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The Effects of Water Content and Grain Size on the Clogging and Abrasivity of Fine-Grained Soils in Mechanized Excavation

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Abstract
Clogging during excavation is one of the common problems in mechanized excavation. Among the influential factors in clogging of the cutter head, we can mention the percentage of fine soil particles (under 200 mesh sieve), soil moisture, and soil type. In this study, to investigate the mechanism of tunnel excavation in the laboratory, a tunnel excavation machine laboratory simulator was designed and built. The features of this device are its horizontal operation, the low rotation speed of the cutter head, continuous contact of the pins with fresh soil during the test, and the continuous injection of additives with a specific injection pressure during the test. The effect of the percentage of fine-grained, soil moisture and the foam injection ratio (FIR) on clogging, energy consumed, and the average wear of cutting tools was studied. The results showed that with an increase in the percentage of fine soil particles from 90 to 100%, the clogging of cutting tools increased by 50%. Also, with an increase of soil moisture from a dry state to moisture content of 5%, clogging of the cutter head is insignificant, and after that, with an increase of moisture from 10 to 25%, clogging is increased by 178%, and the amount of energy consumed in each test is increased by 84%. In addition, by increasing the foam injection ratio from 40 to 60%, clogging decreased by 81% on average, and the wear of cutting tools decreased by 62% on average.

Keywords:
Mechanized excavation, wear of cutting tools, clogging, clay, foam

1. Introduction

Earth pressure balance excavation machines (EPB) are widely used in tunneling in urban areas and soft grounds. The use of these machines is very important due to having advantages such as a high advance rate and minimizing environmental effects. The challenging activity of tunneling is the existence of risks such as surface settlement, damage to the structure, and the slow advance rate due to the variety of soil types in the excavation path, which requires more studies and specific works. Clogging is one of the main problems during excavation. During excavation, by mixing the soil particles with the water flow, the excavated fine-grained soil sticks to the metal parts of the TBM cutter head and causes clogging. In this situation, the excavation operation should be stopped, and the cutting tools on the cutter head should be cleaned, and then the excavation operation should be resumed. This causes an increase in the excavation time, an increase in costs, and a decrease in excavation efficiency (**Hernandez et al., 2018**). The clogging occurs due to the adhesion between the soil and the cutter head and conveyor belt in EPB excavation machines. Clay has a high liquid limit and plasticity index and causes the problem of clogging during excavation. Also, due to the presence of swelling minerals in the vicinity of water, these types of soils tend to stick to the cutter head (**Feng, 2004**). There are two different methods to evaluate the clogging potential of sticky soils during mechanized excavation: experimental classifications and experimental tests (**Thewes and Burger, 2005**). **Thewes (1999)**, by investigating the adhesion mechanism of fine-grained soils to metal parts, proposed four conditions for the occurrence of clogging. These four conditions, as the adhesion and cohesion of soil particles, according to **Figure 1(a)**, and also the mechanism of placement of soil particles in the openings of metal surfaces that act like a bridge, according to **Figure 1(b)** and also the accumulation of rounded particles by the water is defined according to **Figure 1(c)**. According to the theory of **Thewes and Burger (2005)**, the sticky behavior of the excavated soil is one of the important factors in the economical parameters of tunneling projects. **Thewes and Burger (2004)**, have classified soil clogging potential based on its consistency to: a) high clog-

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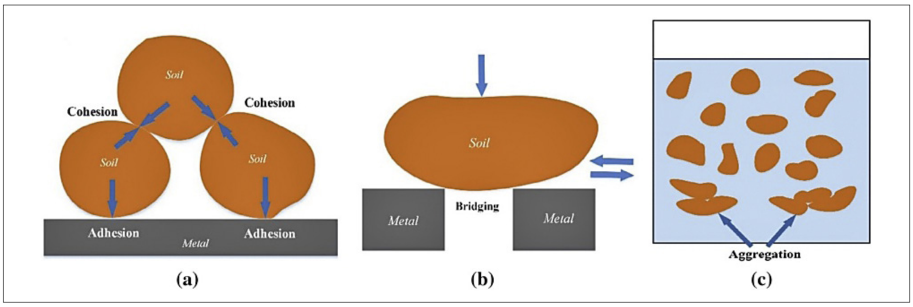

Figure 1: Clogging potential: a) Adhesion and Cohesion, b) Bridging soil particles, c) Aggregation [**Thewes and Burger, 2005**]

ging potential; which leads to major problems and the need for daily cleaning, b) medium clogging potential; which can be resolved by modifications to the TBM cutter head system and c) the potential for low clogging; which has a minor effect on TBM performance.

Abrasion is also one of the basic problems in tunneling projects, which has a significant impact on timing and costs. The amount of soil abrasion faced by cutting tools and excavation machines increases with an increase in the hardness of the elements and minerals in the excavated ground (**Verhoef, 2017**). As the cutting tool wears, a hyperbaric operation should be done to replace the worn tools. Considering that the excavation machine chamber is under pressure, this operation will require a lot of time and money. Therefore, control of wear in cutting tools is important. Several parameters affect the wear of cutting tools in tunnel excavation. The geology, which includes equivalent quartz content, rock strength, grain size, grain roundness, etc. as an abrasive material, has a great influence on the wear rate (**Kohler et al., 2011**). On the other hand, operational factors (including excavation parameters and technical specifications of the excavation machine) also have a great effect on wear. Penetration rate, the rotation speed of the cutter head, ground stresses, torque of the cutter head, soil additives, hardness, material, and the arrangement of the cutting tool are the factors that control the wear of the cutter head (**Amoun et al., 2015**). In **Table 1**, the classification of factors affecting soil wear in mechanized excavation is described.

Despite the widespread use of soil-cutting tools, there is no standard and comprehensive method for measuring the amount of soil abrasion and clogging of the cutter head. For this reason, several research studies and experiments have been conducted to measure the amount of soil abrasion and determine the clogging potential of cutting tools. **Nilsen et al. (2007)**, divided wear into primary, and secondary wear and while reviewing existing wear tests, they introduced the SAT device to measure wear in soil. **Thuro et al. (2006 and 2007)**, evaluated wear by LCPC test. **Thuro and Kasling (2009)**, studied and classified soil and rock wear by LCPC test. **Alavi Qarahbagh et al. (2011 and 2014)**, studied the problems caused by the wear of cutting tools in mechanized

Table 1: Parameters affecting soil wear in mechanized tunnel excavation [**Amoun et al., 2015**].

Parameters affecting soil abrasion	
Excavation parameters	cutter head rotation speed, penetration rate, cutter head torque, rotation time, excavation chamber pressure, type of additives and soil conditioning
Technical specifications of the excavation machine	Type of excavation machine, arrangement of cutting tools, diameter of the machine, amount of opening of the cutter head, number of cutting tools, material, and hardness of the tools
Geological features	Soil grading, soil texture, mineralogy, soil density, grain shape, soil type, density, moisture percentage, and angularity

excavation on soft ground. Also, while introducing parameters affecting wear, they introduced a new wear measurement device called a PSAI. **Rostami et al. (2012)**, investigated and predicted the parameters affecting wear by completing the PSAI wear measurement device. **Jacobsen et al. (2012 and 2013)**, investigated the methods of measuring wear in soft ground and the existing challenges and studied the amount of soil wear in the soft ground by constructing the SGAT device. They also investigated the effect of mineralogy, moisture percentage, ground stresses, compaction, and soil conditioning on the wear of cutting tools. **Barzegari et al. (2013)**, simulated the TBM-EPB excavation machine by developing a device to measure the amount of wear based on the chamber environment. **Kupferle et al. (2016)**, investigated the amount of wear by making a RUB device that performs horizontal excavation. **Salazar et al. (2018)**, also studied the effect of different parameters on soil abrasion. **Pourmand et al. (2018)**, investigated the soil conditioning tests in tunnel boring machines using three-dimensional numerical modeling (PFC3D). **Liu et al. (2020)**, investigated the effect of the moisture content of mudstone during the tunneling process. By comparison, it was found that the wear loss of the disc cutter and cutting efficiency shows a negative and positive correlation with the water content, respectively. **Wei et al. (2020)**, investigated the effect of FIR on the weight loss of steel cubes rotating in conditional soils. They showed that by increasing FIR, weight loss of steel cubes decreases. **Yao et al. (2021)**, investigated the FIR and moisture content of bentonite. They showed that soil conditioning parameters could effectively reduce friction in the cutter head and increase the workability of tunneling operations. **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 amount of wear and the amount of energy required for excavation decreases. **Chen et al. (2022)**, using a laboratory simulator of a mechanized excavation machine, investigated the factors affecting the reduction of clogging of the cutter head. They showed that by increasing the foam injection ratio (FIR), the clogging of cutting tools decreases. Also, **Bazargan et al. (2022)**, investigated the cutting tools of tunnel boring machines using an artificial neural network.

Although, many advances have been made in the field of predicting the amount of abrasion of different soils, limited models have been accepted to predict the wear and clogging potential of cutting tools. In this research, while designing and building a tunnel boring machine laboratory simulator, the effect of the percentage of fine particles, moisture content, and foam injection ratio on the degree of clogging, specific energy, and average wear of cutting tools has been studied. For this purpose, the samples prepared from the subway of Tabriz (Line 2) were used in five different grades, 6 moistures 0, 5, 10, 15, 20, and 25%, and three foam injection ratios (FIR), 40, 50, and 60%. The features of this new laboratory simulator are to create more realistic conditions compared to the previous studies, such as horizontal excavation, the low rotation speed of the cutter head, the possibility of foam injection during and before excavation, and continuous contact of the pins with fresh soil.

2. Introduction of tunnel boring machine laboratory simulator

The tunnel boring machine laboratory simulator was built to simulate the tunnel excavation mechanism (see **Figure 2**). Using this device, it is possible to check the amount of soil abrasion, the wear of cutting tools, and clogging under different conditions. Various components of the tunnel boring machine laboratory simulator, including an air compressor (24 liters), a pneumatic jack (with a maximum course of 50 cm), a motor (3 kW), a gearbox, a torque meter, a shaft and excavation chamber (length 75 cm and diameter 15 cm). **Table 2** shows the measurable parameters of the tunnel boring machine laboratory simulator.

To prepare the device for testing, first, the spring is mounted on the shaft (see **Figure 3**). After that, the polyethylene piece is placed on the shaft, and the cutter head is attached to its end. On the shaft, there is a section for adding additives during the test. The cutter head made for excavation simulation is similar to the real tunnel

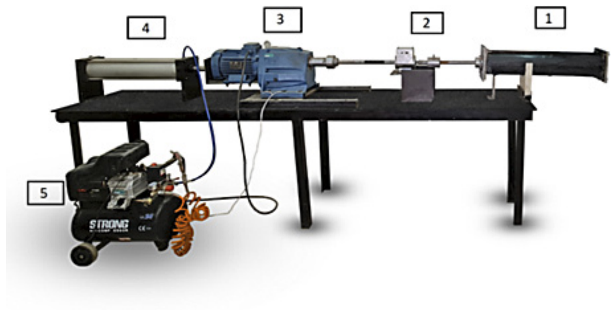

Figure 2: Overview of the tunnel boring machine laboratory simulator (1-shaft and excavation chamber, 2- torque meter, 3- motor and gearbox, 4- pneumatic jack and 5- air compressor)

boring machine and has a circular cross-section. On the cutter head, there are places for installing cutting tools (pins) which are arranged according to **Figure 3(b)** in three external, middle, and central positions. Also, on the cutter head, there are places for injecting additives, which provides the possibility to inject these materials into the excavation face with a certain injection pressure during the test.

Table 2: Measurable parameters of tunnel excavation machine laboratory simulator

Precision instrument design	**9 pins spirally**
cutter head rotation speed (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
additives	Mixing before testing and adding continuously during testing
The type of cutting tools	Steel

The shaft is placed inside a chamber 75 cm long and 15 cm in diameter, so that the spring behind the polyethylene piece is fully compressed. On the other hand, the shaft is connected to the torque meter, and the torque meter is also connected to the gearbox so that the cutter head rotates inside the soil using the rotary motion 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 cutter head. To determine the wear of pins installed on the cutter head, the difference in weight of pins before, and after every test was measured and the percentage of wear was calculated. The excavated soil is directed to the space behind it (the space between the polyethylene piece and the back

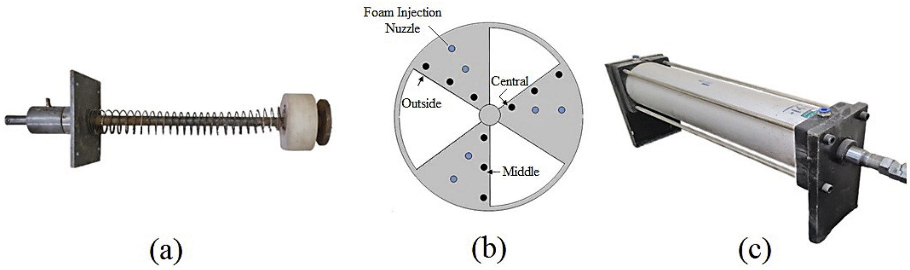

Figure 3: a) A view of the excavation shaft including a spring and a polyethylene piece, b) Cutter head of the tunnel boring machine laboratory simulator, c) Pneumatic jack

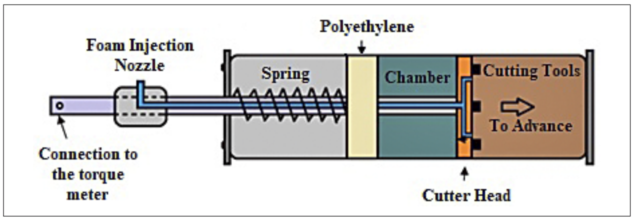

Figure 4: A schematic view of the shaft and soil chamber

of the cutter head) through the spaces on the cutter head. The complete compression of the spring behind the polyethylene piece causes the polyethylene piece to stick to the cutter head and prevent 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 constructed excavation machine shaft and its soil chamber is shown in **Figure 4**.

Due to the need for the cutter head and cutting tools to collide with fresh soil and penetrate it, the engine 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 engine and gearbox on the rail, it is possible to penetrate the cutter head into the soil. Also, to create a different rotation speed in the cutter head, a device for adjusting the rotation speed of the cutter head (inverter) has been used. 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 course of this jack is 50 cm. This pneumatic jack by an air compressor (Strong 24 liters) provides the necessary power to move the engine and gearbox on the rail.

3. Preparation of samples

The soil needed to be used in the experiments was provided from the west of Tabriz city, from the excavation site of Tabriz metro from line 2 - 5th station. 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 fields 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. The gradation, Atterberg limits, and classification according to the available data of the geotechnical report of Tabriz metro line 2 are presented in **Table 3**.

According to the exploratory and geological studies conducted (up to a depth of 30 meters) in this area, the sediments are fine-grained clay and silty. 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 abrasion rate of Tabriz metro tunnel stone samples shows that the CAI value for these stones is around 2.3 to 4.7. According to the classification, the stones of the tunnel path are often in the very abrasive group. Also, the amount of abrasive minerals (quartz) in these stones is between 5 and 20%.

The soil sample provided from the desired location was granulated according to ASTM D 422-63 (**ASTM, 2007**) and by dry method. The fine-grained part of the soil has been used to check the clogging and adhesion of soil particles. For this purpose, particles below 75 microns (200 mesh sieve) and also 40 mesh sub-particles have been used to create granulation for experiments.

Table 3: Characteristics of the geological layers around the case study

No.	Depth (m)	Gradation								Att. Limits		Classification
		Gravel %	Sand %	Fines %	mm	mm	mm	C_u	C_c	LL %	PL %	USCS
1	6.0- 7.0	1.9	52.4	45.7	<0.074		0.16			-	NPI	SM
2	8.0- 8.45	0.9	28.7	70.3						-	NPI	ML
3	8.45- 8.8	0.0	23.8	76.2						60.5	43.7	CL
4*	9.5- 10.7	0.0	3.6	96.4						99.8	82.2	CH
5	12.0- 13.0	14.4	57.6	28.0	<0.074	0.10	0.53	>7.1	>0.23	-	NPI	SM

Table 4: Description of the tests performed on soils with different percentages of fine particles

Soil No.	Passing percentage of a 200 mesh sieve	The remaining percentage between a 40 and 200-mesh sieve	Moisture content	Experiment with foam
1	100	0	0, 5, 10, 15, 20, and 25	Experiment with adding foam with FIR, 50, 40, and 60% and with 20% moisture
2	95	5	0, 5, 10, 15, 20, and 25	Experiment with adding foam with FIR, 50, 40, and 60% and with 20% moisture
3	90	10	0, 5, 10, 15, 20, and 25	No foam
4	85	15	0, 5, 10, 15, 20, and 25	No foam
5	80	20	0, 5, 10, 15, 20, and 25	No foam

Table 5: The results of the tests to determine the Atterberg limits and to determine the potential of clogging

No.	Grading	Liquid limit	Plastic limit	Plasticity index	Consistency index	Clogging potential
1	100% fine grain	125.38	95.32	30.06	1.28	High
2	95% fine grain	109.18	88.42	20.76	1.20	High
3	90% fine grain	92.98	81.52	11.46	1.10	Medium
4	85% fine grain	82.18	76.92	5.26	1.03	Low
5	80% fine grain	76.78	74.62	2.16	0.99	Low

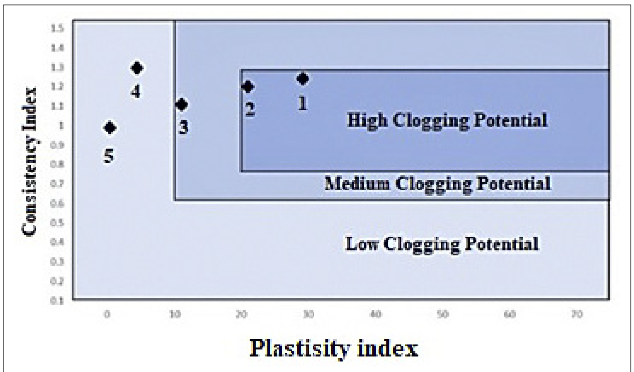

Figure 5: The results of the tests to determine the potential of clogging in the Thewes diagram [**Thewes and Burger (2004)**]

A total of 30 tests were conducted with five different granularities and six different moisture contents using a tunnel excavation machine laboratory simulator. The description of the experiments is according to **Table 4**.

4. Determining the clogging potential in fine-grained soils

Thewes and Burger (2004) determined the clogging potential based on the plasticity index and consistency index (see **Figure 5**). To determine the clogging potential of soils with different amounts of fine grains, the Atterberg limits of the soil were prepared (see **Table 5**). Then, based on the Atterberg limits, was calculated plasticity index, and the consistency index. Finally, the clogging potential using Thewes's diagram (see **Figure 5**) was determined. In Thewes's diagram, among the five gradings, two gradings are in the range of high clogging potential (soil containing 100% passing from a 200 mesh sieve and soil containing 95% passing from a 200 mesh sieve and 5% on a 200 mesh sieve), one grading in the range of medium clogging potential (soil containing 90% passing from a 200 mesh sieve and 10% on a 200 mesh sieve) and two gradings in the range of low clogging potential (soil containing 85% passing from a 200 mesh sieve and 15% on a 200 mesh sieve and soil containing 80% passing from a 200 mesh sieve and 20% on a 200 mesh sieve). This means that with an increase in the percentage passing from a 200 mesh sieve, the potential of clogging in fine-grained soils increases.

5. Investigating the effect of moisture content on clogging and wear of cutting tools

The amount of moisture content and clay minerals in the soil are the most important factors in the phenomenon of clogging and blockage of the mechanized excavation machine. The presence of sticky clay materials with a sufficient amount of water has an important effect on the performance of cutting tools on the cutter head. To investigate the effect of moisture content on the clogging of the cutter head, according to the results obtained from the tests to determine the potential of clogging (see **Table 6**), two grading that is in the range of high clogging potential and one grading that is in the range of medium clogging potential has been used. The obtained results show that with an increase of moisture content from zero to 25%, due to the cohesiveness of the soil particles and the subsequent increase in the amount of

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Table 6: The effect of moisture content and percentage of fine-grain soil on clogging.

No.	Grading	Clogging possibility	Moisture content	Weight of soil adhesion to the pins (g)
1	100% fine grain	High	5	28
			10	114
			15	193
			20	285
			25	317
2	95% fine grain	High	5	23
			10	98
			15	166
			20	240
			25	269
3	90% fine grain	Medium	5	15
			10	71
			15	24
			20	178
			25	211

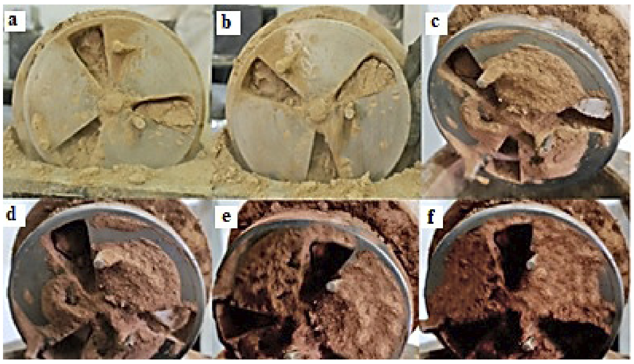

Figure 6: Changes in the degree of clogging with increasing moisture content. a) dry soil b) 5% moisture content, c) 10% moisture content, d) 15% moisture content, e) 20% moisture content, f) 25% moisture content

stress and adhesion between the steel and the soil, clogging on the cutter head increases. The results show that with an increase in the percentage of fine grains from 90 to 100 percent, due to the increase in the cohesion property of the fine-grain particles to each other and adhesion to the cutter head in the presence of moisture content, clogging of the cutting tools increases by 50 percent. On the other hand, an increase in moisture content causes an increase in clogging. With an increase of moisture content from zero to 5%, clogging of the cutter head is insignificant, and after that, with an increase of moisture content from 10 to 25%, clogging increases by 178%. **Figure 6** shows the changes in clogging on the cutter head with the change in the percentage of moisture content in grading No. 1. By weighing the soil adhesion to the pins after the test, clogging was quantified.

Soil moisture is one of the important parameters affecting the wear of cutting tools and clogging. Observations from tunnel excavation projects show that with an increase in soil moisture percentage, the wear of cutting tools usually increases due to the cohesion of fine soil particles to each other in the presence of moisture and the increase in the apparent cohesion of the soil. To investigate this issue, for every five granulations, six tests with a moisture content of 0, 5, 10, 15, 20, and 25%, with a rotation speed of the cutter head of 35 rpm, the penetration rate of 5 , the density of the soil was 1.8 , and the duration of the test was 40 minutes. The obtained results (see **Figure 7**) show that with the increase in soil moisture percentage from zero to 10%, due to the increase in soil adhesion and the increase in the involvement with cutting tools and soil grains, the wear of cutting tools increases. After that, with an increase in moisture percentage from 10 to 25%, because the grains in the soil structure become more mobile, or in other words, by approaching the saturation state, the soil grains are surrounded by water particles, and the wear of cutting tools is reduced. Also, it can be seen that as the percentage of soils above the 200-mesh sieve increases (passing the 40-mesh sieve), the wear of the cutting tools increases due to the presence of grains with larger dimensions.

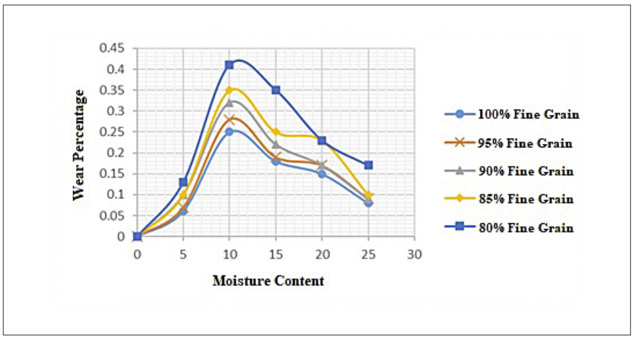

Figure 7: The effect of moisture content on the wear of cutting tools in different grain sizes

6. Investigating the impact of clogging on the torque and specific energy of the excavation machine

Clogging of the cutter head in the mechanized excavation machine reduces the progress of the excavation machine. In such conditions, asymmetric wear occurs in cutting tools and reduces the efficiency of cutting tools. To investigate the impact of clogging in mechanized excavation, fine-grained soil with granularity No. 1 was used, which according to the test to determine the potential of clogging, is in the high potential of clogging range (see **Table 5**). Then, the torque of the device was measured by the torque meter that was installed in the main axis of the excavation machine simulator. Examining the torque and instantaneous power of the device in different moisture contents, according to the diagrams in **Figure**

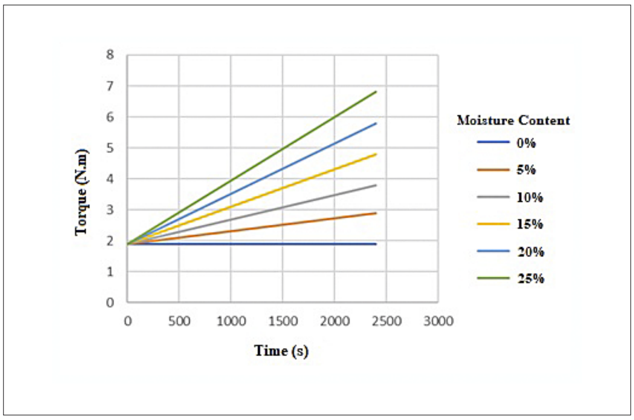

Figure 8: The required torque of the excavation machine in different moisture content in grading number 1

Table 7: Changes in the amount of specific energy in different moisture content

Moisture content	Energy consumed in test (J)	Average wear (kg)	Specific energy (J/kg)
5	21132	×0.02	×1056.6
10	25104	×0.10	×251.04
15	29496	×0.07	×421.37
20	34356	×0.07	×490.80
25	38880	×0.04	×972

8, shows that with an increase in moisture content and clogging, the amount of torque and instantaneous power of the device increases due to the increase in friction between soil particles and cutter head. Also, according to **Table 7**, the energy consumed in each test as well as the specific energy (the ratio of the energy consumed in each test to the amount of wear that occurred on the cutting tools), increases since they have a direct relationship with torque and power.

7. Investigating the effect of adding foam on the clogging and wear of cutting tools

According to research, adding foam during excavation causes non-cohesion of fine soil particles to each other and metal parts, and as a result, the wear of cutting tools and also clogging of the cutter head are reduced. To investigate the effect of adding foam on the wear of cutting tools and clogging on soils that are in the range of high clogging potential according to the Thewes chart, four tests were conducted using soil with granulation numbers 1 and 4. Tests conducted on soil No. 2, with a soil moisture percentage of 25%, the rotation speed of the cutter head at 35 rpm, the penetration rate of 5 , the density of the soil was 1.8 , and the duration of the test was 40 minutes. The properties of the foam produced by the foam machine are with concentration factor (CF) is 3%, and a foam expansion ratio (FER) is 7.5%. In each

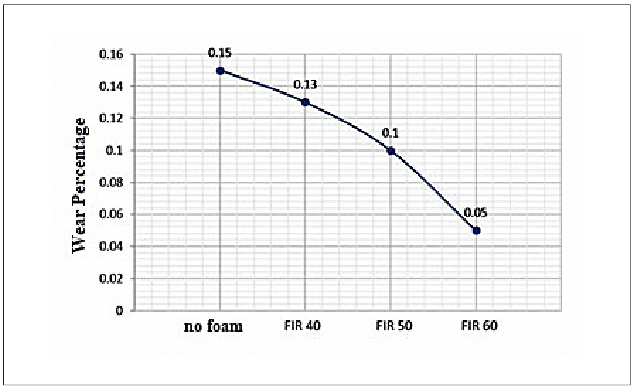

Figure 9: The effect of adding foam on the wear of cutting tools in soil with granulation number 1

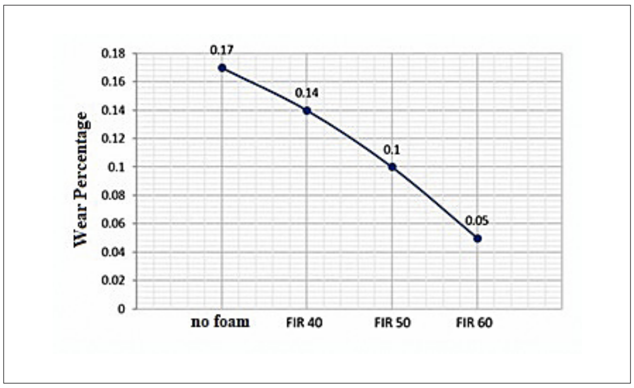

Figure 10: The effect of adding foam on the wear of cutting tools in soil with granulation number 2

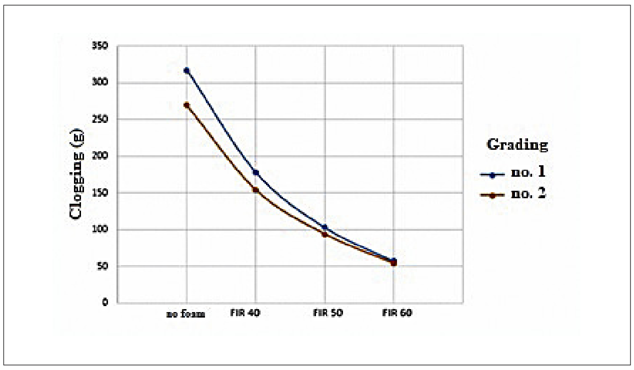

Figure 11: The effect of adding foam on clogging of the cutter head

Figure 12: Reducing clogging due to foam injection

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step of the tests, by changing the foam injection ratio (FIR) with values of 40, 50, and 60%, the effect of adding foam on the wear and clogging of cutting tools has been investigated. The results of the tests are shown according to **Figures 9** to **11** for soils with granulation numbers 1 and 2. The results showed that with an increase of FIR from 40 to 60%, clogging decreased by 81% on average, and the wear of cutting tools decreased by 62% on average. **Figure 12**, as an example, shows the effect of adding foam on reducing clogging in soil with granulation number 1.

8. Conclusion

In mechanized excavation, wear and clogging of cutting tools causes problems such as increasing excavation time, increasing costs, and reducing excavation efficiency. In this study, to investigate the mechanism of tunnel excavation in the laboratory, a tunnel excavation machine laboratory simulator was designed and built. The features of this device are its horizontal operation, the low rotation speed of the cutter head, continuous contact of the pins with fresh soil during the test, and continuous injection of additives with a specific injection pressure during the test. By using the grading prepared from Tabriz metro line 2, the effect of the percentage of fine particles, soil moisture, and foam injection ratio on the clogging, energy consumed, and the average wear of cutting tools was studied. According to the tests, the obtained results are:

- Increasing the percentage of fine soil particles from 90 to 100% causes a 50% increase in the clogging of cutting tools. Also, in fine-grained soils, by increasing the amount of soil on the 200-mesh sieve and under the 40-mesh sieve, the wear of cutting tools increased by 64% due to the increase in the relative size of the soil grains and their abrasiveness.
- With an increase of soil moisture percentage from 10 to 25%, clogging increased by 178% due to the increase of cohesion between soil particles. Also, the amount of wear of cutting tools increased by increasing moisture content up to 10%, and after that, because, since the soil grains become more mobile, the wear of cutting tools decreased on average by 67%.
- With an increase in soil moisture, from dry to 25%, due to the increase in the cohesion of soil particles and the increase in clogging and as a result, the torque and power consumption of the excavation machine increased, and the energy consumed in each test increased.
- The addition of foam during excavation reduced the cohesion of soil particles to each other and metal parts. As a result of adding foam, the amount of wear of cutting tools and clogging of the cutter head decreased. As the foam injection ratio (FIR) increases, under the same conditions, the amount of wear of cutting tools reduction and clogging reduction also increases.
- The built-in laboratory simulator has limitations, such as the impossibility of measuring the chamber pressure, the short length of excavation compared to reality, the impossibility of applying surface load and the inability of excavation in rock samples. Therefore, future research can expand this research by investigating the operational parameters of the device, including the force behind the jack, torque, penetration rate and rotation speed of the cutter head on the wear of cutting tools.

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SAŽETAK

Učinci sadržaja vode i veličine zrna na začepljenje i abrazivnost sitnozrnatog tla kod mehaniziranog otkopvanja

Začepljenje tijekom iskopa je jedan od uobičajenih problema kod mehaniziranog otkopavanja. Među utjecajnim čimbenicima u začepljenju rezne glave možemo spomenuti postotak sitnih čestica tla (čestice koje prolaze kroz otvore sita 200 mesh), vlažnost i tip tla. U ovoj studiji, kako bi se istražio mehanizam iskopa tunela u laboratoriju, projektiran je i izgrađen laboratorijski simulator stroja za iskop tunela. Karakteristike ovog uređaja su horizontalni rad, mala brzina vrtnje rezne glave, kontinuirani kontakt reznog elementa sa svježim tlom i kontinuirano ubrizgavanje aditiva uz specifični tlak tijekom pokusa. Analiziran je učinak udio sitnozrnatih čestica, vlažnosti tla i omjera ubrizgavanja pjene (FIR) na začepljenje, utrošenu energiju i prosječno trošenje reznog alata. Rezultati su pokazali da se povećanjem postotka sitnih čestica tla s 90 na 100% začepljenje reznih alata povećava za 50%. Također, povećanjem vlažnosti tla od suhog stanja do vlažnosti od 5% začepljenje rezne glave je neznatno, a nakon toga, povećanjem vlage od 10 do 25% začepljenje se povećava za 178% dok se količina potrošene energije u svakom pokusu povećava se za 84%. Uz to, povećanjem omjera ubrizgavanja pjene s 40% na 60%, začepljenje se smanjilo u prosjeku za 81%, a trošenje reznog alata u prosjeku je smanjeno za 62%.

Ključne riječi:
mehanizirano otkopavanje, trošenje reznih alata, začepljenje, glina, pjena

Author's contribution

Erfan Khoshzaher (1) (PhD candidate of Mining Engineering) performed experimental tests and processed their results. **Hamid Chakeri (2)** (PhD, Associate Professor) proposed the idea and guided the research. **Mohammad Darbor (3)** (PhD, Assistant Professor) guided the research. **Hadi Shakeri (4)** (MSc, Lecturer) guided the research.