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Investigating Effect of Soil Grading Parameters on Tool Wear in Mechanized Tunneling using EPB-TBM Machine

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Abstract

There is no acceptable method for investigating the tool wear phenomenon in soft grounds. In this article, first, a new equipment made at Sahand University of Technology is introduced, which is used for simulation of TBM tunneling mechanism. Next, the effect of various soil grading parameters such as D10, D30, and D60 (which indicate the corresponding diameters on the soil grading diagram where 10, 30, and 60% of the grains are smaller than these values, respectively), coefficient of gradation, uniformity coefficient, sorting coefficient and effective size on the cutting tools wear. The initial studies show that in soils with fine grains greater than 10%, by increase in the values of D10, D30, D60, and effective size, the tool wear increases. However, in soils with fine grains less than 10%, by increase in the above-mentioned parameters, the soil abrasiveness reduces. Also in soils with more than 10% fine grains, by increase in the coefficient of gradation value, the soil abrasiveness reduces. But in soils with fine grains less than 10%, by increase in the value of this parameter, the tool wear increases. The results of experiments show that sorting coefficient could be a good criterion for investigating the soil abrasiveness.

1. Introduction

Abrasiveness describes the potential of rock or soil grains in causing abrasive wear in the mechanical ground cutting tools. For example, in contact of ground materials with metallic tools, a layer of the metal is scraped, and while reducing the metal thickness, its edges also are worn. Often the most intense contact between the ground materials and metals is observed in tunneling with cutting machines which causes reduced strength and efficiency of the metal and consequently reduced tunneling efficiency [1, 2]. Wear is defined as the continuous and unwanted loss of materials at the surface of a solid material due to mechanical actions such as contact and relative movement between two bodies [3]. The wear phenomenon in the mechanized tunneling of tunnels is constituted from two types of primary wear or excavation wear and secondary wear. In the first type known as the primary or excavation wear, the cutting tools are worn due to direct contact with soil. Among the parts of tunneling machine that are subjected to primary wear, one could refer to disks, buckets, and scrapers of the tunneling machine. In this type of wear, the determining factor for the amount of wear is the contact force between the cutting tools and soil grains present at the tunnel face. The second type of wear, which is known as the secondary wear, includes the supports of cutting tools and parts of the tunneling machine that are indirectly involved in the tunneling process [4, 5]. Figure 1 illustrates different types of primary wear and secondary wear examples during mechanized tunneling with EPBM.

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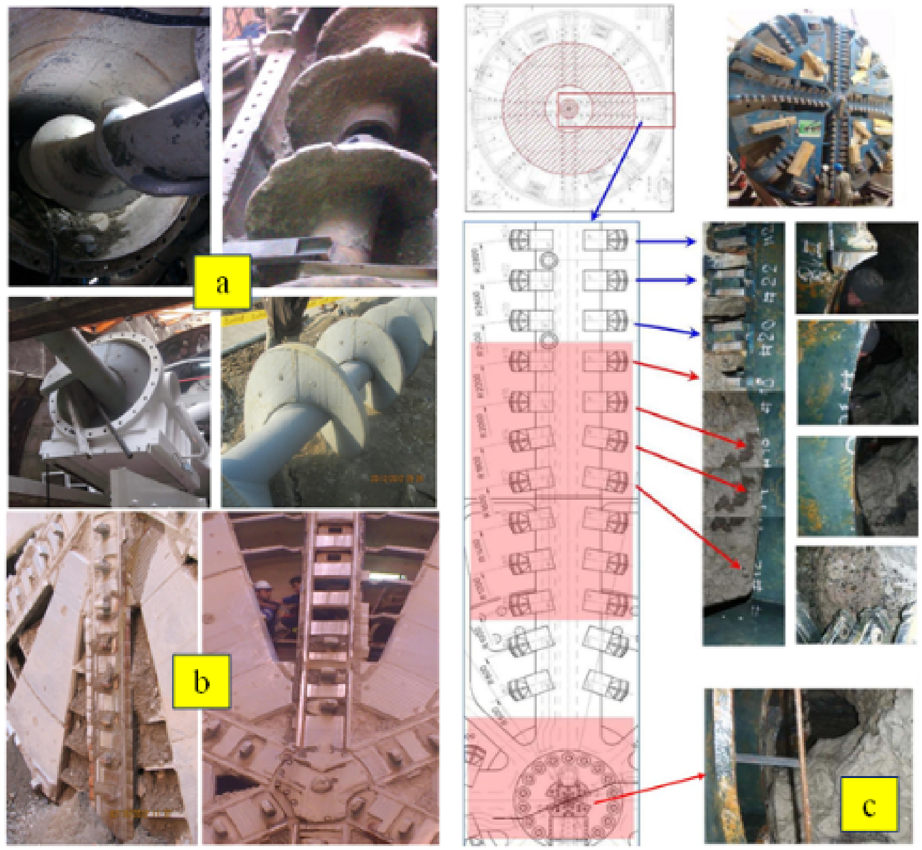


Figure 1. Wear in EPB-TBM tunneling: (a) Screw conveyor before replace showing secondary wear (up) and after replace (down), (b) Primary wear on cutting tools, (c) Excessive secondary wear on the cutterhead.

The wear phenomenon causes stopping of the tunneling process for the sake of replacing depreciated cutting tools, which consequently slows down the advance rate due to blunting of tunneling tool. Therefore, it is recognized as one of the effective parameters in calculating the cost of EPB tunneling in soft grounds. Estimating the actual cost of tunneling is an important point in tunneling projects. Because of the complexity of wear phenomenon and lack of advancement in sciences dealing with accurate estimation of wear phenomenon especially within the soil, cost estimation during contracting process is not precise, which results in improper design of the tunneling machine for the projects. Consequently, this leads to conflict between the contactor, consultant, and employer, and also the tunneling machine manufacturer. Therefore, a prediction closer to the actual phenomenon during the studies while reducing the probability of stopping or delay in the project schedule could greatly help with preventing the above-mentioned conflicts.

2. Challenges of Mechanized Tunneling

Tool wear is often associated with a question about the consumed materials. This value is from one side dependent on the soil and geological conditions, and as the result, is dependent on the geotechnical factors and from the other side is dependent on the features of equipment and devices that are utilized. Among the other influential parameters in the wear phenomenon is the construction management. It determines whether the good performance in terms of maintenance and prevention of tool wear and machine segments due to the present environmental conditions is possible or not, and could in this way have a positive effect on the overall performance of the project. Hence, the involved issues are too complicated which make it very difficult to investigate the issues related to soil abrasion, and sometimes makes it impossible to reach a right decision for their impact on the tunneling machine. Figure 2 illustrates the effective factors on the tool wear [6-8].

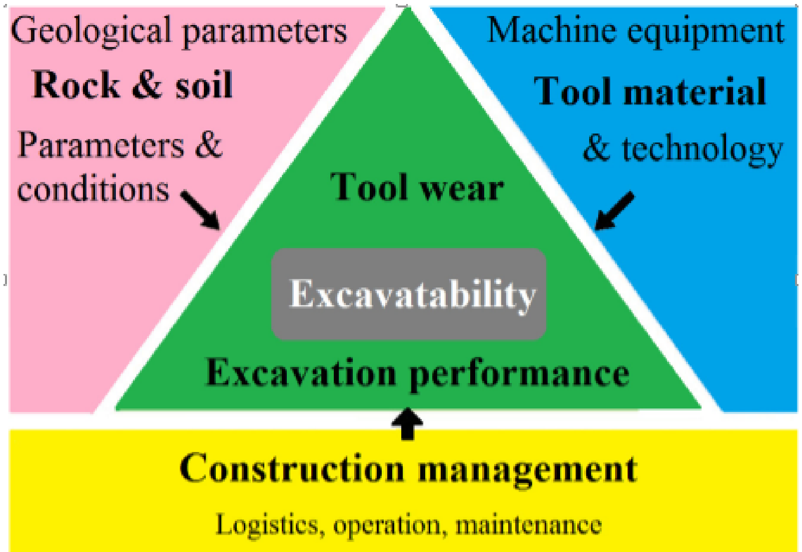


Figure 2. Effective factors on the tool wear and excavation performance [6].

Generally, there are widespread studies on the sensitivity and prediction of abrasion and tool wear in rock materials, but regarding the soil grains and their effect on the tunneling machines in soft grounds, the available research works are limited. This may be due to just accounting sufficient to predict the tool wear, instead of attempting to conduct tests on the tools. For example, decisions are made just on the performance speed of TBM or wear of the tools in this machine. This issue that in tunneling of rock tunnels, wear has the main role in terms of cost and also scheduling has been accepted by the majority of researchers, but abrasive role of coarse-grained soils such as gravels and sands was not important till the past decade. The recent studies have shown that this issue in this type of soils could cause difficulty in the performance of TBMs. In this respect, many research works have been done considering the problems that arise from tools wear in the tunnel projects that implement TBM machines [2, 9-16]. Furthermore, recently a number of devices have been designed and manufactures to simulate the soil mechanical properties wherein the tunneling parameters could be implemented during the experiments, so one could get a more accurate estimation of the wear amount at different conditions and examine precisely the effect of each parameter. Among these one could refer to manufacturing of a device named LCPC in a center in France with the same name, where classification of wear types in different rock and soil environments was presented using this devise in the year 2009 [17]. The problems associated with wear in the soil environment and recognition of the initial and operational effective factors were investigated in Penn State University and finally the PSA device was built [18]. A good investigation has been done on the effective factors on the wear phenomenon from the tribological standpoint [2]. A device was redesigned and manufactured for predicting the effect of some soil parameters on the cutting tools [19]. A devise was built based on the chamber simulation in EPB machine, which could measure abrasion in this environment [20]. The existing challenges in estimating soil abrasivity in soft grounds were investigated by SGAT device [21]. The effect of some operational parameters on the amount of abrasiveness was investigated by RuB device [22]. The effect of grading and conditioning of materials on the cutting tools wear was studied in China in the years 2018-2020 [23-25].

In this research work, also by manufacturing a device for simulation of the soil and cutting tool interaction, attempt is made to investigate the effect of some of the most important parameters of soil grading on the tool wear. Recognition of the interaction between soil structure and cutting tool during mechanized tunnel tunneling has greatly helped with introducing and manufacturing a device for accurate measurement of abrasion in soil environments. By identifying the effects of various factors on abrasion, one could prevent loss of time and extra cost in projects.

3. Materials and Testing Method

The type of graded soil is the most effective factor on cutting tool wear in the mechanized tunneling. In order to investigate the effect of soil grading on the cutting tool wear there is need for recognition and investigation of the effects of various parameters of soil grading on the cutting tool wear. Up to day, most of the performed studies on the problem of abrasion have dealt with coarse grains that lacked cohesion. This means that, in fact, the effect of fine-grained portion of soils on the amount of abrasion has been overlooked, whereas in the nature and often in sedimentary soils, the main portion of soil consists of fine grain materials. Hence, in this study, to solve the problem, a new soil abrasion test device with the capability of using in soils with maximum grain size of 20 mm was manufactured at the Sahand University of Technology in Tabriz (Figure 3).

The new soil abrasion test device was designed and manufactured in a way that the experimental conditions resemble the actual conditions and the TBM machine mechanism, as much as is possible. Among the unique advantages and features of this device, one could refer to the following items:

- It has a tunneling plate similar to the TBM cutterhead with different arrangements of central, middle, and peripheral cutting tools.
- Continuous penetration of cutterhead, which leads to penetration of the cutting tools into the fresh and undisturbed soil.
- Capability of adjusting the rotation speed of the cutterhead.
- Capability of adjusting the penetration speed of the cutterhead in soil.
- Capability of adjusting the pressure behind tunneling plate using the compressed air inlet.

In Figure 3, a view of the soil abrasion test device at the Sahand University of Technology is shown. The different components of the device include:

1) Inverter: for adjusting the rotation speed of the cutterhead from 10 to 500 rotations per minute.
2) Motor: with a power equal to 1.5 kW on the drill rod model MS16 to maintain the required force for rotation and penetration of the cutterhead into the soil sample.
3) Shaft: with 15 mm diameter and length of 270 mm to transfer power from motor.
4) Cutterhead: with 120 mm diameter and 13 mm thickness with an opening space (opening ratio) of 45% of stainless steel.
5) Tunneling chamber: a steel cylinder with 250 X 150 mm dimensions.
6) Air compressor: with 24 liters capacity.
7) Cutting tool: including the central, middle, and peripheral pins with 20 mm length.

The other characteristics of the device are given in Table 1.

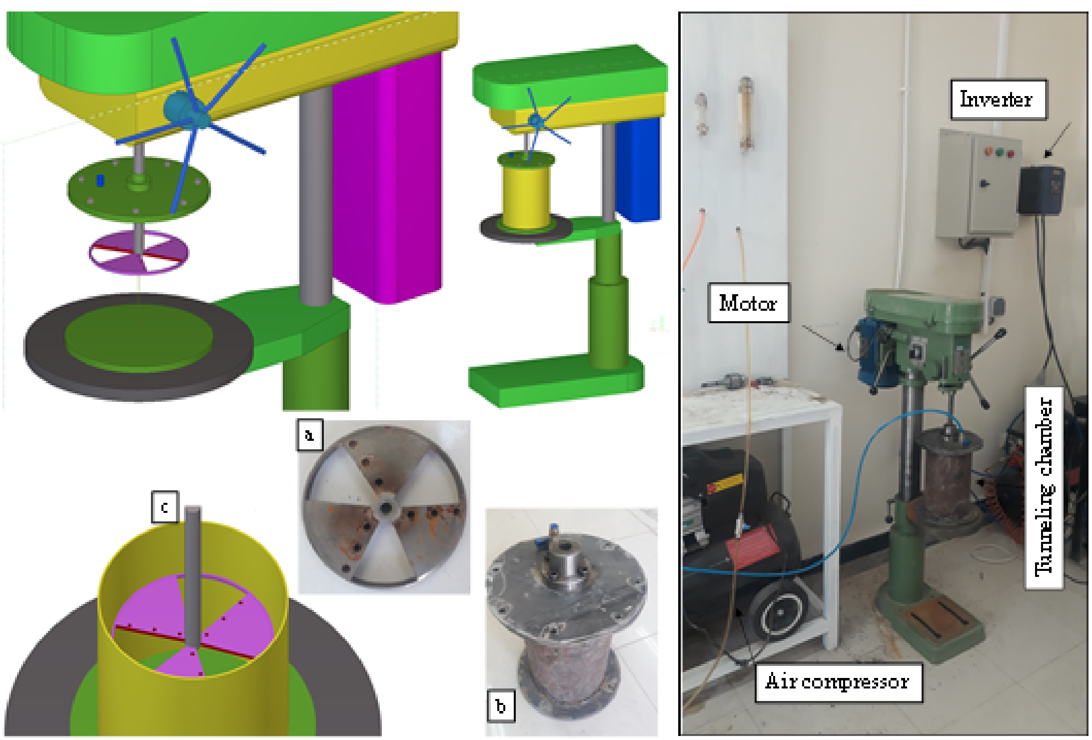


Figure 3. Picture of soil abrasion test device at the Sahand University of Technology: a) cutterhead, b) chamber, and c) shaft.

Table 1. Summary of soil abrasion test dvice specifications.

Cutting tools design	9 pins in a spiral form
Rpm	10 – 500
Penetration length inside in chamber (mm)	100
Penetration rate	Variable
Torque interval	Measurable
Ambient pressure	Measurable
Grain size (mm)	0 – 20
Soil consolidation	Manually before testing
Soil conditioning	Mix before testing and add continuously during testing

The amount of cutting tool wear is calculated by measuring the weight of pins before and after each test using Equation 1.

$$WR = 100 * (m_o - m)/M \quad (1)$$

where WR is the wear rate (%), m_o is the mass of pin before the test, m is the mass of pin after the test, and M is the mass of the soil sample. The soil samples used in this study are taken from alluvial soil of Tabriz Metro Line 2. Figure 4 shows the soil samples used for performing the studies. The grading of coarse-grained portion of the soil was done according to ASTM 422-87 by drying method and use of standard sieves (Figure 5a) [26]. Also the grading of fine-grained portion of the soil is done by hydrometery method (Figure 5b), which is based on the principles of sedimentation of soil grains in water. In this test, 50 g of dried and powdered soil is implemented. Before the start of the test, always deflocculating agents are added to the soil. The most common deflocculating agent is 125 cc solution of sodium hexametaphosphate 4%. The soil should remain for 16 hours in the deflocculating agent and be wetted. After the wetting period, distilled water is added to the solution, and the diluted solution is fully stirred. Distilled water is added to the diluted solution, so that its level reaches the sign 1000 mL, and this solution is fully stirred. Reading the hydrometer often is done every 24 hours [27].

In order to show the effect of soil grading type on the amount of cutting tool wear, 8 different grading schemes were selected, where the curve corresponding to the coarse-grained portion is shown in Figure 6a and the curve corresponding to the fine-grained portion is shown in Figure 6b.

In order to start the tests and investigations, it is necessary to introduce and explain some important parameters of soil grading curve [6, 7, 27, 28]:

- D_{10}, D_{25}, D_{30}, D_{50}, D_{60}, D_{75}: Indicate the corresponding diameters on the soil grading curve, where 10, 25, 30, 50, 60, and 75% of the soil grains are smaller than that diameter, respectively.
- Uniformity coefficient (C_u): Ratio of D_{60} to D_{10} is called the uniformity coefficient, which is calculated from Equation 2.

$$C_u = D_{60}/D_{10} \quad (2)$$

- Coefficient of gradation or curvature (C_c): This parameter is calculated from Equation 3.

$$C_c = D_{30}^2 \Big/ D_{10} * D_{60} \quad (3)$$

- Sorting coefficient (S_o): This parameter of soil grading indicates the amount of soil grains uniformity in terms of shape and size. Sorting is calculated from Equation 4.

$$S_o = \sqrt{\frac{D_{75}}{D_{25}}} \quad (4)$$

- Effective size (ES): This parameter is calculated from Equation 5.

$$ES = 0.1\left(\frac{d_{min} + D_{10}}{2}\right) + 0.2\left(\frac{D_{10} + D_{30}}{2}\right) + 0.3\left(\frac{D_{30} + D_{60}}{2}\right) + 0.4\left(\frac{D_{60} + d_{max}}{2}\right) \quad (5)$$

where d_{min} and d_{max} denote the minimum and maximum diameters of abrasive grains, respectively. The units of all the parameters is mm.

Often different parameters are used to indicate the effect of grain size on the abrasive properties of soil, D_{50} is one of the most important parameters in evaluating the effect of grain size on soil wear properties [7]. However, recently D_{70} (the size where 70% of the grains are smaller than that diameter) has been recommended for the samples with coarse grains. Also, the effective size has been included by some researchers in the study of abrasive soil samples [29].

The investigations done by researchers indicate the effect of soil grain size on the abrasive ability. However, the conducted research has been focused on the size of the grains, especially the coarse ones in the absence of silty and clayey grains. Thus, practically a large portion of soil grains is not taken into account, and the effect of distribution of natural soil grain sizes is not studied. Furthermore, the previous studies have dealt with cutting tools that have been in contact with disturbed soil. In this article, samples of natural soil with different grain size distribution curves have been investigated and tested. Abrasion tests have been performed using the new soil abrasion test device manufactured at the mechanized tunneling laboratory of the Sahand University of Technology, and in continuation, some of the results of these investigations are presented.

Figure 4. Soil samples used for performing the studies.

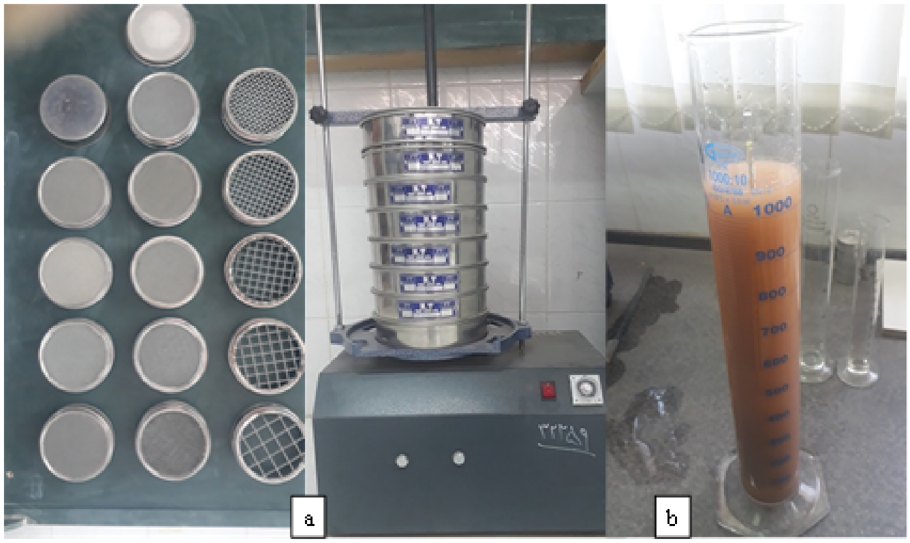


Figure 5. Soil gradation: a) grading of the coarse-grained portion and b) grading of the fine-grained portion.

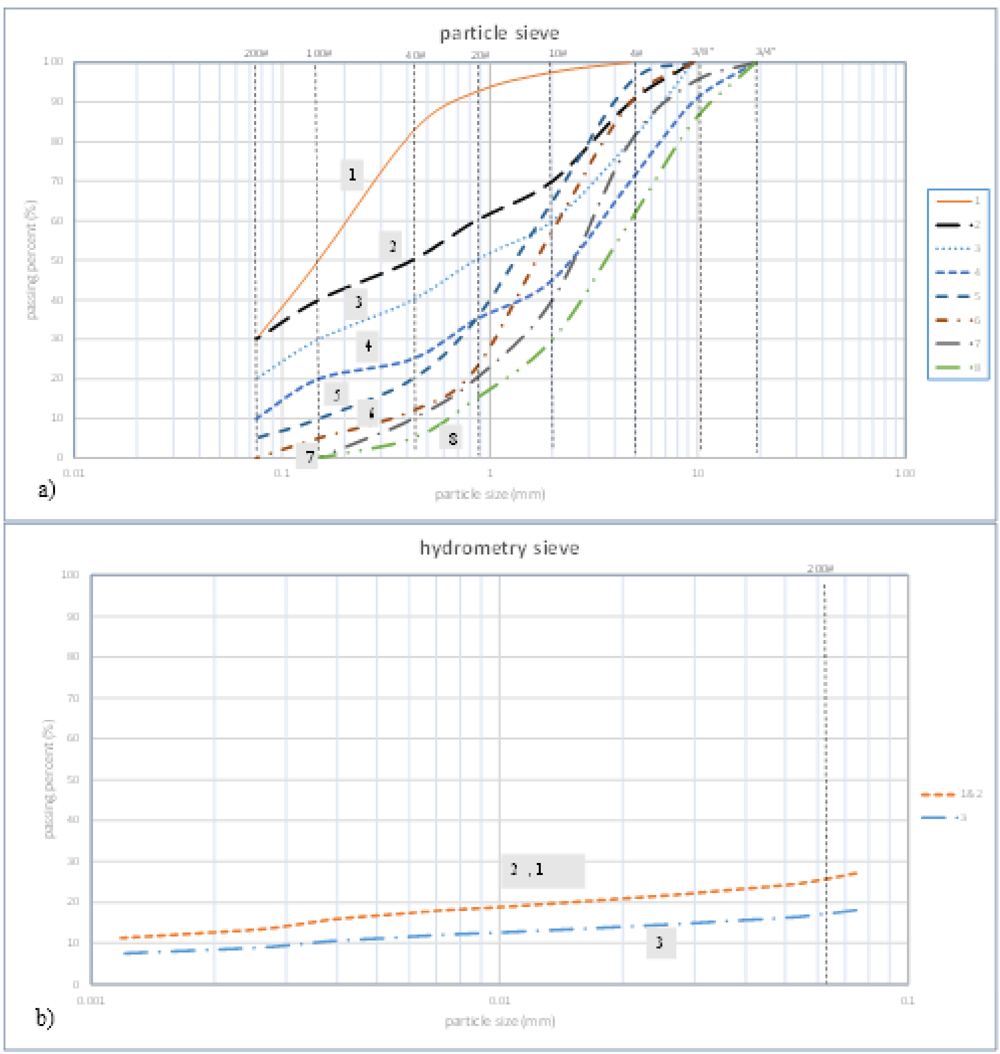


Figure 6. a) Grading curve of coarse-grained portion, and b) Grading curve of fine-grained portion.

4. Results and Discussion

8 specific grading schemes with different percentages of fine and coarse grains have been selected to investigate the effect of various grading schemes on the cutting tool wear. In soil No. 1, the amount of fine grains was 30% and the purpose for selecting this grading was determining the amount of tool wear with maximum presence of fine grains. However, in soil No. 8, which had the largest coarse grains in this research work, fine grains are not present and our purpose is investigation of abrasion in specifically coarse grains without presence of fine grains. In order to start the investigation the D_{10}, D_{30}, D_{60}, C_u, and C_C, percentage of fine grains, percentage of coarse grains, sorting, and ES parameters were determined (Table 2).

Table 2. Geological parameters of the grading curves of used soil samples.

Soil No.	Gravel (%)	Sand (%)	Silt and clay (%)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	ES (mm)	C_c	C_u	Sorting	USCS
1	0	70	30	0.0012	0.075	0.207	0.69	22.6	172.5	2.41	SM
2	10	60	30	0.0012	0.075	0.85	1.67	5.5	708.3	6.61	SM
3	20	60	20	0.0038	0.15	2	2.17	2.9	526.3	6.24	SM
4	30	60	10	0.075	0.601	3.361	3.93	1.4	44.8	3.62	SW-SM
5	5	90	5	0.15	0.67	1.73	2.47	1.7	11.5	2.03	SW
6	10	90	0	0.316	1.02	2.138	2.93	1.5	6.7	1.88	SW
7	20	80	0	0.43	1.3	3.08	5.23	1.3	7.1	1.63	SW
8	40	60	0	0.6	2	4.75	6.04	1.4	7.9	1.94	SW

At the first stage of this research work, considering the importance of determining and examining the initial parameters and calibration of the soil abrasion test device, a number of tests at different stages were designed and conducted to investigate the parameters such as rotation speed of the cutterhead, penetration rate of cutterhead in the soil of the device chamber, duration of test, and soil moisture. The soil sample No. 4 was used at this stage of testing.

For selecting the rotation speed of cutterhead, a number of tests with rotation speeds of 3, 60, 100, 150, and 200 rounds per minute (RPM) were performed. Finally, considering the conditions close to reality and amount of abrasions, the rotation speed of 60 RPM was selected for the cutterhead. The other initial parameters for conducting the main tests are given in Table 3.

Table 3. Initial parameters selected for performing the main tests.

Density (g/cm^3)	Moisture content (%)	Rpm	Penetration rate (mm/min)	Time (min)	Penetration length (mm)	Ambient pressure (bar)
1.7	5	60	2.5	40	100	Atmospheric

4.1. Effect of soil grading

In order to investigate the effect of soil grading on the cutting tools wear, a new soil abrasion test device was manufactured, and 8 soil grading schemes were selected so that from soil type 1 to 8, gradually the coarse-grained amount was increased, respectively, and the fine-grained amount was decreased. It is noteworthy that the amount of soil moisture in the tests is taken equal to 5%.

Soil No. 1 has 30% fine grains and 70% sand. As is seen in Figure 7a, this soil type has a relatively strong structure, and the reason for this is that the fine grains often fill the space between coarser grains, and this prevents free and easy movement of grains along each other.

Soil No. 2, by keeping constant the amount of fine grains, the amount of sand in soil No. 1 was reduced and gravel grains were added to the soil. In describing this soil, it could be stated that with respect to soil No. 1, and due to reduced amount of sand and constant percentage of fine grains, it has a more coherent structure with a small amount of gravel grains (Figure 7b).

Soil No. 3, in this soil, both the fine grains and sand grains are reduced with respect to soil No. 2 but the amount of gravel grains has increased (Figure 7c). In soil No. 4, also this decreasing trend is continued and only larger coarse grains with respect to soil No. 3 are added to the soil (Figure 7d).

In soil No. 5, the gravel coarse grains have decreased both in terms of size and amount with respect to soil No. 4, and the amount of fine grains has been halved. The amount of sand grains in this grading scheme has increased in coarse-grained classes and it has nearly large amounts of uniform sand grains (Figure 7e). In soil No. 6, also the amount of gravel grains has increased slightly, but instead, the fine grains are totally removed (Figure 7f).

Soils No. 7 and 8 have increased gravel grains (both in terms of size and amount) with respect to soil No. 6, respectively. Instead, the amount of uniform sand grains has decreased. Concerning the structure of these two types of soils, it could be stated that the relatively large amounts of gravel grains within a set of coarse sand grains, could easily move. The purpose for selecting these two types of grading was investigating the rate of cutting tools wear in coarse-grained soils (without presence of fine grains) (Figures 7 g, h).

Figure 7. Picture of soil samples (1 to 8): left dry and right) wet.

The obtained results from abrasion tests show different rates of wear have occurred in the cutting tools (central, middle, and peripheral). As was expected, in the peripheral tool, as the travelled path of the tool in soil is greater (greater engagement between the tool and soil) maximum tool wear has occurred, and in the central tool, due to shorter travelled path and less engagement between the tool and soil, minimum tool wear has occurred. In the present research work, for a better demonstration of wear on the pins, it was preferred to use 3 pins instead of 9 pins on the cutterhead and each on a single blade. Figure 8 shows the position of different cutting tools.

Figure 8. Position of cutting tools on the cutterhead.

In Table 4, the overall results of the tests are presented. In these tests, the moisture content of soils was 5%, the density of wet soil was 1.7 g/cm^3, the rotation speed of cutterhead was 60 RPM, the penetration rate of cutterhead in soil was 2.5 mm per minute, and the test duration was 40 minutes.

Table 4. Overall results obtained from the tool wear tests.

Soil No.	Pin position	m_0 (g)	m (g)	WR (%)	Ave. wear (%)
1	Central	1.433	1.422	0.77	18.06
	Middle	1.393	1.340	3.8	
	Peripheral	1.467	0.739	49.6	
2	Central	1.433	1.420	0.9	21.77
	Middle	1.476	1.351	8.6	
	Peripheral	1.390	0.577	58.5	
3	Central	1.477	1.467	1.2	22.9
	Middle	1.495	1.383	7.5	
	Peripheral	1.580	0.634	60	
4	Central	1.351	1.311	0.04	27.3
	Middle	1.399	1.230	0.169	
	Peripheral	1.420	0.465	0.955	
5	Central	1.467	1.458	0.6	9.17
	Middle	1.383	1.343	2.9	
	Peripheral	1.311	0.996	24	
6	Central	1.230	1.226	0.32	6.04
	Middle	1.405	1.379	1.8	
	Peripheral	1.327	1.115	16	
7	Central	1.246	1.239	0.49	3.93
	Middle	1.420	1.387	2.3	
	Peripheral	1.351	1.229	9	
8	Central	1.406	1.405	0.07	2.37
	Middle	1.334	1.327	0.53	
	Peripheral	1.334	1.246	6.5	

In investigating the effect of D_{10}, the test results show that in grading schemes No. 1, 2, 3, 4, by increase in D_{10} value, the amount of tool wear also increases, and from grading scheme No. 4 on, by increase of D_{10} value, the wear rate decreases (Figure 9). Investigating the grading curves of soils No. 1, 2, 3, and 4, it is observed that the percentage of grains passing sieve No. 200 is greater than 10%, whereas this parameter is less than 10% for soils No. 5, 6, 7, and 8. Considering this and the results of abrasion tests, it could be stated that for the soils containing higher than 10% fine grains, simultaneously with increase of D_{10} value, the amount of cutting tool wear increases, whereas in soils with less than 10% fine grains, by increase in the D_{10} value, the amount of cutting tool wear decreases. The reason for relative increase in the mean rate of wear in the first portion of diagram in Figure 9 and decrease in the mean rate of wear in the second portion of the diagram could explained in this way: in the first portion (fine-grained portion), by relative increase of the D_{10} value and simultaneously presence of fine-grained portion of the soil, the amount of coarse and abrasive grains has increased in the soil which leads to increase in the mean rate of the cutting tools wear. In the second portion of the diagram (coarse-grained portion), by increase of the D_{10} value, gradually the fine-grained portion of the soil is decreased or removed which decreased the mean rate of tools wear. In Table 5, the mean percentage of tool wear is shown.

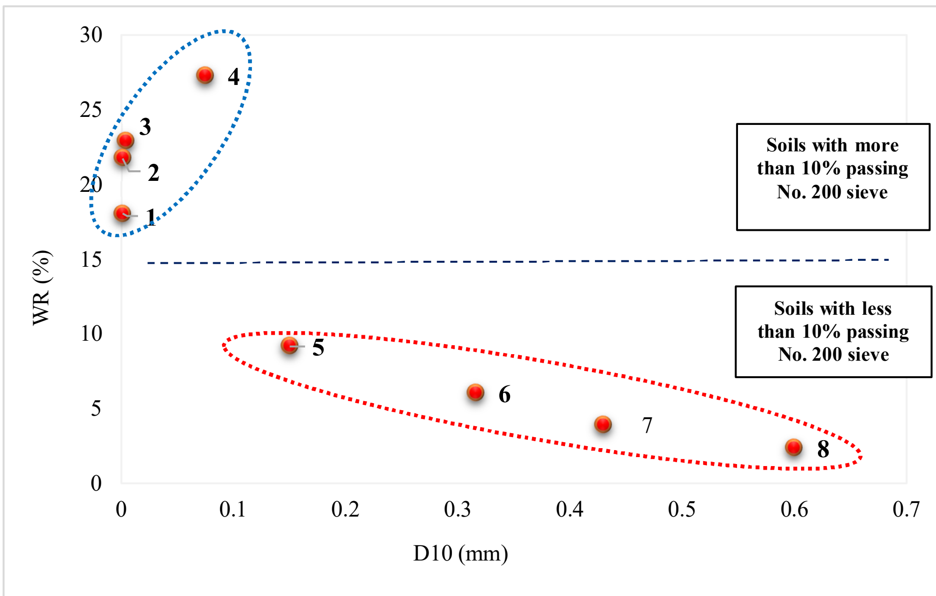


Figure 9. Relationship between D_{10} and wear rate.

Table 5. Variation of wear rate and D_{10}.

Soil No.	1	2	3	4	5	6	7	8
D_{10} (mm)	0.0012	0.0012	0.0038	0.075	0.15	0.316	0.43	0.6
WR (%)	18.06	21.77	22.9	27.3	9.17	6.04	3.93	2.37

Investigating the effect of D_{30}, the tests results show that in grading schemes No. 1-4, by increase in the D_{30} value, the tools wear increases with a small slope, respectively, so that in grading scheme No. 4, the maximum mean of wear has occurred, which is equal to 27.3% (388 mg). From grading scheme No. 4 on, the trend has changed, and by increase in the D_{30} value, the mean of wear takes a descending trend (Figure 10). As is seen in Figure 10, all that was said about D_{10} also is true for D_{30}. Thus, by increase of the D_{30} value to 0.15 mm in grading scheme No. 4, due to presence and effect of fine-grained portion in the soil, the rate of wear increases slightly. But by decrease in the fine-grained portion in grading scheme No. 5 and the next ones, by increase in the D_{30} value the wear rate decreases. In Table 6, the mean percentage of tool wear is shown.

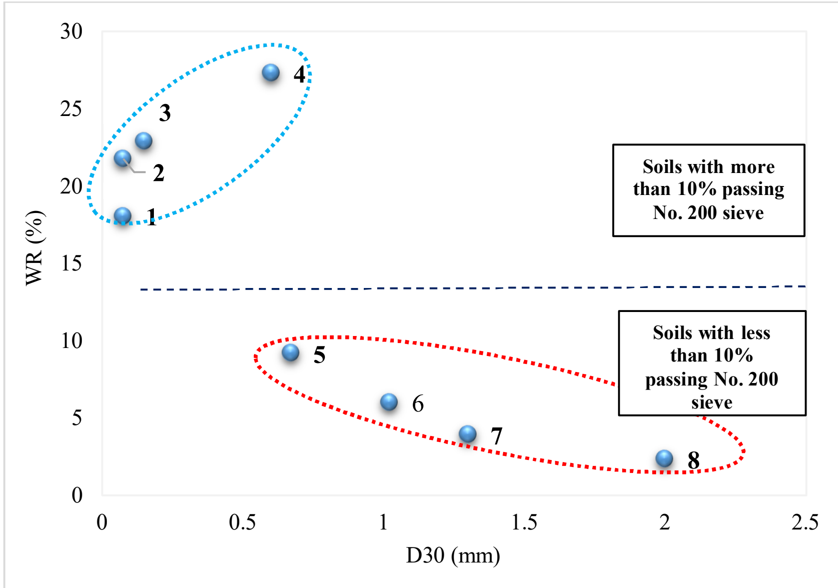


Figure 10. Relationship between D_{30} and wear rate.

Table 6. Variation of wear rate and D_{30}.

Soil No.	1	2	3	4	5	6	7	8
D_{30} (mm)	0.075	0.075	0.15	0.601	0.67	1.02	1.3	2
WR (%)	18.06	21.77	22.9	27.3	9.17	6.04	3.93	2.37

In investigating the effect of D_{60}, as shown in Figure 11, similar to D_{10} and D_{30}, there is a certain trend in the rate of cutting tools wear for the two soil groups with changes in the D_{60} values, so that for the first grading group (soils where the amount of fine grains (passing No. 200 seive) is greater than 10%) by increase in the D_{60} value, the rate of cutting tools wear increases. For the second grading group (soils where the amount of fine grains is smaller than 10%) by increase in the D_{60} value, the rate of cutting tools wear decreases. In Table 7, the mean percentage of tool wear is shown.

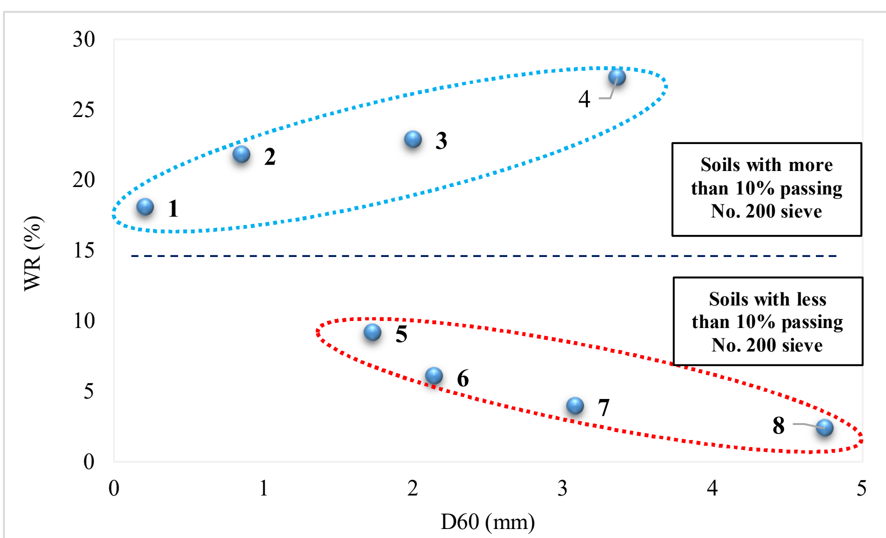


Figure 11. Relationship between D_{60} and wear rate.

Table 7. Variation of wear rate and D_{60}.

Soil No.	1	2	3	4	5	6	7	8
D_{60} (mm)	0.207	0.85	2	3.361	1.73	2.138	3.08	4.75
WR (%)	18.06	21.77	22.9	27.3	9.17	6.04	3.93	2.37

In investigating the effect of coefficient of gradation, as is seen in Figure 12, in soils with more than 10% fine grains, by increase of C_C value the rate of tool wear decreases. In soils No. 3 and No. 4, which have low C_C values in the range 1-3 and are accounted among the well graded soils, we observe maximum rate of tool wear. In soils with less than 10% passing No. 200 seive, by increase in the C_C value, the tool wear does not show a clear difference. The reason for this issue could be attributed to the range of changes in C_C values. As is seen, in this group of soils, the C_C values have not changed considerably, therefore, the effect of C_C value could not be investigated in this group of soils. In Table 8, the mean percentage of tool wear is shown.

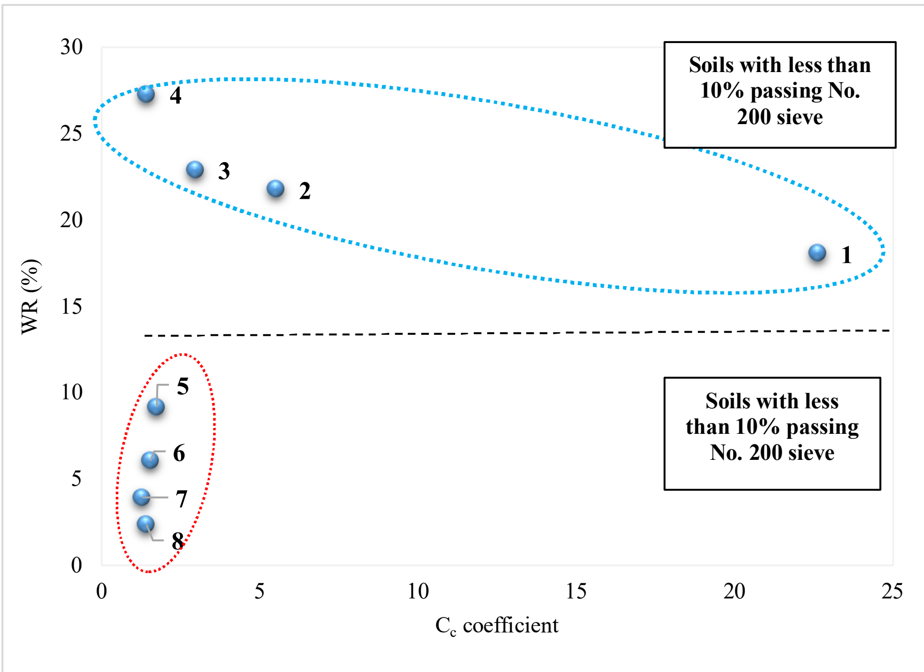


Figure 12. Relationship between C_C and wear rate.

Table 8. Variation of wear rate and C_C.

Soil No.	1	2	3	4	5	6	7	8
C_C coefficient	22.64	5.51	2.96	1.43	1.73	1.54	1.28	1.4
WR (%)	18.06	21.77	22.9	27.3	9.17	6.04	3.93	2.37

In Figure 13, changes in the tool wear rate against the coefficient of uniformity of soil samples are drawn. As is seen, generally, by increase in the C_u value with a coefficient of correlation of 0.6643, the cutting tool wear rate has increased. This is due to presence of different grain sizes in the soil composition by increase of C_u value. In other words, by increase of C_u value the soil grading covers, a wider range of grading curve, which results in a further rate of wear.

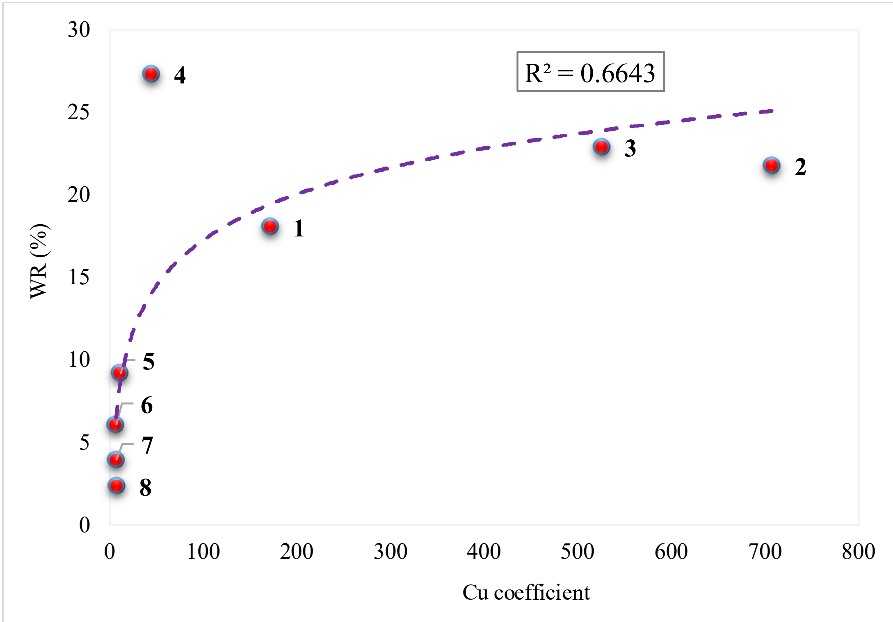


Figure 13. Effect of coefficient of uniformity (C_u) on the tool wear.

Like parameters D_{10}, D_{30}, and D_{60}, the tests results show a relationship between ES and the cutting tools wear for the two different soil groups (Figure 14). In this study, the ES parameter for soils in the first group (soils with fine grains greater than 10%) exhibits a direct relationship with increase in the tool wear rate. Contrary to the first group soils, in the second group soils (soils with fine grains less than 10%) according to the performed studies, by increase in the coarse grains in soil composition, the tool wear rate decreases. This issue shows the importance of fine grains percentage in cutting tools wear. In other words, presence of fine grains could have considerable effect on the probability of contact between coarse grains and cutting tool, which increases the wear rate. Considering the grading curves of various studied soils and Figure 14, it could be concluded that in case the percentage of grains that have passed sieve No. 200 is greater than 10%, by increase of ES value, the cutting tools wear increases. But in case that this percentage is less than 10%, by increase in ES value, the cutting tools wear decreases.

By investigating the results of relationship between the sorting factor in the soil grading curves and the rate of cutting tools wear, it is observed that by increase of sorting factor value from 1.63 to 3.6, the tool wear rate increases with a sharp slope (Figure 15). However, where the value exceeds 3.6, the tool wear rate decreases with a gentler slope. The reason for this behavior could be explained in this way that by increase of sorting factor value up to 3.6, the rate of irregularity in grain size is decreased, and the grains are located in a better and more compact situation along each other, thus the void space between grains has reduced to minimum and they could not move easily. Therefore, when the cutting tools encounter the soil grains, maximum tool wear is observed. But where the sorting factor exceeds 3.6, the grains become similar to each other in terms of the shape and size and the void space between them increases, and grains could move easier when the cutting tools encounter them, and this leads to reduced rate of wear in the tools.

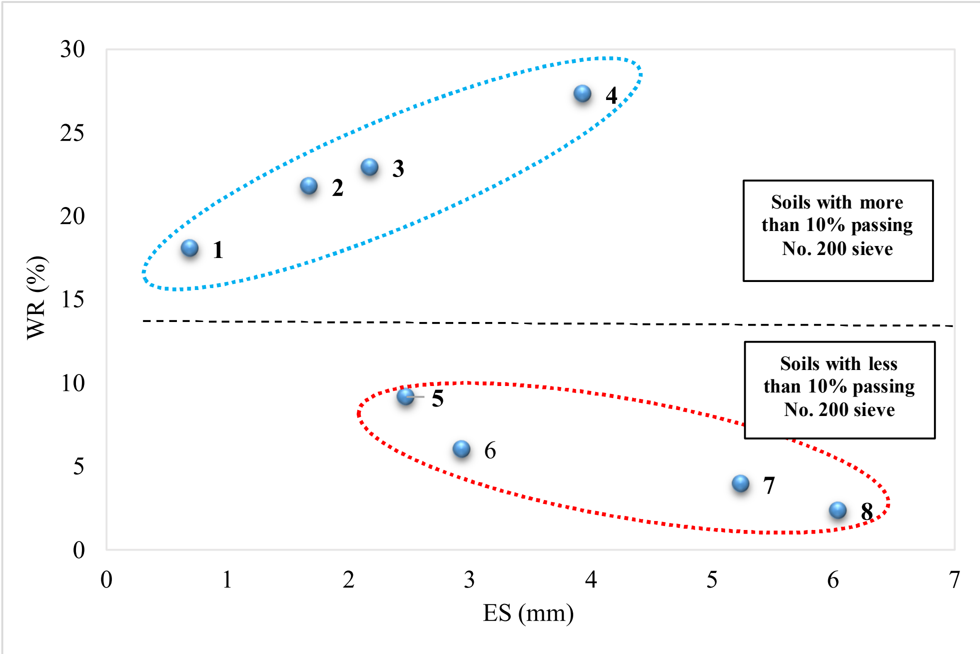


Figure 14. Relationship between ES and wear rate.

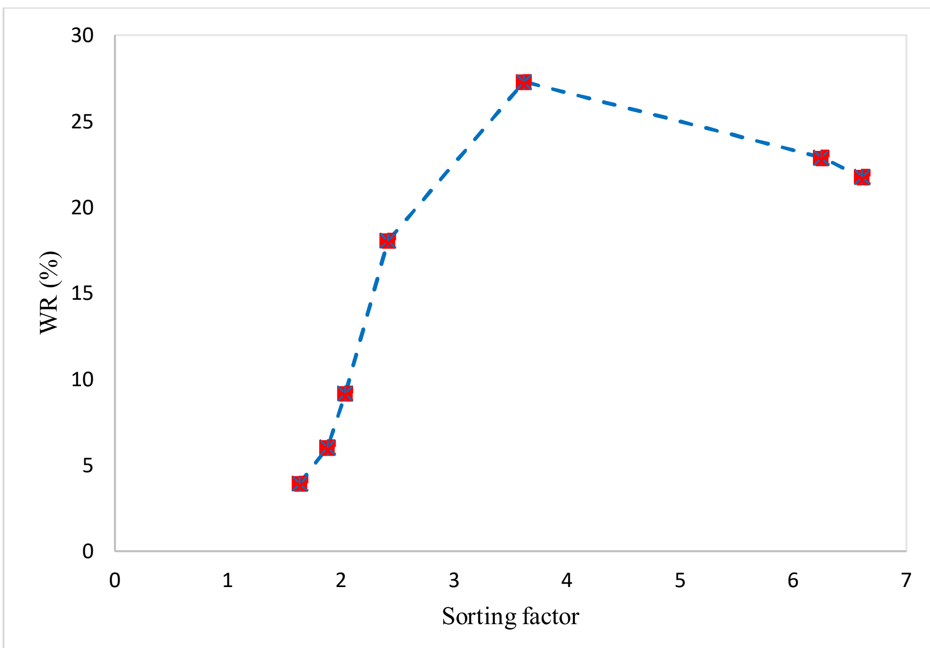
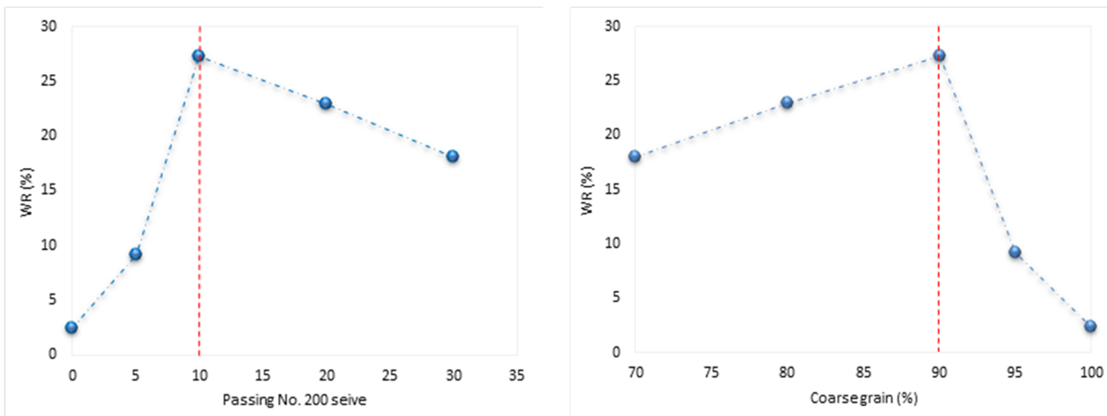


Figure 15. Effect of sorting factor on wear.

In investigating the effect of fine grains and coarse grains on the cutting tools wear, the results revealed that in the absence of fine grains, the wear rate of tools is negligible and near zero. But by a slight increase in the percentage of fine grains in the soil composition, the tool wear rate increases with a sharp slope, so that at 10% fine grains in the soil, maximum cutting tools wear occurs. After this point, and by increase in the amount of fine grains, the tool wear decreases with a gentler slope. The reason for this behavior could be explained in this way that for keeping the coarse grains along each other in a coherent state, there is a need for a minimum of amount of fine grains, so that the soil grains could not move easily during their encounter with the cutting tools. In other words, it could be stated that the fine grains have an indirect role in the tool wear rate (Figure 16a).

Also, by observing the results corresponding to the effect of coarse grains on the tool wear rate, it is found that by increase of coarse grains from 70% to 90% in the soil composition, the wear rate increases by a gentle slope, but from 90% on, a severe decrease is observed in the tool wear rate. The reason for this behavior could be explained in this way that by increase in the amount of coarse grains in the soil from 70% to 90%, the amount of fine grains with low abrasive effect is decreased and the amount of coarse grains with higher abrasive effect is increased, so the tool wear rate slightly increases. But from 90% on, by increase in the amount of coarse grains, the amount of fine grains necessary for making a coherent and integrated soil structure is decreased. As the result, the coarse grains move by a slight force that is applied by the cutting tools, and they separate from the soil structure, and ultimately, we witness a considerable reduction in the tool wear rate (Figure 16b).



(a) (b)

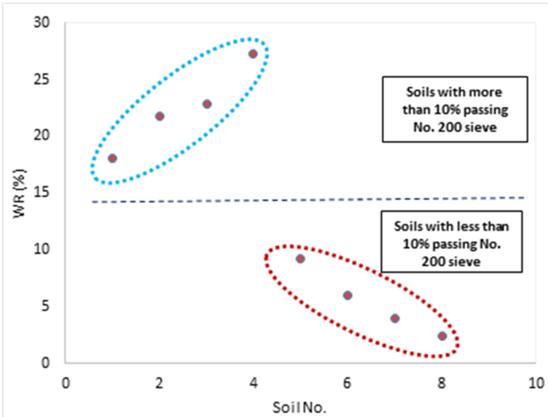
Figure 16. a) Effect of fine grains on cutting tools wear and b) Effect of coarse grains on cutting tools wear.

In order to investigate and compare the obtained results in terms of wear rate in the new soil abrasion test device with other types of devices, the LCPC test was performed on 8 soil types used in this study. It is noteworthy that according to the standard, the grading range in the LCPC test is limited (4-6.3 mm), but in this study, it was utilized just for the purpose of investigating the effects of rotation speed of cutterhead and grading schemes on the results obtained from the two devices in the grading ranges of the 8 soil types. Also another soil sample with a grading in the standard range of LCPC abrasion test device was added to the experiments to compare the rate of tool wear in ordinary soil types with that obtained from the standard soil sample. The results obtained from the LCPC test are given in Table 9.

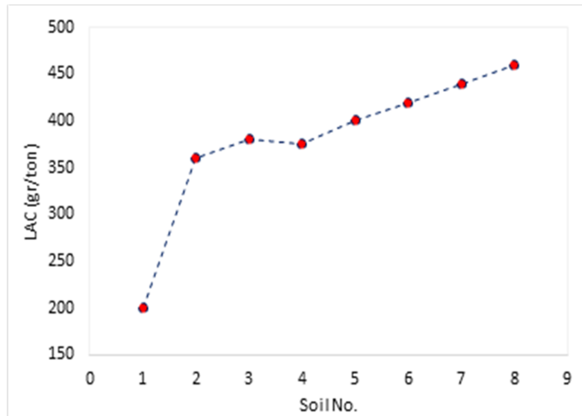
Table 9. Results of LCPC test conducted on 8 soil samples in the study.

Soil No.	m_o (g)	m (g)	LCPC (LAC) coefficient (g/ton)
1	44.57	44.47	200
2	44.82	44.64	360
3	44.51	44.32	380
4	44.69	44.51	376
5	44.88	44.68	400
6	44.88	44.67	420
7	44.51	44.29	440
8	44.7	44.47	460
LCPC (4-6.3 mm)	41.62	40.93	1380

As is seen in Figure 17, it could be stated that the tool wear rate in soils types 1-4 is similar and ascending, but from soil type 4 on, the trend changes. In LCPC device, the same trend with a gentle slope is continued for the rest of soil samples. In the new manufactured device, the trend is ascending in soil types 1-4 but in soil types 5-8, the trend is descending with a gentle slope.



(a)



(b)

Figure 17. Tool wear rates: a) LCPC device, b) New soil abrasion test device

The reason for the reverse behavior of LCPC device could be understood by observing the soil chamber of this device after the end of test. In soils with fine grains up to fine sands, after being placed in the chamber of LCPC device and start of testing, due to very high rotation speed of the blade (4500 rpm), all the fine grains and a large portion of coarse grains are thrown against the chamber wall due to their encounter with the blade. The existing fine grains, which are relatively cohesive form an approximately thick wall that has no contact with the blade. The outer side of the wall is covered with completely fine grains but the inner side contains mainly coarse grains that are trapped. This phenomenon occurs at the initial moments of the test and only a small portion of coarse grains remain within the chamber which are engaged with the blade till the end of the test. By increase in the amount of coarse grains of the soil and removal of fine grains and fine sands, this soil wall gets thinner and is diminished later and more coarse grains are engaged with the blade, which leads to increased tool wear. Figure 18 shows the LCPC test chamber after conducting the test on 8 soil samples.

To demonstrate the difference between the wear rate in LCPC standard soil sample, and wear rate in soils No. 1-8 (ordinary soil samples), an LCPC abrasion test was performed using the standard soil (Figure 19). As is seen in the soil chamber (Figure 20), after the end of test all the grains remained within the chamber, and were engaged with the blade. This has caused severe increase in the tool wear rate with respect to soils that contained fine grains. In Figure 21, the worn blades in the LCPC test are shown (in the soils with standard and ordinary grading schemes). Considering what was stated and as it was expected, the high speed of cutting tool in the LCPC test causes removal of fine grains during the test, and this effect is accounted among the limitations of LCPC device. Use of a cutterhead with low speed similar to TBM could diminish this limitation.

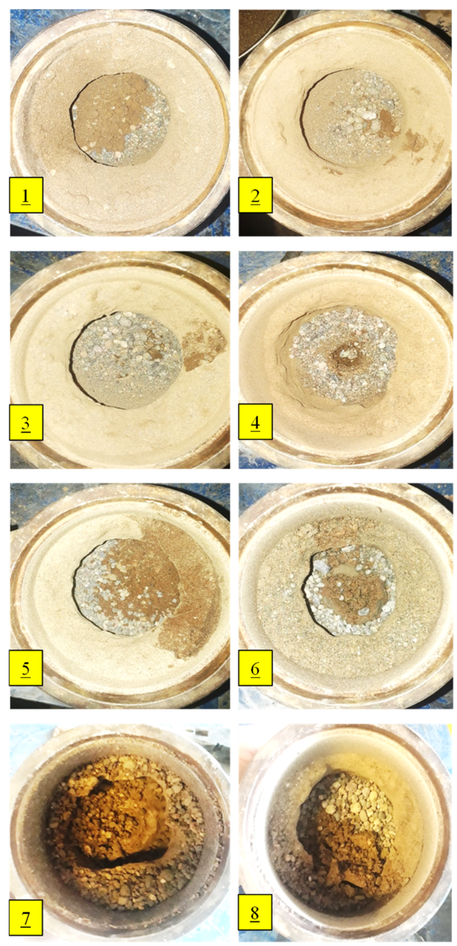


Figure 18. LCPC test chamber after test (soil No. 1-8).

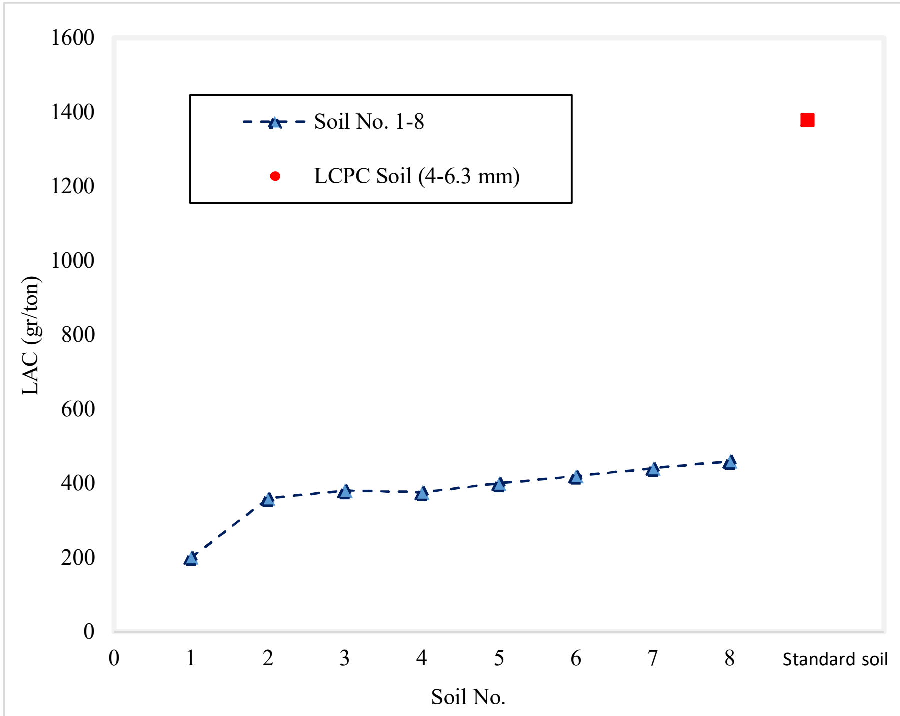


Figure 19. Comparing tool wear in the LCPC test using the standard and ordinary soil samples.

Figure 20. Soil chamber in the LCPC test after the end of testing on the standard soil sample.

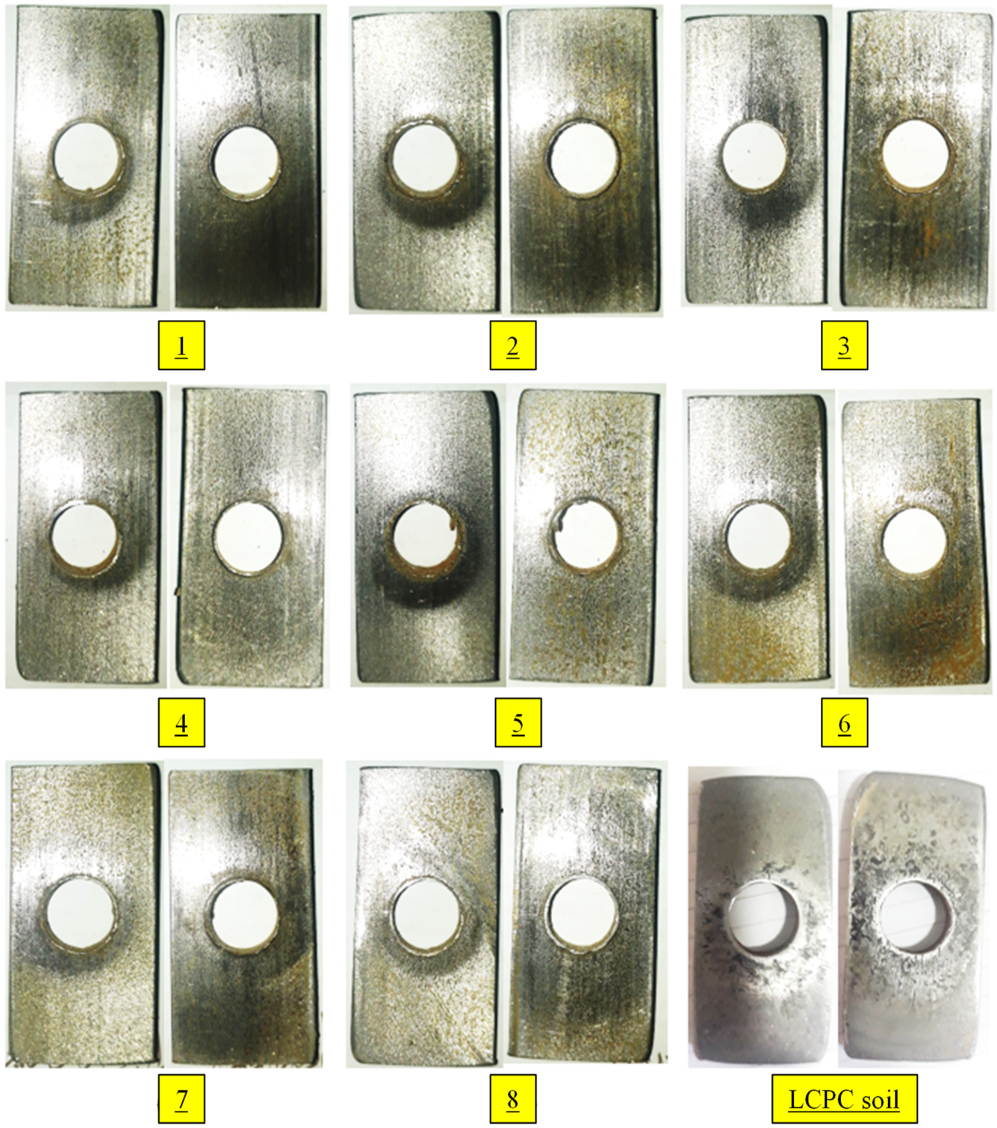


Figure 21. Blades in the LCPC test in the standard and ordinary soil samples (The left side shows the top of blade, and the right side shows the bottom of blade).

5. Conclusions

The obtained results in this research work are as follows:

- In soils containing more than 10% fine grains, by increase in the D_{10} value of the soil grading curve up to the upper limit value of fine grains (0.075 mm), the mean tool wear increases. This could be explained in this way that simultaneously with existing fine grains in soil, the amount of coarse and abrasive grains is relatively increased, and as a result, the mean cutting tools wear increases. However, in soils containing less than 10% fine grains or without any fine grains, by increase in the D_{10} value, gradually the fine-grained portion gets smaller or is removed. Consequently, the coarse-grained portion that does not resist against cutting tools and moves freely, is increased, resulting in reduced mean of tools wear.
- In soils with a fine-grained portion greater than 10%, by increase in the D_{30} value, the tools wear increases. But in soils with fine grains less than 10%, by increase in the D_{30} value, the tools wear decreases. By increase in the D_{30} value in soils of group one, simultaneously, with presence of fine grains needed in the soil composition to maintain the coherence of soil structure, the amount and size of the coarse grains also increase, which results in increased mean of tools wear, and vice versa.
- By increase in the D_{60} value in the group of soils containing more than 10% fine grains, the tools wear increases. But in the group of soils with fine grains less than 10%, the tools wear decreases.

- In the soils with more than 10% fine grains, by increase in the C_C value, the tools wear decreases. In the soils with fine grains less than 10%, by increase in the C_C value, the tools wear does not exhibit a clear difference.
- Generally, by increase in the C_C value, the cutting tools wear increases with a significant coefficient of correlation.
- In case that the amount of grains finer than sieve No. 200 is greater than 10%, by increase in the ES value, the cutting tools wear increases. But in case that the amount of grains finer than sieve No. 200 is less than 10%, by increase in the ES value, the tools wear decreases.
- By increase in the sorting value, the tools wear increases with a steep slope, but from the value 3.6 on, the tools wear decreases with a gentle slope.
- In the absence of fine grains, the amount of tools wear is small. But with increase in the amount of fine grains in the soils composition, the tools wear increases with a steep slope, so that at 10% fine grains, the tools wear reaches maximum value. After this point, by increase of the fine grains, the tools wear decreases with a gentle slope.

Acknowledgments

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بررسی تأثیر پارامترهای دانه‌بندی خاک بر روی سایش ابزار برشی در حفاری مکانیزه با ماشین EPB-TBM

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چکیده:

سـایش به دلیل توقف حفاری برای تعویض ابزاربرش مسـتهلک‌شـده و در نتیجه پایین آمدن سـرعت پیشـروی به دلیل کُندشـدن ابزار حفاری، به عنوان یکی از پارامترهای مؤثر در محاسـبه هزینه پروژه‌های تونلسـازی مکانیزه در زمین‌های نرم شـناخته می‌شـود. بطور کلی مطالعات گسـترده‌ای درباره حسـاسـیت و پیش‌بینی سـایش و سـایندگی در مورد سـنگ‌ها وجود دارد، اما در مورد دانه‌های خاک‌ها و تأثیر آنها بر روی ماشـین‌های حفار در زمین‌های نرم، کارهای بسـیار کمی صـورت گرفته است؛ به‌طوریکه روش و آزمایش جامع و مورد قبولی در خصـوص بررسـی سـایش و سـایندگی در زمین‌های نرم وجود ندارد. در این مطالعه جهت درک بهتر اندرکنش بین خاک و ابزار برش اقدام به طراحی و ساخت دستگاه شبیه ساز حفاری TBM شده است. در این مقاله، پس از معرفی دستگاه جدید ساخته شده در دانشـگاه صـنعتی سـهند تبریز- ایران به منظور شـبیه سـازی مکانیزم حفاری TBM، به بررسـی تاثیر انواع پارامترهای دانه‌بندی خاک از قبیل D10، D30، D60 (گویای قطر متناظری از نمودار دانه‌بندی خاک هسـتند که به ترتیب ۱۰، ۳۰ و ۶۰ درصـد ذرات کوچکتر از این مقدار می‌باشـند)، ضـریب دانه‌بندی، ضـریب یکنواختی، جورشـدگی و اندازه موثر بر روی سـایش ابزارهای برش پرداخته شـده اسـت. نتایج اولیه مطالعات نشـان می‌دهد که در خاک‌هایی با ذرات ریزدانه بالای ۱۰ درصـد، با افزایش پارامترهای D10، D30، D60 و ES سـایش ابزارها افزایش می‌یابد اما در خاک‌هایی با ذرات ریزدانه زیر ۱۰ درصـد، با افزایش پارامترهای مذکور، سـایندگی خاک کاهش می‌یابد. همچنین در خاک‌های با بیش از ۱۰ درصـد ذرات ریزدانه، با افزایش پارامتر Cc، سـایندگی خاک کاهش می‌یابد اما در خاک‌های با درصد ذرات ریزدانه کمتر از ۱۰ درصد، با افزایش این پارامتر، سایش ابزار افزایش می‌یابد. نتایج آزمایشات نشان می‌دهد که جورشدگی می‌تواند یکی از معیارهای خوب برای بررسی قدرت سایندگی خاک باشد.

کلمات کلیدی: آزمایش و ارزیابی، تونل و تونلسازی، زمین‌شناسی، سایش ابزار، سایندگی.