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# Cutting Tools Wear in Soft Ground Tunneling: Field and Experimental Insights

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**Abstract**

This study is an attempt to design and manufacture a tunnel boring machine (TBM) simulator to better understand the interaction between soil and cutting tools, due to the lack of an accepted method for this issue. In this paper, Sahand Soil Abrasion Test (SSAT) is introduced, which is built by the Sahand University of Technology. The experimental and real results of tool wear are presented. The results firstly demonstrate that the cutting tools wear in the coarse-grained soils can be less than in the fine-grained ones in the real conditions. However, in the soils with fine grains higher than 10%, the wear of cuttings tools increases in the laboratory condition when grading parameters increase. In soils with fine grains less than 10%, the wear of tools decreases by increasing the grading parameters. Also, the results reveal that the coefficient of gradation depend on the amount of silt and clay in the soil samples. The investigations show that sorting is another good criterion for investigating the power of soil abrasively. Furthermore, it indicates that the cutting tools wear increases when the moisture content of the soil structure in the dense condition approaches the optimal moisture content. Finally, the results indicate that the wear and torque of the cutterhead could be reduced by 58% and 34%, respectively, when the excavated materials have the appropriate conditioning.

## 1. Introduction

Abrasion is defined as the continuous and undesirable loss of materials at the surface of a solid body, due to the mechanical actions like contact and relative motion between two bodies [1]. Tribology is the science and engineering of interacting surfaces in the relative motion, which is taken from the Greek word Tribo, meaning rubbing. Tribology includes scientific investigation of various types of friction, lubrication, abrasion, and technical application of derived knowledge in this respect. Longtime research on tribology confirms this statement that the frictional and abrasive characteristics of a certain material are not among the intrinsic properties of that material, and are accounted as behavioral factors, which are dependent on the practical conditions. The quantitative values of friction and abrasion are related to the friction coefficient, and the abrasion rate is dependent on factors that are classified as follows [2]:

1. System structure: Constitutive components and characteristics corresponding to each of them,
2. Executive variables: Load, kinematics, temperature and time,
3. Interaction of constitutive components of the system.

Therefore, the wear phenomenon should be investigated in terms of Tribosystems. In Figure 1, different components of a tribologic system are shown. The system includes the section, which causes wear (counter body) and the section, which is exposed to wear (solid body). Also between the two sections is a middle environment (interfacial medium), which comprises the crumbs and various types of lubricants. All the components present in the system interact each other and affect each other, too [3].

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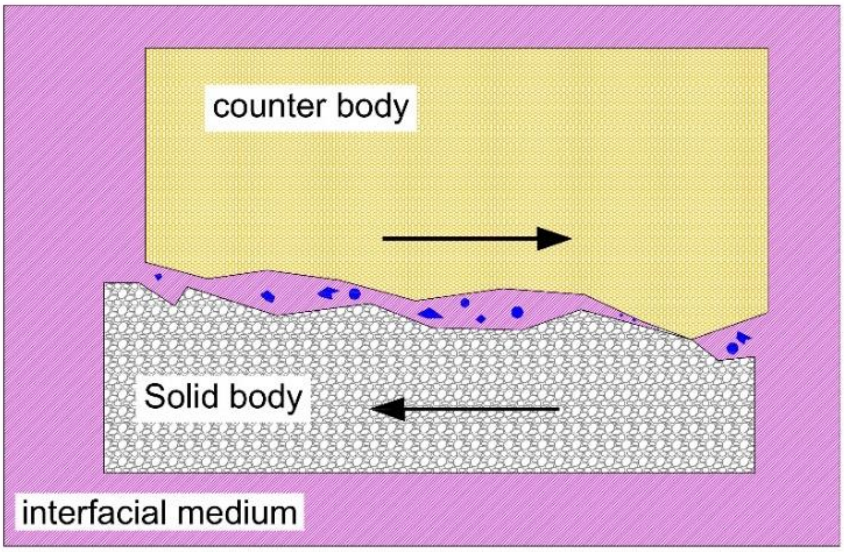



**Figure 1. Components of a tribologic system [3].**

Generally, in the mechanized excavation, the effect of abrasive soils on the machine are defined in terms of primary wear and secondary wear. The expected wear of the excavation tools and surfaces of scrapers, and cutting disks designed for excavation, which need to be replaced in time intervals, is called the primary wear. On the other hand, secondary wear is a non-designed wear and where the primary wear is extensive, results in wear of the cutterhead structure, the sections that support the tools, spokes and saddle of cutters and other surfaces, which had not been expected by the TBM designers and producers [4]. Figure 2 shows the various types of primary wear and secondary wear in the mechanized excavation using the EPBM at Line 7 of Tehran metro project.

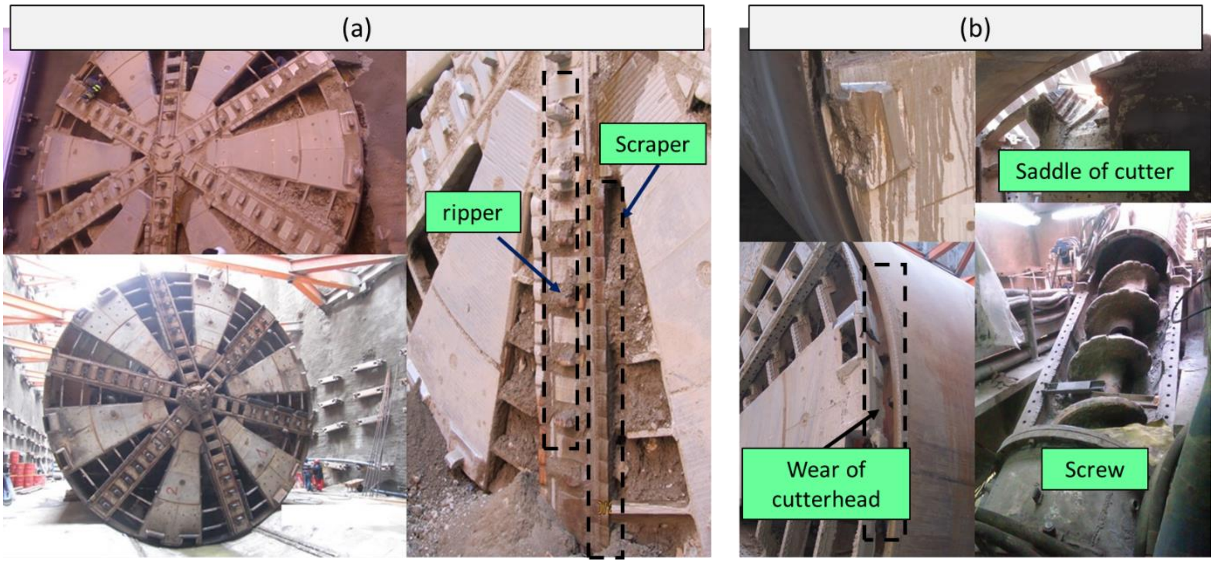



**Figure 2. Types of wear: a) Worn rippers and scrapers, b) Wear of screw, saddle of cutters and cutterhead.**

## 2. Challenges Associated with Assessment of Wear and Abrasivity

Generally, there are extensive studies on the sensitivity and prediction of wear and erosion of rocks, but concerning the soil grains and their impact on the excavation machines, very few research works have been done. This could be due to this fact that always instead of conducting tests, just predictions have been made for abrasion rate of these materials, using just for example the operation speed of TBM or the machine wear. The fact that wear plays the main role both in terms of costs and scheduling is accepted by the public. But the issue of abrasivity in the coarse-grained soils like gravels and sands was not considered a great problem till the past decade. Recent studies have revealed that this problem could create great difficulties during operation of shielded TBMs or excavation tools in large tunnels. Iran also is not an exception in this respect, and in the recent years, wear of cutting tools and other TBM components has created many problems in various projects. For example, one could refer to Line 7 of Tehran metro, Line 2 of Isfahan metro, and Line 1 of Shiraz metro. Figure 3 shows some images related to wear of tools in the mentioned projects.

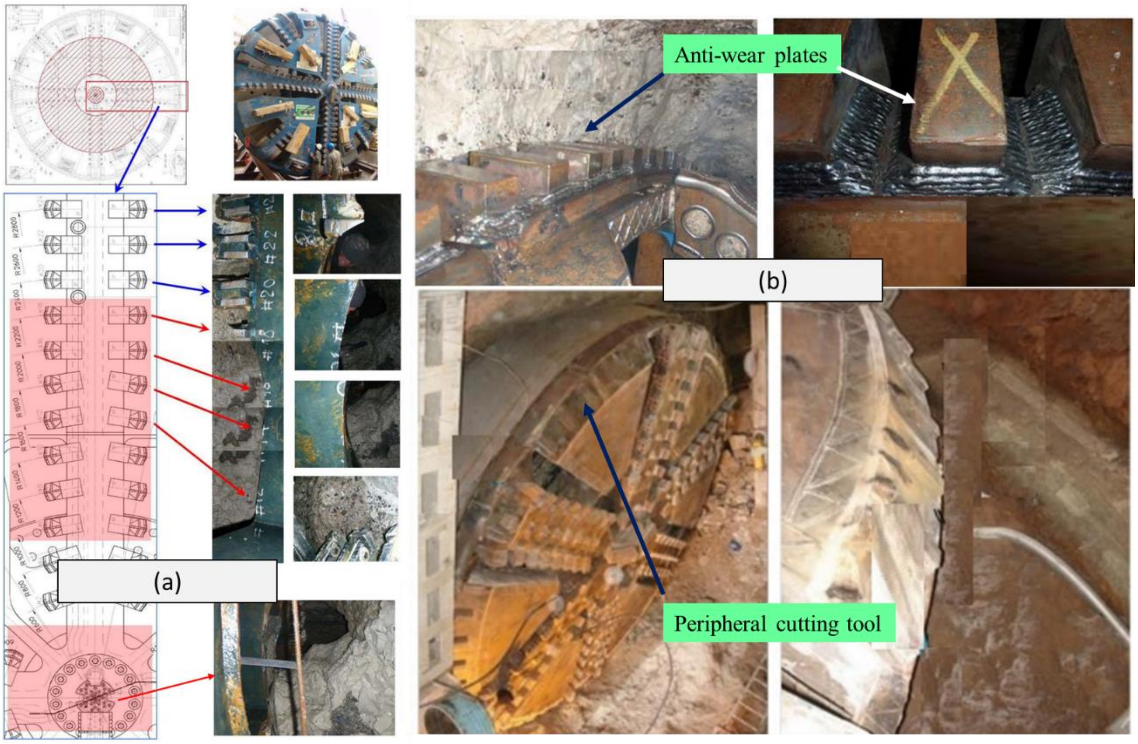



**Figure 3. Wear in Iran's tunneling projects: a) Isfahan cutterhead central tools wear, b) Shiraz cutterhead environmental tools wear [5, 6].**

Although abrasivity is a general term and some soils are introduced as abrasive, but its meaning is not quite clear. Abrasivity is an interactive characteristic, and ground abrasiveness depends on the tools properties or the section, which is exposed to abrasion or the ground or the section, which causes abrasion under certain temperature and pressure values. When discussing abrasivity, always this combination should be taken into consideration. By hardening of the constituent elements, i.e. the mineral components, the chance of exhibiting an abrasive behavior by the ground in contact with cutting tools increases. As abrasivity is a behavioral characteristic one could define it in terms of abrasive capacity [3].

Contrary to the physical and mechanical properties of soils, which are among their intrinsic characteristics. The abrasive properties of soils like other materials are the behavioral properties. As was stated, the occurred abrasion rate depends upon the constituent components of that system, operational variables, interaction of constituent components of the system, and the examined environment. Therefore, precise assessment of occurred abrasion in a system should be done by considering all the above mentioned factors [7]. In Figure 4, the effective factors on wear of cutting tools are presented.

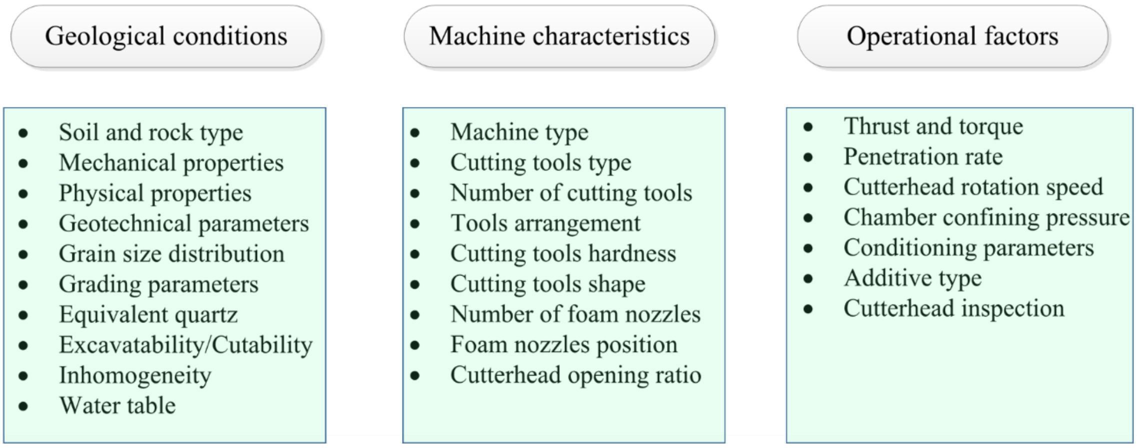



**Figure 4. Effective factors on wear of cutting tools in EPB tunneling [8].**

Many research works have been done considering the problems that arise from tools wear in the tunnel projects that implement TBM machines [9-12]. There are several suggested methods for estimation of cutting tools life in hard rock TBM tunneling [13-24], but there is no acceptable method or standard that can be applied in estimation of tool wear in soft ground or soil tunneling. However, some experimental research has focused on the performance of the TBM in soft ground conditions and have introduced new tests for measurement of soil abrasivity in laboratory environment.

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 [25]. 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 [26]. A good investigation has been done on the effective factors on the wear phenomenon from the tribological standpoint [7]. A device was redesigned and manufactured for predicting the effect of some soil parameters on the cutting tools [27]. A devise was built based on the chamber simulation in EPB machine, which could measure abrasion in this environment [28]. The existing challenges in estimating soil abrasivity in soft grounds were investigated by SGAT device [29]. The effect of grading and conditioning of materials on the cutting tools wear was studied in China in the years 2018-2020 [30-32].

As many tests have been introduced for estimation of abrasivity (Table 1), one could state that the large number of existing abrasivity tests reveal that there is not a general method accepted by the tunneling community for investigating abrasion in soft soils. The reason could be attributed to the behavioral characteristic of abrasion. Therefore, a test is accepted that its components, its motion mechanism, and its environment are similar to the existing condition of the real process of abrasion. Hence, in the present study, attempt is made to introduce a device with less limitations to assess wear of cutting tools in soft grounds considering the abovementioned topics.

In Table 1, a selected list of various tests, which are performed for assessment of wear and abrasivity, are presented and compared to each other. As is seen in Table 1, among the introduced tests, the PSA, SGAT, NDAT, and CUGB tests have a better application in soft grounds with respect to other options. Nevertheless, the goal of the present article is manufacturing a device with less limitations, easy implementation for simulation of interaction between soil structure, and cutting tools under the condition of mechanized excavation with EPB-TBMs. Recognizing the interaction of soil and cutting tools during excavation greatly helps with introducing and manufacturing a device for accurate measurement of wear in the soft environments. By recognition of the effect of different factors on wear of cutting tools, one could prevent the extra cost and time spent for urban mechanized tunneling projects.

**Table 1. Review of selected soil abrasivity measurement methods for soft ground tunnelling applications.**

| Abrasion test name | Cutter tool pattern | Tool hardness | Cutterhead rotational speed (rpm) | Depth of penetration (mm) | Thrust (N) | Torque variation (Nm) | Ambient pressure (bar) | Grain size range (mm) | Soil compaction | conditioners | Range of application | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soft Ground Abrasion Tester (SGAT)** | 4 Steel spokes | Vickers hardness 227 | Up to 100 | Up to 200 | 0-3000 | 0-32 | Atm – 6 (4 bars with cont. foam injection) | < 10 | Manually by proctor hammer prior to testing. Compaction as desired | Continuous addition through the drilling tool | Applicable for replicate an in situ soil – TBM excavation tool contact, in a small scale | [29] |
| **Penn state soil abrasion (SAI) testing system** | Propeller blade with var. pitch angle. Standard pitch angle is 10° | 17, 31, 43, 51 and 60 HRC | Up to 180 | Fixed position, with 150 mm soil above and below the propellers | Not known, but axial load is measured | Not known, but torque is measured | Atm – 10 | Similar the in situ conditions of soil | Compaction under the propeller blade during the Test | Premix and continuous addition through pre-installed ports | Applicable for obtaining a representative soil abrasivity index in soft ground tunnelling | [26, 27, 33-36] |
| **China University of Geosciences in Beijing (CUGB)** | 4 metal blocks are fixed along the rods | Q235, WC, or both | 0 to 80 | Fixed position, with 30, 55, 80 and 110 mm from the center of the propellers | Not known | torque is recorded | Not reported | < 10 | Manually before testing | Mix before testing and add continuously during testing | Applicable for replicate an in situ soil – TBM excavation tool contact, in a small scale | [30-32] |
| **The Ruhr – University Bochum (RUB)** | Star-shaped screens on which pins are mounted | S275 JR Made under normal conditions | 45 – 140 | 465 | Not known | Not known | Not known | 0.06 – 4 Published results | Manually before testing | Mix before testing and add continuously during testing | Applicable for testing clay, silt and sand fractions | [37] |
| **The LCPC test** | Rectangular impeller | Rockwell hardness of B 60-75 | 4500 | Fixed position | Not known | Not known | Not Applicable (N/A) | 4-6.3 | N/A | N/A | Applicable for abrasiveness classification of different soil types | [25, 38] |
| **The NTNU abrasion test (AV/AVS)** | Steel piece | Tungsten carbide /Cutter ring steel | 20 | Fixed position | Not known | Not known | N/A | > 1 mm | N/A | N/A | Applicable for estimate the CLI and BWI | [39-42] |
| **New NTNU soil abrasion Test (SAT)** | Steel piece | 55 HRC | 20 | Fixed position | Not known | Not known | N/A | > 4 | N/A | N/A | Applicable for testing clay, silt and sand fractions | [43, 44] |
| **Newly Developed Abrasion Test (NDAT)** | Circular plate | Rockwell hardness of B 60-70 | 20 | Depended on compression pressure | Applicable via a pneumatic jack with capacity of 3 bar | Not known | Atm – 3 | Similar the in situ conditions of soil – up to 100 mm | Compaction under the circular plate via pneumatic jack during the test | Premix and continuous addition through pre-installed ports | Applicable for measuring and evaluating the impact of soil abrasivity on a TBM in soft ground tunnelling | [28] |
| **Ball mill test** | 20 steel bits | Ordinary construction steel | 90 | N/A | Not known | Not known | N/A | > 16 | N/A | Premix with soil conditioning additives and water | Applicable determine the influence of soil conditioning additives on the abrasivity properties of crushed rock and natural soil | [45, 46] |
| **The cerchar test** | Steel pin | 54-56 HRC | Sliding displacement with a steady speed with a range of 0–1.7 cm/s | Not known, but vertical displacement is measured | 70 N | Not known | N/A, but lateral confining stress can be applied | < 10 | N/A | N/A | Applicable for determining rock abrasivity for hard rock tunneling applications | [47] |
| **Miller test** | Steel block | Standard materials | Reciprocating motion for 6 hours | Fixed position | 22.24 N | Not known | N/A, but Ambient temperature is used | 0.045-0.075 | N/A | Premix with lubricant or additives | Applicable for investigation the response of different materials to an abrasive slurry | [48, 49] |
| **The los Angeles abrasion test** | 6-12 Spherical balls (varies with aggregate size) | Standard materials | 30-33 | N/A | Not known | Not known | N/A | 2.36-25 | N/A | N/A | Applicable for study the abrasion of aggregates to be used in road pavement works | [50] |
| **Nordic ball mill test (NBMT)** | 7000±10 g of steel ball with diameter size 15 mm | Standard materials | 90±3 | N/A | Not known | Not known | N/A | 11.2-16 | N/A | N/A | Similar to the L.A. abrasion test | [45, 46] |
| **Dorry's abrasion test** | Steel plate | Standard materials | 20-30 | Fixed position | Underweight 13.7 kg | Not known | N/A | 11.2-12.5 | N/A | N/A | Similar to the L.A. abrasion test | [51] |
| **Micro-deval test** | 5000 ± 5 g of steel ball with diameter size 9.5 mm | Standard materials | 100 ± 5 | N/A | Not known | Not known | N/A | 4.75-16 | N/A | N/A | Applicable for assessing aggregate resistance to abrasion | [52, 53] |
| **Mineralogical methods** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | Applicable for preliminary estimates of cutter wear | [54-56] |

## 3. Methodology and Equipment

### 3.1. Wear evaluation device of Sahand University of Technology

Figure 5 shows a view of the device used for assessment of cutting tools wear, which is built at the Sahand University of Technology in Tabriz. The SSAT device is made for simulation of tunnel boring mechanism. Using this device, one could investigate the amount of soil abrasivity and wear of cutting tools at different conditions. Among the characteristics and advantages of the device one could refer to the low speed of propeller rotation, continuous contact between the pins and undisturbed soil (*in situ*) during experiments, continuous injection of conditioning material with a certain injection pressure during the test and its horizontal application. In addition, the following items could be listed:

- Possibility of investigating the effect of different gradations,
- Possibility of investigating the effect of soil physical and mechanical properties,
- Possibility of investigating the effect of cutterhead opening ratio,
- Possibility of investigating the effect of arrangement and location of pins,
- Possibility of measurement of thrust force (on the rear of jack) and torque of the device,
- Possibility of investigation the effect of penetration rate in soil.

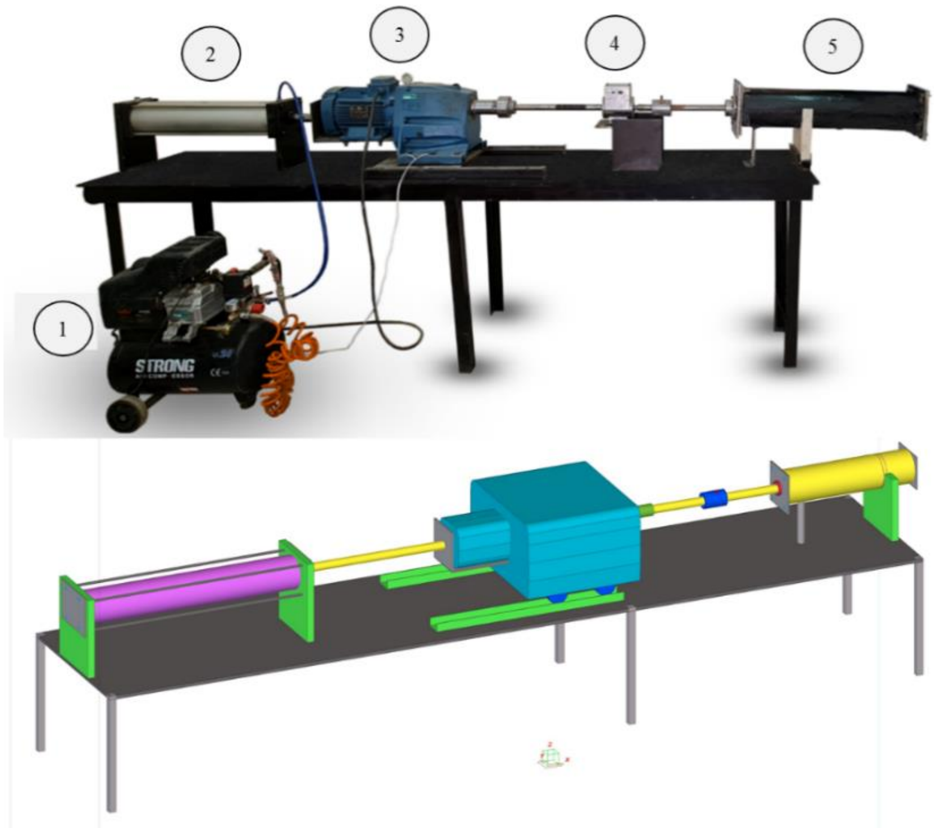



**Figure 5. SSAT testing device: 1) air compressor, 2) pneumatic jack, 3) motor and gearbox, 4) torque-meter sensor, 5) excavation chamber**

The most important parts of SSAT device are the air compressor, pneumatic jack, motor and gearbox, shaft, inverter, excavation chamber, and torque-meter. Over the shaft length with 1100 mm length and 30 mm diameter, an area is considered for addition of soil conditioning materials. The shaft is located within a chamber with 750 mm length and 100 mm diameter. On the other side, the shaft is connected to the gearbox so that by the rotational movement of gearbox, the propeller could rotate in the soil and by applying the jack force and its forward movement could drill the soil and cause wear of cutting tools installed on the propeller. The excavated soil is directed through the channels provided on the propeller to the space behind it (space between the polyethylene segment and rear of the propeller). The polyethylene segment is used for preventing collapse of the excavation face. The force generated by the excavated soil causes movement of the polyethylene segment backward and thus the chamber space of TBM could be well simulated. A schematic view of the inside of excavation chamber in the SSAT device is shown in Figure 6.

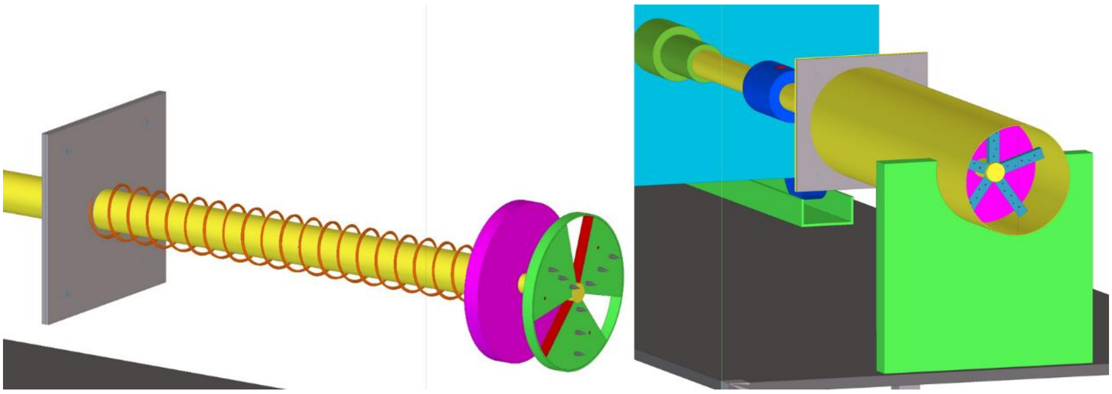


**Figure 6. Schematic view of the SSAT device chamber.**

The propeller of SSAT device is similar to that of a TBM with a circular section and 43% opening. On the propeller, there are 9 pins located with different cutting lines (similar to the TBM cutting tools). In addition to the pins located on each blade, there are locations for addition of soil conditioning materials, which provide the possibility of continuous injection of additives into the chamber during conducting the test. Figure 7 shows a view of the propeller and arrangement of cutting tools on it. The wear of tools is calculated according to Equation 1 based on the difference between the initial and secondary weights of pins with an accuracy of 0.001 g. Some of the SSAT device properties are given in Table 2.

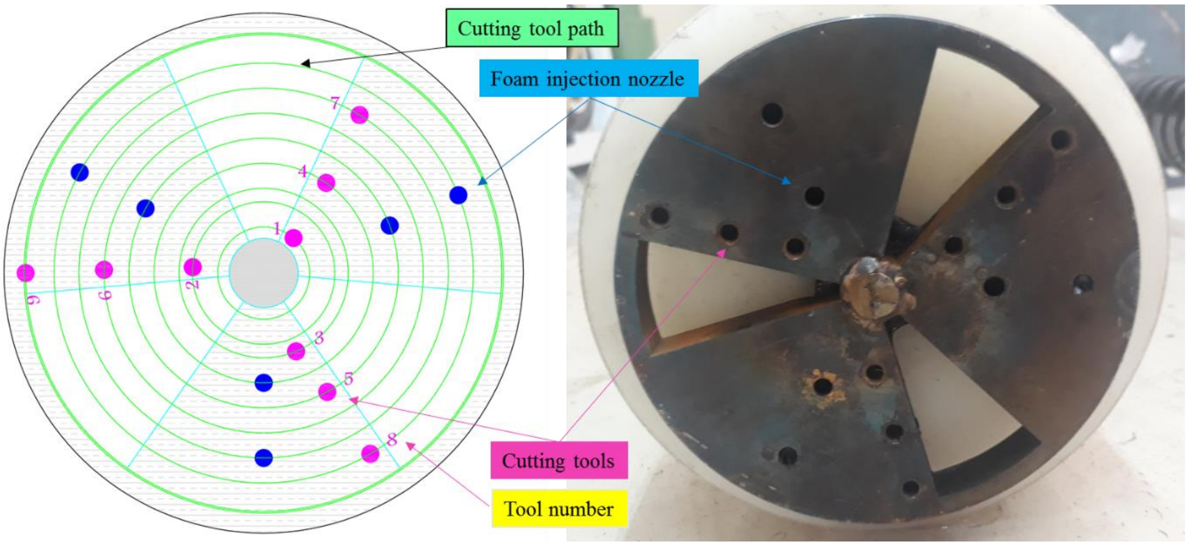



**Figure 7. Cutting tools arrangement of SSAT device.**

$$WR(\%) = ((m_o - m)/M)*100 \tag{1}$$

where WR is the wear rate (%), $m_o$ is the weight of tool before the test, m is the weight of tool after the test, and M is the weight of the soil sample.

**Table 2. Additional specifications of SSAT device.**

| Cutting tools design | 9 pins in a spiral form |
|---|---|
| RPM | 0-35 |
| Penetration length, mm | 500 |
| Penetration rate | 0-10 mm/min |
| Torque interval | Up to 10 kN.m |
| Ambient pressure | Up to 3 bar |
| Granulation range, mm | 0 – 19.05 (SM-SP, SM, SC) |
| Soil consolidation | Manually before testing |
| Soil conditioning | Mix before testing and add continuously during testing |

### 3.2. Methodology

The used samples in the experiments are taken from Line 7 of Tehran metro [8], [57]. The prepared samples in the testing environment lose their moisture, and during the test depending on the conditions whether dry or humid, by addition of water to soil the test is conducted in wet condition. The prepared samples in the laboratory are graded according to the ASTM D422-87 standard using the dry method [58]. The grading schemes performed in the present study are shown in Figure 8. Totally, 9 grading schemes are used for testing (Figure 8). The stages of soil preparation are as follows: first, the soil is graded and wetted to reach the desired moisture content. Then the soil is placed within the chamber to reach up to 500 mm height. Next, the propeller and other components are placed within the chamber, and the chamber cap is closed. After installing the chamber on the device, the test is conducted in certain operational and geo-technical conditions.

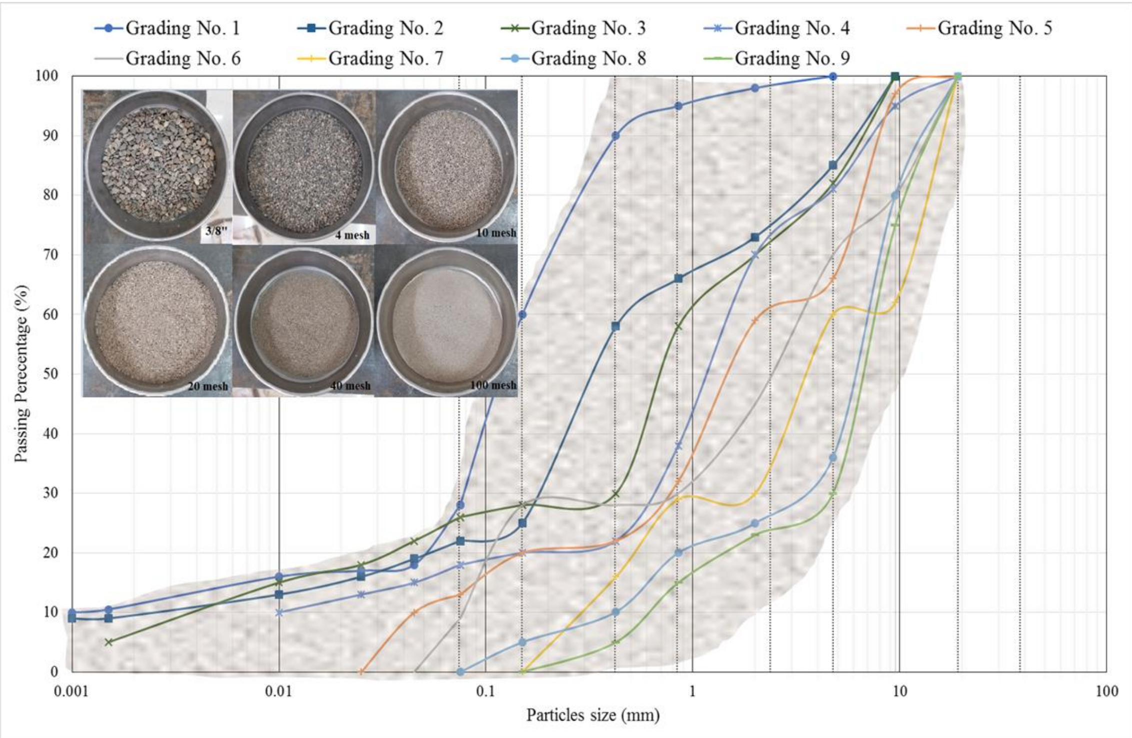



**Figure 8. Grain size distribution curve of the samples.**

Different parameters are used for expressing the effect of gradation on the abrasivity studies of soft grounds. For example, $D_{50}$ and $D_{70}$ and effective size (ES) have been utilized for the study of abrasive samples. Hence, in order to start the investigations, some important parameters are introduced as follows [59-63]:

- $D_{10}$, $D_{30}$ and $D_{60}$: these parameters denote the corresponding diameters in the soil grading curve, where 10, 30, and 60% of the soil grains are smaller than that diameter, respectively.

- Uniformity coefficient ($C_u$): the ratio of $D_{60}$ to $D_{10}$ is called the uniformity coefficient and is derived from Equation 2:

$$C_u = D_{60}/D_{10} \tag{2}$$

- Coefficient of gradation or curvature ($C_c$): The parameter is calculated using Equation 3:

$$C_c = D_{30}^2 / D_{10} * D_{60} \tag{3}$$

- Sorting ($S_0$): This soil grading parameter shows the extent of soil grains uniformity in terms of shape and size, and is calculated using Equation 4:

$$S_o = \sqrt{\frac{D_{75}}{D_{25}}} \tag{4}$$

- Effective size: This parameter is obtained from Equation 5:

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

where $d_{min}$ and $d_{max}$ denote the minimum and maximum diameters of abrasive grains. In all the equations, the parameters are calculated in mm.

Table 3 shows the selected parameters for 9 grading schemes in the experiments.

**Table 3. Geological parameters of soil samples.**

| Soil No. | Gravel (%) | Sand (%) | Silt and Clay (%) | $D_{10}$ (mm) | $D_{30}$ (mm) | $D_{60}$ (mm) | ES (mm) | $C_c$ | $C_u$ | $S_o$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 70 | 30 | 0.001 | 0.080 | 0.150 | 1.05 | 42.67 | 150.00 | 2.01 |
| 2 | 15 | 62 | 23 | 0.003 | 0.180 | 0.500 | 2.18 | 25.92 | 200.00 | 3.65 |
| 3 | 0 | 73 | 27 | 0.004 | 0.420 | 0.950 | 2.47 | 46.42 | 237.50 | 6.11 |
| 4 | 4 | 78 | 18 | 0.010 | 0.640 | 1.500 | 2.78 | 27.31 | 150.00 | 2.34 |
| 5 | 3 | 84 | 13 | 0.040 | 0.700 | 2.300 | 5.01 | 5.33 | 57.50 | 3.25 |
| 6 | 30 | 60 | 10 | 0.075 | 0.850 | 3.600 | 5.57 | 2.68 | 48.00 | 7.36 |
| 7 | 40 | 60 | 0 | 0.290 | 2.000 | 4.200 | 6.50 | 3.28 | 14.48 | 3.85 |
| 8 | 64 | 36 | 0 | 0.400 | 3.500 | 6.700 | 8.26 | 4.57 | 16.75 | 2.06 |
| 9 | 70 | 30 | 0 | 0.600 | 4.900 | 7.900 | 9.54 | 5.07 | 13.17 | 1.73 |

The effect of soil grains size on the soil abrasivity is studied by many researchers. However, the previous studies have focused more on the effect of grains size, especially coarse grains in the absence of silt and clay grains. Thus, practically a wide variety of soil grains and also the impact of grains size distribution of natural soils have remained non-investigated. Furthermore, in most of the previous studies the cutting tools were always in contact with undisturbed soil. In the present article, the natural soil samples with different grain size distribution curves have been investigated and tested. The abrasivity tests are performed using the SSAT device manufactured at the mining engineering faculty of Sahand University of Technology in Tabriz. In continuation, some of the research results are presented.

### 3.3. Introduction of Tehran metro Line 7 project

Although the scale effect has not been considered in manufacturing of SSAT device like other devices and methods introduced in Table 1, but in order to investigate the trend of changes in investigating the different parameters, use has been made of the real data recorded along 6500 m length of Line 7 of Tehran metro project. The tunnel of Line 7 was excavated using the EPBM with 9164 mm diameter made by Lovat Co. in Canada and is segmented. Figure 9 shows a view of the TBM and plan of Line 7 of Tehran metro. The Line 7 tunnel is located in quaternary alluvial deposits of Tehran plain. The soil type of tunnel path is mainly of gravelly sand together with silt and clay and sandy gravel with silt and clay. In Figure 9, the soil grading curve corresponding to the area of Line 7 project is presented. As is seen, there are some existing differences and overlaps between the soil grading of Line 7 project and the soil grading curve used in the tests. Along this length of tunnel, a total number of 1169 cutting tools are utilized, of which 645 are rippers, 357 are scrapers, and 153 are disc cutters.

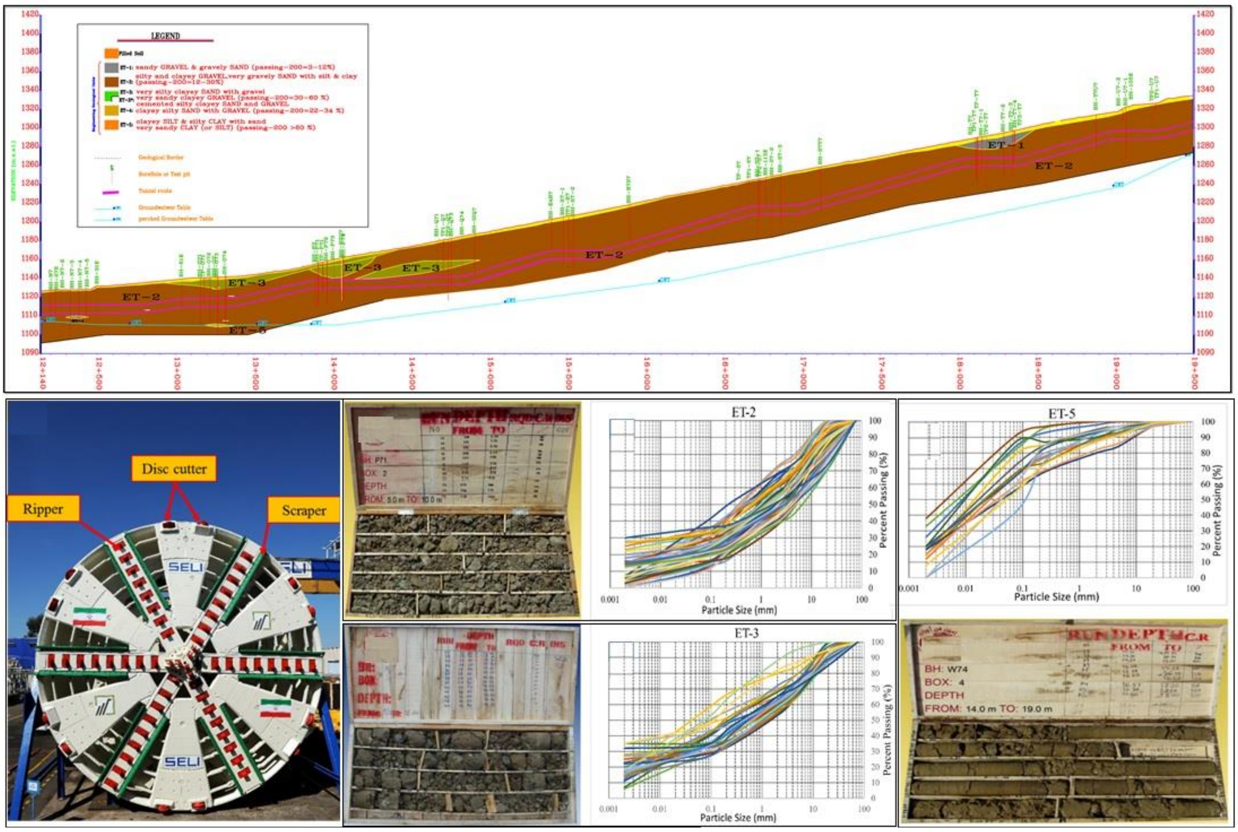


**Figure 9. Additional specifications of Tehran metro line 7: a) geo-technical profile, b) picture of the EPB-TBM, and c) picture of soil samples (Left) and grain size distribution curves (Right).**

## 4. Tests Results and Discussion

In order to investigate the effect of different factors corresponding to soil grading on the wear of pins, 9 different grading schemes were selected. The selection was based on the extension of the grading range. Grading curves No. 1 and No. 3 are used for investigation of the fine-grained soils, in absence of gravel. An example of these grading curves per zero and 10% moisture contents is given in Figure 10. Grading No. 2 was prepared by adding 15% gravel. Grading curves No. 4 and 5 are mainly based on sand, and gravel and fine grains constitute a small percentage of it. Grading curves No. 6 to 9 are mainly based on gravel, in which the amount of gravel is increased. A view of this grading curve at zero and 10% moisture contents is shown in Figure 10.

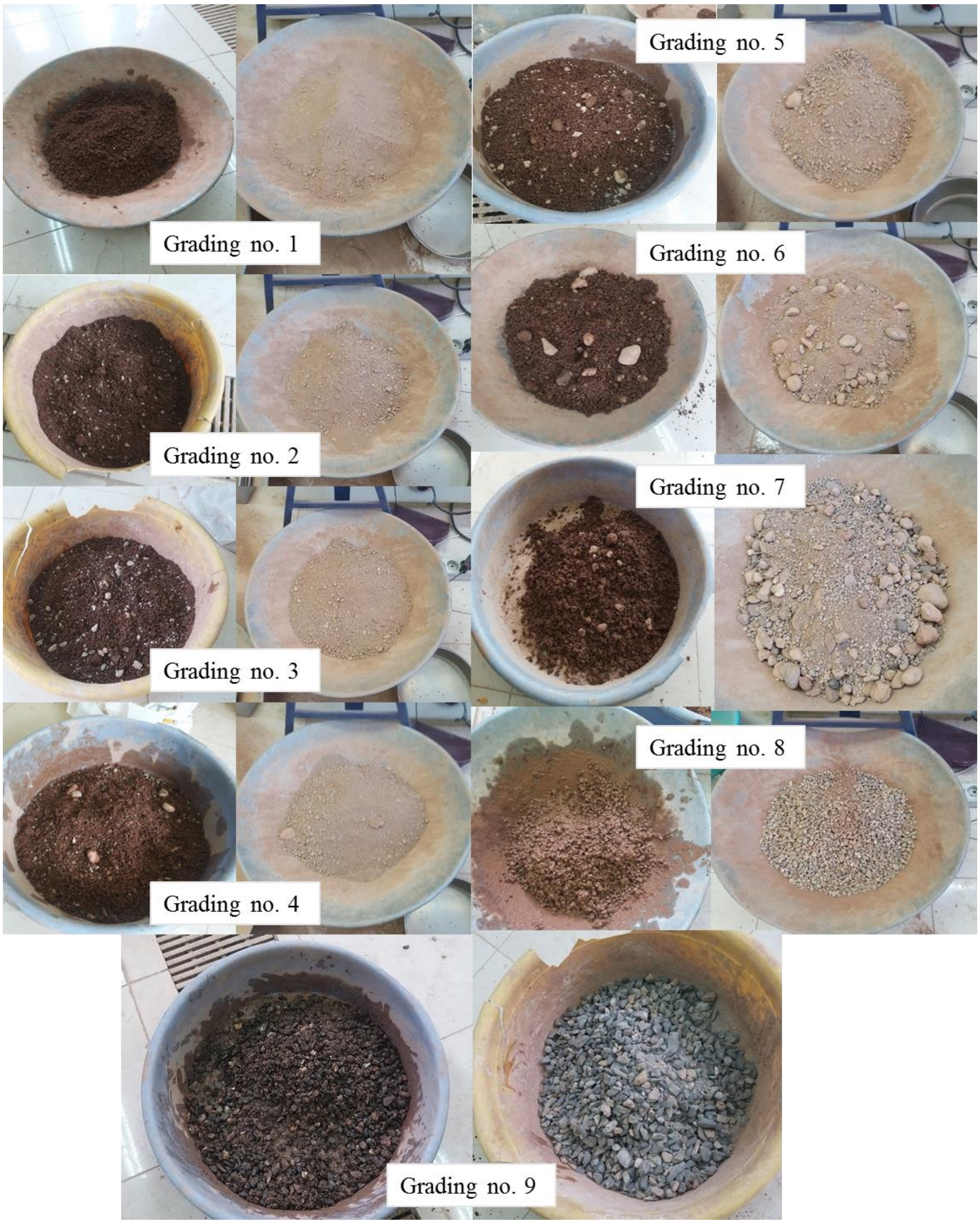



**Figure 10. Picture of soil samples: (left) 10% moisture contents and (right) dry.**

In this section, the effects of such parameters as $D_{10}$, $D_{30}$, $D_{60}$, $C_c$, $C_u$, $S_0$, ES, moisture content, and foam on wear of the cutting tools have been investigated. Considering the obtained results from the tests, the rate of wear differs at different parts of the cutterhead. By classifying the results, it was found that the maximum wear, considering the arrangement of pins, corresponds to the external pins and minimum wear occurs in the internal pins. As it was expected, by increase of radial distance from the center of the propeller, the amount of wear has increased. The issue also is clearly observed in real condition of excavation by EPB-TBMs. Figure 11 shows a view of relationship between position of cutting tools and their consumption at Line 7 of Tehran metro project.

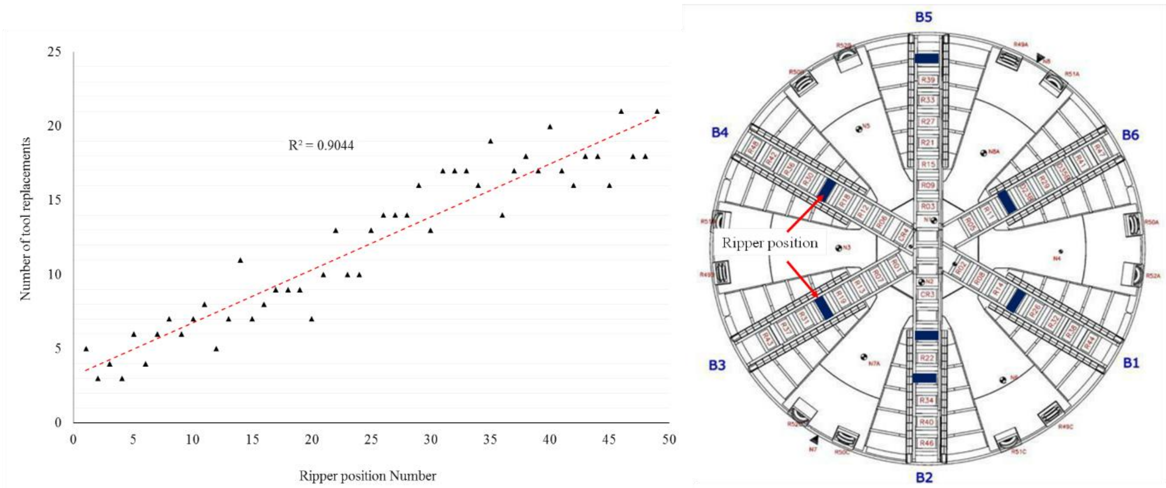



**Figure 11. Relation between cutter position and cutter consumption for rippers in 6500 m of Tehran metro line 7.**

### 4.1. Effect of grading on wear of cutting tools

In the present research work, considering the necessity of investigating and determining of initial needed parameters (operational parameters of the device), first a number of designs and tests were performed and based on them, the operational parameters were selected according to Table 4 for continuation of the studies. In order to investigate the effect of grading on wear of the pins, the abrasion test was performed at zero, 5, 10, and 15% moisture contents.

**Table 4. Selected parameters of tests used in this study.**

| Soil No. | Density ($g/cm^3$) | Moisture content (%) | RPM | Penetration rate (mm/min) | Time (min) | Ambient pressure (bar) |
|---|---|---|---|---|---|---|
| 1 to 9 | 1.5-2.0 | 0, 5, 10 and 15 | 35 | 4.16 | 150 | atmospheric |

In order to investigate the effect of $D_{10}$ on wear of the pins, the wear values at different moisture contents are drawn against $D_{10}$ parameter values (Figure 12). As is seen in Figure 12, by increase of $D_{10}$ values from 0.001 to 0.010 mm, the wear values exhibit an ascending trend. But by increase of $D_{10}$ values from 0.010 to 0.60 mm, the average wear of the pins has decreased. The maximum wear of pins has occurred at $D_{10}$ = 0.075 mm and 10% moisture content and minimum wear of pins has occurred at zero moisture content and $D_{10}$ = 0.001 mm.

$D_{10}$ in the soil grading curve refers to a corresponding diameter at which 10% of the soil grains are smaller than that value. By increase of $D_{10}$ in the soil grading curve, in fact, the percentage of soil grains diameter per a certain weight of soil increases. In soils with small $D_{10}$ values, the soil is mainly fine grained. In this state (according to Figure 12), the average occurred wear of pins is a small value. In other words, in this type of fine-grained soils, a small percentage of abrasive aggregates is present in the soil grading. For this reason, within this range of grading, the amount of wear is small. On the other hand, due to cohesion of fine grained soils, at 10 and 15% moisture contents, the clogging phenomenon occurs in the propeller which causes reduction in wear of the pins. Figure 13 shows the clogging of propeller and cutting tools for soil grading curves No. 1, 2, and 3 at 10 and 15% moisture content.

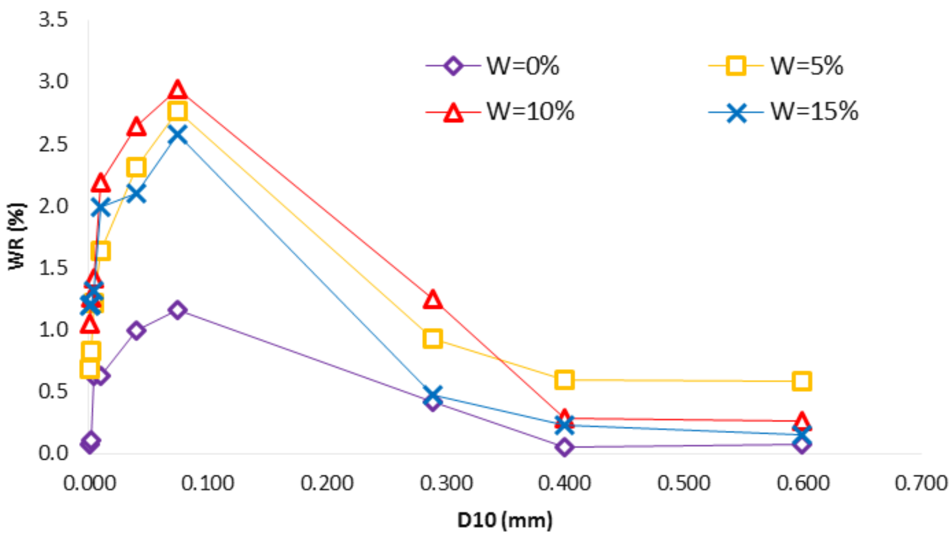



**Figure 12. Correlation of $D_{10}$ and WR.**


**Figure 13. Clogging of propeller for grading No. 1 to 3: left) 15% moisture content and right) 10% moisture content.**

By increase of $D_{10}$, the ratio of abrasive grains to fine grains increases in the soil sample and presence of these abrasive grains in the fine grains causes increase of tools wear. By further increase of $D_{10}$, due to small interlocking of aggregates, they are easily displaced when encountering cutting tools and as the result the wear is reduced compared to the previous state.

In order to investigate the effect of $D_{30}$ parameter on the wear of pins, the amounts of wear at different moisture contents against $D_{30}$ parameter are shown in Figure 14. In investigating the effect of $D_{30}$, the results show that in soil grading curves No. 1-6, by increase of $D_{30}$ values the amount of tools wear also increase. But from grading No. 6 on, by increase of $D_{30}$, the amount of tools wear decreases. Investigating the soil grading curves No. 1-6, it is observed that the amounts of silt and clay (percentage of grains passing sieve No. 200) is greater or equal to 10%, while this value for samples 7-9 is less than 10%. Considering this and the results of wear tests, one could state that for soils with more than 10% fine grains, simultaneous with increase of $D_{30}$, the cutting tools wear also increases. But in case that the percentage of fine grains is less than 10%, by increase of $D_{30}$, the wear of cutting tools decreases (these observations also are true for $D_{10}$ parameter).

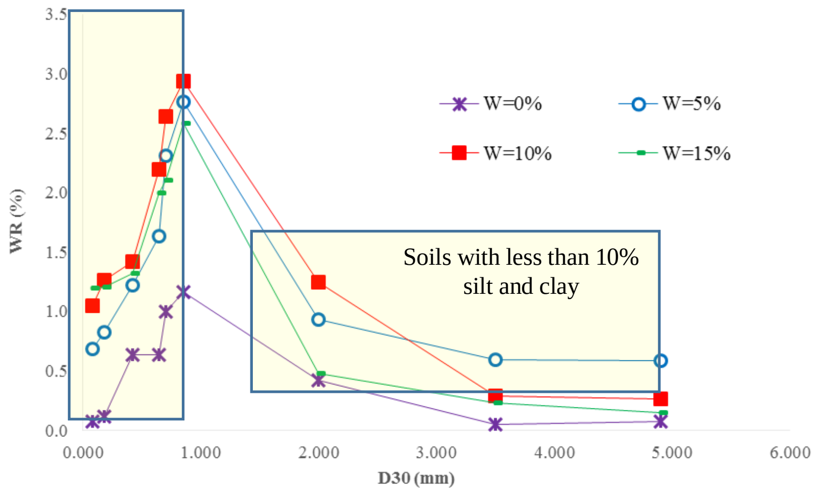



**Figure 14. Correlation of $D_{30}$ and WR.**

The reason for increase of relative mean of wear in the first portion of the curve in Figure 14 and decrease in the mean of wear in the second portion of the curve, could be stated in this way that in the first portion (fine grained), by relative increase of $D_{30}$, simultaneous with the fine-grained portion of soil, the coarse and abrasive grains increase relatively in the soil and thus the mean of wear of cutting tools increases. But in the second portion of the curve (coarse grained), by increase of $D_{30}$, gradually the fine-grained portion is decreased or removed, and these causes decrease in the wear of tools.

In investigating the effect of $D_{60}$ parameter, as is seen in Figure 15, a similar trend of changes in wear is observed. Investigation of $D_{60}$ parameter is done in the range of 0.150-7.9 mm. First, by increase in $D_{60}$ value up to 3.6 mm, the wear value takes an increasing trend, then by increase of $D_{60}$, the wear trend changes and lower values are recorded for this range. The performed analyses concerning the trend of changes in terms of wear for parameters $D_{10}$ and $D_{30}$ are also true for $D_{60}$. It should be noted that in the presented diagrams and curves, increase in the wear occurs at 10% moisture content and the reason could be found in increase of soil density

Investigating the effect of coefficient of gradation (as is seen Figure 16), it is found that in soils with more than 10% fine grains, by increase of $C_C$ value, the tools wear decreases. For soils with fine grains less than 10%, by increase of $C_C$ value, the wear increases. The soil samples No. 3-6, which have high $C_C$ values in the range of 0.08-1.2 and are accounted as well-graded soils, the highest wear values are observed.

In Figure 17, the effect of uniformity coefficient on the pins wear is shown. As is seen, there is not a strong relationship between the uniformity coefficient and pins wear. However, by increase of parameter $C_u$, the pins wear increases in power function with R-squared in the range of 0.3-0.4. This is due to presence of different sizes of grains in the soil compound with increase of $C_u$ value. In other words, by increase of $C_u$ value, the soil grading includes a wide portion of the grading curve and causes increase of wear.

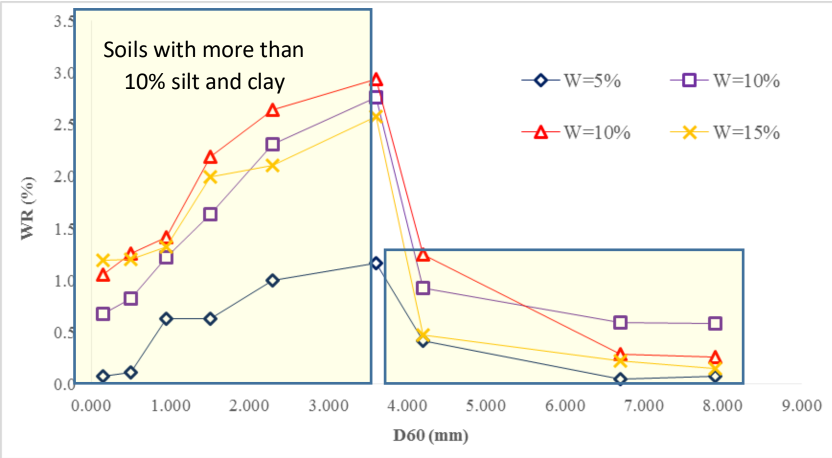
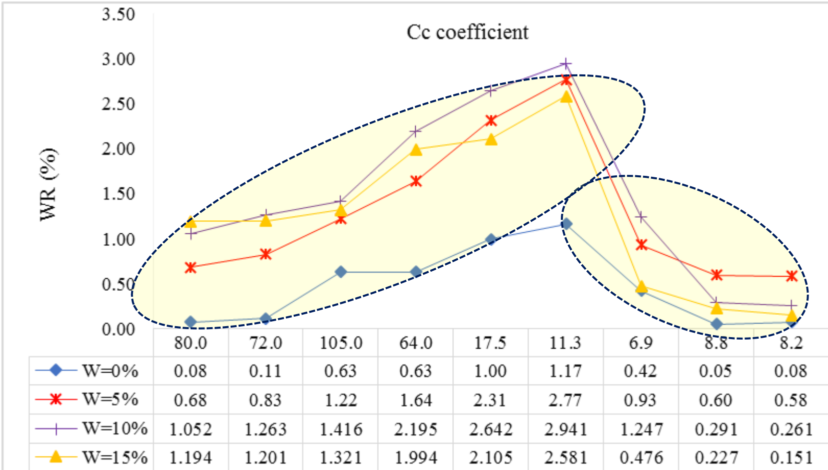



**Figure 15. Correlation of $D_{60}$ and WR.**




| | 80.0 | 72.0 | 105.0 | 64.0 | 17.5 | 11.3 | 6.9 | 8.8 | 8.2 |
|---|---|---|---|---|---|---|---|---|---|
| W=0% | 0.08 | 0.11 | 0.63 | 0.63 | 1.00 | 1.17 | 0.42 | 0.05 | 0.08 |
| W=5% | 0.68 | 0.83 | 1.22 | 1.64 | 2.31 | 2.77 | 0.93 | 0.60 | 0.58 |
| W=10% | 1.052 | 1.263 | 1.416 | 2.195 | 2.642 | 2.941 | 1.247 | 0.291 | 0.261 |
| W=15% | 1.194 | 1.201 | 1.321 | 1.994 | 2.105 | 2.581 | 0.476 | 0.227 | 0.151 |

**Figure 16. Correlation of $C_c$ and WR.**

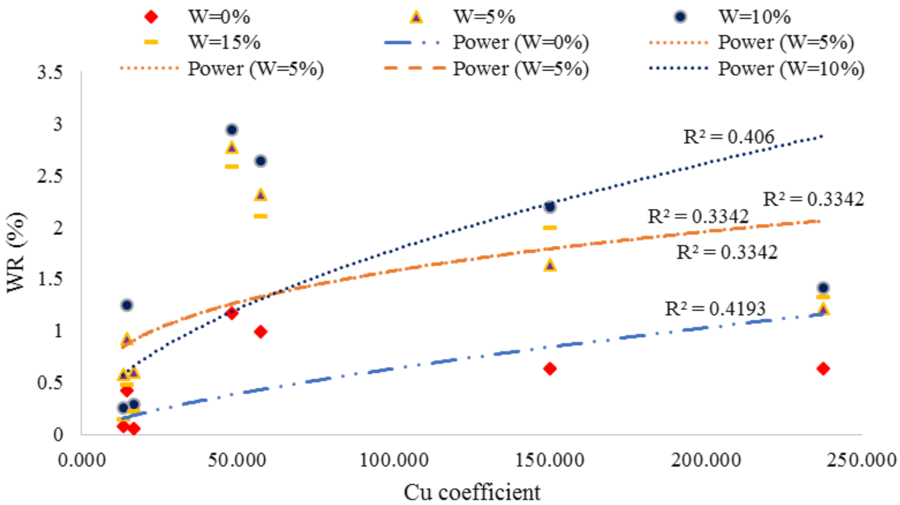



**Figure 17. Relationship between the $C_u$ and wear.**

In investigating the effective size impact on the pins wear, the results show that the mean of pins wear has an increasing trend in the range of 1.047-5.56 mm of effective size changes. By increase in the effective size value up to 9.54 mm, the mean of tools wear decreases. Similar to the $D_{10}$, $D_{30}$, and $D_{60}$ parameters, the results of the tests show the existing relationship between ES value and pins wear for two different groups of soil (Figure 18). The ES parameter in the present study, for soils with fine grains greater than 10%, shows a direct relationship with increase of wear. In soils with less than 10% fine grains, by increase of coarse grains, the wear values decrease. This shows the importance of fine grains percentage of soils in terms of cutting tools wear.

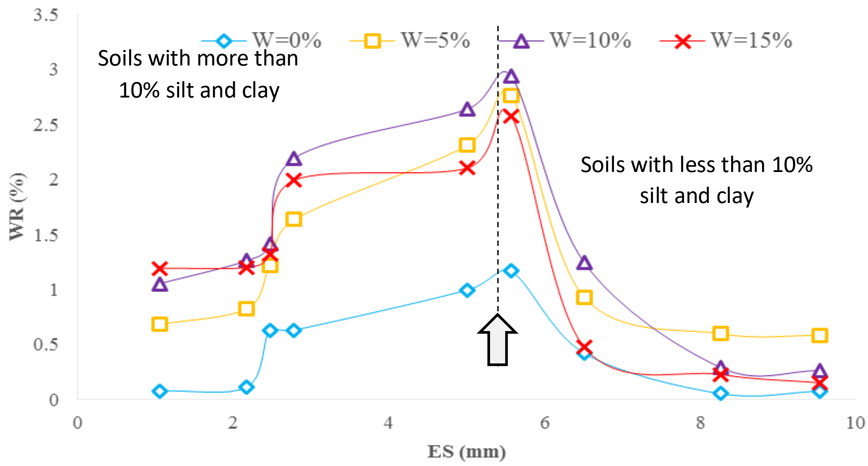



**Figure 18. Relationship between the ES value and wear.**

Investigating the effect of sorting factor, the results show that where the sorting factor value changes in the range of 2.008-7.36, the wear takes an increasing trend. Sorting in fact indicates the uniformity of soil grains in terms of shape and size. By increase of sorting, the irregularity (or multi shapedness) of grains is decreased and grains become more dense along each other. This leads to decrease of the void space between the grains to minimum, and when soil grains encounter the cutting tools, maximum wear occurs. Figure 19 shows the relationship between the sorting factor and pins wear at 0, 5, 10, and 15% moisture contents. As is seen, by increase of sorting factor value, the pins wear increases in power function with a coefficient of correlation value (R-Squared) of 0.3-0.5. It should be noted that the maximum wear corresponds to grading No. 6 at 10% moisture content.

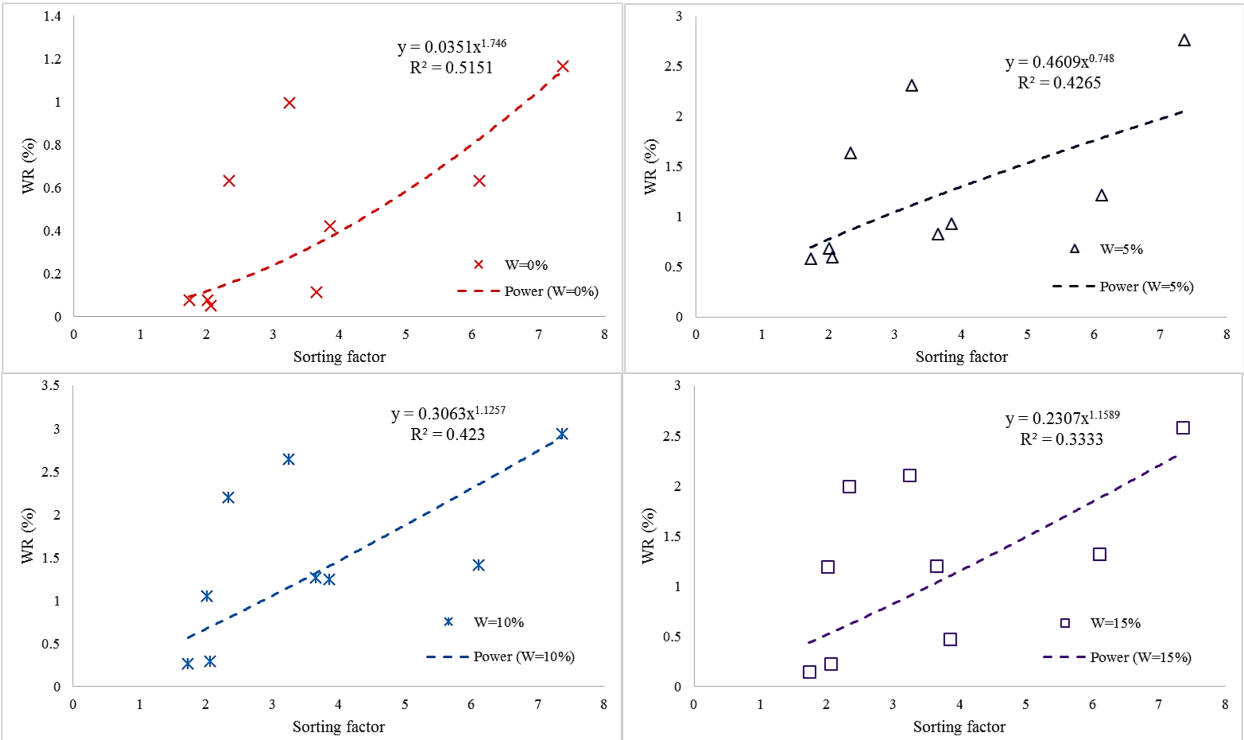



**Figure 19. Effect of soil sorting on the wear at 0, 5, 10, and 15% moisture.**

Investigating the role of grading in tools wear, the results reveal that in absence of the fine grains, the wear decreases. By increase of fine grains in the soil compound, the wear decreases, so that for fine grains less than 10%, maximum wear occurs. Then by increase of the fine grains, the pins wear decreases. The reason for this behavior could be explained in this way that for establishing consistency of coarse grains along each other in a type of soil, there is need for a minimum amount of fine grains, so that these grains could not move easily during encountering the cutting tools. In other words, this statement that amount of wear is higher in coarse grained soils compared to the fine-grained ones is not always true and it depends on various parameters. This issue could also be observed in Figure 20 for the data obtained from Line 7 of Tehran metro project.

In Figure 20, the changes of soil grading parameters such as $D_{50}$ (i.e. 50% of soil grains have a diameter less than this value), $D_{75}$ (i.e. 75% of soil grains have a diameter less than this value), gravel amount (i.e. a portion that passes through the 75 mm (3 inches) sieve and remains on the 4.75 mm sieve (sieve No. 4)) and fine grained portion (i.e. passing percentage through 0.075 mm sieve (sieve No. 200) or called the percentage of silt and clay) against lifetime of cutting tools (m/c: the ratio of excavated distance between two adjacent stations for replacement of tools to the number of consumed cutting tools) are shown.

The results show that $D_{50}$ and $D_{75}$ from chainage 15 + 279 to 18 + 998 are greater than their average value, whereas the lifetime of cutting tool from chainage 16 + 254 to 18 + 988 is greater than that of chainage 12 + 500 to 16 + 254. Also Figure 20 shows that the percentage of grains from chainage 15 + 279 to 18 + 998 is greater than the average value, whereas the percentage of gravel for this distance is reduced to less than the average values. In addition, the results reveal that the lifetime of tools from chainage 16 + 254 to 18 + 998 is greater than their lifetime from chainage 12 + 500 to 16 + 254.

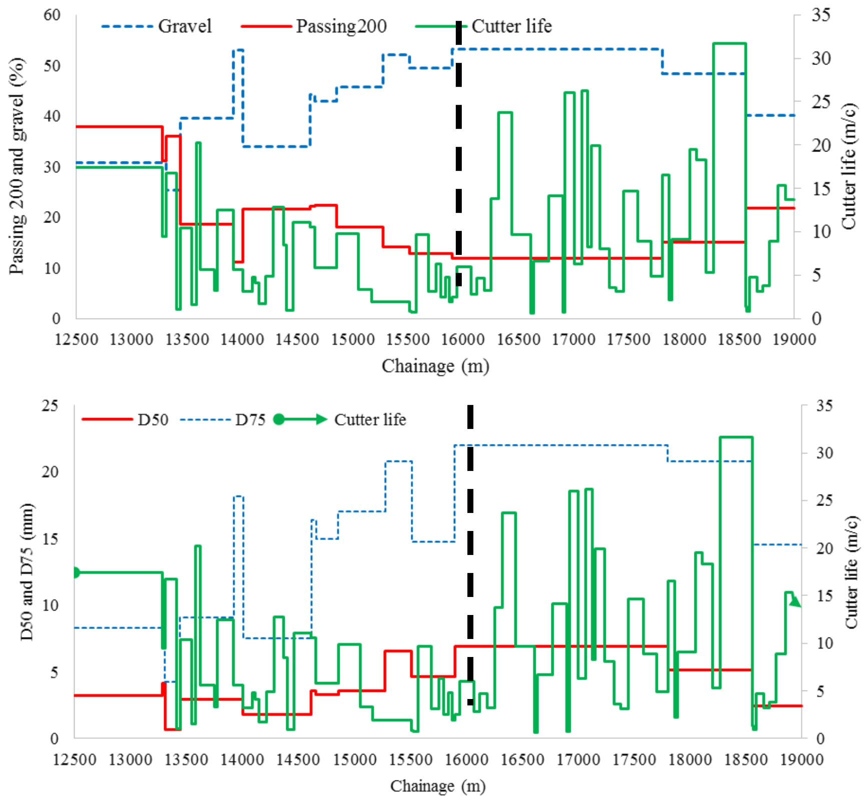



**Figure 20. Variation of grading and cutter life for Tehran metro line 7, a) distribution of gravel and passing 200, b) distribution of D50 and D75.**

As is seen, nearly from chainage 15 + 279 to 18 + 998, the soils located within the tunnel path has become coarser by increasing of gravel percentage, D50% and D75%, whereas the lifetime of cutting tools from chainage 16 + 254 to 18 + 998 is greater than its value from chainage 12 + 500 to 16 + 254. This issue reveals that the lifetime of cutting tools, in addition to dependence upon the grading factors is also dependent on other parameters that have more impact on the lifetime of the cutting tools and their wear.

### 4.2. Effect of moisture content on cutting tools wear

In order to investigate the role of moisture content in wear of cutting tools, the wear tests at 0, 5, 10, and 15% moisture contents were designed and conducted according to conditions explained in previous sections. The obtained results are summarized in Table 5.

**Table 5. Wear values in different moisture contents.**

| | Grading number | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Moisture content (%)** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| **0** | 0.078 | 0.114 | 0.631 | 0.632 | 0.996 | 1.116 | 0.421 | 0.052 | 0.075 |
| **5** | 0.681 | 0.826 | 1.219 | 1.636 | 2.314 | 2.766 | 0.93 | 0.597 | 0.582 |
| **10** | 1.052 | 1.263 | 1.416 | 2.195 | 2.642 | 2.941 | 0.886 | 0.291 | 0.261 |
| **15** | 1.194 | 1.201 | 1.321 | 1.994 | 2.105 | 2.581 | 0.476 | 0.227 | 0.151 |

Also in Figure 21, the mean of pins wear against changes of moisture content is presented. It is observed that all the research works by previous researchers are confirmed in the present study, too [26-29, 33, 31]. However, there are issues that should be taken into account. The selected samples have different percentages of fine and coarse grains. Some of these samples, depending on the amount of fine grains, reach a point at low water contents in which most of the grains are hydrated. As the result of decreased friction between grains, the wear decreases. The results show that, by increase of the percentage of fine grains in the soil structure, the sample reaches this point with delay. For example, in samples No. 1-3 and at 15% moisture content, due to non-hydration of grains, and increase of resistance of fine grains against movement of coarse grains, the tools wear increases. In samples No. 4 to 7 and at 10% moisture content, the grains have approached saturated state and this state has caused change in the sample behavior and decrease of wear at 15% moisture content. In the coarse-grained samples, this state has occurred at 5% moisture content. The reason is due to presence of a lower percentage of fine grains. Generally, the effect of moisture content on wear greatly depends on the size of soil grains and also their percentage of moisture content. Figure 21 shows images from the cutting tools and propeller after conducting the tests.

As the torque of device during excavation has an important role in determining the cost of tunneling projects, changes in the torque of propeller are recorded to investigate the relationship between it and pins wear. Considering the size of grains in each sample, the torque values at different moisture contents, differ. In the grading curves No. 1 and 2, which mainly contain fine grains in their structure, by increase of the moisture content, the apparent cohesion also increases between the fine grains of soil. Consequently, as the result of the cohesion, soil crumbs are formed in the soil structure, and when encountering the pins, cling to the propeller and increase the torque value. Increase of the moisture content percentage in the fine-grained samples causes decrease of friction between the soil grains. Considering the fine-grained nature of samples No. 1 and 2, there is need for high percentages of moisture content to cover the grains and reduce the torque but this issue has not occurred in these samples. In samples No. 3 to 7, the grading curves include both fine and coarse grains. In this case, at first by increase of the moisture content the water particles prevent the rapid separation of grains from pins, which results in increase of torque value. In continuation, due to hydration of soil grains, the torque value decreases. In the soil grading curves No. 8 and 9, considering the low percentage of the fine grains at lower moisture contents, the sample becomes saturated and the torque value decreases. In Figure 22, changes in the torque of propeller together with changes in the mean wear of pins at different moisture contents and soil grading types are depicted.

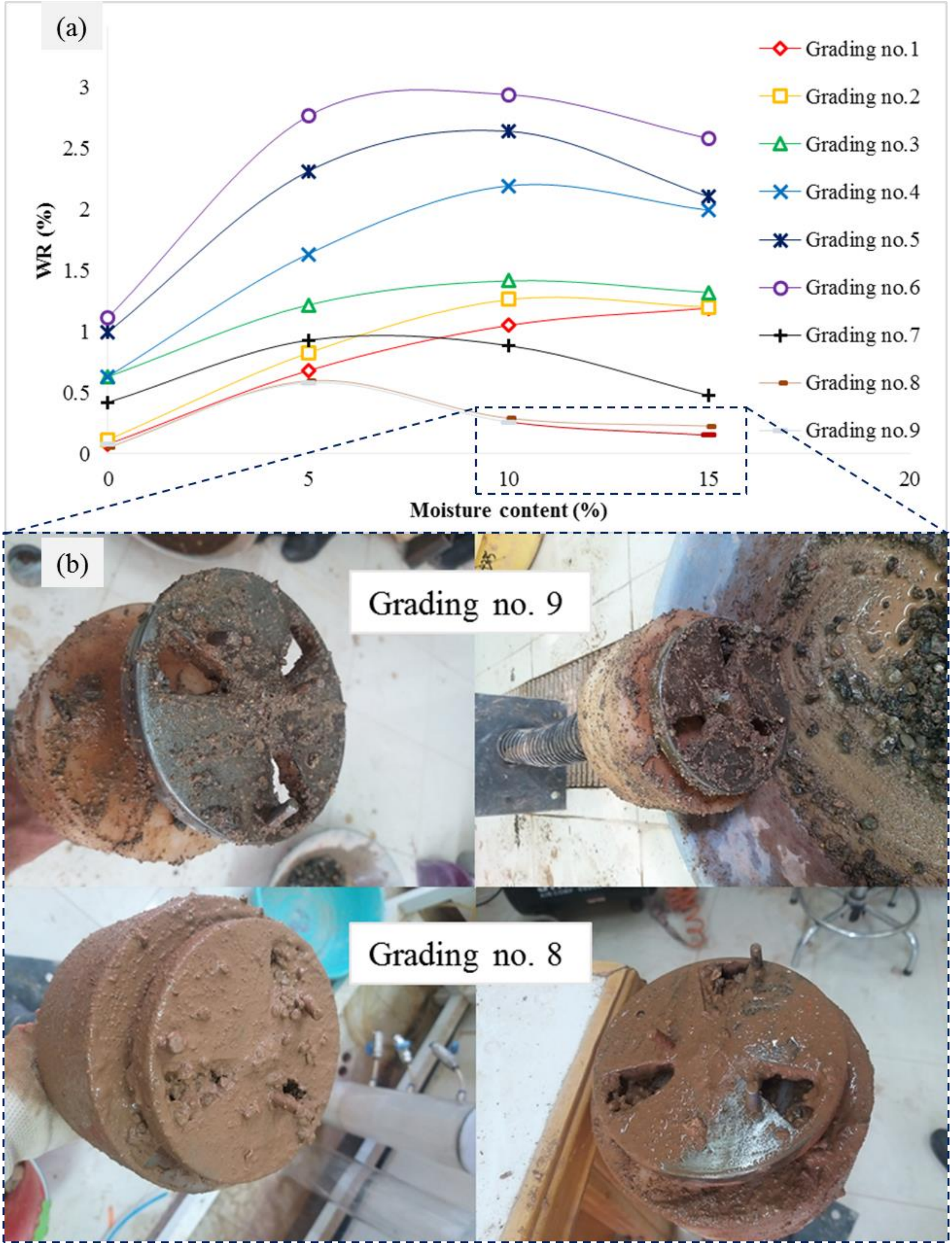



**Figure 21. (a) Relationship between the moisture content values and wear and (b) propeller and cutting tools in grading No. 8 and 9: left) 15% moisture content and right) 10% moisture content.**

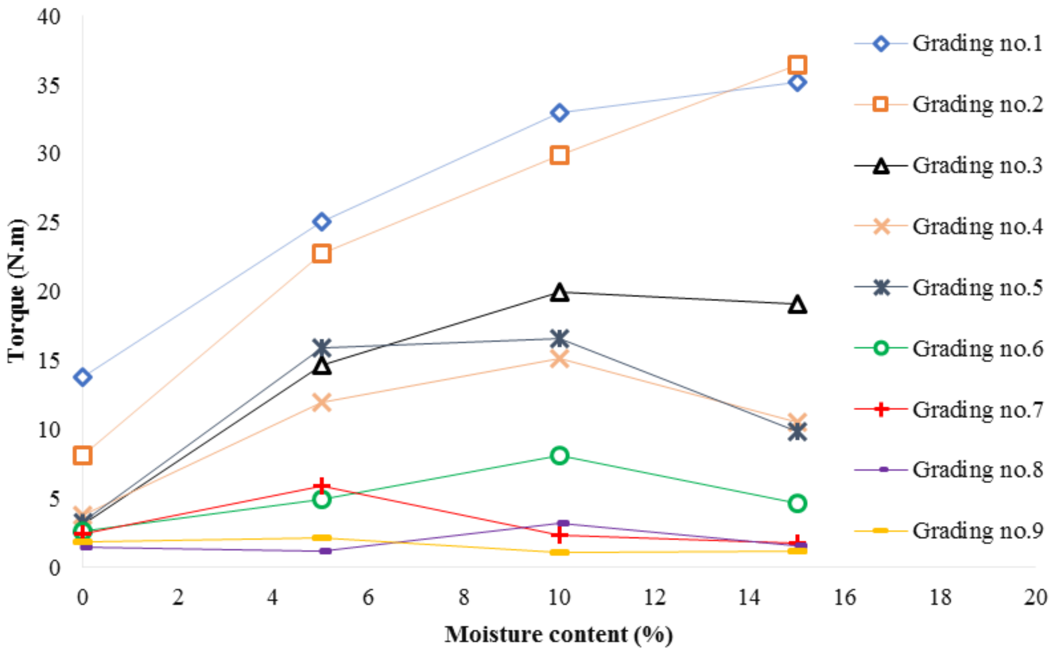



**Figure 22. Relationship between torque and wear of pins.**

The cutterhead torque has the task of rotating the cutterhead for cutting the ground and transfer of excavated materials to the excavation chamber. The cutterhead torque has a direct relationship with the thrust force and is among the factors that its value is not directly determined by the machine operator, but it is a function of other factors.

In order to investigate the effect of cutterhead torque on the lifetime of cutting tools, the values of torque which is recorded over 6500 m length of Line 7 of Tehran metro project, together with changes in the lifetime of cutting tools (in $m^3/c$: i.e. ratio of excavated materials values at each station of tools replacement to the number of consumed cutting tools) are given in Figure 23.

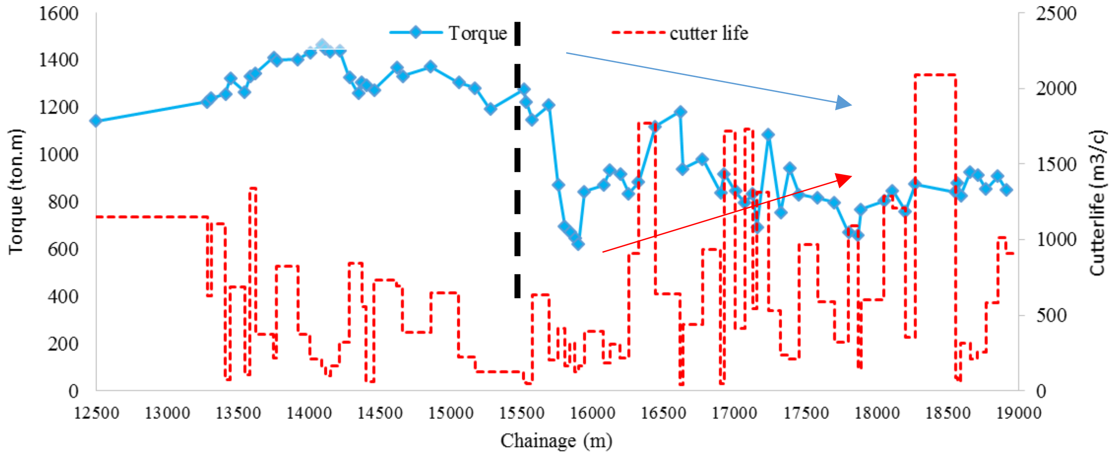



**Figure 23. Variation of torque and cutter life in 6500 m of Tehran metro line 7.**

Investigating the corresponding values of torque in the cutterhead (Figure 23) reveals that its values in the length from chainage 12 + 500 to 15 + 690 are greater than the experienced mean values along the excavated path, whereas the lifetime of cutting tools recorded for this length are less than those obtained for the length from chainage 15 + 690 to 18 + 998. Generally, where the cutterhead encounters a hard excavation front, the amount of excavated materials decreases and thus the thrust force and torque values of cutterhead to reach the required excavation rate increase. This condition results in damage and over usage of cutting tools. As is observed, such conditioned have been experienced in the length from chainage 12 + 500 to 15 + 690 of the projects.

### 4.3. Effect of foam on wear of cutting tools

Determining the type of additives and also estimating the value of important improvement factors such as concentration of foaming solution ($C_f$), foam expansion ratio (FER), and foam injection ratio (FIR) are among the main concerns of designers and manufacturers of mechanized tunnels in earth and soft grounds [64].

In order to investigate the role of foam in the wear of tools, the tests were planed and performed according to conditions given in Table 6 per FIR values of 40, 50, 60, and 70%. Finally, based on the slump of materials, the FIR = 60% was selected for continuation of investigations. In Figure 24, the slum of materials at different FIR values are shown.

**Table 6. Performance parameters and tests characteristics used for investigating the role of foam in wear.**

| Soil No. | Density ($g/cm^3$) | Moisture content (%) | RPM | Penetration rate (mm/min) | Time (min) | $C_f$ (%) | FER |
|---|---|---|---|---|---|---|---|
| 6 | 1.5-2.0 | 0, 5, 10, and 15 | 35 | 4.16 | 60 | 3 | 14 |


**Figure 24. Slum of materials at different FIR values.**

In Table 7 and Figure 25 also the results of pins wear for two states with and without conditioning are given.

As is seen in Figure 25, the corresponding values of wear and torque of cutterhead in the conditioned state with respect to the non-conditioned state are decreased by 58 and 34%, respectively, which are considerable values. It is clear that after adding foam to the soil, the air bubbles reduce the soil density and friction between soil grains and also friction between pins and soil grains is reduced. Consequently, this causes reduction in the tool's temperature and wear.

**Table 7. Wear values of pins in two states of with and without conditioning.**

| | Moisture (%) | | | |
|---|---|---|---|---|
| | 0 | 5 | 10 | 15 |
| **Non-conditioned** | 0.996 | 2.314 | 2.642 | 2.105 |
| **Conditioned** | 0.335 | 0.697 | 1.370 | 1.067 |
| **Changes (%)** | 66.3 | 69.9 | 48.1 | 49.3 |

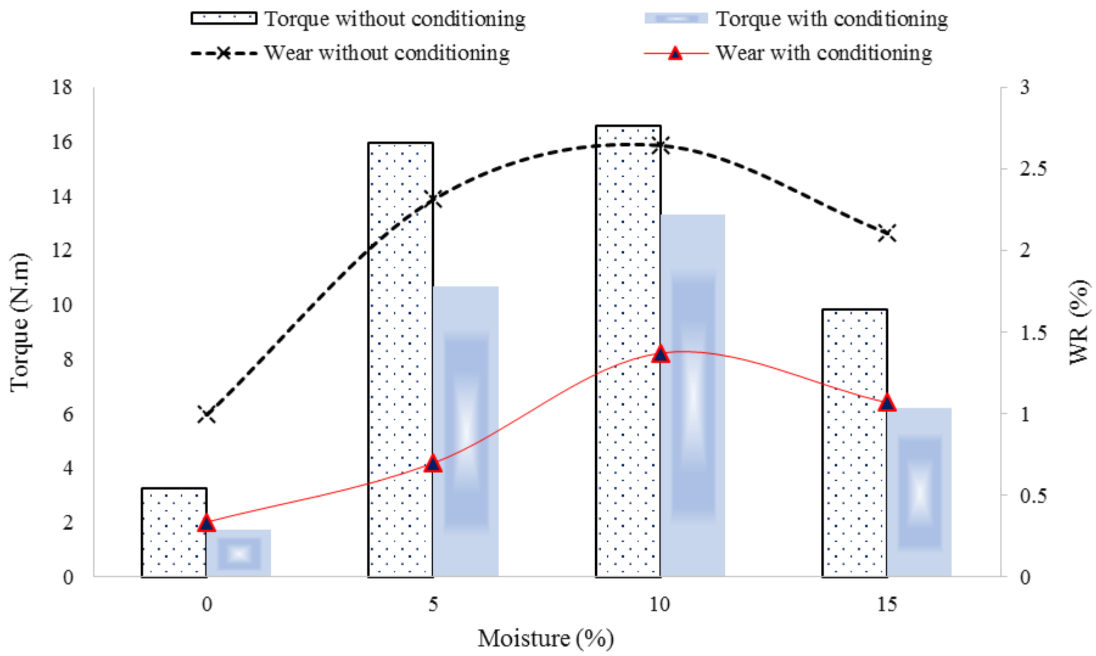



**Figure 25. Relationship between torque and wear in two states of with and without conditioning.**

Generally, for excavation using the TBM, there is need for improvement of soil layers in the tunnel path using different additives (foam, polymer, bentonite, etc.) to control ground hazards and to have a normal trend during excavation. The reason is this fact that a soil is considered ideal for TBM that when entering the excavation chamber turns into a pasty and plastic material with capability of applying pressure on the excavation front, also it should have low permeability to prevent drainage of groundwater and its sealing. Furthermore, it should have low cohesion to prevent clogging of cutterhead and avoid increase of machine torque. A real soil in nature rarely possesses these characteristics. Therefore, for its proportioning to be used in EPB and also control of ground hazards, there is need for materials to be added to soil for conditioning purposes. In order to investigate the effect of foam on wear of cutting tools in real conditions, the values of three parameters; Cf, FER and FIR together with the lifetime of cutting tools (in $m^3/c$) are given over 6500 m length of Line 7 of Tehran metro project in Figure 26.

It is seen in Figure 26 that the FER and FIR values are kept constant along the path length and the percentage of the foaming solution from chainage 12 + 500 to 16 + 254 is about 0.8, whereas from chainage 16 + 254 to 18 + 998, its value has increased by average to 1.2%. It should be noted that the lifetime of cutting tools has increased from chainage 16 + 254 to 18 + 998, and this reveals the strong effect of foam on the lifetime of cutting tools. As the foam expansion ratio and foam injection ratio values are kept constant over the path length, one could conclude that small amounts of foaming solution cause weak conditioning of the soil within the tunnel path, and this leads to increase of cutting tools wear.

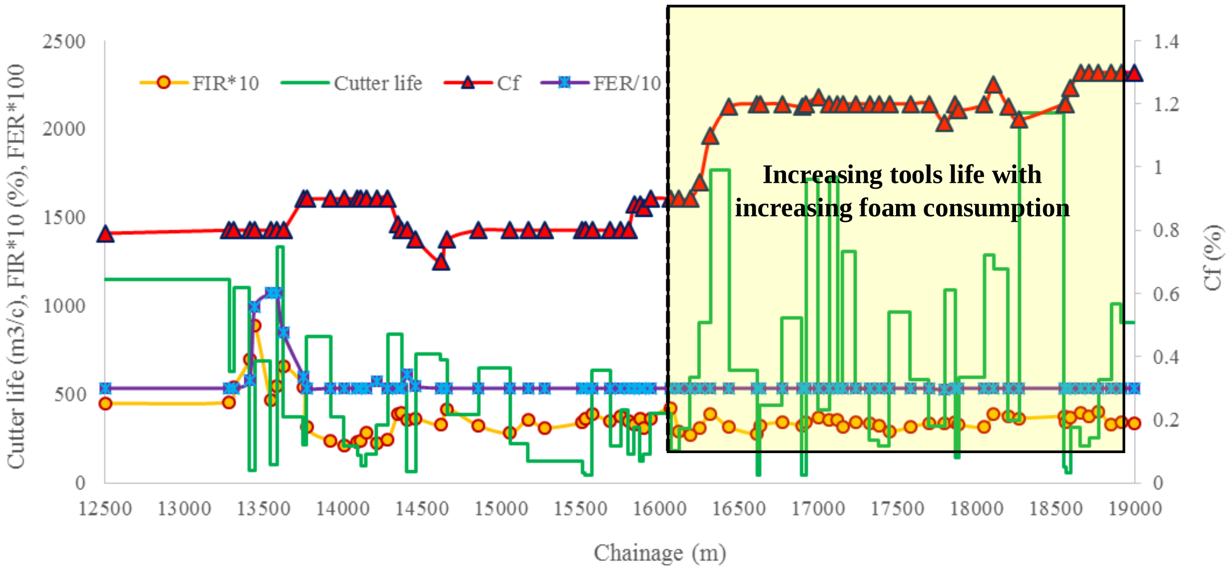



**Figure 26. Variation of tool life and conditioning parameters in Tehran metro line 7.**

## 5. Conclusions

This study attempts to design and manufacture a TBM simulator to better understanding the interaction between soil and cutting tools. The obtained results show that the SSAT has a good capability for simulation of EPBM. In addition, the SSAT device has the capability to investigate the impact of operational parameters such as speed of cutterhead rotation, penetration rate, torque and cutterhead opening, conditioning parameters, etc. on the cutting tools. The obtained results are as follows:

- The results were obtained from the recorded data for Line 7 of Tehran metro project show that despite increase in distribution of soil gradation dimensions along the tunnel path, the lifetime of cutting tools has increased. This issue reveals that the geological factors are only a part of factors affecting on the wear of the cutting tools in soft grounds.
- In the soils with more than 10% fine grains, the wear value increases when $D_{10}$, $D_{30}$, and $D_{60}$ values were increased.
- In soils with more than 10% fine grains, the tools wear decreases when $C_C$ value increase; however, soils with less than 10%, the tools wear increases when the $C_C$ value increases. It should be noted that the highest rates of wear are recorded when there is well-graded soils.
- Despite presence of a strong relationship between the uniformity coefficient and pins wear, the pins wear increases in power function with a coefficient of correlation value in the range of 0.3-0.4, when the $C_u$ parameter value increases.
- When the percentage of the silt and clay in the soil sample exceeds 10%, the tools wear increases by increasing ES. However, when the percentage of the silt and clay in the soil sample is less than 10%, the tools wear decreases by increasing the ES.
- By increasing the moisture content up to a certain value, the pins wear increases, and after that, by increasing moisture content, the tools wear decreases.
- The cutterhead torque is among the factors, which its value is not directly adjusted by the TBM operator. Generally, when the cutterhead of machine encounters to hard face during excavation, the amount of the excavated materials decreases. The required thrust force and cutterhead torque increase to reach the desired excavation rate. These conditions lead to damage and overuse of the cutting tools.
- The results indicate the important and effective role of materials conditioning in terms of cutting tools wear and cutterhead torque. Thus, the values of wear and cutterhead torque in the conditioned state are reduced by average to 58% and 34% compared to the state of unconditioned materials, respectively. This issue is clearly seen in the real conditions, too.

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# سایش ابزار برشی در تونلسازی مکانیزه در زمین‌های نرم: از منظر آزمایشگاهی و میدانی

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**چکیده:**

با توجه به اینکه روش و آزمایش پذیرفته شده و مورد مقبولیت جامعه تونلسازی در زمینه ارزیابی سایش در زمین‌های نرم وجود ندارد؛ هدف از این مطالعه رفع برخی از محدودیت‌ها و کاستی‌های موجود در بحث ارزیابی ساینذگی زمین‌های نرم می‌باشد. از این‌رو در این پژوهش اقدام به معرفی دستگاه ارزیابی ساینذگی دانشگاه صنعتی سهند تبریز با رویکرد شبیه‌سازی شرایط واقعی حفاری مکانیزه با ماشین‌های EPB-TBM در مقیاس آزمایشگاه شده است. در این مقاله پس از مقایسه انواع روش‌ها و آزمایشات معرفی شده در زمینه ارزیابی سایش و ساینذگی، به بررسی تاثیر انواع پارامترهای دانه‌بندی خاک بر روی سایش ابزارهای برشی در شرایط آزمایشگاهی و بر اساس داده‌های واقعی پرداخته شده است. نتایج اولیه مطالعات نشان می‌دهد اگرچه در شرایط واقعی، سایش ابزارهای برشی در خاک‌های درشت‌دانه می‌تواند کمتر از خاک‌های ریزدانه باشد اما در شرایط آزمایشگاهی در خاک‌هایی با ذرات ریزدانه بالای ۱۰ درصد، با افزایش پارامترهای اندازه موثر، $D_{10}$، $D_{30}$ و $D_{60}$ (گویای قطر متناظری از نمودار دانه‌بندی خاک هستند که به ترتیب ۱۰، ۳۰ و ۶۰ درصد ذرات کوچکتر از این مقدار می‌باشند) سایش ابزارها افزایش می‌یابد اما در خاک‌هایی با ذرات ریزدانه زیر ۱۰ درصد، با افزایش پارامترهای مذکور، سایش ابزار کاهش می‌یابد. همچنین نتایج حاکی از وابستگی پارامتر ضریب دانه‌بندی به مقدار سیلت و رس نمونه‌های خاکی می‌باشد. بررسی‌ها نشان می‌دهد با افزایش مقدار پارامتر ضریب یکنواختی، مقادیر سایش پین‌ها به صورت توانی افزایش می‌یابد. نتایج نشان می‌دهد جورشدگی نیز یکی دیگر از معیارهای خوب برای بررسی قدرت ساینذگی خاک می‌باشد. همچنین بررسی ها نشان می دهد با نزدیک شدن رطوبت ساختار خاک به رطوبت بهینه در حالت متراکم، میزان سایش ها افزایش می‌یابند. در انتها نیز نتایج حاکی از نقش مهم و بی بدیع عمل آوری مصالح در مقدار سایش ابزار و گشتاور کله حفار می‌باشد؛ به گونه‌ای که مقادیر سایش و گشتاور کله حفار می‌تواند با عمل‌اوری مناسب مصالح حفاری به طور متوسط به ترتیب ۵۸ و ۳۴ درصد کاهش یابد.

**کلمات کلیدی:** سایش، ابزار برشی، ساینذگی، دانه‌بندی، رطوبت، TBM.