 20]. Barzegari et al. (2013) simulated the TBM-EPB excavation machine by building a device to measure the wear rate based on the chamber environment [5]. Kupferle et al. (2016) studied the wear rate by making a RUB device that performs horizontal excavation [21]. Salazar et al. (2018), also studied the effect of different parameters on soil abrasivity in natural and conditioned soils [8]. Jakobsen et al. (2020) studied the effect of soil grain size distribution on wear in non-cohesive soil. They used the mixing of crushed silica grains and fine silica particles in different ratios. In this research, with the increase of the effective size (ES), the wear values increased [22]. Lee et al. (2022), investigated the effect of different parameters on the wear of cutting tools. They showed that by increasing the foam injection ratio (FIR), the wear and energy required for excavation decrease [23]. Chen et al. (2022), using a laboratory simulator of a mechanized excavation machine, investigated the factors affecting the reduction of wear. They showed that by increasing the foam injection ratio (FIR), the advance speed of excavation increases [24].

In order to investigate the effect of TBM operational parameters on the wear of cutting tools, studies have been conducted by some researchers. Using the Penn State soil abrasion testing system., Rostami et al. (2011) investigated the effect of the machine's operational parameters (rotation time, rotation speed of cutterhead, and torque) in samples of dry clay at three rotation speeds of 60, 105, and 180 rpm. The results of their studies showed that by increasing the rotation speed of the cutterhead, the wear of cutting tools decreases. In order to investigate the effect of rotation time on the wear of cutting tools, Rostami et al. (2011), were performed the tests in dry and wet conditions at rotation times of 5, 10, 30 and 60 minutes. Their investigations showed that the wear of cutting tools increases with the increase in rotation time. Also, with the increase in torque, the wear increased [18]. Jakobsen et al. (2013), using the SGAT device, investigated the effect of the rotation speed of the cutterhead on the wear rate of cutting tools. Their studies showed that with the increase of the rotation speed of the cutterhead from 25 to 100 rpm, the wear of the cutting tool increases from 6 mg to 71 mg [25]. Kupferle et al. (2016) conducted experiments to investigate the effect of penetration rate and rotation speed on the tribological system and wear rate. Their studies showed that the relative speed of wear and its path increase with the decrease of the radius of the path. Also, the wear of pins has a relatively constant decrease for all rotation speeds. In addition, weight loss decreases with increasing rotation speed [21]. Wei et al. (2019), investigated the effect of rotation time on the wear of cutting tools in dry sand, at rotation times of 10, 20, 30, 40, 50, and 60 minutes. Their studies showed that with the increase in rotation time, the wear on cutting tools increases [26]. The results of the investigation by Park et al. (2021), using an EPB tunnelling machine with a diameter of 7.73 meters, showed that the overall compressive force acting on all of the disc cutters and their impact wear increases linearly as the cutterhead rotation accelerates [27].

Although, many advances have been made in the prediction of the abrasivity of different soils, but limited models have been accepted for predicting soil abrasivity and wear of cutting tools. In this paper, while designing and building the tunnel boring machine laboratory simulator, the effect of the operational parameters of the machine, including the rotation speed of the cutterhead, penetration rate, and rotation time, on the wear of the cutting tools has been investigated. For this purpose, the samples prepared from Tabriz metro line 2 were used at three moisture contents of zero, 7, and 13%.

2. INTRODUCING THE TUNNEL BORING MACHINE LABORATORY SIMULATOR

The tunnel boring machine laboratory simulator was built to simulate the tunnel excavation mechanism in the mechanized excavation laboratory of Sahand University of Technology (Figure 1). Using this device, it is possible to determine the soil abrasivity, and the wear of cutting tools under different conditions. Among the features and advantages of this device, we can mention the low rotation speed of the cutterhead, the continuous contact of the pins with fresh soil during the test, the continuous injection of soil conditioning additives with a specific injection pressure during the test, and its horizontal operation. Various components of the tunnel boring machine laboratory simulator, including an air compressor (24 liters), a pneumatic jack (one-way with a maximum stroke of 50 cm), a motor (3 kW), a gearbox, a torque meter, a shaft and an excavation chamber (length 1.1 m and 3 cm in diameter). Table 2. shows the measurable parameters of the tunnel boring machine laboratory simulator.

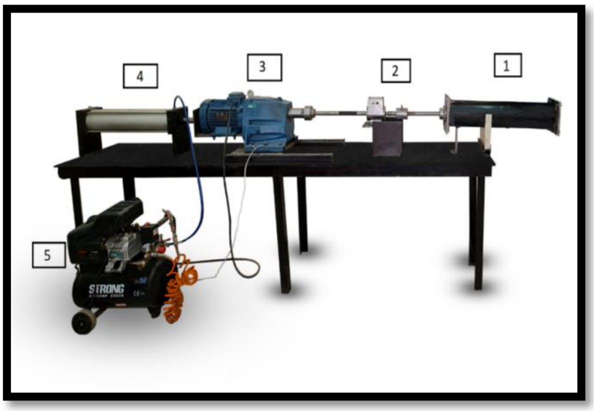

Fig. 1. Overview of the tunnel boring machine laboratory simulator, 1- shaft and excavation chamber, 2- torque meter, 3- motor and gearbox, 4- pneumatic jack, and 5- air compressor.

Table 2. Measurable parameters of tunnel boring machine laboratory simulator

Precision instrument design	12 pins spirally
Rotation speed of cutterhead (rpm)	0-35
Maximum excavation length (mm)	500
Penetration rate	measurable
Torque	measurable
Ambient pressure	measurable
Maximum grain size (mm)	0-19.5
Soil consolidation	Manually before testing
Soil conditioners	Mixing before testing and adding continuously during testing
The type of cutting tools	Aluminum

In order to prepare the device for testing, first, the spring is mounted on the shaft (Figure 2). On the shaft, there is a section for adding additives during testing. After that, the polyethylene piece is placed on the shaft, and the cutterhead is attached to its end. A total of 12 places for installing cutting tools are provided on the blades of the cutterhead. Also, on each blade, there are places for the injection of soil conditioning additives, which makes it possible to inject these materials into the chamber during the test and continuously, with specific injection pressure. The shaft is placed inside a chamber 75 cm long and 15 cm in diameter. The spring behind the polyethylene piece is fully compressed. On the other hand, the shaft is connected to the gearbox so that the cutterhead rotates inside the soil using the rotary movement of the gearbox. By applying the force of the jack and its forward movement, the soil is excavated, and wear occurs on the cutting tools installed on the cutterhead. The excavated soil is directed to the space behind it (the space between the polyethylene piece and the back of the cutterhead) through the channels on the cutterhead. The complete compression of the spring behind the polyethylene piece makes the polyethylene piece stick to the cutterhead and prevents the excavation face from falling. The force from the excavated soil causes the polyethylene piece to move backward, and in this way, the chamber space of the TBM machine is well simulated. A schematic view of the shaft of constructed excavation machine and its soil chamber is shown in Figure 3.

Due to the need for the cutterhead and cutting tools to collide with fresh soil and penetrate it, the motor and gearbox are placed on a 70 cm long rail. In this way, by applying the force of the jack and the movement of the motor and gearbox on the rail, it is possible to penetrate the cutterhead into the soil. Also, to create a different rotation speed in the cutterhead, a device for adjusting the rotation speed of the cutterhead (inverter) has been used. Access to different rotation speeds of the cutterhead allows to check the effect of different rotation speeds on the wear of cutting tools (pins). The one-ton jack used in this machine, model SC-125X500S, is a type of one-way jack that works with air pressure. The maximum stroke of this jack is 50 cm. This pneumatic jack by an air compressor (Strong 24 liters) provides the necessary power to move the motor and gearbox on the rail.

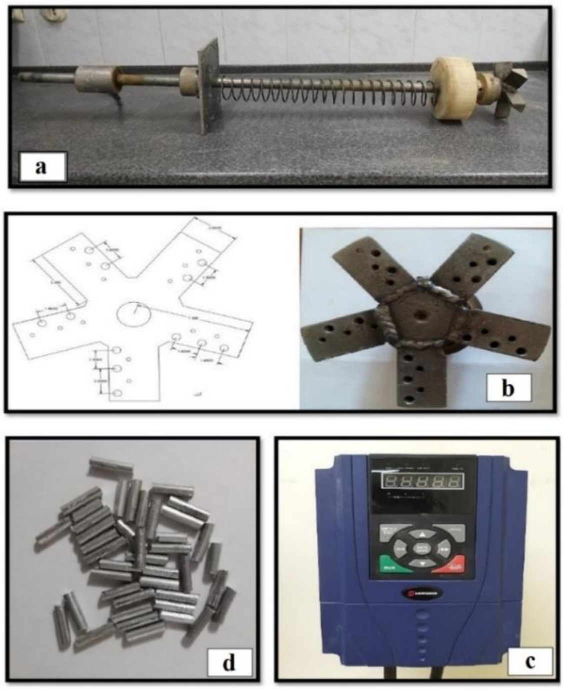

Fig. 2. a) A view of the shaft and cutterhead set, b) Cutterhead of the tunnel boring machine laboratory simulator, c) The device for adjusting the rotation speed of the cutterhead ,d) Aluminum pins (cutting tools) used in the experiments.

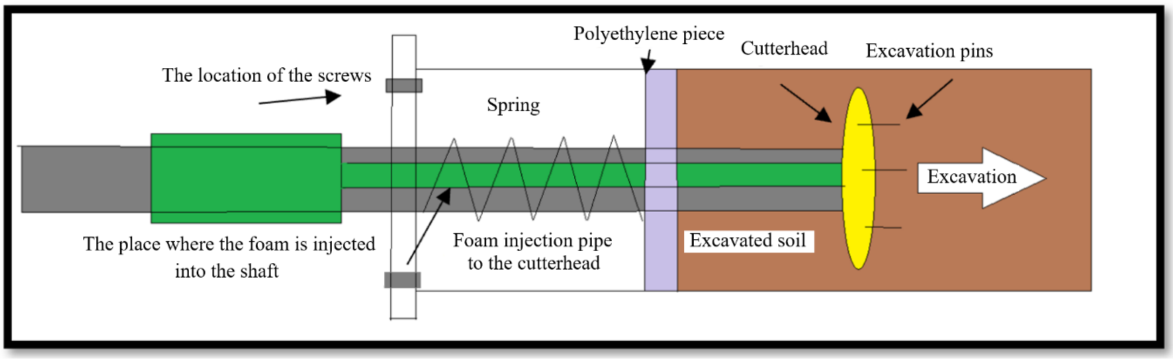

Fig. 3. A schematic view of the shaft of constructed excavation machine and its soil chamber.

The cutterhead of the device is made with a circular section and an opening of 43%. The two-dimensional view of the cutterhead is shown in Figure 4. The distance between the blades of the cutterhead and the body of the excavation chamber is one millimeter, so that almost all the soil passes through the built-in channel.

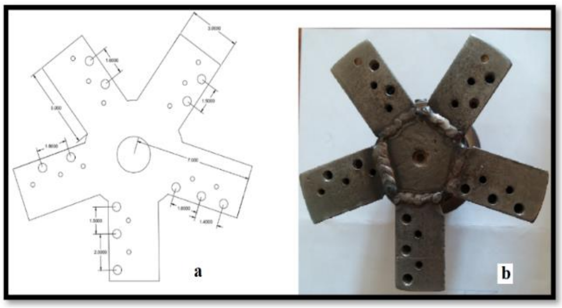

Fig. 4. a) Two-dimensional view of the cutterhead drawn in AutoCAD, b) Constructed cutterhead.

3. PREPARATION OF SAMPLES

The soil used in the experiments was provided from the west of Tabriz city, from station 5 of Tabriz metro line 2. The second line of the Tabriz metro is 22.4 km long. Currently, it is the longest route of the Tabriz rail network. This line includes 20 stations, which start from the area of Qaramalek in Tabriz and finally end in Basij Square. In the development plan of this line, passing through the Khavaran area and connecting to Tabriz-Mianeh railway station is considered (Figure 5).

Fig. 5. The map of Tabriz metro line 2.

According to the geological studies conducted (up to a depth of 30 meters), the sediments are fine-grained clay and silty alluvium. Among these fine-grained alluvial sediments, there are also sand layers, but often the tunnel route passes through the fine-grained alluvial sediments. The research conducted on the abrasivity of rock samples of the Tabriz metro tunnel shows that the Cerchar Abrasivity Index (CAI) for these rocks is around 2.3 to 4.7. According to the classification made by Plinninger et al. (2003), the rocks of the tunnel path are often in the very abrasive group. Also, the amount of abrasive minerals (quartz) in these rocks is between 5 and 20%.

The soil sample was granulated according to ASTM D 422-87 standard [28]. The samples were graded according to the highest wear rate that occurred (Figure 6), and the effect of the operating parameters of the device on the wear rate of the pins was investigated at moisture contents of 0, 7, and 13%. Figure 7 shows the samples prepared with zero and 7% moisture content. Table 3 shows the parameters selected to perform the tests in this grain size distribution.

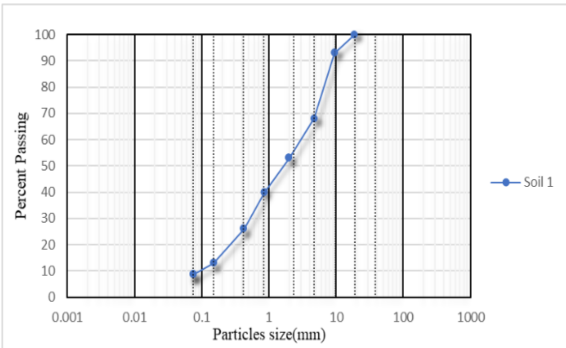

Fig. 6. The grain size distribution of the soil sample.

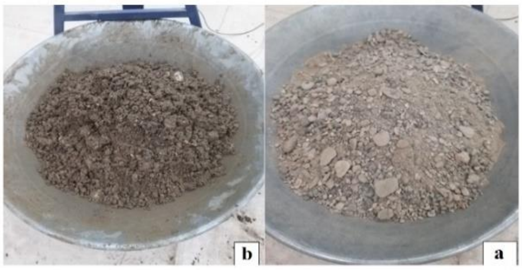

Fig. 7. Prepared sample a). dry sample, b). sample with 7% moisture content.

Table 3. Selected parameters for conducting experiments

The rotation speed of the cutterhead (rpm)	15, 25, 35
Rotation time (minutes)	30, 90, 150
The wet specific weight of soil ($\frac{gr}{cm^3}$)	1.8
Soil moisture content (percent)	0, 7, 13
Penetration rate ($\frac{mm}{min}$)	3.33, 5.56, 16.67

4. THE EFFECT OF THE OPERATIONAL PARAMETERS OF THE TUNNEL BORING MACHINE ON THE WEAR OF CUTTING TOOLS

In this study, the effect of the operational parameters of the excavation machine on the average wear of the cutting tools has been investigated using the tunnel boring machine laboratory simulator. In the following, using the selected grain size distribution in three moisture contents, 0, 7, and 13%, the effect of the rotation speed of the cutterhead, rotation time, and penetration rate on the wear of cutting tools will be explained. The measurement of the wear on the pins has been done by weighing them primary and secondary with a scale with an accuracy of 0.001 gr:

$$\text{The wear of the cutting tool } (\%) = \left(\frac{\text{Primary weight} - \text{Secondary weight}}{\text{Primary weight}} * 100\right) \quad (1)$$

4. 1. The influence of the rotation speed of the cutterhead on the wear of cutting tools

In order to investigate the effect of the rotation speed of the cutterhead on the wear of cutting tools (pins), wear tests were carried out in the desired granularity. The rotation time was 90 minutes, and the penetration rate was 5.56 mm/min. Then, the graph of changes in the average wear on the cutting tools of the cutterhead was drawn in relation to the rotation speed of the cutterhead (Figure 8).

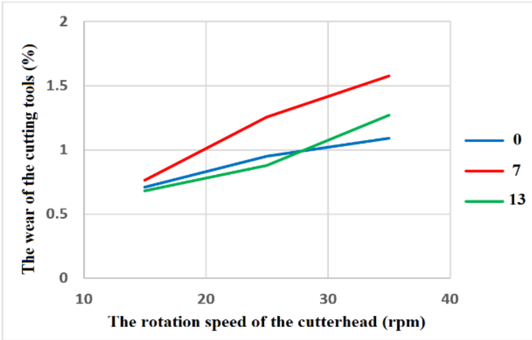

Fig. 8. The effect of the rotation speed of the cutterhead on the wear of cutting tools at 0, 7, and 13 % moisture contents.

The effect of increasing the rotation speed of the cutterhead on the wear of cutting tools is undeniable. This requires more studies in order to achieve an optimal rotation speed, to create a balance between increasing excavation efficiency and also reducing possible costs due to the wear of cutting tools and increasing the life of the excavation machine. The obtained results show that with the increase in the rotation speed of the cutterhead, the wear of the cutting tools increases because the number of revolutions of the cutterhead rises and cutting tools collides more with soil particles. This increase is since in cohesive soils, due to the cohesiveness of the soil particles with each other, the cutting tools are involved with a higher contact pressure with the soil, which causes an increase in wear in the cutting tools. The results of the tests show that when the moisture content is 7 percent, with the increase in the rotation speed of the cutterhead from 15 to 35 rpm, the wear has increased from 0.76 to 1.57%. A similar trend can be observed when the moisture contents are 0 and 13 percent. By increasing the rotation speed of the cutterhead at a constant penetration rate, in the same time, the cutting tool moves more times inside the soil, and the number of collisions between the soil and the cutting tool increases. This increase in rotation time increases the wear of cutting tools. Figure 9 shows the cutting tool with the highest and the lowest wear, as well as the worn surfaces of the tools installed on the tunnel boring machine laboratory simulator.

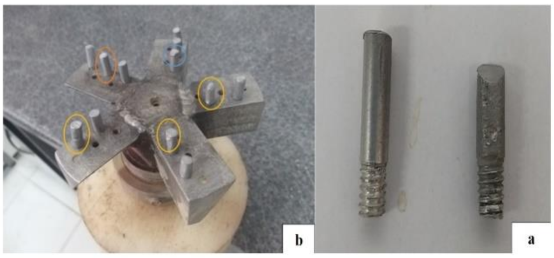

Fig. 9. a). The cutting tool with the highest and the lowest wear, b). the worn surfaces of the tools installed on the tunnel boring machine laboratory simulator.

4. 2. The influence of rotation time on the wear of cutting tools.

In order to investigate the effect of rotation time on the wear of cutting tools, tests were performed for 30, 90, and 150 minutes. The rotation speed of the cutterhead in this series of experiments was chosen to be 35 rpm. Also, the experiments were performed at three moisture contents of 0, 7, and 13%. The obtained results showed that with increasing rotation time, the wear has an increasing trend (Figure 10). The increase in average wears occurred in all three moisture contents. By increasing the rotation time, the cutterhead collides more with the soil particles, which results in an increase in the wear.

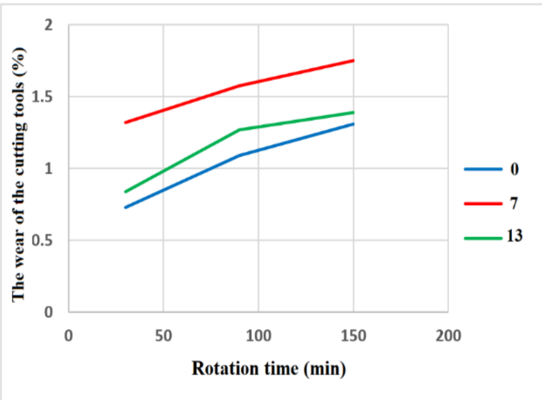

Fig. 10. The effect of the rotation time on the wear of cutting tools at 0, 7, and 13 % moisture contents.

4. 3. The influence of penetration rate on the wear of cutting tools

In order to investigate the effect of the penetration rate of the excavation machine on the wear of the cutting tools, experiments were conducted at 0, 7 and 13% moisture contents. The rotation speed of the cutterhead for this series of tests was 35 rpm. The obtained results are shown in Figure 11.

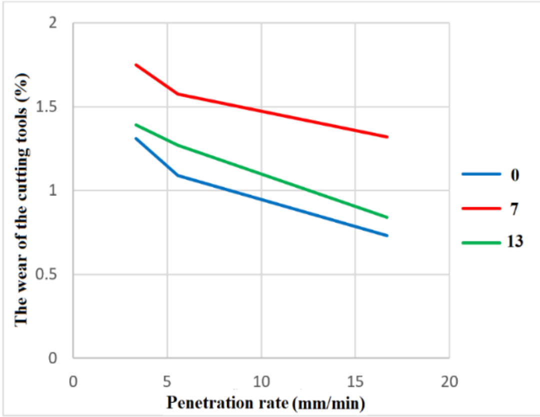

Fig. 10. The effect of the penetration rate on the wear of cutting tools at 0, 7 and, 13 % moisture contents.

The penetration rate of the tunnelling machine is one of the significant factors in predicting tunnel advancement. The increase in the penetration rate, on the one hand, has caused an increase in the excavation rate in the tunnel, but on the other hand, it causes the cutting tools to engage with the face and soil particles with more pressure. This causes the torque of the tunnelling machine to increase with increasing the excavation penetration rate. Establishing a balance between increasing the excavation rate and decreasing the torque, and because of that, reducing the excavation costs, makes determining the appropriate penetration rate be one of the important challenges in tunnel excavation projects. The obtained results show that with the increase in penetration rate, the wear of cutting tools decreases due to the reduction of excavation time and, consequently, the reduction of the duration of engagement of cutting tools with soil particles in the same excavation path.

4. 4. The influence of soil moisture content on the wear of cutting tools

The studies conducted using the tunnel boring machine laboratory simulator show that with the increase in soil moisture content, the wear of cutting tools increases, initially, up to 7% moisture, due to the increase in soil adhesion and the increase in the engagement of cutting tools and soil grains. Then, with the increase of moisture content from 10% onwards, the wear of cutting tools decreases (Figures 8, 10, and 11). The reason for this is that by increasing the soil moisture to values higher than 7%, the soil grains in the soil structure become more mobile and buoyant. In other words, by approaching the saturation state, the grains are surrounded by water particles, and as a result, the soil structure has lost its continuous state. Coarse and abrasive particles are freer and show less resistance against cutting tools, and so the wear of cutting tools reduces.

5. CONCLUSION

The conducted studies show that several factors affect the wear of cutting tools in mechanized excavation. In order to study the wear of cutting tools, tests should be standard and acceptable to simulate all the conditions governing the working environment. These conditions include grain size distribution, moisture content, the pressure inside the chamber, soil conditioning additives, etc. In this research, a tunnel boring machine laboratory simulator was designed and built. Using this device, it is possible to check the soil abrasivity and the wear of cutting tools under different conditions. Among the features and advantages of this device, we can mention the low rotation speed of the cutterhead, the continuous contact of the pins with fresh soil during the test, the continuous injection of soil conditioning additives with a specific injection pressure during the test, and its horizontal operation. In the following, experiments were conducted with specific granulation, in three different moisture content, and the influence of the rotation speed of the cutterhead, rotation time, and penetration rate of the excavation machine was investigated using this laboratory device. The obtained results showed:

1. By increasing the rotation speed of the cutterhead from 15 to 35 rpm, the wear of cutting tools increases. The increase in the wear of cutting tools has occurred at three moisture contents of 0, 7, and 13%. Comparison of the obtained results with previous studies, such as the study by Jacobsen et al. [25], shows a good agreement.
2. The investigations show that the wear has increased with the increase in rotation time. As the rotation time increases, the engagement between soil particles and cutting tools increases, which increases the wear rate. The continuous contact of cutting tools with fresh soil has caused no change in the slope of the increase of wear in cutting tools during the test.
3. To investigate the effect of penetration rate on the wear of cutting tools, penetration rates of 3.33, 5.56, and 16.67 mm/min were considered. By increasing the penetration rate, a certain length of the soil is excavated in a shorter time, and the time of the engagement between the cutting tools and the soil is reduced. As a result, the average wear is reduced.
4. Investigating the effect of soil moisture content on the wear of cutting tools shows that, initially, the wear of cutting tools increases with an increase in moisture content up to 7%, due to the increase in soil adhesion and the increase in the engagement of cutting tools and soil grains. Then, with the increase of moisture content from 10% onwards, the wear of cutting tools decreases. The reason for this is that by increasing the soil moisture to values higher than 7%, the soil grains in the soil structure become more mobile and buoyant. In other words, by approaching the saturation state, the grains are surrounded by water particles, and as a result, the soil structure has lost its continuous state. Coarse and abrasive particles are freer and show less resistance against cutting tools, and so the wear of cutting tools reduces.

REFERENCES

[1] Alavi Gharahbagh, E., Mooney, M., Frank, G., Walter, B., Diponio, M., 2013. “Periodic inspection of gauge cutter wear on EPB TBMs using cone penetration testing". Tunnelling and underground space technology, pp. 279-286.

[2] Barzegari, G., Uromeihy, A., Zhao, J. 2015."Parametric study of soil abrasivity for predicting wear issue in TBM tunneling projects". Tunnelling and Underground Space Technology, pp. 43-57.

[3] Amoun, S., Shahriyar, K., Sharifzade, M., Azali, S., 2015. “Evaluation of wear abrasion tools in mechanized tunneling in soft grounds - case study: north - south section tunnel of Tehran metro line 7. Tunneling & Underground Space Engineering. pp. 233-246

[4] Zum Gahr, H.1987.Microstructure and wear of materials, Vol.10.

[5] Barzegari, G., Uromeihy, A., Zhao, J. 2013. "A newly developed soil abrasion testing method for tunnelling using shield machines". Quarterly Journal of Engineering Geology and Hydrogeology, pp. 63-74.

[6] Küpferle, J., et al., "Influence of the slurry-stabilized tunnel face on shield TBM tool wear regarding the soil mechanical changes–Experimental evidence of changes in the tribological system", Tunnelling and Underground Space Technology, Vol. 74, pp. 206-216 , (2018).

[7] Düllmann, J., "Ingenieurgeologische untersuchungen zur optimierung von Leistungs- und verschleißprognosen bei hydroschildvortrieben im lockergestein,"(2014).

[8] Salazar, C., Todro, C., Bosio, F., Bassini, E., 2018. "A new test device for the study of metal wear in conditioned granular soil used in EPB shield tunneling". Tunnelling and Underground Space Technology, pp. 212-221.

[9] Kohler, M., Maidl, U., Martak, L., 2011. "Abrasiveness and tool wear in shield tunnelling in soil". Abrasivit/itund Werkzeugverschleißbeim Schildvortriebim Lockergestein, pp. 36-54.

[10] Thuro, K., Käsling, H., 2009. "Classification of the abrasiveness of soil and rock". Geomechanics and Tunnelling". pp. 179-188.

[11] Barzegari, Gh., Oromiehei, A., 2012. "Evaluation of soil abrasiveness in mechanized tunneling with special attitude to the Tabriz metro line1". Engineering Geology, Vol. 5, pp. 41-58.

[12] Alavi Gharahbagh, E., Rostami, J., Palomio, AM., 2011. "New soil abrasion testing method for soft ground tunneling applications". Tunnelling and Underground Space Technology, pp. 604-613.

[13] Nilsen, B., Dahl, F., Holzhauser, J., Raleigh, P,2007. "New test methodology for estimating the abrasiveness of soils for TBM tunneling". in Proceedings of the rapid excavation and tunneling conference (RETC).

[14] Nilsen, B., Dahl, FE., Holzhauser, J., Raleigh, P., 2007. "Abrasivity of soils in TBM tunnelling". Tunnels & Tunnelling International.

[15] Thuro, K., Singer, J., Kasling, H., Bauer, M., 2007. "Determining abrasivity with the LCPC test". in st Canada-US Rock Mechanics Symposium. American Rock Mechanics Association.

[16] Thuro, K., Singer, J., Kasling, H., Bauer, M., 2004. "Soil abrasivity assessment using the LCPC testing device". Felsbau, pp. 37-45.

[17] Alavi Gharahbagh, E., Rostami, J., Talebi, K., 2014. "Experimental study of the effect of conditioning on abrasive wear and torque requirement of full-face tunneling machines". Tunnelling and Underground Space Technology, pp. 127-136.

[18] Rostami, J., Alavi Gharabagh, E., Palomino, AM., Mosleh, M., 2012. "Development of soil abrasivity testing for soft ground tunneling using shield machines". Tunnelling and Underground Space Technology, pp. 245-256.

[19] Jakobsen, P., Langmaack, L., Dahl, F., Breivik, T., 2012. "Predicting the abrasivity of in-situ like soils". Tunnels and Tunnelling International, pp. 41-44.

[20] Jakobsen, P. Lohne, J., 2013. "Challenges of methods and approaches for estimating soil abrasivity in soft ground TBM tunneling". Wear, pp. 166-173.

[21] Küpferle, J., Rottger, A., Thesien, W., Alber, M., 2016. "The RUB Tunneling Device–A newly developed test method to analyze and determine the wear of excavation tools in soils". Tunnelling and Underground Space Technology, pp. 1-6.

[22] Jakobsen, P. D., Hamzaban, M. T., Rish Sefid Mohammadi, N., 2020. "The effect of the particle size distribution curve on the abrasivity of non-cohesive soils in LCPC test". Tunnelling and Underground Space Technology, Vol. 105.

[23] Lee, H., Kim, D., Shin, D., Oh J., Choi, H., 2022. "Effect of foam conditioning on performance of EPB shield tunnelling through laboratory excavation test". Transportation Geotechnics, Vol. 32.

[24] Chen, Z., Bezuijen, A., Fang, Y., Wang, K., Deng, R., 2022. "Experimental study and field validation on soil clogging of EPB shields in completely decomposed granite". Tunnelling and Underground Space Technology, Vol. 120.

[25] Jakobsen, P.D., Langmaack, L., Dahl, F., Breivik, T., 2013b. "Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust". Tunnelling and Underground Space Technology, Vol. 38, pp. 398-408.

[26] Wei, Y., Zheng, X., Su, F., Li, M., Li, F., Yang, Y., 2019. "Evaluation of cutting tool wear of earth pressure balance shield in granular soil based on laboratory test". Journal of Testing and Evaluation, Vol. 47, pp. 927-941

[27] Park, B., Lee, C., Choi, S.W., Kang, T., Chang, s., 2021. "Discrete-element analysis of the excavation performance of an EPB shield TBM under different operating conditions". Applied Sciences, Vol. 11.

[28] ASTM D422-63, "Standard Test Method for Particle-Size Analysis of Soils", ASTM International, West Conshohocken, PA, (2007).