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Evaluating the wear of cutting tools using a tunnel boring machine laboratory simulator

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Abstract

Purpose. One of the most common problems in mechanized excavation is the cutting tool wear, which has a great impact on the final cost of the project and its duration. Also, one of the most important factors affecting the wear of cutting tools is the operating parameters of the tunnel boring machine (TBM). Within the framework of this research, a tunnel boring machine laboratory simulator was designed and constructed to investigate the tunnel excavation process in the laboratory.

Methods. A few of the features of this device are that it operates horizontally, has a low rotation speed, keeps the pins in contact with fresh soil throughout the test, and has the possibility of measuring the torque of the device during the test. A study of the cutting tool wear was conducted using granulation prepared from Tabriz metro line 2, as well as using operating parameters of mechanized excavation machines, such as penetration rate and cutter head rotation speed.

Findings. The research results showed that by reducing the rotation speed of the cutter head from 35 to 10 rpm, the average wear of cutting tools is reduced by 63%. Also, by reducing the excavation time from 80 to 10 minutes, the cutting tool wear is reduced by 58%. The wear of cutting tool increases with increasing moisture content from 0 to 10%, and then decreases with increasing moisture content from 10 to 25%.

Originality. During this research, a new device was designed and built to simulate tunnel excavation mechanisms. This laboratory simulator measures wear percentage, penetration rate and torque.

Practical implications. There has been significant progress in predicting soil abrasion rates, but there are few accepted models for predicting cutting tool wear and soil abrasion rates. During the design and construction of the tunnel boring machine laboratory simulator, the effect of operating parameters on wear of cutting tool was examined.

***Keywords:** mechanized excavation, cutting tool wear, penetration rate, cutter head rotation speed, torque*

1. Introduction

Earth pressure balance (EPB) mechanized excavation machines are widely used in tunneling in urban areas and on soft ground. These machines are preferred over normal tunneling in the soft ground due to the advantages of high penetration rate and minimized environmental effects. The challenging excavation activity due to high risks such as surface settlement, structure damage and low penetration rate caused by the diversity of soil types along the excavation route requires special measures to be studied and implemented [1].

The schedule and cost estimation for various tunneling projects are directly influenced by the ability to predict tool wear when tunneling in pressurized soft ground using EPB and slurry shields. Effective planning for dealing with primary and secondary wear on the machines, from machine design and fabrication to site management, is a key element for the success of projects [2]. Presently, evaluation of soil abrasivity is not standard or unified. Most of the processes used are complex index processes that use highly simplified models and test conditions. These processes can measure the efficiency of the wear mechanism and are not able to reflect the bonding strength of the inner fabric, which is an essential factor in determining the level of operational demands, i.e., the resistance to excavation [3]. Wear occurs not only in excavation tools, but also in the cutter head and shield, screw conveyors on EPB TBMs, slurry pipes, valves and pumps on TBMs [4].

Tool life may be lower in the area of the cutter head center due to the clogging and its adverse effect on cutting performance. A study of the wear of the EPB machine scrapers in the active and passive mode of excavation shows that tool wear is higher in an active mode. The difference in tool wear between active and passive excavation modes can be up to 50% [5].

The wear risks associated with various machine parts depend on a variety of factors, including geological conditions, machine characteristics, and operational factors (Table 1) [6].

The LCPC rock abrasivity test was carried out by Abu Bakar et al. (2020) using two different sample preparation methods to study the effect of grain angularity. Preliminary test results for both test modes show an increase in the LCPC abrasivity coefficient with an increase in the grain angularity achieved after crushing and mixing of the sample in proportion to the original rounded grain fraction [7].

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Table 1. Parameters influencing tool wear in EPB tunneling [6]

Parameters influencing tool wear in EPB tunneling	
Geological conditions	Soil and rock type Grain size distribution Grain roundness Equivalent quartz Density Ability/Cutability Inhomogeneity Water table
Machine characteristics	Excavation machine type The number of cutting tools Planning cutting tools Hardness of cutting tool Cutter shape The number of foam nozzles Position of foam nozzles
Operational factors	Thrust and torque Penetration rate Rotation speed of cutter head Chamber confining pressure Soil conditioning parameters Additive type Cutter head inspection

The LCPC test was used by Thuro and Kasling (2009) to study and classify soil and rock wear [8]. Zhang et al. (2021) investigated the alloy hardness effect on cutting tool wear and found that wear extent increases as alloy hardness decreases [9]. Jakobsen and Lohne (2013) examined abrasivity properties at different moisture contents in a soil sample and found that weight loss of steel tools increases with an increase in water content from 0 to 8%, and decreases with an increase in water content from 8 to 25% [10]. Rong et al. (2019) evaluated cutter wear from operational parameters in EPB tunneling of Chengdu Metro, then developed quantitative relationships between two input variables and cutter wear. It was found that the average torque was 2000-4500 kN·m, and with an increase in the number of rings, the cutter head torque increases [11].

Within the framework of the relevant system properties, Dullman et al. (2014) examined whether model mill tests with simplified tools, such as the LCPC test, can approximate the wear mechanism efficiency. Due to the test method, influences on the results are inevitable, for example, disturbed soil with altered grain size and shape, propeller geometry, and operator influence. In this case, it seems rational to rely instead on conventional geotechnical-mineralogical parameters, which are usually well-standardized and easily reproducible. In this case, quartz content, grain angularity, and grain size are relevant parameters [3]. Rostami et al. (2012) developed a soil abrasivity test for tunneling in soft ground using shield machines with Penn state soil abrasion testing device. The value of tool wear and weight loss increases significantly to an apparent maximum from a dry sample to the soil condition that is only wet, in this case at a water content of 7.5%. But, when the moisture content exceeds 7.5%, the measured weight loss decreases [2]. Jakobsen et al. (2013) recorded wear on soil samples. They show that wear increases with increasing rotation speed. The soil moisture influences the wear (weight loss) of steel when excavating soft ground in the new SGAT apparatus up to 500%. Proper application of correct soil conditioning can in some cases reduce torque by up to 40% [10]. The effect of geomechanical properties on Cerchar Abrasivity Index (CAI) and its application for tunnelling was studied by Young Ko et al. (2016) who found that the variation of CAI has the greatest effect on disc cutter life predictions [4]. Based on experimental performance prediction models developed by Avunduk and Copur (2018), cutter head torque increases as the vane shear strength and consistency index increase. The thrust force also decreases as the penetration depth of the fall cone increases. With an increase in the plastic limit, the consistency index, fall cone penetration depth and the instantaneous cutting rate decrease. A higher plastic limit, a higher plasticity index, as well as a higher liquid limit all result in an increase in the field-specific energy. When soil samples were grouped according to their consistency index values, it was observed that the average field-specific energy values increase with increasing consistency index [12].

According to Tarigh Azali et al. (2012), in underground structures, clay soils can clog machines and adhere to steel surfaces of machines, significantly reducing their efficiency. According to this study, no high risk of clogging was found along the proposed tunnel route [13]. As shown by Amoun et al. (2017), low penetration rates at high face pressure increase tool wear. Based on the results, tool wear can be reduced by optimizing soil conditioning as well as other operational parameters such as earth pressure, machine torque, thrust, penetration rate, and rotation speed [6]. The effect of moisture content on the LCPC test results and tool wear in mechanized tunneling was studied by Abu Bakar et al. (2018) [14]. According to Lee et al. (2022), an increase in Foam Injection Ratio (FIR) is associated with a decrease in wear of cutting tools [15]. According to Sun et al. (2020), particle size distribution, test time, and moisture content affect the LCPC abrasivity tests of the sandy stratum. By drying out or raising the soil moisture content than its saturated moisture content, the abrasivity of the soil can be reduced [16]. According to Kupperle et al. (2018, 2016), pin wear increases sharply as water content increases. The weight loss decreases as the water content increases to 15% and then remains nearly constant until 25% water content. It is also shown that with a decreasing penetration rate, weight loss increases [17], [18]. According to Tang et al. (2022), an appropriate water content facilitates redistribution of sand particle and increases cutter head torque, whereas excessive water content damages the contacts between scrapers and sand particles and decreases cutter head torque. With an increase in water content, scraper wear first increases and then decreases [19]. According to Lan et al. (2020), inner disc cutter wear rate is linearly related to the position of the cutter head. They examine the relationship between wear capacity and penetration in terms of rock UCS, as well as thrust in view of the factors affecting disc cutter wear rate [20]. According to Pelia et al. (2016), the machine torque increases continuously with increasing test time [21].

Despite progress in predicting soil abrasivity, only a few models have been recognized for predicting cutting tool wear caused by soil abrasion and operational parameters of excavation machine. This study focuses on examining the impact of machine operating parameters, such as cutter head rotation speed, cutter head torque, penetration rate and rotation time, on cutting tool wear while creating a laboratory simulator for tunnel boring machines. To achieve this goal, samples from Tabriz metro line 2 were used at varying moisture levels of 5, 10, 15 and 20%.

2. Materials and methods

In the laboratory of the Sahand University of Technology, a tunnel boring machine laboratory simulator was developed to simulate tunnel excavation mechanisms (Fig. 1). It is possible to determine the abrasion and wear of cutting tools in the cutter head using this device.

Figure 1. Overview of the tunnel boring machine laboratory simulator: shaft and excavation chamber, torque meter, motor and gearbox, pneumatic jack, and air compressor

This device has a horizontal operation, is capable of injecting additives, is continuously in contact with fresh soil, and has a cutter head similar to the TBM cutter head, which includes central, middle and external cutting tools, as well as the ability to adjust the penetration rate and rotation speed, representing to a large extent the excavation conditions in a tunnel. Figures 2-4 illustrate the components of the laboratory simulator for tunnel boring machines, including the shaft and excavation chamber, torque meters, gearboxes, pneumatic jacks, and air compressors.

Figure 2. Excavation shaft including spring, polyethylene piece, and cutter head

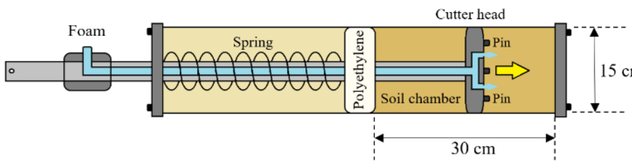

Figure 3. Schematic view of the excavation chamber

Figure 4. Overview of the cutter head

The laboratory simulator for tunnel boring machines has five measurable parameters, as shown in Table 2.

The samples were obtained from the western area of the Tabriz city, the excavation site of the 5th station of the Tabriz metro line 2. The Tabriz metro line 2 extends from the west of Tabriz to the east of Tabriz with a length of 22.4 km.

Table 2. Parameters of the tunnel boring machine laboratory simulator that can be measured

Parameters	Quantity
Excavation pins	15 pins
Rotation speed (rpm)	1-35
Excavation range (mm)	0-300
Penetration rate	Variable
Torque	Variable
Maximum grain size (mm)	0.001-19.5
Consolidation of soil	when adding soil
Additives	Adding continuously during the test
Cutting tool material	Steel

As a result of exploration and geological studies conducted in this area, fine-grained clay and silty alluvium occur in the sediments. In addition to fine-grained alluvial sediments, there are also sand layers, but the tunnel often passes through these fine-grained alluvial sediments. According to Plinninger et al. (2003), the percentage of abrasive minerals in the tunnel route of the Tabriz metro line 2 is between 5 and 20% [22]. Soil sample was granulated using the dry technique (Fig. 5) and standard of ASTM D 422-87 [23]. Figure 6 displays the grain size distribution of the samples chosen to conduct the wear tests.

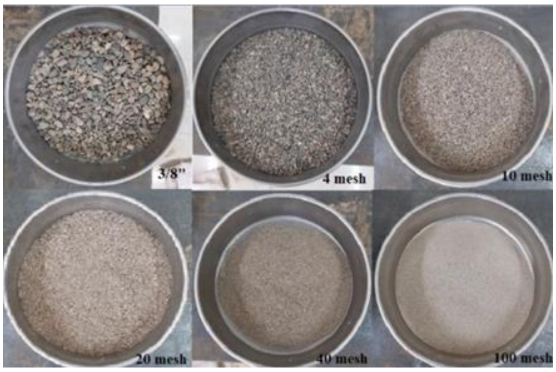

Figure 5. Granulation of the sample prepared from the 5th station of the Tabriz metro line 2

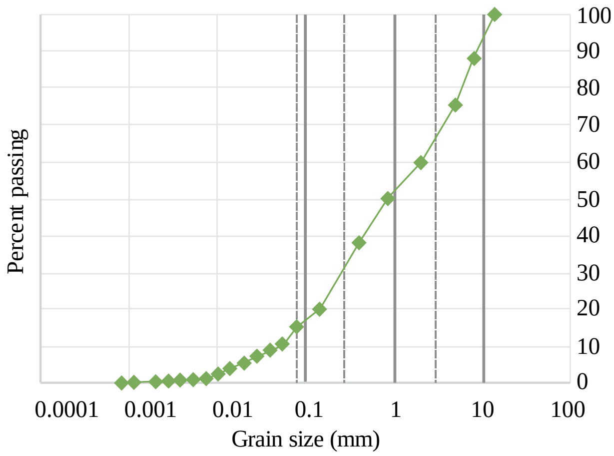

Figure 6. The grain size distribution of the soil sample

The impact of soil moisture content, cutter head torque, cutter head rotation speed, excavation duration, and penetration rate on cutting tool wear was investigated using 43 separate tests (Table 3).

In order to study the wear of cutting tools, the laboratory tests were performed using tunnel boring machine laboratory simulator. This new device is able to reproduce the excavation conditions of a tunnel to a large extent.

Table 3. Description of the tests performed on different samples

Test No.	Soil moisture content (%)	Rotation speed of cutter head (rpm)	Excavation time (min)	Penetration rate (mm/min)
1-36	10	10, 15, 20, 25, 30 & 35	10, 20, 30, 40, 60 & 80	2.5, 3.3, 5, 6.6, 10 & 20
37-40	5,10,15 & 20	35	40	5
41-43	5,10,15 & 20	35	60	5

3. Results and discussion

In this paper, using the tunnel boring machine laboratory simulator, the influence of the excavation machine operating parameters on the wear of the cutting tools has been studied. For this purpose, 36 different tests were performed on samples prepared with 10% moisture content. The cutting tool wear is measured by their primary and secondary weighing according to the following Equation:

$$Wear\ percentage\ of\ cutting\ tool = \frac{Primary\ weight - Secondary\ weight}{Primary\ weight} \cdot 100\%. \quad (1)$$

The study found that the wear of cutting tools is influenced by the excavation machine operating parameters.

3.1. Effect of cutter head rotation speed on cutting tool wear

Research conducted in recent years shows that the cutter head rotation speed has a significant effect on the wear of cutting tools. Therefore, more research is required to achieve the balance between improving machine performance and reducing costs associated with tool wear. In this research, the cutter head rotation speed was examined in 36 tests to determine how it affects wear of cutting tools using a tunnel boring machine laboratory simulator on samples prepared with a 10% moisture content and a density of 1.8 g/cm^3. Tests were conducted at six rotation speeds of 10, 15, 20, 25, 30 and 35 rpm and excavation times of 10, 20, 30, 40, 60 and 80 minutes. The results obtained, according to Figure 7, with an increase in the cutter head rotation speed, the cutting tools wear out more, because they collide with soil particles more frequently. Due to the cohesiveness of soil particles with each other, cutting tools in cohesive soils are also subjected to higher contact pressures with the soil, resulting in an increased wear rate of the cutting tools.

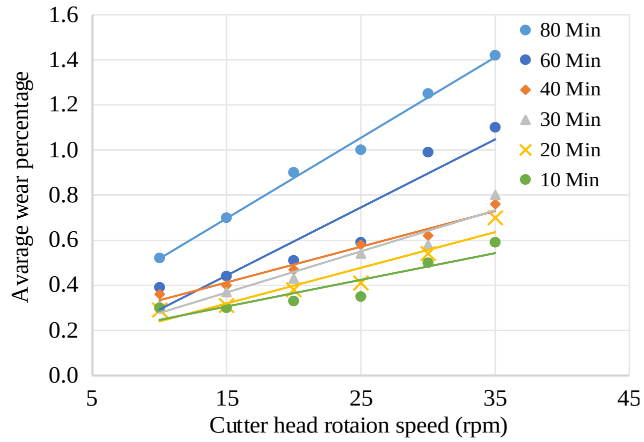

Figure 7. Effect of cutter head rotation speed and excavation time on cutting tool wear

According to the obtained results, with an increase in the cutter head rotation speed from 10 to 35 rpm, the wear of cutting tools has a relatively constant increase throughout the entire excavation times. By increasing the cutter head rotation speed from 10 to 35 rpm, wear increases by more than 150%.

3.2. Effect of penetration rate on cutting tool wear

In tunneling, one of the most important factors is the penetration rate of the excavation machine. Increasing penetration can increase excavation rate, but can also cause cutting tools to engage with soil particles under greater pressure. As a result, the excavation machine torque increases. One of the important challenges in tunnel excavation projects is to determine the appropriate penetration rate, taking into account the increased excavation rate and the reduced machine torque to reduce the excavation cost. In the previous section, 36 tests were prepared, which were also used to determine how this affects the wear of cutting tools, using a tunnel boring machine laboratory simulator on samples prepared with 10% moisture content and density of 1.8 g/cm^3, in 6 penetration rates of 2.5, 3.3, 5, 6.6, 10 and 20 mm/min with rotation speeds of 10, 15, 20, 25, 30 and 35 rpm.

Figure 8 shows the results of tests performed with different rotation speeds and penetration rates.

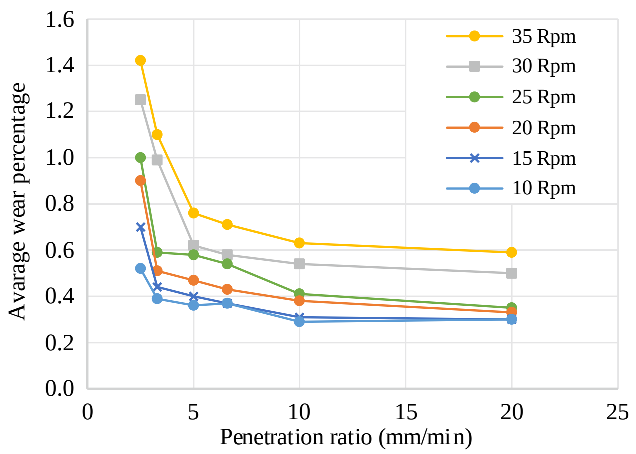

Figure 8. Effect of penetration rate and rotation speed on cutting tool wear

It is shown that under the same excavation conditions, a reduction in penetration rate decreases the cutting tool wear, because the excavation time is reduced and the engagement of cutting tools with soil particles is reduced. At all speeds of the cutter head rotation, the cutting tool wear decreases relatively constantly with an increase in penetration rate from 2.5 to 20 mm/min. The average wear percentage of cutting tool decreases by 58% with increasing penetration rate from 2.5 to 20 mm/min.

3.3. Effect of excavation machine torque on cutting tool wear

The excavation machine torque plays an important role in the cost of excavation projects. The excavation machine torque depends on factors such as penetration rate, soil moisture content, soil physical properties, cutter head shape, and cutter head rotation speed. An increase in torque due to the increase in pressure on the excavation machine causes an increase in the costs related to the maintenance of the machine, and the costs related to the increased wear of the cutting tools and the cutter head.

To investigate the effect of the excavation machine torque on the cutting tool wear, excavation was made for 10, 20, 30, 40, 60, and 80 minutes (Fig. 9).

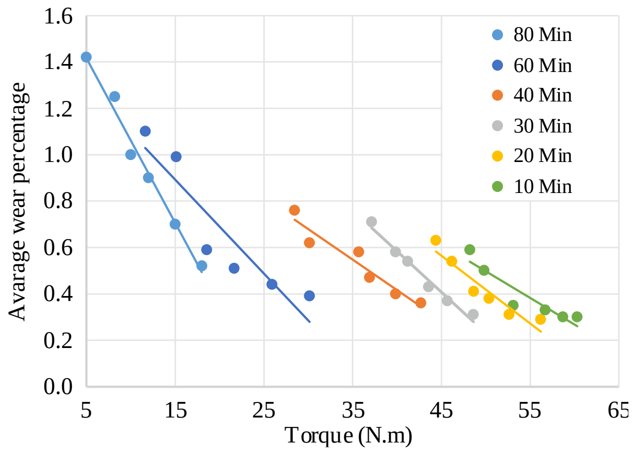

Figure 9. Effect of machine torque on cutting tool wear

The results obtained from the tests show that with increasing torque of the tunnel boring machine laboratory simulator, the cutting tool wear decreases by about 60%.

3.4. Effect of soil moisture content on cutting tool wear

Another parameter affecting the cutting tool wear is soil moisture content. Studies have shown that the cutting tool wear increases with increasing soil moisture content up to a certain value, and then decreases. To investigate the effect of soil moisture content on the cutting tool wear, 4 tests were performed under the same conditions, with a rotation speed of 35 rpm, excavation time of 60 minutes and a soil density of 1.8 g/cm^3. Soil moisture contents were 5, 10, 15, and 20%. Also, for a more detailed investigation, 4 other tests were performed with the same specifications during the excavation time of 40 minutes. The results show that the wear of cutting tools increases, at first, up to 10% moisture content (Fig. 10) as a result of increased soil adhesion and increased engagement between cutting tools and soil grains.

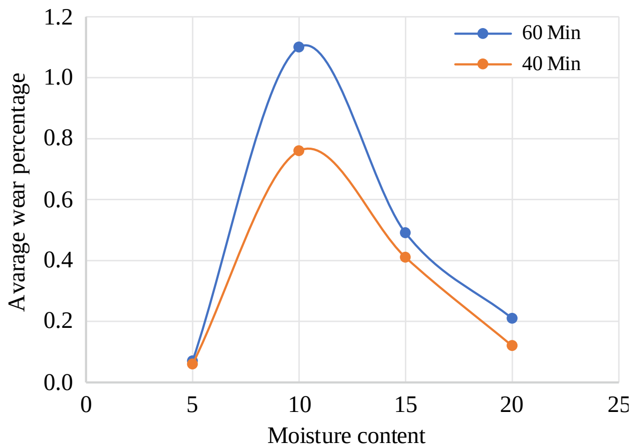

Figure 10. Effect of soil moisture content on cutting tool wear in different time periods

The cutting tool average wear decreases when the moisture content increases above 10%, because soil grains become more mobile and buoyant with increasing soil moisture; this leads to a decrease in the average wear of cutting tools. Thus, when the soil structure approaches saturation, the grains are surrounded by water particles, which leads to erosion of the continuous soil structure. In addition, coarse and abrasive particles become looser and less resistant to movement, reducing tool wear. According to the experiments, with an increase in moisture content from 10 to 20%, the average percentage of wear of cutting tools decreases by 80%.

3.5. Effect of soil moisture content on the torque and specific energy required by the excavation machine

To investigate the effect of soil moisture on the torque of the excavation machine, as well as on the specific energy, power diagrams and excavation machine torque related to each test, according to data obtained, a torque meter was installed in the main axis of the tunnel boring machine laboratory simulator (Figs. 11 and 12).

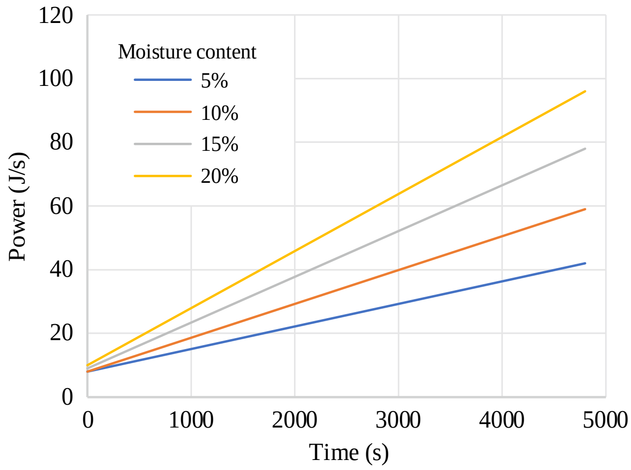

Figure 11. Diagram of power at different moisture contents

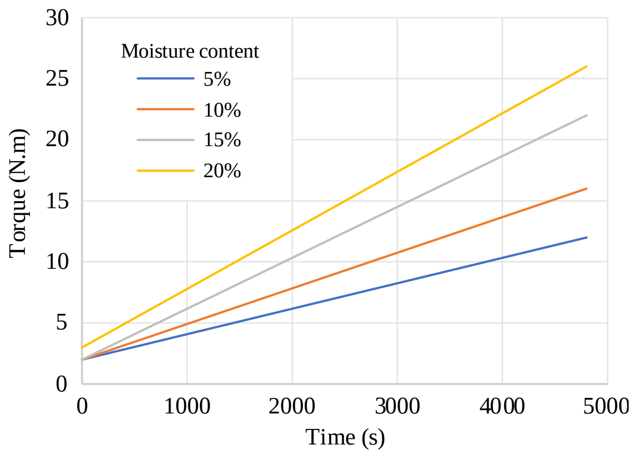

Figure 12. Diagram of torque at different moisture contents

With the increase in soil moisture content from 5 to 20%, the machine torque increases by 116% due to the cohesiveness of soil particles to each other and increased friction between soil particles and cutting tools. By increasing the torque of the device, the power increases, since it has a direct dependence on the torque. Also, the energy consumed in each test increases. Specific energy (the ratio of energy used in each test to average wear) first decreases by 91% from 5 to 10% moisture content and then increases by 900% from 10 to 20% moisture content (Table 4).

The torque of laboratory simulator increases with soil moisture content, and as torque increases, power and energy consumption also increase. The specific energy first decreases with increasing moisture content, and then sharply increases.

Table 4. Changes in the specific energy at different moisture contents

Moisture content	Energy consumed in each test (J)	Average wear (kg)	Specific energy (J/kg)
5	91818	$0.07 \cdot 10^{-3}$	$1311.69 \cdot 10^{6}$
10	118908	$1.1 \cdot 10^{-3}$	$108.10 \cdot 10^{6}$
15	152586	$0.49 \cdot 10^{-3}$	$311.40 \cdot 10^{6}$
20	191574	$0.21 \cdot 10^{-3}$	$912.26 \cdot 10^{6}$

Suggestions for future studies include:

1. Evaluating the effect of soil moisture on the wear of cutting tools under different conditions and granulations.
2. Studying the influence of foam parameters on the wear of cutting tools.
3. Investigating the effect of the arrangement and location of the cutter head cutting tools on wear rate and its mechanism.

4. Conclusions

It is common for cutting tools to wear out during mechanized excavation, which greatly influences on the project final cost. To study the tunnel excavation mechanisms, a tunnel boring machine laboratory simulator was designed and constructed within the framework of this research. In addition to horizontal operation, low cutter head rotating speeds, continuous contact with fresh soil during testing, and specific injection pressures of additives, this new device has several other characteristics. By analyzing the grain size distribution prepared from the Tabriz metro line 2, the effect of soil moisture content, cutter head torque, cutter head rotation speed, excavation duration and penetration rate on cutting tool wear was investigated using 43 separate tests. The results obtained from this study are as follows:

1. As a result of increasing rotation speed of the cutter head from 10 to 35 rpm, the wear rate of cutting tools increases by 150%. This is due to the fact that cutting tools are more likely to collide with soil particles as the cutter head rotates faster. Moreover, in cohesive soils, due to the cohesiveness of soil particles with each other, the cutting tools are more likely to engage with the soil with a greater contact pressure, thus leading them to their faster wear.

2. The wear of cutting tools decreases by 40% when the penetration rate increases from 3.3 to 10 mm per minute. This is due to the fact that as penetration rate increases, the wear of cutting tools decreases, since excavation time decreases. Therefore, the duration of the cutting tool interaction with soil particles decreases with increasing penetration rate.

3. Based on the results of research into soil moisture and cutting tool wear, it has been determined that with an increase in soil moisture content by 10%, wear increases due to increased soil adhesion and contact between cutting tools and soil. With an increase in soil moisture content by 20%, wear is reduced by an average of 80%. As soil moisture content increases, soil grains become more mobile and buoyant. The soil structure loses its continuous state as it approaches saturation as grains are surrounded by water particles, and coarse and abrasive particles become looser, resulting in less tool wear.

4. When the soil moisture content increases from 5 to 20%, the machine torque increases by 116%, because soil particles become more cohesive with each other, and friction increases between soil particles and cutting tools. Increasing the torque of the device also increases its power, which will increase the amount of energy consumed during testing.

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References

[1] Avunduk, E. (2018). *Investigation of effects of soil conditioning*. Istanbul, Turkey: Istanbul Technical University.

[2] Rostami, J., Gharahbagh, E.A., Palomino, A.M., & Mosleh, M. (2012). Development of soil abrasivity testing for soft ground tunneling using shield machines. *Tunnelling and Underground Space Technology*, (28), 245-256. https://doi.org/10.1016/j.tust.2011.11.007

[3] Düllmann, J., Alber, M., & Plinninger, R.J. (2014). Determining soil abrasiveness by use of index tests versus using intrinsic soil parameters. *Geomechanics and Tunnelling*, *7*(1), 87-97. https://doi.org/10.1002/geot.201310028

[4] Ko, T.Y., Kim, T.K., Son, Y., & Jeon, S. (2016). Effect of geomechanical properties on Cerchar Abrasivity Index (CAI) and its application to TBM tunnelling. *Tunnelling and Underground Space Technology*, (57), 99-111. https://doi.org/10.1016/j.tust.2016.02.006

[5] Farrokh, E. (2021). Primary and secondary tools' life evaluation for soft ground TBMs. *Bulletin of Engineering Geology and the Environment*, (80), 4909-4927. https://doi.org/10.1007/s10064-021-02223-4

[6] Amoun, S., Sharifzadeh, M., Shahriar, K., Rostami, J., & Azali, S.T. (2017). Evaluation of tool wear in EPB tunneling of Tehran Metro, Line 7 Expansion. *Tunnelling and Underground Space Technology*, (61), 233-246. https://doi.org/10.1016/j.tust.2016.11.001

[7] Bakar, M.A., Zafar, Z., & Majeed, Y. (2020). Abrasiveness evaluation of selected river gravels of Pakistan using LCPC rock abrasivity test. *Bulletin of Engineering Geology and the Environment*, (79), 2561-2577. https://doi.org/10.1007/s10064-019-01719-4

[8] Thuro, K., & Käsling, H. (2009). Classification of the abrasiveness of soil and rock. *Geomechanics and Tunnelling*, (2), 179-188. https://doi.org/10.1002/geot.200900012

[9] Zhang, X.P., Tang, S.H., Liu, Q.S., Tu, X.B., Chen, P., & Li, F.Y. (2021). An experimental study on cutting tool hardness optimization for shield TBMs during dense fine silty sand ground tunneling. *Bulletin of Engineering Geology and the Environment*, (80), 6813-6826. https://doi.org/10.1007/s10064-021-02327-x

[10] Jakobsen, P.D., & Lohne, J. (2013). Challenges of methods and approaches for estimating soil abrasivity in soft ground TBM tunnelling. *Wear*, *308*(1-2), 166-173. https://doi.org/10.1016/j.wear.2013.06.022

[11] Rong, X., Lu, H., Wang, M., Wen, Z., & Rong, X. (2019). Cutter wear evaluation from operational parameters in EPB tunneling of Chengdu Metro. *Tunnelling and Underground Space Technology*, (93), 103043. https://doi.org/10.1016/j.tust.2019.103043

[12] Avunduk, E., & Copur, H. (2018). Empirical modeling for predicting excavation performance of EPB TBM based on soil properties. *Tunnelling and Underground Space Technology*, (71), 340-353. https://doi.org/10.1016/j.tust.2017.09.016

[13] Azali, S.T., Ghafoori, M., Lashkaripour, G.R., & Hassanpour, J. (2013). Engineering geological investigations of mechanized tunneling in soft ground: A case study, East-West lot of line 7, Tehran Metro, Iran. *Engineering Geology*, (166), 170-185. https://doi.org/10.1016/j.enggeo.2013.07.012

[14] Bakar, M.A., Majeed, Y., & Rostami, J. (2018). Influence of moisture content on the LCPC test results and its implications on tool wear in mechanized tunneling. *Tunnelling and Underground Space Technology*, (81), 165-175. https://doi.org/10.1016/j.tust.2018.07.021

[15] 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*, (32), 100692. https://doi.org/10.1016/j.trgeo.2021.100692

[16] Sun, Z., Yang, Z., Jiang, Y., Gao, H., Fang, K., & Yin, M. (2021). Influence of particle size distribution, test time, and moisture content on sandy stratum LCPC abrasivity test results. *Bulletin of Engineering Geology and the Environment*, (80), 611-625. https://doi.org/10.1007/s10064-020-01927-3

[17] 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*, (59), 1-6. https://doi.org/10.1016/j.tust.2016.06.006

[18] Küpferle, J., Zizka, Z., Schoesser, B., Röttger, A., Alber, M., Thewes, M., & Theisen, W. (2018). 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. *Tunnel-*

ling and Underground Space Technology, (74), 206-216. https://doi.org/10.1016/j.tust.2018.01.011
[19] Tang, S.H., Zhang, X.P., Liu, Q.S., Xie, W.Q., Wang, H.J., Li, X.F., & Zhang, X.Y. (2022). New soil abrasion testing method for evaluating the influence of geological parameters of abrasive sandy ground on scraper wear in TBM tunneling. *Tunnelling and Underground Space Technology*, (128), 104604. https://doi.org/10.1016/j.tust.2022.104604
[20] Lan, H., Xia, Y., Miao, B., Fu, J., & Ji, Z. (2020). Prediction model of wear rate of inner disc cutter of engineering in Yinsong, Jilin. *Tunnelling and Underground Space Technology*, (99), 103338. https://doi.org/10.1016/j.tust.2020.103338
[21] Peila, D., Picchio, A., Martinelli, D., & Negro, E.D. (2016). Laboratory tests on soil conditioning of clayey soil. *Acta Geotechnica*, *11*(5), 1061-1074. https://doi.org/10.1007/s11440-015-0406-8
[22] Plinninger, R., Käsling, H., Thuro, K., & Spaun, G. (2003). Testing conditions and geomechanical properties influencing the CERCHAR abrasiveness index (CAI) value. *International Journal of Rock Mechanics and Mining Sciences*, (40), 259-263. https://doi.org/10.1016/S1365-1609(02)00140-5
[23] ASTM D422-63. (2007). Standard test method for particle-size analysis of soils. West Conshohocken, United States: ASTM International.

Оцінювання зношування ріжучого інструмента з використанням лабораторного симулятора прохідницької бурової машини

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Мета. Оцінювання зношування ріжучого інструмента нового розробленого лабораторного симулятора прохідницької бурової машини для експериментального дослідження процесу проходки тунелю.

Методика. Використано розроблений лабораторний симулятор, що функціонує горизонтально, і має низьку швидкість обертання, утримує штифти в контакті зі свіжим ґрунтом протягом усього випробування, а також володіє можливістю вимірювання обертального моменту пристрою під час випробування. Дослідження зношування ріжучого інструменту було проведено із використанням грануляції, отриманої з другої лінії метро у Табрізі, а також із застосуванням робочих параметрів механізованих виїмкових машин, таких як швидкість проникнення та швидкість обертання ріжучої головки.

Результати. Встановлено, що при зниженні швидкості обертання ріжучої головки з 35 до 10 обертів на хвилину середнє зношування ріжучих інструментів знижується на 63%. Встановлено, що зношування ріжучого інструменту знижується на 40% при збільшенні швидкості проходки з 3.3 до 10 мм за хвилину. Це пов’язано з тим, що зі збільшенням швидкості проходки зменшується знос ріжучого інструменту, оскільки скорочується час проходки. Також за рахунок скорочення часу виїмкових робіт з 80 до 10 хвилин зношування ріжучих інструментів знижується на 58%. Зношування ріжучого інструменту збільшується зі збільшенням вологості від 0 до 10%, а потім знижується зі збільшенням вологості від 10 до 25%.

Наукова новизна. Спроектовано та побудовано новий пристрій для імітації механізмів проходки тунелів, що вимірює відсоток зношування, швидкість проникнення і обертальний момент.

Практична значимість. Було досягнуто значного прогресу в прогнозуванні швидкості стирання ґрунту, але існує кілька загальноприйнятих моделей для прогнозування зношування ріжучого інструменту та швидкості стирання ґрунту. Під час проектування та виготовлення лабораторного симулятора прохідницької бурової машини було досліджено вплив робочих параметрів на зношування ріжучого інструменту.

Ключові слова: *механізовані виїмкові роботи, зношування ріжучих інструментів, швидкість проникнення, швидкість обертання ріжучої головки, обертальний момент*