DEVELOPMENT OF A SOIL ABRASION TEST AND ANALYSIS OF IMPACT OF
SOIL PROPERTIES ON TOOL WEAR FOR SOFT-GROUND MECHANIZED
TUNNELING

A Dissertation in
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by

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Primary and secondary wear in soft-ground tunneling using various types of shields has a major impact on machine operation, utilization, and tunneling costs. Wear occurs due to interaction between abrasive soils and cutters, as well as other components of the machine which come into contact with the muck. However, the lack of a standard or universally accepted test for soil abrasivity in geotechnical investigations has made the prediction of tool wear a difficult task.

The primary objective of this thesis was to develop a new test device, specifically designed to simulate the working conditions of soft-ground mechanized tunneling as much as possible and quantify different soil types in terms of abrasivity. The testing system which directly measures the wear on wear plates mounted on a propeller that is submerged in a chamber filled with soil is capable of simulating the high contact stresses between the tool and the soil, maintaining the original soil size distribution, field moisture conditions, and the possibility of applying high ambient pressures as well as soil conditioners.

Several key testing parameters such as soil overburden, pitch angle of the propeller, tool material hardness, moisture content, ambient pressure, particle angularity, grain size distribution, propeller speed, and applied torque to the soil were studied in order to see the impact of these parameters on soil abrasion. The parametric study was performed on various soil samples with known properties including grain size distribution, mineral content, and grain sphericity and roundness. This included high quartz-content Silica sand, Limestone sand, ASTM Graded sand, ASTM 20/30 sand and a sample of Silty sand. Based on the results of the parametric study, which showed the importance of soil particle size and angularity, moisture content, ambient pressure, etc. on soil abrasion, a standard setting for the testing system was selected. The standard setting includes a rotational speed of 60 rpm, a propeller pitch angle of 10°, and cover hardness of 17
In the standard setting, tests were performed at various moisture contents including dry sample, soil with water content dry of optimum compaction, and saturated soil.

By using the standard setting, the Penn State Soil Abrasion Index (PSAI) is developed in order to allow comparisons of the weight loss of covers in the same testing conditions for different soil types. The variation of wear on the cover as a function of time is expressed by using a power function in which \( W = AT^b \), where \( W \) is the wear in grams, \( T \) is time in minutes, and \( A \) and \( b \) are constants defining the shape of the curve.

In addition, a study on the effect of relative hardness on soil abrasion was performed in both dry and moist conditions. In this study, different cover hardness (17-60 HRC) and mixtures of Silica sand and Limestone sand at controlled proportions were used to create variable ratios of tool/mineral hardness. This study confirmed that the anticipated inverted S-curve that is well-known in tribology studies can be generated when the tool hardness is kept constant and material hardness is changed by changing the mixing ratio of abrasive and non-abrasive soils. The change in tool hardness will shift the inverted S-curve, meaning that the absolute value of relative hardness is not the determining factor for wear. Furthermore, the behavior of the tribological system and wear of tools in various soil mixtures will change with the presence of water.

Moreover, the effect of reducing the wear and torque by using soil conditioners is studied by using the testing device. The testing of various soil types by the soil abrasion testing device shows that the application of proper soil conditioning can reduce the abrasion, and hence the wear of the tools and inner parts of the tunneling machine as well as give a significant reduction of the required torque. The magnitude of the reduced wear and torque could be measured in the testing device.

Finally, a comparison was made between the Soil Abrasion Test (SAT) testing system developed by SINTEF/NTNU and the Penn State Soil Abrasion Testing system. This study showed several advantages of the Penn State Soil Abrasion system as compared to the SAT
testing system such as quantifying the abrasivity of the fine-grained soil, non-abrasive material, and impacts of sphericity and roundness of the particles. The PSAI testing offers less operator sensitivity and higher repeatability and consistency of the test results, combination of two- and three-body abrasion as a main wear method, ability to perform tests with different moisture contents and by applying different ambient pressure, and there is no need for a change of grain size and shape of the soil samples during the sample preparation.

The outcome of this study can be used for establishing a framework to assist in quantifying the abrasivity of the soil during the design phase of the mechanized soft-ground tunnels and understanding the key soil properties and operational parameters influencing the wear phenomena in soft-ground mechanized tunneling.
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Chapter 1
Introduction

Introduction and Problem Statement

Mechanized excavation methods have become more or less the standard method of tunneling because of many advantages that they offer over conventional methods. The Tunnel Boring Machine (TBM) is the most common mechanized tunneling machine for excavation of long circular tunnels (typically over 1 km) in variety of geological conditions from soft ground (soil) to hard rocks. These machines are used for construction of tunnels ranging from under 2 m to over 17 m in diameter for various applications from water works and sewers to utility tunnels, metro/subway constructions, and for road/rail transportation. The boring cycle in TBM tunneling involves excavation of the tunnel face, muck removal, installation of ground support, and extension of the utilities. The process is quite efficient and faster than conventional methods, leading to various advance rate records in the past few decades. As such, achieving daily advance rates of 30-40 m in rock tunneling and 15-20 m in soft ground for TBMs with a diameter of about 5-6 m is very typical.

In particular, shielded TBMs have almost become the exclusive tunneling method in soft grounds and soil. A variety of machines have been introduced in the past couple of decades for soft-ground applications. These include the Slurry shield TBMs and Earth Pressure Balance (EPB) TBMs. Home (2010) estimated the total number of TBMS (Slurry and EPB) that are used globally between 2005 and 2010 to be around 350 units (Figure 1-1). While the area of application of these machines, as well as their size, has expanded rapidly, especially in the past
decade, the issues of tool wear and soil abrasion in soft-ground mechanized tunneling have not been fully addressed.

Figure 1-1. Number of EPB and Slurry TBMs used globally between 1990 and 2010 (Home, 2010)

Soil abrasion is an important subject in the excavation of large volumes of soil, but due to the relatively low cost of tool replacement and maintenance in surface applications, it is often overlooked. However, in tunneling and underground construction, the issue of tool wear, tool life and tool replacement can become very crucial since in many cases tool inspection, maintenance, and replacement are done under extremely difficult conditions. In soft-ground tunneling, especially when the ground is unstable, cutterhead inspection and tool maintenance are performed under pressurized conditions or so-called “hyperbaric interventions.” This involves creating a plug at the face, removing the spoils (muck), applying and maintaining compressed air to counter the groundwater and soil pressure, and allowing the crew (divers) into the cutting chamber via an air lock. Often times, if the pressure is above 4-5 bars, the crew needs to be transferred to a decompression chamber and may spend up to a couple of days gradually acclimating back to atmospheric pressure. Even if the pressure is not high enough to require decompression, the conditions at the face can be unstable and thus pose a dangerous work condition that needs to be
carefully monitored. The cost of tools, which is in the range of thousands of dollars, is negligible compared to the cost of downtime, which could amount to several hundred thousand dollars per day. Each intervention could take a couple of days, depending on the condition of the ground and the severity of the damage to the cutters. Consequently, tool inspection and maintenance in soft-ground tunneling are time consuming, dangerous, and costly steps. Yet, there is typically no useful and representative information provided in geotechnical baseline reports (GBR) and geotechnical data reports (GDR) on the soil abrasion for bidding, scheduling and evaluating the tunneling cost. This can be explained as the result of existence of no universally accepted method for quantitative measurement of soil abrasivity for practical or scientific purposes. Therefore, a collaborative effort was needed to develop a new testing system to allow for quantitative and reliable measurement of soil abrasivity for use in the tunneling industry during the design phase and preparation of contract documents as well as the excavation phase of the tunnel. The main reasons for the necessity of such a study included:

1) The demand for underground structures such as metro/subway, road, storage, water/sewer, and utility tunnels in urban areas has been on the rise around the world. Many urban areas are located in soil or weathered rock and that’s because early settlements started close to rivers, seas, and agricultural areas. With the exception of a few labor-intensive tunneling methods, the tunnel structures are mainly bored by using TBMs in challenging geologic conditions. TBM downtime caused by unpredicted tool wear, which requires complete stoppage of the operation for maintenance and replacement purposes, could increase the chance of structural surface settlement significantly.

2) The ability to predict tool wear in pressurized soft-ground tunneling has a direct impact on developing the schedule and cost estimation of tunneling projects.

3) Effective planning for handling primary and secondary wear on the TBMs is a key to the success of the project.
4) The amount of research on the subject of tool wear in soft-ground mechanized tunneling has been very limited.

5) The subject of tool wear and soil abrasion presents a special challenge to many scientific fields and industries beyond tunneling and could open new horizons in various fields of science and technology with specific application in earth moving and more particularly the dire need of the tunneling industry to address this issue.

Scientific Objectives and Intellectual Merit

Despite the widespread use of rock and soil excavation tools, there is no universally accepted method for measurement of soil abrasivity for practical or scientific purposes. In general, what is currently known about the impact of soil composition and ground conditions (pressure, presence of water, etc.) on the interaction between the soil and cutting tools is very limited. The main objective of this study is to develop a test to look into a soil’s physical, mechanical, and tribological properties as it pertains to the interface of the soil and excavation tools. In the practical sense, the main goal of this study is to develop a simple, reliable, and repeatable testing method that simulates the working conditions of the pressurized, shielded TBMs in the field (as much as possible) and quantitatively distinguish different soil types in the case of abrasivity. After finalizing the testing set-up by performing a set of parametric tests, a soil abrasion index will be developed that can be used as a tool to distinguish different soils in the case of abrasivity. In addition, the impact of different soil parameters on tool wear will be studied.

The outcome of this study is establishing a framework to assist designers in the classification of soil abrasive properties. This will provide an extremely useful tool in the GBRs
and GDRs in order to help contractors, owners, and consultants for preparation of bid documents, scheduling, and cost estimation of the soft-ground tunnels.

The need to excavate soil and the science of making the right tools for soil excavation is as old as human society and dates back to the first attempts of the cultivation of plants and farming. The first uses of many of the alloys invented through the course of history have been in ploughshares, to allow better and more effective soil-cutting devices. This has continued to the present day, where soil is excavated in large volumes for various purposes in civil construction, farming, and many other industries. Although the development of hardened steel and subsequently tungsten-carbide tooling in large-scale earth-moving applications has marginalized the need to study tool wear by abrasion, there are many other applications in which tool wear is of significant importance, or even crucial to the success of the tasks at hand. One such case is soft-ground tunneling, especially below the groundwater table. Similarly, with the advance of directional drilling, horizontal-directional drilling (HDD), pipe jacking, micro-tunneling, and ground piercing, these systems have become an integral part of utility installation around the world. As such, a failure of the tool, caused by accelerated wear of the cutters in abrasive soils, can be a costly incident. This illustrates the need for a better understanding of the wear mechanism and development of a reliable testing system for soil abrasivity. Once such a measurement or index is developed, it can lead to:

1) Developing better and more-suitable materials for the cutting tools and wear surfaces.

2) Investigating the effect of soil conditioners and soil additives on preventing excessive wear on the cutting tools in crucial conditions. It can also help in comparing the effectiveness of different types of soil conditioners and different operational settings such as water-to-foaming agent ratio, Foam Injection Ratio (FIR), and Foam Expansion Ratio (FER).

3) Understanding of the tool surface-soil interaction and wear phenomena in a more-detailed and systematic way, and study of the impacts of relative hardness.
Background of Studies on Soil Abrasion

Since the development of the first TBM in hard rock in the 1950’s, many researchers have made an effort to investigate the abrasivity of rock and tool wear in hard-rock TBMs. In contrast, the amount of work for measuring soil abrasivity is quite limited. Due to the need in several pertinent industries, some attention has been paid to the issue of soil abrasivity in the past decade. Related published work in the soil mechanics literature generally focuses on studies of soil-structure interaction and interface friction (Kishida and Uesugi, 1987; Tsubakihara et al., 1993; Frost, 2010; among many others). More recent studies have approached identifying the mechanisms of wear between sands and artificial materials such as high-density polyethylene and stainless steel (Dove et al., 2006). On the other hand, from the tribological viewpoint, the available literature focuses on the surface characteristics of certain components of soil, namely some minerals and their impact on engineered surfaces of tools and the relative friction between the two. Only a few publications have been found that address the issue of soil abrasion, but none in its entirety and complexity.

Methodology

The scope of this research included development of a simple, reliable, and repeatable testing system that can simulate the actual working conditions of soft-ground TBMs and quantify abrasivity of different soil types. After finalizing the testing condition and investigating the impact of different soil properties on soil abrasion, a soil abrasion index was developed. To reach these goals, the following steps of research were followed:

• An extensive literature review on laboratory soil-abrasion testing, rock-abrasion testing, and tool wear in hard-rock and soft-ground TBMs were performed. This
was to identify the main parameters impacting the abrasion phenomena and to review the current knowledge on the subject of abrasivity of minerals and soil.

- Based on the results of the literature review, various concepts for testing of soil abrasion were developed.
- A new testing system that simulates the actual conditions of soft-ground mechanized TBMs was designed and fabricated.
- The new testing system was used to study the impact of different parameters influencing tool wear.
- The results of the testing program were analyzed and a standard testing procedure for measurement of soil abrasion was proposed.
- A soil abrasion index was introduced to be used in geotechnical site investigations to represent soil abrasion.

**Structure of the Thesis**

Chapter 1 is the introduction to the study of wear and its importance for successful completion of a tunnel. The problem statement and the research methodology are also discussed in this chapter.

Chapter 2 addresses the background and literature review on the available rock and soil abrasion testing systems. In addition some examples of practical wear in soft-ground TBMs are discussed at the end of this chapter.

Chapter 3 summarizes a study on the prediction of wear for three different tunneling projects in Seattle, WA. This was done by using the results of X-Ray Diffraction testing and calculation of weighted-average hardness on the soil samples along the tunnel alignment, and discusses the issues related to wear prediction based solely on mineral hardness.
Chapter 4 covers the discussion of various concepts for a new soil-abrasion testing system as well as the results of preliminary testing on a miniature testing device.

Chapter 5 presents the proposed soil-abrasion testing system including the testing device, instrumentation, and the testing procedure.

Chapter 6 contains the results and discussion of the performed parametric study on soil abrasion. This includes the testing parameters and various soil types used in the preliminary testing.

Chapter 7 introduces the final set-up of the testing system in addition to the developed soil abrasion index (PSAI) and the preliminary classification of different soils based on the testing results.

Chapter 8 presents the relationship between relative hardness and wear in dry and moist conditions.

Chapter 9 covers the basic concepts of soil conditioning in EPB tunneling and also presents the study on the effect of soil conditioners on soil abrasion.

Chapter 10 addresses a comparison between the SAT testing system and the proposed soil-abrasion-index testing system introduced in this study.

Finally, Chapter 11 is the summary of the findings of this study followed by recommendations for future work.
Chapter 2

Literature Review on Abrasion

Introduction

Worldwide urbanization calls for more infrastructures in densely populated areas. When the surface is fully utilized, subsurface construction is the most feasible solution. The tunneling industry has improved rapidly since the 1970s and several problems regarding the stability and security of the tunnels have being addressed. The usage of TBMs is becoming more popular in tunneling in various geological conditions because of many advantages that they offer over conventional methods. Table 2-1 summarizes some of the advantages and disadvantages of TBM excavation method.

Table 2-1. Advantages and disadvantages of TBM excavation method (modified from Maidl et al., 2008)

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher advance rate</td>
<td>More geological information needed</td>
</tr>
<tr>
<td>Exact excavation profile</td>
<td>High investment</td>
</tr>
<tr>
<td>Automated and continual work process</td>
<td>Longer lead time for machine designing and manufacturing</td>
</tr>
<tr>
<td>Low personnel expenditure</td>
<td>Specific profile (circular)</td>
</tr>
<tr>
<td>Better working conditions and safety</td>
<td>Limits on curve driving</td>
</tr>
<tr>
<td>Mechanization and automation of the drive</td>
<td>Detailed planning required</td>
</tr>
<tr>
<td></td>
<td>Limits on adaptation to highly variable rock</td>
</tr>
<tr>
<td></td>
<td>Limits on adaptation to high water inflow</td>
</tr>
<tr>
<td></td>
<td>Limits on transportation system</td>
</tr>
</tbody>
</table>

The success of using TBM as a method of excavation in tunneling is strongly dependent to the selected type and design of the TBM, the geological and geotechnical conditions, and experience of contractors. The key to successful TBM performance is to estimate the time and overall costs as close as possible to the real construction stage in the design phase of the tunnel. One of the primary parameters that can significantly impact the cost and schedule of the project is
the tool wear. Poor prediction of the anticipated amount of wear during the project as well as considering inaccurate intervals for cutterhead maintenance during the design phase of the tunnel can cause significant damage to the cutterhead which requires timely repair work. To rectify this problem, the main purpose of this study is to develop a testing system that offer more reliable estimates of tool wear in soft-ground TBMs for project bidding and planning purposes. As part of the literature review of this thesis, an overview is given for classification of TBMs in both hard rock and soft ground and discussion with respect to available experimental tests, models and indices that look into rock and soil abrasivity is offered.

As a prelude to discussion of the soil abrasion testing and measurement system, it is important to understand some of the basic terminologies and machine types in use in the tunneling industry today. TBMs that are the primary choice of mechanical excavation in tunnel construction can be divided into two main groups of open-type machines used in stable rock, and shielded machines used in various ground conditions from joined and faulted rock to soil. The shielded TBMs can be divided into two main groups including open mode and pressurized-face machines. The former shield machines are used in ground where the face is generally stable, and the later is used in the conditions where face is unstable and often under groundwater pressure. Figures 2-1 through 2-3 show various TBM machines used in the industry. Various testing systems have been proposed for measurement of the soil and rock abrasivity and their impact on performance of TBMs which will be discussed in the following section.
Figure 2-1. Open TBM system descriptions (WBI, 2007)

Figure 2-2. Single-shield TBM (The Robbins Company, 2012)
There are few available tests that measure the abrasiveness of the minerals, but they do not consider mechanical properties of the mixtures nor the related other factors including grain size and shape, water, or stress conditions in the rock or in the interface with the tool. Atkinson and Singh (1986) listed the important factors affecting the rock abrasiveness as mineral composition, hardness of mineral constituents, grain shape and size, type of matrix material, and physical properties of the rock including strength, hardness and toughness. In this section several definitions and major rock abrasion tests are described.
Mohs Hardness

To define the hardness, the Mohs hardness scale is most commonly used. The Mohs hardness which quantifies the scratch resistance of minerals (harder mineral on softer mineral) was introduced by Friedrich Mohs in 1812 (All about gemstones, 2012). The scale is divided into ten increments, ranging from talc, with a hardness of 1, as the softest to diamond, with a hardness of 10, as the hardest (Figure 2-4).

Cutter life can be estimated from the relative percentage of minerals of different Mohs hardness classes (>7, 6, 4–5 and <4). This is most commonly determined by petrographic analysis using a microscope, mineral content by X-Ray Diffraction (XRD), and sometimes supplemented by differential thermal analysis (DTA). The higher the percentage of hard minerals found in the rock, the more abrasive the rock, and the shorter the cutter life (Nilsen et al., 2006a, b, c). It should be noted that using Mohs hardness falls short of providing a reasonable basis for evaluation of rock abrasivity and tool wear since it fails to account for many of the parameters.
that reflect the real-life application of excavation tools such as strength and bonding of the grains, moisture content, grain size distribution, grain shape, and material properties.

**Vickers Hardness**

Another test method that is used for estimation of the abrasivity of minerals is Vickers hardness which defines the micro-indentation hardness of a mineral, and provides a Vickers hardness number (VHN). The hardness number is defined as the ratio of the load applied to the indenter, gf, divided by the contact area of the impression, $\mu m^2$. The Vickers indenter is a square based pyramidal diamond with face angles of $136^\circ 0'$ as it is shown in Figure 2-5. Based on ASTM E384 (2011), the Vickers hardness is calculated by using the following formula:

$$HV = 1854.4 \times \frac{P}{d^2}$$  (1)

Where $P$ is the applied force in gf and $d$ is the mean diagonal length of the indentation in $\mu m$.

![Figure 2-5. Vickers test indenter (ASTM E384, 2011)](image-url)
Vickers is best for homogeneous materials, such as minerals, metals, etc., but is not appropriate for a combination of minerals, such as those found in rock. Figure 2-6 shows the schematic principles of Vickers hardness test as well as a Vickers hardness testing device.

Figure 2-6. (a) Schematic principles of operation of Vickers hardness machine (TWI Ltd, 2012) (b) Vickers hardness tester (Qualitest International, Inc, 2012)
Abrasive Mineral Content, AMC

Abrasivity of the minerals in the rock is used widely by researchers as a method of reporting the rock abrasivity. AMC is calculated based on the relative percentage of minerals by using Mohs hardness of the minerals. In order to find the relative percentage of each mineral in the rock sample, microscopic examination of the rock surface or X-Ray Diffraction analysis can be performed.

Equivalent Quartz Content, EQC

EQC is calculated by using the Rosiwal hardness of the minerals by the following formula:

\[ EQC \, (\%) = \sum_{i=1}^{N} \frac{A_i R_i}{120} \]  

(2)

Where:

A= mineral amount (\%)
R= Rosiwal hardness
N= Number of minerals

As it is shown in equation (2) the Rosiwal hardness of each mineral is divided by the Rosiwal hardness of quartz (120). This means that the hardness of all the constituent minerals is compared with the hardness of quartz.

Burbank Test

This test which is designed to estimate the relative abrasiveness of rock on metal parts of mining equipment is displayed in Figure 2-7. An Alloy paddle counter rotates (632 rpm) inside a
drum that contains rock and rotates at 74 rpm. The alloy paddle wears down due to high-speed impact (Burbank, 1995).

![Diagram of Burbank abrasion test](image)

Figure 2-7. Burbank abrasion test (Bond, 1963)

**Dynamic Impact Abrasion Index Test**

This test that is mainly used for transportation of materials by using conveyors was originally developed by Cassapi. Al-Amen and Waller (1992) developed the Dynamic Impact Abrasion Index test (DIAI). In this test, 1000 g of crushed rock is air blown into a duct containing steel shims with 600 Vickers hardness. The weight loss of steel shims after the test is compared to a standard abrasive material (made from artificial corundum) and is calculated as DIAI (Al-Ameen and Waller, 1992). Figure 2-8 shows the schematic drawing of the DIAI.
Modified Schmidt Hammer Test

A modified version of an M-type Schmidt hammer is developed by Janach and Merminod (1982) for abrasion measurement. A hardened-steel indenter with an angle of 45° is attached to the front of the hammer (Figure 2-9). The impact energy for each blow is 30 J. The test is repeated for 20-50 times and the weight loss of the imposed impact energy in mg/KJ is reported as rock abrasivity index.
Modified Taber Abrasivity Test

In this testing system, a 6 millimeter-thick disk prepared from an NX core sample of rock is rotated 400 times under an abrading wheel loaded by a 250-gram dead weight. The abrader weight loss is a measure of rock abrasivity and the inverse of rock weight loss is a measure of the abrasive resistivity of the rock.

Abrasion Resistance Test Subjected to Foot Traffic

This testing Method, ASTM C241(2009), is used for examining the abrasion resistance of different stones used for floors, steps, etc. with respect to foot traffic (Figure 2-10). In this testing, three specimens (50 mm squares with 25 mm thickness) are abraded for 225 revolutions in the testing apparatus with a No. 60 Alundum abrasive. The weight loss of the specimen is measured.
to the nearest 0.01 g. In addition the bulk specific gravity of the testing specimen is measured as well. The abrasion resistance of each specimen is calculated by using the following equation (ASTM C241, 2009):

\[
H_a = 10 G \frac{W_s}{2000 W_a + W_s} \quad (3)
\]

Where:

\( G \) = bulk specific gravity of the sample

\( W_s \) = average weight of the specimen (original weight plus final weight divided by 2), in g

\( W_a \) = Weight loss during the grinding, in g

---

Figure 2-10. Testing apparatus for ASTM C241 (ASTM C241, 2009)
Cerchar Abrasivity Test

The Cerchar test, which is one of the most commonly used tests for rock abrasion, was originally developed in 1970s by the Cerchar Institute in France (Al-Ameen and Waller, 1994 and Alber, 2008). This test is performed by scratching a freshly broken rock surface with a sharp pin of heat-treated alloy steel. The pin has a 90° cone tip and 70 N of load is applied to the rock constantly during the test. The Cerchar Abrasivity Index (CAI) is then calculated as the average diameter of the abraded tip of the steel pin in tenths of a millimeter after 10 millimeters of travel across the rock surface. The advantage of this test is that it can be performed on freshly broken surfaces of rock samples. The CAI value is related directly to cutter life in the field. The CAI values vary between less than 0.5 for soft rocks such as shale and Limestone to more than 5.0 for hard rocks such as quartzite (Plinninger et al., 2003 and Plinninger et al., 2004). Schematic drawing of various testing devices are presented in Figure 2-11.

While the original formal standard of the test was the French standard NF P 94-430-1 (Michalakopoulos et al., 2006), recently an ASTM standard (ASTM D7625, 2010) for Cerchar testing has been issued. Yet the availability of the standard does not preclude the spread in the
test results as has been observed in practice. This is because of some minor variations in the test procedures and the inherent characteristics of the testing concept.

NTNU Rock Drillability Testing System (SINTEF)

This test was developed by the Norwegian University of Science and Technology (NTNU) in 1960. This test is a combination of three tests and indices, one of which is rock abrasion testing as described below.

The Abrasion Values AV/AVS represent the time-dependent abrasion of a tungsten carbide/cutter steel caused by crushed rock powder. The same test equipment as for the AV is used to measure the AVS. The two tests are defined as follows: The Abrasion Value (AV) is the mean value of the measured weight loss in milligrams of 2–4 tungsten carbide test bits after 5 minutes, i.e., 100 revolutions of testing, by using an abrasion apparatus and crushed rock powder (less than 1 mm in size). The AVS test is the same as AV, but with 1 minute, i.e., 20 revolutions of testing and on a hardened-steel wear piece (Nilsen et al., 2006a, b, c). Figure 2-12 shows the schematic of the abrasion testing device (Bruland, 1998) and the fabricated abrasion testing device at Penn State University.
LCPC Test

The LCPC abrasimeter test was developed in France (French Standard AFNOR P18-579, 1990) to test the “abrasivity” and “breakability” of granular material such as crushed rock or synthetically created materials. In this test, rock samples should be crushed and sieved after drying at typically 105 °C (Limestone at <50 °C) to the grain size between 4 to 6.3 mm diameter (Mathier and Gisiger, 2003). A total amount of 500 g of the prepared sample is filled into a steel cylinder at an internal diameter of 93 mm. Within the cylinder a rectangle steel impeller with a dimension of 50x25x5 mm is rotated at 4,500 rpm for 5 minutes. The grain size distribution of the sample before and after the test should be compared (Thuro et al., 2009). The impeller is made of relatively soft steel (Rockwell B 60-75). The abrasion coefficient ABR corresponds to the weight loss of the impeller per ton of sample (Thuro and Plinninger, 2007) and is calculated by using the following formula. This value varies between 0 and over 2000. Figure 2-13 shows the LCPC testing device (Nilsen et al., 2007).

\[
ABR = \frac{(P_0 - P)}{G_o}
\]  

(4)
Where

\[ P_0 = \text{weight of metal impeller before test (g)} \]
\[ P = \text{weight of metal impeller after test (g)} \]
\[ G_0 = \text{weight of sample material (t)} \]

Figure 2-13. The LCPC abrasion test device according to French standard P18-579,1- motor, 2- funnel tube, 3- steel impeller, 4- sample container (Kasling and Thuro, 2010)

**Soil Abrasion Tests**

Many factors influence the soil abrasivity such as in-situ soil conditions (inhomogeneity, density, and porosity), sedimentary conditions (mineral composition, roundness) and mechanical properties (uniaxial compressive strength and abrasivity of the individual grains). To date, there is no universally accepted test or suggested method, nor any national or international standard for soil abrasivity testing (Thuro et al., 2007).
As it was described before, Mohs hardness, Abrasive Mineral Content, Vickers hardness, and Equivalent Quartz Content can be used to measure the abrasiveness of the constituent minerals both for rock and for soils, but it should be noted that the grain size of soil particles is not taken into account (Nilsen et al., 2007). As there are many different parameters affecting tool wear, the use of these four methods is restricted mainly to preliminary estimates of cutter wear. Therefore, these methods are not used directly as input in any TBM performance-prediction models or formulas for estimation of the cutter life in soil and also rock applications. There exist some abrasion model tests for soils such as the Los Angeles Abrasion Test, the Nordic Ball Mill Test, and Dorry’s Abrasion Test which are developed to study the abrasion of aggregates to be used in road pavement works and are explained in the next sections.

**Los Angeles Abrasion Test**

The Los Angeles Abrasion test is used to measure the resistance of aggregates by impact through a rotating cylinder which contains steel balls. This test can be used for both small- (ASTM C131, 2006) and large-size particles (ASTM C535, 2009). Some of the researchers including Rogers (1998) specified that the Los Angeles Abrasion Test measures the impact resistance compared to abrasion. Figure 2-14 shows the schematic drawing of the Los Angeles Abrasion Testing Device. 5000 g of material is required for this test. Grading of the test specimen should be selected based on Table 2-2. The sample and the specified number of steel spheres should be placed in the drum and rotated for 500 revolutions (30-33 rpm). Los Angeles abrasion loss is reported by using the following formula (California Test 211, 1995):

\[
\text{Percent Wear} = \left(\frac{A-B}{A}\right) \times 100
\]

(5)

Where:

A = Mass of original sample
B = Mass of the sample retained on the 1.70-mm sieve after the specified number of revolutions.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Mass for Each Grading, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passing</td>
<td>Retained</td>
</tr>
<tr>
<td>37.5 mm</td>
<td>25.0 mm</td>
</tr>
<tr>
<td>25.0 mm</td>
<td>19.0 mm</td>
</tr>
<tr>
<td>19.0 mm</td>
<td>12.5 mm</td>
</tr>
<tr>
<td>12.5 mm</td>
<td>9.5 mm</td>
</tr>
<tr>
<td>9.5 mm</td>
<td>6.3 mm</td>
</tr>
<tr>
<td>6.3 mm</td>
<td>4.75 mm</td>
</tr>
<tr>
<td>4.75 mm</td>
<td>2.36 mm</td>
</tr>
<tr>
<td>Total Mass</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-14. Schematic drawing of the Los Angeles abrasion testing device (California Test 211, 1995)
Nordic Ball Mill Test

This test, which is close in concept to the Los Angeles abrasion test, is mainly used in Scandinavia to estimate the abrasion resistance of aggregate related to wear of road surface by studded tires. The Nordic abrasion value is defined as the passing percentage of the original sample after 5400 revolutions (with a speed of 90 rpm) through a 2-mm sieve (Jakobsen et al., 2009). Figure 2-15 shows the Nordic Ball Mill Testing device.

![Nordic Ball Mill testing device](Jakobsen et al., 2009)

Dorry's Abrasion Test

This test determines the aggregate resistance to wear due to abrasion. The test is developed for selection of aggregate for road surfacing and describes the textural strength of the aggregate. In this test, the aggregate particles (10-14 mm in size) are mounted on a resin mold and abraded in the testing machine. The weight loss of two specimens that are pushed with an applied force of 3650 Pa opposed to a steel disk rotating for 500 revolutions are reported as the
Aggregate Abrasion Value (AAV), (Harrison and Bloodworth, 1994). Figure 2-16 displays the Dorry’s abrasion testing apparatus.

![Figure 2-16. Dorry’s abrasion testing device (Zeal International, 2012)](image)

In the Los Angeles abrasion test, the Nordic Ball Mill test, and Dorry’s abrasion test, the main target is the grain-grain abrasion and potential for decomposition and degradation of the soil minerals. Therefore, these tests are not valid to look into the wear and abrasion phenomena in soft-ground mechanized tunneling. Plinninger and Restner (2008) have performed an overview of the developed abrasion tests for rock and soil since the 1970s and specified that future test developments on this subject should focus on real-scale set-ups and case studies in order to capture all the important parameters influencing the wear.

As will be described in the following sections, new attempts have been made to develop a soil abrasion test that incorporates these points and mimics conditions of soil in real applications. Currently, there are three different test methods used to determine soil abrasivity for tunneling purposes. They are the NTNU Soil Abrasion Test (SAT), the LCPC test, and the Miller test which was originally designed and used in the petroleum industry. Both the LCPC test and the NTNU
Soil Abrasion tests are modifications of the corresponding rock abrasiveness tests and are currently in their first stages of development and require further improvement for widespread application. In the next section, a general description of each of these tests is presented.

Miller Test

The Miller test was originally developed for the excavation of vertical borings in the petroleum industry but it has been used for Slurry TBMs. The test sample which is the combination of slurry (water or bentonite/water mix) and soil is charged to a rectangular-shape container. The bottom of the container is covered with a sheet of Neoprene to act as a lap. A new sheet is supposed to be used for every test. A constant normal load of 22.24N is applied to a metal block (27% Chrome iron) which is located inside the test sample. The steel block with a reciprocating motion moves through the test sample for 6 hours. The steel block will be weighed before and after the test and the measured weight loss generates the Miller number. Higher weight loss (Miller number) corresponds to the higher abrasivity of the test sample, or the wear. Materials other than the standard metal block can be used in testing as well. In this case, the measured weight loss is called the Slurry Abrasion Response (SAR Number). Figure 2-17 shows the Miller Number machine (ASTM G75, 2007). This test is time consuming and expensive.
New NTNU Soil Abrasion Test

The new NTNU Soil Abrasion Test (SAT) is a further development of the existing NTNU abrasion tests for rock which generates the Abrasion Value – AV/AVS that is described in the rock abrasion testing systems. Compared with the AVS test, only one detail differs in the SAT test: instead of a crushed rock powder <1 mm, a sieved soil sample <4 mm is used. In order to reduce or avoid changes of the original properties, soil samples should be dried gently in a ventilated oven at 300°C for 2–3 days. SAT testing of the sieved fraction can then be carried out according to the same procedures as for AVS testing. The SAT value is calculated as the mean value of the measured weight loss in milligrams (Nilsen et al., 2007). Nilsen et al. (2007) stated

Figure 2-17. (a) Miller Number machine (ASTM G75, 2007) (b) Schematic drawing of the Miller test (http://www.isaf.tu-clausthal.de)
that the test results provide a good basis for comparing the abrasiveness of the respective soils, and by comparing the results with those for rock, useful indications of relative abrasiveness may be obtained. A preliminary classification is recently being generated by Jakobsen and Dahl (2010) by using the results of testing on 210 samples that are from 20 different tunneling projects in 8 different countries. Figure 2-18 shows the distribution of the SAT test results in addition to the preliminary classification.

![Cumulative distribution and classification of SAT values (Jakobsen and Dahl, 2010)](image)

Figure 2-18. Cumulative distribution and classification of SAT values (Jakobsen and Dahl, 2010)

**LCPC Test**

The concept of the LCPC test for soil completely follows the concept of the LCPC test in rock. The only difference is in the process of sample preparation. Two procedures have been stated for sample preparation in order to perform soil abrasivity testing by using the LCPC device (Nilsen et al., 2006, a, b, c).

1- Testing the entire soil sample leads to a representative value for all grain sizes.
2- Testing the fraction of soil sample, e.g. 4-8, 8-16, 16-32, 32-64, and larger than 64 millimeter. Abrasivity values for each fraction can be obtained and the summation of the values according to the grain size distribution leads to an abrasivity value for the entire soil sample.

No matter which procedure is selected, a grain size-distribution analysis should be carried out before separation and crushing of the sample. Without a proper characterization of the soil material, a geotechnical interpretation of the obtained abrasivity values is not possible. In addition to the grain size distribution, a mineralogical and petrologic analysis of the components should be performed.

When using the entire soil sample, the following procedure has proven to be useful: after sieving the entire sample, the grain fraction above 6.3 mm is crushed by a jaw crusher to the point that the whole sample has a grain size below 6.3 mm. The crushed material is mixed with the original fraction of < 6.3 mm material. The roundness of the crushed grains provides an indicator of the original grain size distribution: the larger the original grains are, the more angular are the processed grains and the higher is the abrasivity of the processed soil sample. This is, of course, a basic change of the natural soil composition. Hence, the obtained abrasivity does not necessarily represent that of the original natural soil sample (Nilsen et al., 2006a, b, c). The LCPC Abrasivity Coefficient (LAC) is calculated as the mass loss of the impeller divided by the same mass (500g) and varies between 0 and 2000 g/t for natural soil samples.

**Evaluation of the LCPC and SAT Tests**

As the SAT and LCPC tests are recently used for characterization of soil abrasivity, albeit with different approaches, Table 2-3 is a brief comparison of the results of these two tests and their suitability for measuring soil abrasiveness.
Neither SAT nor LCPC were designed for soft-ground tunneling applications, and consequently there is not enough data on tool wear of various soft-ground tunneling operations using mechanized systems to allow for development of a predictive model for estimation of tool wear based on these tests.

<table>
<thead>
<tr>
<th>Table 2-3. Comparison between SAT and LCPC test (Nilsen et al., 2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAT Test (modified AVS)</strong></td>
</tr>
<tr>
<td>Material to be tested</td>
</tr>
<tr>
<td>Grain size range</td>
</tr>
<tr>
<td>Material of test piece which is subject of abrasion</td>
</tr>
<tr>
<td>Rotation speed within contact surface which is subject of abrasion</td>
</tr>
<tr>
<td>Type of contact causing abrasion on test piece</td>
</tr>
</tbody>
</table>

In the case of tribology, a shortcoming of the SAT method is that the tool wear mechanism according to the test is a three-body abrasion. Due to the nature of the pin-on-disk set-up which creates unconstrained contact geometry, the abrasive gains in soil entering the contact can roll or slide against the pin or the disk and exit the contact area. It is only sliding against the pin that will induce wear on the tool. On the other hand, the actual tool wear mechanism during soft-ground tunneling is a combination of two-body and three-body abrasion wear. Since the typical wear rate in two-body abrasion is much higher than that of three-body abrasion (Harsha and Tewari, 2003), the SAT method is expected to underestimate the tool wear in soft-ground tunneling.

In comparison, the LCPC test uses soft steel, which is for the purpose of getting a tangible loss of weight in the tool by the abrasion process during the test, and thus deviates from the actual conditions in the field. This is due to the impacts of relative hardness and other peripheral conditions on the wear. Also, the rotation speed in the SAT test is close to the rotation speed in TBMs but the LCPC test has a very high rotation speed, which is not comparable to the operational conditions of tunneling or similar excavation machines in soil. Consequently, LCPC
results are not representative of abrasiveness measurements pertinent to soft-ground tunneling since the wear can result from impacts between the impeller and soil grains. Some of the factors in existing methods that are incompatible with the wear mechanism in soft-ground tunneling machines but can have an impact on the abrasion results are as follow:

- The tests are performed in dry conditions, whereas the field conditions are in variable moisture conditions, most often saturated soils.
- In-situ soil conditions, including grain size distribution, are altered during the sample preparation.
- Grain shapes are disturbed during the sample preparation for testing.
- The tool and the soil pressure/contact stress are not comparable between the field conditions and the test conditions.
- Other parameters such as the presence of high ambient water pressure (which could reach up to 17 bars) are not accounted for.
- Both tests are limited by the size of the largest grain that the testing equipment can handle (4 mm and 6.3 mm), but in the field, it is possible to have gravel and cobbles (<300 mm or 12 in).
- Tunnel practitioners often utilize various types of soil conditioners to improve cutting efficiency. The existing tests cannot measure such working conditions and their impact on soil abrasion.

Therefore, a number of important parameters affecting soil abrasivity pertinent to tunneling applications and issues related to tool life are ignored in existing tests. In addition, mechanical properties of soils, such as cohesion, friction angle, compaction, consolidation behavior, and similar factors are not addressed in the current tests. Overall, it can be stated that the existing test methods are not suitable for the evaluation of soil abrasiveness for application in pressurized-face shield TBMs. Due to the expansion in use of mechanical tunneling in soft
ground in recent years, soil abrasiveness and its impact on tunneling projects has become an operational, safety, and contractual issue that needs to be addressed. In the next section, some of the practical issues related to tool wear that are encountered by the tunneling industry are addressed.

**Wear in Soft-Ground TBMs**

Abrasion is the major means of wear that takes place on the cutters, cutterhead, excavation chamber, and conveyance systems of a soft-ground shielded TBM. This is because of the slow turning speed of the cutterhead and thus the cutting tools, and the high contact pressure between the tool (or wear surfaces) and the soil. Figure 2-19 illustrate the wear of different cutters on an EPB cutterhead.

One of the risks often overlooked by engineers and contractors in the tunneling industry is the effect of abrasive soil on the costs and schedule of a given project (Nilsen et al., 2007; Nilsen et al., 2006a, b, c). During the design phase or in the geotechnical baseline reports (GBR), TBM manufacturers could benefit from having access to objective wear characteristics of the ground to be encountered in order to develop a rational approach for TBM component selection and wear protection. It is clear that the ground abrasiveness characteristic is only one of the factors that affect wear. The type of TBM, corresponding operational parameters, the additives used for ground conditioning, the timely maintenance of the machine components, and mucking system are among other important factors.
Wear in mechanized tunneling can be classified into two categories: primary wear and secondary wear. Primary wear refers to the expected wear on the excavation tools and surfaces such as drag bits, disc cutters, scrapers, and shell bits, etc. which are designed for excavation and require ‘‘normal’’ replacement at appropriate intervals (Figure 2-20).
Secondary wear, on the other hand, occurs when soil comes into contact with various components of the machine, particularly when the primary wear on the cutting tools described above is excessive. Secondary wear can lead to wear of the structures designed to hold in place or support the cutting tools, such as the cutting-head spokes or cutter mounting saddles, as well as wear on other surfaces not anticipated by the designers and TBM manufacturers (Nilsen et al., 2007). If primary wear remains undetected, subsequent secondary wear on the cutterhead structure itself can develop rapidly as observed in many tunneling projects using shielded machines. Figure 2-21 is an example of wear on the cutterhead and the gap between the head and the front end of the shield on an EPB machine.

The idea of measuring soil abrasion and developing new methods for predicting tool wear has been discussed recently by researchers and industry due to severe problems encountered in several projects worldwide (Nilsen, 2007; Newby et al., 2008; Langmaack, 2009; Langmaack et al., 2010). This includes the need for frequent tool inspection, maintenance, and repair in a hyperbaric condition which is costly, dangerous and a risky procedure. Severe wear on the cutterhead and cutting chamber has required complete stoppage of the operation for major cutterhead repairs in some projects.

As an example, mining on the two central tunnels of the Brightwater project (BT2 and BT3) was halted in May 2009 due to severe wear damage to the cutterhead on both machines (North American Tunneling Journal, 2011). Although the BT2 machine was repaired and finished its run, the BT3 machine was abandoned in the ground. When the inspection revealed the wear damage on the BT3 machine, it was about 90 m below the City of Lake Forrest Park under 5 bars of pressure. Since the ground was unstable, any repairs to the cutterhead had to be done under a hyperbaric intervention. Working times at these high pressures are restricted and resulted in productive repair time of just three hours per day. Due to the complexity of the repairs, coupled with the limited work time, the estimated costs of repairs were substantial and schedule delays
were significant. This led to the decision of abandoning the plan to fix this machine and deeming it unrecoverable. Figure 2-22 shows the wear pattern on the rear cutterhead rim of both BT2 and BT3 TBMs.

Figure 2-21. Severe secondary wear to the rear of an EPB cutterhead

Figure 2-22. Wear pattern on the rear cutterhead rim of both BT2 and BT3 TBMs.
Another example is the wear on the outside of the cutterhead rim caused by inappropriate gauge-cutter material that resulted in failure and loss of an originally fitted chromium carbide wear plate on the cutterhead rim on the ECIS project in Los Angeles. In this case the cutterhead radius showed a loss of 20 mm of carbide plate in addition to 20 mm of structural wear. Extensive underground repair works were required, delaying the project for several months. Figure 2-23 shows the excessive secondary wear on this project. It is crucial to notice the importance of early detection of primary wear, since undetected primary wear could result in excessive wear on various other parts. This includes carbide inserts of drag bits, pre-cutters, gauge cutters, or the disk-cutter steel ring and body of these tools fitted to the face of cutterhead. Subsequently, secondary wear on the cutterhead structure or TBM shield develops rapidly within the aggressive environments, especially when primary wear is excessive, that can cause significant delays for repair.
Some of the early work on the study of soil abrasion and importance of tool wear for the Brightwater tunnel project in Seattle, WA, goes back to studies by Gwildis et al. (2010), Nilsen et al. (2007), and Nilsen et al. (2006 a, b, c). On the operational side, the papers by Shinouda et al. (2011 and 2009) and Frank et al. (2010) have investigated the practical implications and potential mitigation plans for reducing the operational interruptions due to high soil abrasion and tool wear.
Chapter 3

Wear Prediction Case Studies

Introduction

In this Chapter, the geology and abrasivity properties of the Beacon Hill and Brightwater (BT4) tunnels are compared with the University Link (U230) tunnel project (all three projects are constructed in Seattle, WA). This comparison is based on the detailed wear study of the former two projects in order to predict the amount of wear for the U230 project. In this analysis, X-Ray Diffraction testing results of soil samples from different exploration borings along the tunnel alignment is used to compare the abrasivity of the ground in these projects. The prediction result is then compared to the actual wear measured at the end of tunneling in the northbound tunnel of the U230 project. The next section briefly illustrates the history of tunneling in Seattle as well as the general geology of the area.

Seattle Geology

During the last 10 years, several tunneling projects in Seattle including the Brightwater tunnels, Beacon Hill tunnels, Mercer Street Tunnel, Henderson Way Tunnel and Sound Transit’s U-Link tunnel have been excavated by using pressurized shielded machines. Seattle is located inside the central part of the Puget Sound. The Cascade Mountains on the east and the Olympic Mountains on the west are surrounding this area that has been influenced by repeated cycles of glaciations (at least six) and tectonic activities for more than two million years.

Goetz Troost et al. (2008) have categorized the subsurface of the Seattle area to Vashon glaciation and Pre-Vashon glaciation deposits with numerous unconformities. Distribution of
sediments in this area is quite complicated and that is because each glacial advance influenced and eroded older deposits to some extent and deposited new sediments as well. In the next section, the general description of the projects used in this analysis as well as their geotechnical properties is described.

**Beacon Hill Tunnel Project**

The Beacon Hill contract consists of several portions; the twin-bored tunnels were one of the main sections of this contract. Both tunnels were excavated using an EPB TBM and lined with segmental precast concrete rings that have an internal diameter of 5.74 meters. Midway along the alignment of the tunnels, a station platform was constructed using the Sequential Excavation Method (SEM). The northbound and southbound tunnels west of the station were approximately 543 m and 539 m, and the northbound and southbound tunnels east of the station were approximately 756-m and 779-m long, respectively. The subsurface geology of the twin tunnels was categorized to a complicated combination of overlying Holocene (post-glacial) deposits, Vashon glacial deposits, and Pre-Vashon glacial and non-glacial soils. Six engineering classes were defined for the Beacon Hill tunnel project based on the Geotechnical Baseline Report (GBR). Loose to dense granular deposits (class 1, 2% of tunnel envelope), soft to very stiff clay and silt (class 2, 3% of tunnel envelope), till and till-like deposits (class 3, 27% of tunnel envelope), very dense sand and gravel (class 4, 7% of tunnel envelope), very dense silt and fine sand (class 5, 7% of tunnel envelope), and very stiff to hard clay (class 6, 54% of tunnel envelope). To classify the abrasivity of the different soil classes along the alignment of the Beacon Hill tunnel, X-Ray Diffraction (XRD) analysis was performed in different coring
samples. The GBR defined class 3, class 4, and class 5 as the most abrasive engineering classes along the tunnel alignment (Beacon hill GBR, 2004).

**Brightwater Tunnel Project**

The 21-km-long Brightwater tunnel is the main component of a wastewater treatment system that is being constructed northeast of Seattle. The tunnel has been split into three excavation contracts dividing it into four relatively equal sections each around 6.4-km long. Since the tunnel was bored at depths of up to 145 m, there were no intermediate access shafts within the length of each section. The diameter varied between the sections with the inner diameter between 3.96 to 5.18 m. Excavation on the project was completed in August 2011 when JayDee-Coluccio Joint Venture successfully mined into a gutted TBM shield finishing the last leg of the tunnel. The tunnel was bored using two Earth Pressure Balance machines (EPB) and two Slurry machines.

The data that is used for prediction purposes in this Chapter was collected from the BT4 tunnel that was bored using a Caterpillar (LOVAT) EPBM. The BT4 tunnel was 6,400-m long and was mined by the joint venture of Jay Dee and Coluccio. This tunnel was lined with precast segmental rings having an inner diameter of 3.96 m. Based on the GBR; the geotechnical condition of this tunnel was defined by glacial geology of the Pleistocene era. Four engineering classes were defined for this tunnel: Fine-grained plastic soils (class 1, 65.9% of the tunnel alignment), fine-grained non-plastic soils (class 2, 1.9% of the tunnel alignment), fine to medium sand with varying amounts of gravel, silt and clay (class 3, 16.6% of the tunnel alignment), coarse sand and gravel with varying amounts of fine to medium sand, silt, and clay (class 4, 0% of the tunnel alignment) and combinations of these classes in the face (Brightwater GBR, 2006).
University Link Light Rail (U230) Tunnel Project

The University Link Project consists of approximately 5.1 km of a twin Light Rail Transit tunnel commencing from the north end of the Pine Street Stub Tunnel in downtown Seattle to the University of Washington Station near Husky Stadium. Jay Dee Contractors, Inc., Frank Coluccio Construction Company, and Michels Corporation have formed a Joint Venture (JCM U-LINK, JV) to construct the portion of the tunnels from Capitol Hill Station (CHS) to the Pine Street Stub Tunnel (PSST) which is called contract U230. This contract includes the construction of twin tunnels which are each around 1.2 km in length.

The geologic description of this project can be divided to fluvial deposits, glacial deposits and lacustrine and glacio-lacustrine deposits, all of which have been glacially over-ridden. Engineering classes that are defined for the U230 project based on the GBR are as follow: over-consolidated fine–grained, plastic soils (class 1, 66-70% of the tunnel alignment), over-consolidated fine-grained, non-plastic soils (class 2, 10-14% of the tunnel alignment), over-consolidated fine to coarse sand (class 3, 8-12% of the tunnel alignment), Mixed Face (1 – 8 % of the tunnel alignment), and Controlled Density Fill (CDF) or Ground Improved Zones (5 – 6 % of the tunnel alignment) (U230 GBR, 2009; U220 GBR, 2008).

Prediction of Tool Wear in U230 Project

Despite the fact that the cutter life prediction for hard-rock TBMs has been well understood and developed, the prediction of soft-ground TBM cutter life is a complex task that is still relatively unknown to the tunneling industry. Regardless of all the efforts that are underway for predicting the tool wear during the design and construction phases of soft-ground mechanized tunneling systems, the most reliable analysis and predictions are based on historical data. In this
Chapter, the XRD analysis data from the Beacon Hill and Brightwater tunnels are used in an attempt to predict the wear in the U230 project. The result of this prediction is compared with the actual amount of wear that is recorded at the end of the northbound tunnel of U230 project.

**Beacon Hill Tunnel XRD Data**

A detailed analysis is performed on the XRD testing results from the exploration borings of the Beacon Hill Tunnel. In this study, all the boring data from the same engineering group (reported in the GBR) were combined and finally reported as two quantitative values (weighted-average Mohs Hardness and Equivalent Quartz Content or EQC) for each engineering group. The average of the weighted-average Mohs hardness and EQC from each engineering group was used for the final analysis. Because there were no XRD data available for engineering class 1 and 2, the maximum value of the other engineering groups was used in the analysis. The recorded wear data from the Beacon Hill project was related to the excavation of the northbound tunnel with the total length of 1299 m. In order to compare the Beacon Hill and U230 projects, it was decided to use the length-adjusted weighted-average Mohs hardness and EQC by using the relative length of the alignment for each engineering group along the tunnel (Table 3-1). In this analysis, two quantitative values from each project were used for prediction.
### Table 3-1. Length-adjusted weighted-average Mohs hardness and EQC for Beacon Hill tunnel

<table>
<thead>
<tr>
<th>Engineering group</th>
<th>Relative length of alignment (%)</th>
<th>Length (m)</th>
<th>Weighted-average of Mohs hardness for each eng. group</th>
<th>Weighted-average of EQC (%) for each eng. group</th>
<th>Length-adjusted weighted-average Mohs hardness for the tunnel</th>
<th>Length-adjusted weighted-average EQC (%) for the tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>2</td>
<td>26.0</td>
<td>5.07</td>
<td>54.30</td>
<td>3.82</td>
<td>25.25</td>
</tr>
<tr>
<td>Class 2</td>
<td>3</td>
<td>39.0</td>
<td>5.07</td>
<td>54.30</td>
<td>3.82</td>
<td>25.25</td>
</tr>
<tr>
<td>Class 3</td>
<td>7</td>
<td>90.9</td>
<td>4.37</td>
<td>39.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 4</td>
<td>7</td>
<td>90.9</td>
<td>5.07</td>
<td>54.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 5</td>
<td>27</td>
<td>350.7</td>
<td>4.43</td>
<td>37.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 6</td>
<td>54</td>
<td>701.5</td>
<td>3.17</td>
<td>10.91</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Because of the lack of data, the maximum calculated value from the other engineering groups is assigned to these engineering groups. This was deemed reasonable due to small percentage of these soil types.*

### U230 Tunnel XRD Data

The same procedure for soil abrasion analysis was followed for the University Link project. As mentioned earlier the University Link project consists of 5.1 km of twin tunnels where around 1.2 km of these tunnels was done under the contract U230. The rest of the 5.1 km is under the contract U220. The Geotechnical Baseline Report (GBR) and Geotechnical Data Report (GDR) for these projects were prepared by Northlink Transit Partners (NTP) and are similar to each other. The combination of available XRD data for these two contracts was used for the XRD analysis. The weighted-average Mohs hardness and EQC from each soil group was used for the final analysis (Table 3-2). Please note that because there were no XRD data available for Mixed Face and Controlled Density Fill (CDF), the maximum value of the other engineering groups was used in the analysis.
Table 3-2. Length-adjusted weighted-average Mohs hardness and EQC for U230 tunnel

<table>
<thead>
<tr>
<th>Engineering group</th>
<th>Relative length of alignment (%)</th>
<th>Length (m)</th>
<th>Weighted-average of Mohs hardness for each eng. group</th>
<th>Weighted-average of EQC (%) for each eng. group</th>
<th>Length-adjusted weighted-average Mohs hardness for the tunnel</th>
<th>Length-adjusted weighted-average of EQC (%) for the tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>68</td>
<td>787.4</td>
<td>5.01</td>
<td>34.61</td>
<td>5.32</td>
<td>41.36</td>
</tr>
<tr>
<td>Class 2</td>
<td>12</td>
<td>139.0</td>
<td>5.82</td>
<td>50.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 3</td>
<td>10</td>
<td>115.8</td>
<td>6.08</td>
<td>58.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed Face*</td>
<td>4.5</td>
<td>52.1</td>
<td>6.08</td>
<td>58.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDF*</td>
<td>5.5</td>
<td>63.7</td>
<td>6.08</td>
<td>58.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The maximum calculated value from the other engineering groups is assigned to these groups.

**Tool Wear and Travel Distance**

Tool wear depends on tool travel length which is a function of tool position on the cutterhead and the number of cutterhead revolutions per unit advance. Figure 3-1 displays the cutterhead of a Lovat EPB TBM. As shown on this Figure, the ripper-type cutter located close to the periphery of the cutterhead travels much more than the one close to the center of the cutterhead therefore, it is anticipated to undergo a higher rate of wear compared to the cutter close to the cutterhead center.
Figure 3-1. Picture of CAT (Lovat) EPBM and marked boxes show the relationship between the tool wear and travel distance of cutters

Prediction of Wear on U230 Based on the Beacon Hill Wear Data

Figure 3-2 shows the Beacon Hill cutterhead arrangement. The wear on the cutters were measured at the end of the excavation of the northbound tunnel with the total length of 1299 m. During the excavation, only two Auxiliary cutters were changed (the wear data of these two cutters were not available and are excluded from the analysis).

Table 3-3 shows the type of cutters and their total numbers on the cutterhead. In this analysis only the data from the cutter bits (scrapers) and knife-edge bits (pre-cutting bits) are used for prediction because of the similarity of these cutters to the U230 cutterhead. In addition, only 21 out of 106 cutter bits experienced a low amount of carbide breakage that could be caused due
to encountering larger particles (cobbles and boulders). These data points were excluded from the analysis as well since this study is focused on wear and not breakage.

Figure 3-2. Beacon Hill cutterhead arrangement

<table>
<thead>
<tr>
<th>Cutter Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary Bit</td>
<td>12</td>
</tr>
<tr>
<td>Side Protection Bit</td>
<td>12</td>
</tr>
<tr>
<td>Knife-Edge Bit, replaceable</td>
<td>14</td>
</tr>
<tr>
<td>Knife-Edge Bit, welded</td>
<td>10</td>
</tr>
<tr>
<td>Knife-Edge Bit (W), replaceable</td>
<td>2</td>
</tr>
<tr>
<td>Wear Detection Bit, welded</td>
<td>2</td>
</tr>
<tr>
<td>Cutter Bit, Trim</td>
<td>12</td>
</tr>
<tr>
<td>Cutter Bit (Type I)</td>
<td>24</td>
</tr>
<tr>
<td>Cutter Bit (Type II)</td>
<td>70</td>
</tr>
</tbody>
</table>
The amount of wear for the U230 project is predicted based on the hypothesis that there is a linear relationship between the wear and abrasivity of the ground. Figure 3-3 shows the predicted wear for cutter bits and pre-cutting bits of the U230 project based on the weighted-average Mohs hardness and EQC as well as the actual measured wear at the end of tunneling. The estimated values are based on the wear that has been recorded for the Beacon Hill tunnel, using the Average Mohs hardness and EQC of the two-tunnel alignment.

As displayed on Figure 3-3 (a), there is no correlation between the total traveled distance and the wear of the scrapers that is measured after the excavation of the Beacon Hill Tunnel ($R^2=33\%$). This is because the actual amount of wear experienced in the Beacon Hill project was very low and the precision of measurement was only 5 mm. In contrast, Figure 3-3 (b) shows a reasonable correlation between the wear of the knife-edge bits and the travelled distance of the cutters ($R^2=54\%$). This behavior is expected since knife-edge bits are supposed to primarily cut the ground and therefore they experience higher wear as compared to cutter bits, which are responsible for transferring the excavated material to inside the chamber.

It should be noted that despite the similarity of these two projects in several key parameters, such as geology, the predicted number of boulders along the alignment, shape of the
cutters (Figure 3-4) and operational parameters of the TBM, as it is displayed in Figure 3-3(a), the actual wear of scrapers that was experienced in the U230 project was much higher than the predicted wear. However, the actual wear of knife-edge bits (Figure 3-3 b) and predicted wear was in the same range. This prediction was only based on the abrasivity of the minerals in the soil that was measured by using the XRD analysis and did not include several key parameters which could have a significant effect on wear. This includes grain size distribution, grain shapes, water content, ambient pressure, applied torque to the cutterhead, cutterhead rpm, etc.

Figure 3-4. Cutter bits and knife-edge bits (pre-cutting bits) of (a) Beacon Hill EPB TBM (b) U230 EPB TBM

**Brightwater Tunnel XRD Data, Wear and Analysis**

Based on the GBR, soils to be encountered along the BT4 tunnel alignment were divided into four soil groups which were tagged with colors teal, purple, yellow and red on the geological maps of the project. The exposed BT4 face condition could contain one, two or more soil groups. Based on the GBR and also the paper by Shinouda et al. (2011), the typical face conditions for different locations along the alignment were being categorized. In the mean time, during the excavation of the BT4 tunnel, 11 man-entry inspection stops were made and the wear of specific cutters was measured at each stop. The length of tunneling and the face conditions between each of these inspection stops were studied and, based on the XRD data provided in the GBR, the
length-adjusted weighted-average Mohs hardness and EQC were calculated for each of these sections (Table 3-4).

Table 3-4. Length-adjusted weighted-average Mohs hardness and EQC (%) in tunnel alignment between different inspection stops in Brightwater tunnel

<table>
<thead>
<tr>
<th>Inspection stop</th>
<th>Ring Number</th>
<th>Tunneling length</th>
<th>Length-adjusted weighted-average Mohs hardness</th>
<th>Length-adjusted weighted-average of EQC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>749</td>
<td>1141.5</td>
<td>5.63</td>
<td>47.98</td>
</tr>
<tr>
<td>9</td>
<td>1120</td>
<td>565.4</td>
<td>5.33</td>
<td>40.05</td>
</tr>
<tr>
<td>15</td>
<td>1719</td>
<td>912.9</td>
<td>5.34</td>
<td>39.78</td>
</tr>
<tr>
<td>21</td>
<td>2704</td>
<td>1501.1</td>
<td>5.74</td>
<td>51.14</td>
</tr>
<tr>
<td>22</td>
<td>2747</td>
<td>65.5</td>
<td>5.9</td>
<td>55.40</td>
</tr>
<tr>
<td>24</td>
<td>3041</td>
<td>448.1</td>
<td>5.82</td>
<td>53.01</td>
</tr>
<tr>
<td>29</td>
<td>3482</td>
<td>672.1</td>
<td>5.43</td>
<td>42.61</td>
</tr>
<tr>
<td>31</td>
<td>3681</td>
<td>303.3</td>
<td>5.47</td>
<td>44.04</td>
</tr>
<tr>
<td>33</td>
<td>3905</td>
<td>341.4</td>
<td>5.36</td>
<td>40.96</td>
</tr>
<tr>
<td>35</td>
<td>4002</td>
<td>147.8</td>
<td>5.75</td>
<td>51.43</td>
</tr>
<tr>
<td>End of tunneling</td>
<td>4198</td>
<td>298.7</td>
<td>5.66</td>
<td>48.79</td>
</tr>
</tbody>
</table>

Figure 3-5 shows the average normalized wear ($10^5 \times$wear (mm)/traveled length (m)) of the cutters that were recorded during each inspection stop with respect to the stationing of the tunnel alignment. As shown in this Figure, the alignment was divided into two main sections with respect to abrasivity, non-glacial and glacial deposits. Glacial deposits have caused higher wear on the cutters as compared to non-glacial deposits.

![Normalized wear vs. stationing of the tunnel alignment](image-url)
Figure 3-6 and 3-7 show the length-adjusted weighted-average Mohs hardness and EQC plotted along with normalized wear versus the tunnel alignment.

Comparison between Figures 3-6 and 3-7 shows that the abrasivity of the ground, as defined by EQC or Mohs hardness, can indeed impact the wear phenomena. Because of the
significant shape difference of the cutters between the U230 and Brightwater TBMs (Pre-cutters versus rippers) and also non-uniformity of the Mohs hardness (or EQC) along the alignment, it was not practical to predict the wear in U230 based on the XRD data of the Brightwater project. Figure 3-8 shows the wear in the Brightwater project with respect to the traveled distance of the cutters in glacial and non-glacial deposits.

![Figure 3-8. Wear of cutters vs. travelled distance of (a) Glacial deposits (b) Non-glacial deposits for Brightwater tunnel project](image)

**Discussion**

The results of analysis show that XRD data alone cannot be used as a tool to predict the wear of the cutters and machine components for soft-ground tunneling using mechanical excavators. Now, the question that needs to be addressed is: how can the prediction of wear for soft-ground tunneling projects be improved? This question can be addressed by analyzing the provided information during the design phase of a tunneling project, along with the specification of the EPB and Slurry TBMs that are going to be used for the tunneling, experience of contractors and machine manufacturers, and the operating parameters of TBMs, etc. However, it is essential to have a measurement of soil abrasion that can closely simulate the working conditions of the cutting tools at the excavation chamber of the tunneling machines. As it will be explained in more detail in Chapter 8, the damage to the cutterhead can be classified into three categories: plastic
deformation, breakage, and wear. Plastic deformation and breakage are the main form of cutter damage in grounds with a significant amount of large particles (cobbles and boulders). On the other hand, in abrasive ground with limited number of boulders, wear is the main cause of cutter damage.

To predict damage due to breakage during the design phase of the tunnel, an estimate of the number of boulders to be encountered along the alignment is usually reported in the GBR. The main problem with this prediction is the uncertainty of the provided data with respect to the type of boulders and their strength, their setting, surrounding material, and their location in the face. There have been several studies focusing on providing a reasonable estimate for counting the number of boulders along the alignment of the tunnel (Frank and Chapman, 2001; Theys et al., 2007). Until now there is no accurate method for counting the exact number of boulders encountered along the alignment during mining and comparing it with the provided data in the GBR. Nevertheless, recently a system for counting the number of boulders has been developed and used during the excavation of the U230 northbound tunnel in Seattle, WA, (Walter et al., 2012).

In general during the construction of a tunnel, there are several operational parameters that can significantly influence the wear of the cutters and cutterhead. Among those parameters are managing the penetration rate, cutterhead rpm, selection of the soil conditioner with respect to the ground type, selection of the foam injection ratio (FIR) and foam expansion ratio (FER), cutter type, cutterhead design, and cutterhead torque.

Despite the extensive amount of research and work regarding the wear of the cutterhead and cutters in soft-ground tunneling, it seems that there are many uncertainties that need to be addressed in the future. However, the development of a new soil abrasion testing system to measure the soil abrasivity pertinent to soft-ground tunneling, combined with field data from various tunneling projects, are the initial steps towards development of a reasonable tool-wear
prediction model for this application. Figure 3-9 displays a suggested flowchart that can be implemented for wear prediction purposes.

![Suggested flowchart for wear prediction](image)

As shown in the flowchart, cutter and cutterhead wear is a function of soil abrasion, as well as operational parameters of the machine. As such, wear is not an intrinsic parameter of soil, rather an operational parameter. The wear on the machine components in the same soil can vary drastically by changing the operational parameters including FER, FIR, and face pressure. This even applies to the same machine working at the given site. As such, it would be very difficult, if not impossible, to make predictive models for estimation of the wear, even with the best of soil abrasion measurement systems. Meanwhile, it is anticipated that with sufficient measurements and comparison of the cutter/cutterhead wear with that of the soil abrasion index, it is ultimately possible to develop a prediction model to estimate wear on various machine components. This is based on the assumption that the machine operators will operate the machine at optimum
conditions and apply the best practice in soil conditioning to minimize wear on the machine components.
Chapter 4

Concept Development for Soil Abrasion Testing

Introduction

Based on the performed literature review and the wear case studies, the importance of studying soil abrasion and its impact on soft-ground mechanized tunneling machines is confirmed. The lack of a universally accepted testing system has become a major contractual issue in the tunneling industry. In this Chapter, a preliminary study was conducted to investigate the possibility of using any of the available rock and soil abrasion testing systems as a measure of soil abrasion for application in soft-ground mechanized tunneling. This study is followed by developing a miniature testing device that would be helpful in the design and fabrication of the proposed soil abrasion testing device.

Preliminary Testing

A study on soil abrasion and its impact on soft-ground tunneling equipment was performed at the Pennsylvania State University (PSU) in collaboration with Camp Dresser McKee (CDM), Alavi Gharahbagh et al. (2010). Based on the initial studies and evaluation of available literature, a series of tests were performed to examine the possibility of using any of the existing rock/soil abrasion tests (other than SAT or LCPC tests) as a potential replacement or representative indicator for soil abrasivity and offer a decisive trend or a reliable quantitative measure for soil abrasivity. The main purpose of the preliminary testing was to explore the possibility of using one of the standard tests or a modified version of these tests for quantification of soil abrasivity.
Two categories of tests were considered in the preliminary study. One set of tests consisted of placing a soil sample in a ball-mill test to evaluate particle abrasion on the steel balls. The second group of tests consisted of casting the soil samples in a PVC resin for the Cerchar test and ASTM C241 abrasion testing.

A total of 6 soil samples from the Brightwater Conveyance tunnel project in King County, WA, were selected by CDM staff and sent to PSU for testing. The samples were taken from the TBM muck in various soil groups along the tunnel alignment. Figures 4-1 and 4-2 display the testing apparatus for the modified Cerchar test, ASTM C241 and the Nordic ball mill testing device. The rightmost image in Figure 4-1 enlarges the view of the turn table where the blocks are pressed against the abrader. The table is turned by a sun gear at the top to ensure the entire block surface remains in contact with the abraders. The samples are weighed before and after the test with a scale to the nearest 0.01 g. The weight loss is an indicator of the resistance of the material against wear. Figure 4-2 shows the ball mill used for soil abrasion testing. For this test, the weight of the balls is measured before and after testing using a scale with the precision of 0.001 g. The test is performed for 1 hour with dry samples to maintain uniformity and avoid the impact of the moisture content (for the preliminary phase of the study).

Figure 4-3 shows the samples cast in PVC resin (epoxy). The standard methodology for casting of rock and soil samples for surface microscopic analysis was applied. In addition to 5 samples which were selected for casting in this resin, an additional pure resin block was used as a reference to see the property of the solidified resin and to consider this value in calculations of abrasivity of the soil samples.
Figure 4-1. Picture of the Cerchar testing apparatus (left) and the ASTM C241 testing device (right)

Figure 4-2. Picture of the Ball Mill testing device

Figure 4-3. Picture of the samples cast in PVC resin (epoxy) for testing. The scratch marks on the samples are for Cerchar tests
Results of the testing program are shown in Figure 4-4. The results indicate that the existing rock abrasion testing methods are not directly applicable to measurement of soil abrasivity. Even when some level of modification is implemented to match the properties of the soil, the results do not conclusively indicate a preferred test method for soil abrasion measurements. In addition, there is no correlation between the results from different tests. Obviously, a more detailed and more extensive testing plan could show some correlation between tests. However, even at best, most of the tests considered for this study will not satisfy many of the requirements for simulation of the real working conditions in soil excavation by any of the soft-ground tunneling equipment.

Figure 4-4. Results for various preliminary testing of soil abrasivity
After this stage of analysis, it was concluded that a new approach may be needed to measure soil abrasion. This was followed by development of a miniature testing device and performing a series of tests to examine the possibility of developing a more accurate simulation of soil-tool interaction at the cutterhead of soft-ground machines as will be discussed in the next section.

**Miniature Soil Abrasion Testing**

In order to investigate the possibility of developing a new testing device that measures soil abrasivity related to soft-ground mechanized tunneling, a miniature soil abrasion testing system was developed. This device consisted of a steel ring, a 150-mm diameter by 150-mm long, that was fixed on a drill-press platform as a mixing chamber. Two 125-mm diameter impellers with pitch angles of 10° and 20° were fabricated and used as propelling/mixing impellers. In addition, the testing system was instrumented for measurement of axial force and torque. The axial force was measured by using a scale with up to a 180-kg capacity and simultaneously, the torque was measured with a spring-loaded force meter installed at a 80-mm distance from the center of rotation (Figure 4-5).

Once the system was calibrated, preliminary testing confirmed the accuracy and consistency of the measurements and that the measured parameters are repeatable. Using this miniature testing system, several samples of soil were tested in dry and moist conditions. Gravel, sand, and clay samples with different combinations were obtained and used in the testing to mimic a range of soil types to be encountered in the field. The results of miniature testing yielded several important factors that needed to be considered for the design of the new soil abrasion testing system. This was especially true for calculation of the required torque on a full-scale machine.
Figure 4-5. The miniature testing device

Results of Measurement of Axial Force and Torque on the Miniature Soil Abrasion Testing Machine

The propelling force, the propeller driving torque, and the propeller blade pitch were among the important factors that needed to be addressed in the design of the desired testing system. The push-down or propelling force was defined as the force generated along the axis of
the drive shaft. This push down force represents the pressure between the soil and propeller blades. Another important factor was the amount of torque needed to drive the propeller through the soil as it rotates. Both the propelling force and driving torque were a function of the pitch or the angle of the blade relative to the axis of rotation. A set of tests with different combinations of gravel, sand, and clay in dry and moist conditions were performed, and for each test the amount of axial force and torque were measured. The results of testing are shown in Figures 4-6 and 4-7.

The summary of the results shows a good correlation between the axial force and torque and indicates that the assumption of creating a high force between the soil and the blade in the chamber is realistic and can be controlled by changing the pitch angle of the blade.

In addition to sand and gravel samples, mixtures of gravel and clay, sand and clay, and other combinations were tested under moist conditions. However, the measured amount of force and torque were minimal when clay was present. The presence of the clay material significantly reduced the shear strength of the soil mixture. The water content for the moist samples was subsequently measured. The water content range varied from 10–20%. As it is clear in Figure 4-6, the amount of force and torque in a moist condition was higher than the dry condition tests.
Grain Size Distribution

Choosing an optimum running time for the test was a crucial factor in order to get realistic results because the ultimate goal of testing is to simulate the in-situ working condition of an EPB or Slurry TBM and quantify the impact of soil type on tool wear.

At the face of the machine, excavation tools are in contact with the soil for a limited time, meaning that the soil that comes into contact with these parts passes through and the tools are exposed to new soil on a continuous basis. Therefore, if the grain size distribution of the soil was to be altered in the testing, the test results could be unrealistic and the proposed models unsuccessful in predicting tool wear. Altering soil particle characteristics could potentially influence the abrasion characteristics of the soil if longer durations were to be used in testing. For this purpose, the grain size distribution of the soil before and after testing was measured. In order to measure the optimum processing time for testing, various tests were performed on gravel and sand under both dry and moist conditions with different test durations (3, 5, and 10 minutes). The grain size distribution curves for gravel, sand and clay before and after testing at different durations are shown in Figures 4-8, 4-9, and 4-10, respectively. These results indicate that the larger grain size samples, i.e. gravel, is more sensitive to changes in grain size distribution. Also,
no apparent significant difference in grain size distribution was observed between the dry and moist conditions.

Figure 4-8. Grain size distribution curves for gravel in (a) Dry and (b) Moist condition before and after 3 minutes of testing.

Figure 4-9. Grain size distribution curves for sand with different mixing times in (a) Dry condition and (b) Moist condition.

Figure 4-10. Grain size distribution curves for clay with different mixing times in dry condition.
Grain Shapes

The second potential change of the soil characteristics could be particle shape. Particle shape is as important as particle size in changing the abrasive characteristics of the soil. As particles break, the shape of the particle tends to become more angular. Increasing particle angularity could contribute to increasing abrasivity. One method for quantifying changing particle shape is by measuring sphericity and roundness. Sphericity is the ratio between the surface area of a sphere with equal volume and the surface area of the particle. Roundness is the ratio between the average radius of curvature of the particle surface features and the radius of the maximum sphere that can be inscribed in the particle (Santamarina et al., 2001). Sphericity and roundness of the particles were also examined before and after each test at different grain sizes using Krumbein and Sloss’ (1963) sphericity and roundness chart. Tables 4-1, 4-2, 4-3, and 4-4 show the sphericity and roundness results for sand in dry and moist condition with different processing time.

It was concluded that by increasing the processing time the overall sphericity decreases for most of the sizes under both dry and moist conditions. Also, the results of measuring grain roundness indicated that by increasing the processing time the variation in roundness under dry and moist conditions for most of the size categories was very limited. In addition, the comparison between the samples tested for 3 minutes under dry and moist conditions showed that the moist condition contributes to particle breakage (less sphericity). The results for 5 minutes testing time under moist and dry conditions show little variation in sphericity, thus there was no significant trend in variation of sphericity with time observed in the initial testing. Finally, the comparison between 10 minute test runs under dry and moist conditions showed that the dry condition case resulted in more particle breakage (less sphericity).
Table 4-1. Sphericity of sand in dry condition with different processing time

<table>
<thead>
<tr>
<th>Size</th>
<th>Opening (mm)</th>
<th>Sand sphericity (Dry)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Original sample</td>
</tr>
<tr>
<td>1/4 in</td>
<td>6.35</td>
<td>0.8</td>
</tr>
<tr>
<td>#4</td>
<td>4.75</td>
<td>0.8</td>
</tr>
<tr>
<td>#6</td>
<td>3.35</td>
<td>0.7</td>
</tr>
<tr>
<td>#20</td>
<td>0.85</td>
<td>0.6</td>
</tr>
<tr>
<td>#40</td>
<td>0.425</td>
<td>0.6</td>
</tr>
<tr>
<td>#60</td>
<td>0.25</td>
<td>0.8</td>
</tr>
<tr>
<td>#100</td>
<td>0.15</td>
<td>0.7</td>
</tr>
<tr>
<td>#200</td>
<td>0.075</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 4-2. Sphericity of sand in moist condition with different processing time

<table>
<thead>
<tr>
<th>Size</th>
<th>Opening (mm)</th>
<th>Sand sphericity (moist)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Original sample</td>
</tr>
<tr>
<td>1/4 in</td>
<td>6.35</td>
<td>0.8</td>
</tr>
<tr>
<td>#4</td>
<td>4.75</td>
<td>0.8</td>
</tr>
<tr>
<td>#6</td>
<td>3.35</td>
<td>0.7</td>
</tr>
<tr>
<td>#20</td>
<td>0.85</td>
<td>0.6</td>
</tr>
<tr>
<td>#40</td>
<td>0.425</td>
<td>0.6</td>
</tr>
<tr>
<td>#60</td>
<td>0.25</td>
<td>0.8</td>
</tr>
<tr>
<td>#100</td>
<td>0.15</td>
<td>0.7</td>
</tr>
<tr>
<td>#200</td>
<td>0.075</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 4-3. Roundness of sand in dry condition with different processing time

<table>
<thead>
<tr>
<th>Size</th>
<th>Opening (mm)</th>
<th>Sand roundness (Dry)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Original Sample</td>
</tr>
<tr>
<td>1/4 in</td>
<td>6.35</td>
<td>Rounded</td>
</tr>
<tr>
<td>#4</td>
<td>4.75</td>
<td>Rounded</td>
</tr>
<tr>
<td>#6</td>
<td>3.35</td>
<td>Well Rounded</td>
</tr>
<tr>
<td>#20</td>
<td>0.85</td>
<td>Rounded</td>
</tr>
<tr>
<td>#40</td>
<td>0.425</td>
<td>Rounded</td>
</tr>
<tr>
<td>#60</td>
<td>0.25</td>
<td>Rounded</td>
</tr>
<tr>
<td>#100</td>
<td>0.15</td>
<td>Well Rounded</td>
</tr>
<tr>
<td>#200</td>
<td>0.075</td>
<td>Rounded</td>
</tr>
</tbody>
</table>

Table 4-4. Roundness of sand in moist condition with different processing time

<table>
<thead>
<tr>
<th>Size</th>
<th>Opening (mm)</th>
<th>Sand roundness (moist)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Original sample</td>
</tr>
<tr>
<td>1/4 in</td>
<td>6.35</td>
<td>Rounded</td>
</tr>
<tr>
<td>#4</td>
<td>4.75</td>
<td>Rounded</td>
</tr>
<tr>
<td>#6</td>
<td>3.35</td>
<td>Well Rounded</td>
</tr>
<tr>
<td>#20</td>
<td>0.85</td>
<td>Rounded</td>
</tr>
<tr>
<td>#40</td>
<td>0.425</td>
<td>Rounded</td>
</tr>
<tr>
<td>#60</td>
<td>0.25</td>
<td>Rounded</td>
</tr>
<tr>
<td>#100</td>
<td>0.15</td>
<td>Well Rounded</td>
</tr>
<tr>
<td>#200</td>
<td>0.075</td>
<td>Rounded</td>
</tr>
</tbody>
</table>
The initial results showed that there was not much difference in roundness of the sample grains for different processing conditions, i.e. moist vs. dry. Figure 4-11 shows the graphs of sphericity versus roundness of sand for different processing times under dry and moist conditions.

![Graphs showing sphericity vs. roundness of sand](image)

Figure 4-11. Sphericity vs. roundness of sand with different mixing time in (a) Dry and (b) Moist condition

Tables 4-5 and 4-6 show the sphericity and roundness results for gravel under dry and moist conditions after 3 minutes processing time. The changes in particle shape were so significant for gravel, even after only 3 minutes of testing, that testing at higher processing time was not performed.

**Table 4-5. Sphericity of gravel in dry and moist condition with 3 minutes processing time**

<table>
<thead>
<tr>
<th>Size</th>
<th>Opening (mm)</th>
<th>Gravel sphericity</th>
<th>Original sample</th>
<th>3 min (Dry)</th>
<th>3 min (Moist)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8 in</td>
<td>9.53</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>1/4 in</td>
<td>6.35</td>
<td>0.7</td>
<td>0.7</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>4.75</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td>3.35</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>#20</td>
<td>0.85</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>#40</td>
<td>0.425</td>
<td>0.7</td>
<td>0.6</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>#60</td>
<td>0.25</td>
<td>0.5</td>
<td>-</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>#100</td>
<td>0.15</td>
<td>0.6</td>
<td>0.8</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>#200</td>
<td>0.075</td>
<td>0.7</td>
<td>0.8</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

It was concluded that the moist condition contributes to less particle breakage (less sphericity) than the dry condition, and there was little difference in roundness between moist and
dry condition. Figure 4-12 shows the graph of sphericity versus roundness for gravel after 3 minutes testing under moist and dry conditions.

**Table 4-6. Roundness of gravel in dry and moist condition with 3 minutes processing time**

<table>
<thead>
<tr>
<th>Size</th>
<th>Opening (mm)</th>
<th>Gravel roundness</th>
<th>3 min (Dry)</th>
<th>3 min (Moist)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8 in</td>
<td>9.53</td>
<td>Rounded</td>
<td>Rounded</td>
<td>Rounded</td>
</tr>
<tr>
<td>1/4 in</td>
<td>6.35</td>
<td>Sub-rounded</td>
<td>Rounded</td>
<td>Rounded</td>
</tr>
<tr>
<td>#4</td>
<td>4.75</td>
<td>Sub-rounded</td>
<td>Sub-angular</td>
<td>Rounded</td>
</tr>
<tr>
<td>#6</td>
<td>3.35</td>
<td>Rounded</td>
<td>Rounded</td>
<td>Well Rounded</td>
</tr>
<tr>
<td>#20</td>
<td>0.85</td>
<td>Sub-rounded</td>
<td>Rounded</td>
<td>Rounded</td>
</tr>
<tr>
<td>#40</td>
<td>0.425</td>
<td>Well Rounded</td>
<td>Sub-rounded</td>
<td>Rounded</td>
</tr>
<tr>
<td>#60</td>
<td>0.25</td>
<td>Well Rounded</td>
<td>-</td>
<td>Rounded</td>
</tr>
<tr>
<td>#100</td>
<td>0.15</td>
<td>Rounded</td>
<td>Rounded</td>
<td>Rounded</td>
</tr>
<tr>
<td>#200</td>
<td>0.075</td>
<td>Rounded</td>
<td>Rounded</td>
<td>Rounded</td>
</tr>
</tbody>
</table>

Figure 4-12. Sphericity vs. roundness of gravel with 3 minutes mixing time in dry and moist condition

**Other Observations**

One of the main observations on the miniature testing set-up was that some wear was visible on the blades (Figure 4-13). This observation confirms that it was possible to incur measureable wear during the testing which could be used directly or in conjunction with other parameters to develop a soil abrasion index.
The results of the preliminary study indicated that in order to obtain a realistic soil abrasion index, the testing system must be able to mimic the actual working conditions of the machine components (cutters for primary wear and other surfaces for secondary wear) as they encounter soil layers. This includes the actual soil with the original grain size distributions, soil-metal contact pressure, moist/dry conditions, ambient pressures, and possibly application of soil conditioners or slurry. The initial miniature testing device shows that such conditions can be created in a test chamber and cause measureable wear on steel or other metallic components. Overall obtained results from the miniature testing system helped for the final design of the new soil abrasion testing system which is discussed in the next Chapter.
Chapter 5

Proposed Soil Abrasion Testing System

Penn State Soil Abrasion Testing Device

A unique test device was designed specifically for this study. The device consists of a cylindrical chamber 350 mm in diameter and 450 mm in length (14x18 inch). The chamber dimensions were selected to allow for soils potentially containing large gravel-size particles, to simulate the in-situ conditions of the soil as closely as possible and avoid altering grain size distribution as in some other tests. Figure 5-1 and 5-2 display the testing chamber and its lid, respectively.

Figure 5-1. Schematic drawing and the picture of testing chamber
Figure 5-2. Schematic drawing and picture of the testing chamber’s lid

The chamber is partially filled with the soil sample. The propeller, which is intended to create maximum contact forces with the soil, is attached to a drive shaft and rotates inside the cylindrical chamber. The propeller has three blades with the outer radius of 150 mm that are welded at an angle of 120° on a cylindrical base (Figure 5-3). This leaves an annular space of about 12 mm between the edge of the propeller blades and the walls of the chamber that allows for limited material flow inside the chamber. During the test, the propeller is located 150 mm from the chamber base, covered by 150 mm (6 in) soil on top of the blades. The setting leaves the propellers surrounded by soil on the top and bottom and provides some space for soil to move around if the rheological properties of the soil allow for any such movements.

In order to avoid severe wear on the blades and also allow for more accurate measurement of the weight loss on the tools, the blades are fitted with steel covers (Figure 5-3 b,c). The covers weigh much less than the blades and can be easily removed and weighed using a high-precision scale. These covers provide protection to the blades to minimize the need for frequent fabrication or repair of the propeller assembly, which is costly and time consuming. The covers are weighed before and after each test to determine the weight loss during the test within a given time span. Weight loss is directly affected by soil abrasion, contact stresses, moisture conditions, and the material hardness of the covers.
The whole assembly is mounted on a drill press with a 3,728-W (5-hp) drive unit (Figure 5-4). The drill press allows for various rpm settings down to 60 rpm.

The chamber is constructed as a pressurized chamber having the capability of performing tests under ambient pressures of up to 1000 KPa (10 bars). For this purpose, an intricate flange and seal arrangement was included in the design of the chamber as can be seen in Figure 5-5. The required drive torque for rotation of the propeller is delivered by a 50-mm-diameter steel shaft through a sealed bearing assembly that can react to the anticipated axial and lateral forces. This includes a double-roller bearing with a series of seals on the main shaft and bearing housing as well as a flange mounting system from the underside of the chamber cover or upper lid. This arrangement provides for the most effective protection of the shaft, propellers, and chamber, while maintaining the high ambient pressure inside the chamber.
Figure 5-4. Penn State soil abrasion testing system

Figure 5-5. Schematic drawing and picture of the shaft, flange, and sealing arrangement
Testing Procedure

The soil samples were tested either in a dry state or at a predetermined moisture content. The soils were initially dried in air and then either placed in the chamber directly or brought to the appropriate water content by mixing thoroughly with the correct amount of water prior to the test. Care was taken to ensure that the water was uniformly distributed and mixed with sample prior to being charged into the chamber. For each test, the chamber was filled with approximately 40 kg of soil. This amount of soil is required to fill the chamber to the height of about 300 mm from the bottom. In default configuration, the propeller is positioned with about 150 mm of soil under and 150 mm of soil above the centerline of the blades. The sample is charged into the chamber without any alteration to the soil properties or any additional preparation. This procedure is applied to all of the performed tests.

The chamber assembly is placed on the drill-press platform after loading of the sample and secured on the mounting table using a special clamping arrangement on the lower flange at the bottom of the chamber. The blade covers are labeled and separately weighed before each test using a high-precision scale with a resolution of 0.0001 g. After weighing, the covers are installed on the propeller using two bolts (Figure 5-3c). The propeller which is attached to the bearing assembly and the main drive shaft/lid is then lowered into the chamber to position the propeller within the soil sample. For this purpose, the propellers are rotated in reverse, counter clockwise, until the blades reached the level of 150 mm from the bottom of the chamber and the lid touches the upper flange. The upper lid is then bolted on the flange to seal the chamber (Figure 5-6a, b) using a set of twelve bolts.
Figure 5-6. (a,b) Lowering the propeller and shaft inside the chamber and bolting the lid to the chamber and (c) Assembly raised from the chamber after the test

After each test, the blades are cleaned and covers are removed for measurement of the weight loss. The blade covers can be placed back on the blades for the next set of testing if the wear is minimal and the blade coverage is complete. Figure 5-6c shows the picture of the assembly raised from the chamber.

**Instrumentation of the Testing Device**

**Torque Measurement System**

Torque plays a significant role in wear. Therefore, it is quite important to monitor the torque applied to the soil sample during the test. Two separate systems are utilized in order to measure the applied torque to the soil. They are discussed in the following sections:

**Indirect Measurement System**

A power transducer is installed on the electrical control box of the drill-press drive unit. For each test, the amount of voltage and amperage of the motor is monitored by using this device. The data from the power transducer is recorded by using a computer-based data acquisition
system. The measured torque is back calculated from the performance chart of the electric drive unit. This allows for monitoring the variation of the torque during the test. Figure 5-7 shows the power transducer installed for measuring the torque. The measured torque, by using this method, is not very accurate because of the sensitivity of the system to several parameters such as gearbox of the drill press, peripheral conditions, efficiency of the motor, etc.

![Power Transducer](image)

Figure 5-7. Power transducer installed in the electrical box of the testing device

**Direct Measurement System**

In order to address the shortcomings of the indirect torque measurement system, a direct-measuring system was designed and installed on the testing device. This system contains a 4500 N (~1000 lbs) capacity round turn table with a diameter of 31 mm (~12 inches) that is bolted to the base of the drill press (Figure 5-8a). The chamber is centered and secured on top of the turn table (Figure 5-8b). The turn table allows for the rotation of the chamber during the test. Two arms instrumented by using individual S-shape, 100-kg-capacity load cells are attached to the
chamber in order to measure the applied force for rotation of the chamber and also to secure the chamber from rotation (Figure 5-8c). By considering the clockwise rotation of the propeller during the test, the arm on the left side of the chamber registers compression forces while the arm on the right side of the chamber registers tension forces. The data from two S-shape force meters are monitored by using the computer-based data acquisition system. By considering the distance between the center of propeller inside the chamber and the location of the attached arm to the chamber (22 cm), torque can be calculated.

Figure 5-8. Direct torque measurement system set-up (a) Installed turn table on the base of the testing device (b) Secured chamber by using four rollers (c) S-shape force-meters installed on both sides of the chamber
Pressure Measurement System

For elevated ambient-pressure testing, air pressure is applied to the chamber through a high-pressure hose, and connected to a port mounted on the lid. Air pressure was controlled by a regulator and monitored by a vibrating-wire pressure transducer (Figure 5-9). The pressure transducers are monitored by using a computer data acquisition system.

![Image of pressure regulator and sensor](image.png)

Figure 5-9. Pressure regulator and pressure sensor installed on the testing device for monitoring the applied air pressure for elevated ambient-pressure tests
Chapter 6

Parametric Study of the Soil Abrasion Testing Variables

Testing Variables

To understand the impacts of various testing parameters on soil abrasion, a series of tests were designed and conducted. Test variables for this study include rotational speed of the propeller (rpm), test duration, propeller pitch angle, soil moisture content, hardness of the propeller blade covers, ambient pressure, soil weight, and soil type. These variables are chosen in order to determine the significance of each factor on the wear of the blade covers, hence the abrasive behavior of the soil samples.

To see the impact of time on the weight loss of the covers, each test was stopped at preset time intervals to measure the amount of weight loss experienced by the blade covers. The covers were washed and dried completely before the weight measurement. The time steps used in the testing program were 5, 5, 20, and 30 minutes representing test durations of 5, 10, 30, and 60 minutes.

For a selected series of tests, grain size distribution analysis on the soil samples were performed before and after the tests to evaluate the impact of testing on the soil grains and to assess the extent of crushing of the particles during the test. A corresponding study of the sphericity and roundness of the soil particles was also conducted to allow for comparison of various soil types and the impact of soil abrasion testing on soil particle size and shape. At the end of testing (and if needed, at intermediate stages of tests), a representative sample was selected from the soil material by using a sample splitter. The grain size distribution analysis as well as sphericity and roundness evaluation of the soil samples were conducted on these samples.
A special series of tests with variable height of soil on top of the blade was performed to see the impacts of the overburden weight in test results. The procedures, range of variation of parameters, and the results of these parametric tests will be discussed in following sections.

**Artificial Soil Types Used in the Testing**

In order to investigate the influence of each of the testing variables on the abrasion issue in a systematic way, it was decided to perform a set of parametric studies by using artificial soils so that all the variables could be kept constant except the selected testing parameters of interest during a specific test. The main reason for using the uniform soil samples was to avoid natural variation of the soil samples obtained in the field from various locations. Five types of soils were utilized to conduct the parametric study. This includes Silica sand, Limestone sand, ASTM Graded sand, ASTM 20/30 sand, and a quartz-rich fine-grain soil sample (Silty sand). Selected properties of the soils are listed in Table 6-1.

The grain size distributions of the samples were obtained by sieve analysis, and the mineral composition was determined by performing XRD testing at the Materials Testing Lab at Penn State University or by the available information from the distributor. The friction angles are determined following ASTM D 3080 (2011). The soil specimens were prepared at void ratios similar to those used in the testing chamber. Figure 6-1 shows the grain size distributions of the samples used in the testing program.
<table>
<thead>
<tr>
<th>Property</th>
<th>Soil Type</th>
<th>Silica Sand</th>
<th>Limestone Sand</th>
<th>ASTM Graded Sand</th>
<th>ASTM 20/30 Sand</th>
<th>Silty Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral (Mohs Hardness)</td>
<td></td>
<td>Quartz (7):</td>
<td>Dolomite (3.5): 61.9%</td>
<td>Quartz (7): 99.7%</td>
<td>Quartz (7): 99.7%</td>
<td>Quartz (7): 65%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>97.1%</td>
<td>Calcite (3): 28%</td>
<td>Aluminum Oxide(9):</td>
<td>Aluminum Oxide(9):</td>
<td>Kaolinite (2.5): 15.4%</td>
</tr>
<tr>
<td>Percentage by Mass</td>
<td></td>
<td>Mica (2.5): 7.3%</td>
<td>Orthoclase (6): 0.06%</td>
<td>Iron Oxide (6): 0.02%</td>
<td>Iron Oxide (6): 0.02%</td>
<td>Muscovite (2.5): 6.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5%</td>
<td>Quartz (7): 2.9%</td>
<td>Titanium Dioxide (5.5): 0.01%</td>
<td>Titanium Dioxide (5.5): 0.01%</td>
<td>Metahalloysite (2.5): 5.9%</td>
</tr>
<tr>
<td>USCS Classification</td>
<td></td>
<td>SP</td>
<td>SP</td>
<td>SP</td>
<td>SP</td>
<td>SW-SM</td>
</tr>
<tr>
<td>Friction Angle</td>
<td></td>
<td>40°</td>
<td>62°</td>
<td>26°</td>
<td>32°</td>
<td>13°</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td></td>
<td>2.67</td>
<td>2.75</td>
<td>2.58</td>
<td>2.63</td>
<td>2.62</td>
</tr>
<tr>
<td>Mass Weighted-Average Vickers Hardness</td>
<td></td>
<td>1113</td>
<td>253</td>
<td>1158</td>
<td>1158</td>
<td>633</td>
</tr>
</tbody>
</table>

Figure 6-1. Grain size distribution curve of the samples used in this study
Results and Discussion of Parametric Study

In order to select a consistent setting for the initial soil abrasion tests, examine the performance characteristics of the testing device, and develop the testing parameters that could allow for a close examination of the impact of soil type and working conditions of the soft-ground mechanized TBMs on tool wear, a parametric study is designed and conducted. Table 6-2 shows the range of parameters that were selected for this study. In addition to these parameters, several other parameters such as grain size distribution, sphericity and roundness of the samples before and after the test were measured along with mechanical properties of the soil including friction angle of the samples. Also applied torque was monitored for further analysis. The following sections describe the test results and related analyses for different testing variables.

Table 6-2. Soil abrasion testing parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Silty sand (fine-grained)</td>
</tr>
<tr>
<td></td>
<td>Sand (coarse-grained)</td>
</tr>
<tr>
<td>Grain hardness / mineralogy</td>
<td>Quartzitic - Limestone</td>
</tr>
<tr>
<td>Soil overburden</td>
<td>22-57 kg</td>
</tr>
<tr>
<td>Speed of propeller</td>
<td>60-180 rpm</td>
</tr>
<tr>
<td>Test duration</td>
<td>5, 10, 30, and 60 min</td>
</tr>
<tr>
<td>Pitch angle of the propeller</td>
<td>10°, 20°, 30°</td>
</tr>
<tr>
<td>Pressure of the soil chamber</td>
<td>0-6 bars</td>
</tr>
<tr>
<td>Moisture condition</td>
<td>Dry- moist - saturated</td>
</tr>
<tr>
<td>Material hardness of the steel covers</td>
<td>17, 31, 43 , 51, and 60 Rockwell hardness (HRC)</td>
</tr>
</tbody>
</table>

Effect of Soil Overburden on Abrasion

In order to study the effect of sample size and weight on soil abrasion measurement by the new device, four sets of tests with a 60-rpm rotational speed were performed at atmospheric pressure in dry Silica sand samples by using a 10° pitch-angle propeller. The material hardness used for these tests were 17 Rockwell Hardness (HRC) covers and each of these tests were performed for 15 minutes. In these tests, the amount of soil placed in the chamber was changed.
The variation of sample weight and effectively the depth of soil on top of the propeller blade were found to have a major impact on the wear and weight loss of the covers. The results of testing are presented in Table 6-3 and Figure 6-2.

Table 6-3. Weight loss of 17 HRC covers with respect to material weight in 15 minutes of testing

<table>
<thead>
<tr>
<th>Sample Weight (Kg)</th>
<th>Soil Cover Over the Blade (mm)</th>
<th>Weight Loss (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>50</td>
<td>0.06</td>
</tr>
<tr>
<td>27</td>
<td>100</td>
<td>2.13</td>
</tr>
<tr>
<td>40</td>
<td>150</td>
<td>8.18</td>
</tr>
<tr>
<td>57</td>
<td>200</td>
<td>19.17</td>
</tr>
</tbody>
</table>

Figure 6-2. Weight loss of 17 HRC covers versus material weight after 15 minutes of testing

The main purpose of these tests was to provide sufficient information for the selection of sample volume in the chamber (and cover on the blade) for standard testing. The results indicate that by increasing the material weight (depth of overburden on top of the blade), the amount of weight loss increases significantly. Based on the results of testing, it has been decided to use 40 kg of soil for each test. By using this amount of soil, the chamber is filled up to the height of about 300 mm from the bottom with 150 mm of soil on top of the blade. Obviously, this volume is arbitrary and can be argued but for the time being it is deemed suitable, given the size of the chamber and trying to keep the amount of required sample as small as possible. While increasing the sample size is likely to yield more pronounced measurement of soil abrasion, it should be
noted that in practice, obtaining sufficient samples from geotechnical site investigation could be an issue.

**Effect of Pitch Angle and Applied Load on Abrasion**

Various propeller pitch angles (angle relative to the axis of the drive shaft or alternatively a horizontal plane) were fabricated and examined to evaluate the impact of pitch angle on the contact stresses between the blades and the soil in the chamber. In this study, three different propellers with 10, 20, and 30 degrees pitch angle were designed and manufactured for testing (Figure 6-3).

![Figure 6-3. Picture of the propellers with different pitch angles used for the testing, from left to right: propeller with 30°, 20°, and 10° pitch angle](image)

The tests were performed at 60 rpm in atmospheric pressure, with air-dried and saturated Silica sand samples using covers with 17 and 43HRC hardness. Figure 6-4 shows the results of testing in dry and saturated conditions. In this Figure, the weight loss is the cumulative weight loss of the three covers measured at different time steps (5, 10, 30, 60 minutes into testing). The comparison between 10, 20, and 30 degrees pitch angle propellers shows that the propeller with the 10° pitch angle exhibits the maximum weight loss of the covers both in dry and saturated conditions. This clearly indicates that the 10° pitch angle causes the maximum compression and mutual pressure between the soil grains and propeller blades. While it is possible that other
propeller pitch angles could create higher compression on the soil grains at higher speeds or possibly in other soil types and moisture contents, the difference is deemed convincing enough to continue the testing using the 10° propeller. Therefore this angle is selected for all the follow-up studies and tests which will be discussed hereafter.

Figure 6-4. The effect of propeller pitch angle on the weight loss of the covers in (a) Dry Silica sand using 17HRC covers and (b) Saturated Silica sand using 43 HRC covers

Figure 6-5 shows one of the steel covers used for the 10° pitch angle test before and after the test in the dry Silica sand sample and the related representative contour and surface plots of the removed material from the cover. In other words, the contour plot shows the thickness of the cover before (at 0.4 mm) and after the test as well as the pattern of wear on the cover.
The possibility of changing grain size and shape during the testing and its impact on changing the abrasion characteristics of the soil was examined by a follow-up study of the soil grains. For this purpose, grain size distribution and sphericity and roundness of the soil before and after the testing were studied (Figure 6-6). The results confirmed that after one hour of testing, grain size distribution and sphericity and roundness did not significantly change. A previous study of gravel specimens tested in a miniature testing device showed that the impact of testing on the grains of a coarser soil was more pronounced but not decisively high enough to change their abrasive characteristics (Alavi Gharahbagh et al., 2011).
Figure 6-6. Plots of (a) Grain size distribution curve, and (b) Sphericity and roundness of Silica sand before and after 1 hour of testing in dry condition with 10° pitch angle propeller

The concern over the proposed testing system was that if the soil characteristics and behavior (i.e. grain size distribution and shape) were to change during the test, the results could not represent the abrasion characteristic of the soil in a field condition, as it was discussed in more details in Chapter 4. The analysis of the test results on the initial set of tests in the chamber using a 10° pitch angle propeller showed that the proposed testing system does not alter the soil composition and characteristics in such way to warrant a significant change in its wear behavior.

Effect of Tool Material Hardness on Abrasion

To observe the impact of material type and hardness on wear behavior of soil excavation tools, a series of tests were conducted using blade covers with different hardness. The purpose of these tests were to observe the general trends and also to be able to objectively select tool hardness as a standard hardness that could provide a tangible, reliable, repeatable, and measureable weight loss during the test. Five sets of tests with a 60-rpm rotational speed were performed at atmospheric pressure in dry Silica sand samples. The material hardness used for these tests were 17, 31, 43, 51, and 60 HRC covers. In addition, four sets of tests were performed in Silica sand at 10% water content and saturated condition (W=22.5%). The results of testing in
dry condition are summarized in Figure 6-7 and the results of testing in 10% water content and saturated condition are reported in Figures 6-8 and 6-9, respectively.

Figure 6-7. Weight loss of various hardened covers in different time steps in dry Silica sand sample

Figure 6-8. Weight loss of various hardened covers in different time steps in 10% water content Silica sand sample
Figure 6-9. Weight loss of various hardened covers in different time steps in saturated (W=22.5%) Silica sand sample

From these results one can deduce that the effect of various material hardness on wear heavily depends on the moisture content. While the increased hardness will decrease material loss in dry conditions, under moist conditions, increased hardness resulted in increased wear. In other words, the relationship between tool wear and the surrounding moisture condition seem to be opposite under dry and moist conditions. This is somewhat counterintuitive and needs further investigation, but the obvious conclusion is that the relationship between wear and tool hardness is a function of the working conditions, including mineral composition of soil and water content.

As it can be seen from Figure 6-7, by increasing the hardness from 17 to 60 HRC, the amount of weight loss decreases from 22.55 g to 18.70 g. This is not a significant decrease with respect to the change in hardness. Also, there is little to no change in the amount of weight loss between 17, 31 and 43 HRC covers. A series of analyses was performed to evaluate the results of these tests with respect to the relative hardness of tool and soil to see their compliance with established tribological trends relative to abrasive wear of dissimilar materials as it will be discussed later on.
**Effect of Moisture Content on Abrasion**

It is well known that moisture content and the presence of water changes soil abrasion characteristics and tribology of soil grain-metal part interactions. Many contractors and machine manufacturers have observed this phenomenon in the field where the presence of water at the face typically (not always) increases the wear on various machine parts. This could be due to many reasons, including the cohesion between the soil particles in finer soils that could create a matrix to hold larger and more abrasive grains, changes in mechanical properties of the soil, and finally increased ductility of the medium, meaning that ridges easily build up between the cutters at the face and rub against the face plate. The other issues are related to soil particles sticking to various parts of the cutterhead and cutting chamber, thus restricting the flow. Soil compaction could also result in a relatively strong sedimentation (deposition) in parts of the cutterhead and cutting chamber.

No comprehensive investigation has been conducted to investigate this phenomenon in the past. To evaluate the effect of water content on tool wear, tests were conducted using steel covers with Rockwell Hardness of 17, 31, 43, and 51 in Silica sand samples with water content $W = 0\%$ (i.e., dry condition), $W = 10\%$, and $W = 22.5\%$. The results of these tests are shown in Figures 6-7, 6-8, and 6-9. For all the samples tested at $W = 22.5\%$, a thin layer of free standing water with a thickness of up to 10 mm was observed after mixing was stopped. At this water content, therefore, the samples were slightly submerged.

The comparison of the testing results in Figures 6-7, 6-8, and 6-9 indicates that the samples with $W = 10\%$ produced higher weight loss of the covers in 10 minutes than the dry samples in 60 minutes; whereas the samples with $W = 22.5\%$ produced substantially less weight loss than the dry samples in 60 minutes of testing. These results demonstrate that the water content plays an important role in tool wear.
When the impact of moisture on wear on various tool hardness is analyzed, the trend of the results appears to be in reverse in that the material with higher Rockwell hardness experienced slightly higher wear than those with lower hardness under moist conditions. This contradicts the common belief that increasing hardness will always increase wear life of tools.

In order to investigate the effect of water content on tool wear more systematically, a set of tests with \( W = 7.5\%, 10\%, 12.5\%, 15\%, 17.5\%, \) and 22.5\% were performed in the Silica sand samples using 17 HRC covers for 5 minutes. The results of these tests are shown in Figure 6-10.

![Figure 6-10. Weight loss of covers (17 HRC) in Silica sand samples after 5 minutes of testing with different water contents](image)

As it can be observed, the amount of weight loss increases significantly to an apparent maximum as the water content increases from \( W = 0\% \) (i.e., dry condition) to approximately \( W = 7.5\% \). But as the water content continues to increase beyond 7.5\%, the measured weight loss decreases. This trend continues until the sample is slightly submerged (i.e., \( W = 22.5\% \)), which yields a weight loss less than that of the dry sample.

Due to the pitch angle, high torque was required to drive the propeller to rotate clockwise in the sand samples. The grains of sand seem to undergo dynamic compaction under the propeller. Compaction tests on the Silica sand were conducted to investigate the relationship
between water content and dry density to explain the trend observed in Figure 6-10. The results of these tests, as shown in Figure 6-11, indicate that the optimum water contents for the standard Proctor test (ASTM D698, 2012) and the modified Proctor test (ASTM D1557, 2012) are 12.6% and 10.5%, respectively.

![Figure 6-11. Results of compaction tests of Silica sand](image)

As shown in Figure 6-10, the water content corresponding to the maximum cover wear (17 HRC) is approximately 7.5%, which is lower than the optimum water contents shown in Figure 6-11. In light of these test results, several mechanisms emerge to explain the trend observed in Figure 6-10. According to the theory of soil compaction, the compacted dry density increases with water content up to the optimum water content (i.e., dry of optimum), primarily due to water acting as a lubricant and facilitating particle rearrangement. During the soil abrasion tests, as water content initially increases from dry condition, the sand below the propeller was compacted to a higher density by the clockwise rotation of the propeller. This push-down motion of the propeller resulted in higher shear strength and stiffness of the particle assemblage below the propeller. The increase in strength and stiffness increases the frictional resistance and contact pressure on the covers as they rotate in the soil sample, resulting in more wear of the cover.
The decrease of cover wear as the water content increases beyond 7.5% can be attributed to several mechanisms. First, as water content continues to increase, water starts to replace soil particles and the sand below the propeller is compacted to a lower density, resulting in lower shear strength and stiffness. The decrease in strength and stiffness reduces the frictional resistance and contact pressure on the covers as they rotate in the soil samples, resulting in less cover wear. Second, the lubrication induced by water reduces the interface friction between the sand particles and the covers. Third, the lubrication also reduces the friction between sand particles, resulting in less frictional resistance and contact pressure on the covers as they rotate in the chamber. These mechanisms ultimately result in less cover wear. Although not tested in this study, it is anticipated that as the water content increases beyond 22.5%, cover wear could further decrease as individual sand particles become suspended within the flow of sand-water mixture driven by the propeller. The compaction energy imposed by the propeller to the soil is unknown; therefore, the exact reason for the maximum cover wear occurring at water content lower than the optimum water contents from the standard and modified Proctor tests is unknown.

These measurements demonstrate the importance of water content on tool wear, which is not considered in other soil abrasion testing systems (e.g., SAT and LCPC). The relationship between water content and tool wear is a valuable finding because during the excavation of a tunnel, water content of the excavated soil can be measured/monitored. If the water content at the face of an excavation is close to the critical value, corresponding to the maximum tool wear for the specific soil, extra water can be injected to the face (if the condition of the face allows) to increase the water content and significantly decrease the amount of abrasion and wear on the cutting tools.
Effect of Ambient Pressure on Abrasion

To address the issue of tool wear under high ambient pressure on a laboratory scale, a series of 12 tests were performed at 0, 3.1, and 6.2 bars pressure on 17, 31, 43, 51 HRC covers. The results of testing are summarized in Figures 6-12 to 6-15.

Figure 6-12. Weight loss of 17 HRC covers in saturated Silica sand sample with different applied pressure

Figure 6-13. Weight loss of 31 HRC covers in saturated Silica sand sample with different applied pressure
Figure 6-14. Weight loss of 43 HRC covers in saturated Silica sand sample with different applied pressure

Figure 6-15. Weight loss of 51 HRC covers in saturated Silica sand sample with different applied pressure

The results indicate that by increasing the ambient pressure, the amount of weight loss on the covers increases. This confirms the actual phenomena that happens in the field and has been observed by various machine manufacturers and operators. The amount of additional wear due to increased ambient pressure is not significant and it seems like the impact of pressure is more pronounced on tools with lower hardness.
Effect of Particle Angularity on Abrasion

The effects of particle sphericity and roundness on abrasion have been investigated by Alavi Gharahbagh et al. (2011). A simple example is presented herein to demonstrate the effect of particle angularity on abrasion. Quartz is the most abrasive constituent mineral among the minerals listed in Table 6-1 (Rostami et al., 2012). Based on the relatively consistent quartz contents and weighted-average hardness, the Silica sand, ASTM Graded sand and ASTM 20/30 sand are selected to study the effect of particle angularity on soil abrasion. The Silica sand is categorized as angular sand; whereas the ASTM Graded sand and ASTM 20/30 sand are round Ottawa sands. Figure 6-16 shows the results of these tests in dry and slightly submerged (i.e., \( W = 22.5\% \)) conditions using 31 HRC covers. Figure 6-16 indicates that in dry condition, the angular Silica sand produces substantially higher cover wear than the round Ottawa sands (i.e., ASTM Graded and ASTM 20/30 sands). This is due to a combination of several mechanisms. First, the interface friction between the cover and sand particles is much higher in the angular Silica sand than in the round Ottawa sand. Second, the angular Silica sand creates higher inter-particle locking and yields higher strength and stiffness of the particle assemblage, resulting in higher frictional resistance and contact pressure on the covers as they rotate in the soil samples. Figure 6-16 also indicates that the slightly submerged condition results in substantially less cover wear than the dry condition in the angular Silica sand, which is consistent with Figure 6-10.
Figure 6-16. Weight loss of 31 HRC covers with different time steps in Silica sand, ASTM Graded sand, and ASTM 20/30 sand in (a) Dry condition; (b) Saturated condition

Effect of Grain Size Distribution on Abrasion

A quartz-rich Silty sand sample is used in the initial study to represent fine-grain soil samples and their impact on abrasion properties. The sample is obtained from a project site in Northern Virginia where geotechnical investigation of a site containing a difficult layer of fine-grain material was underway. The results of testing on dry Silty sand after 1 hour of testing on 17 and 43 HRC covers are presented in Figure 6-17.

Figure 6-17. Weight loss of 17 and 43 HRC covers in different time steps on dry Silty sand sample
This Figure confirms that although the amount of abrasive minerals in the sample of Silty sand tested was rather high, the finer-grained soil sample caused less weight loss and wear as compared to Silica sand samples (Figure 6-7). In addition, in contrast to the results of hardness in Silica sand samples, by increasing the hardness of covers from 17 HRC to 43 HRC the amount of weight loss decreases significantly.

In addition, a test was performed in a fine-grained soil sample using 45% water content to observe the effect of moisture on soil abrasion. Figure 6-18 shows the summary of test results. The same behavior as dry condition is observed and the finer-grained soil sample caused less weight loss. The impact of near-saturated soil conditions on the wear characteristics is to reduce the tool wear as it was observed in Figure 6-9. These tests are quite challenging due to difficulty of making a uniform sample of clay soil with various moisture contents.

![Graph showing weight loss of 17 HRC covers in different time steps on a dry and 45% moisture content Silty sand sample](image)

**Figure 6-18. Weight loss of 17 HRC covers in different time steps on a dry and 45% moisture content Silty sand sample**

**Effect of Propeller Speed on Abrasion**

Due to the low weight loss in the Silty sand sample, it was decided to investigate the effect of rotational speed of the propeller on the weight loss of the tool. For this purpose three
tests with 60, 105, 180 rpm were performed on a dry Silty sand sample. The results of testing are presented in Figure 6-19.

![Figure 6-19. Weight loss of 17 HRC covers with different time steps on a dry Silty sand sample with different propeller speed](image)

As it can be seen, by increasing the propeller speed, the amount of weight loss on the covers decreases. It is important to note that by increasing propeller speed from 60 to 180 rpm, the amount of torque applied to the sample decreased from 135-80 N.m. This also confirms that the contact between the soil particles and cutter surface due to a very high speed is not a good representative for simulation of what really happens at the face of a tunneling machine or inside the cutterhead as it is used in the LCPC testing system.

**Relationship between Torque and Abrasion**

For each of the soil abrasion tests, the amount of voltage and amperage of the motor was monitored by using a power transducer and the results were recorded with a data acquisition system. Table 6-4 and Figure 6-20 show the measured torque on the propeller shaft (back calculated from the performance chart of the electric drive unit) on some of the performed soil
abrasion tests and the measured weight loss after 5 minutes of testing. The results showed a
correlation between the measured torque and the weight loss of the tools (in this case blade
covers). Since some of the variations of the torque could be attributed to the indirect method of
measurement, through the drive unit, it was decided to implement a direct-measuring system as it
was discussed earlier in Chapter 5. Meanwhile, the observed correlation from the power
transducer data indicates that the weight loss of the tools is indeed a function of the friction
between the excavated soil and tools, cutterhead parts, and other contact surfaces on its path.

Table 6-4. Indirect measured torque for soil abrasion tests

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Testing condition</th>
<th>Torque (N.m)</th>
<th>Weight Loss after 5 min (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty sand</td>
<td>Dry (60 rpm)</td>
<td>135</td>
<td>0.28</td>
</tr>
<tr>
<td>Silty sand</td>
<td>Moist (W=45%)</td>
<td>113</td>
<td>0.07</td>
</tr>
<tr>
<td>Silty sand</td>
<td>Dry (105 rpm)</td>
<td>79</td>
<td>0.12</td>
</tr>
<tr>
<td>Silty sand</td>
<td>Dry (180 rpm)</td>
<td>52</td>
<td>0.09</td>
</tr>
<tr>
<td>Limestone sand</td>
<td>Dry</td>
<td>201</td>
<td>0.39</td>
</tr>
<tr>
<td>Limestone sand (25%)-Silica sand (25%)</td>
<td>Dry</td>
<td>202</td>
<td>1.49</td>
</tr>
<tr>
<td>Limestone sand (50%)-Silica sand (50%)</td>
<td>Dry</td>
<td>223</td>
<td>2.41</td>
</tr>
<tr>
<td>Limestone sand (25%)-Silica sand (75%)</td>
<td>Dry</td>
<td>229</td>
<td>3.35</td>
</tr>
<tr>
<td>Silica sand</td>
<td>Dry</td>
<td>240</td>
<td>3.52</td>
</tr>
<tr>
<td>Limestone sand</td>
<td>Saturated (W=22.5%)</td>
<td>154</td>
<td>0.92</td>
</tr>
<tr>
<td>Silica sand</td>
<td>Saturated (W=22.5%)</td>
<td>148</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Figure 6-20. Weight loss of different testing set-ups after 5 minutes of testing with respect to indirect measured torque
Several key tests were repeated in order to investigate the relationship between torque and different parameters of interest such as rotational speed of the propeller, water content, pitch angle, and weight loss of the covers using the direct torque measurement system.

Figure 6-21 displays the measured torque on Silica sand samples in dry condition and by using different rotational speeds during the first 5 minutes of testing.

![Figure 6-21. Measured torque on dry Silica sand by using 10° pitch angle propeller with different rotational speeds](image)

As it can be seen in Figure 6-21, by increasing the rotational speed, torque increases as it was expected. In addition, the applied torque to the sample by using 60 and 105 rpm is more stable in compare to the applied torque by using 180 rpm set-up.

Figure 6-22 shows the measured torque for individual tests by using 60 rpm, 105 rpm, and 180 rpm in 5 and 15 minute time steps in addition to the maximum measured torque with respect to rotational speed and weight loss after 15 minutes of testing. As it can be seen from parts (a) to (c) of Figure 6-22, in contrast to 105 rpm and 180 rpm set-ups in which, as the test progressed, the amount of applied torque decreases, in 60 rpm set-up the amount of applied torque increases as the test progressed. One of the explanations can be that, at higher rotational speeds, while the overall applied torque is higher, the amount of dynamic compaction of the
sample is less and thus torque gradually decreases as the test proceeds. Meanwhile part (d) of Figure 6-22, confirms a linear relationship between rotational speed and mean value of torque as well as rotational speed and weight loss in the Silica sand samples.

![Figure 6-22](image.png)

Figure 6-22. Measured torque on dry Silica sand by using 10° pitch angle propeller with (a) 60 rpm (b) 105 rpm (c) 180 rpm and (d) Rotational speed of propeller versus torque and weight loss after 15 minutes of testing.

Two sets of tests with 60 and 180 rpm were performed on dry Limestone sand samples. The results of testing follows the same trend as Silica sand samples, as it is reported in Figure 6-23. Figure 6-24 summarizes the results of testing on dry clay samples (sample is obtained from U230 project tunnel in Seattle, WA) at 60 and 180 rpm. Figure 6-24 (a) displays the comparison of the testing results in the first 5 minutes of testing by using 60 and 180 rpm. As it can be seen, during the first 5 minutes of the test at 60 rpm, the amount of torque continuously increases as the test progressed until it reaches a stable compaction level. After this stage, the amount of applied
torque remains constant during the next 10 minutes of testing (Figure 6-24 (b)). In contrast, at 180 rpm, the amount of applied torque continuously decreases as the test progressed. The amount of weight loss decreases by increasing the rpm (Figure 6-24 (d)). This result is consistent with the results of testing in Silty sand samples as discussed earlier in this Chapter.

![Graphs showing torque and rotational speed](image)

Figure 6-23. Measured torque on dry Limestone sand by using 10° pitch angle propeller with (a) 60 and 180 rpm in 5 minutes (b) 60 rpm in 5 and 15 minutes time steps (c) 180 rpm in 5 and 15 minutes time steps and (d) Rotational speed of propeller versus torque and weight loss after 15 minutes of testing.

In addition, the effect of pitch angle on torque was studied by performing a set of tests using 10, 20, and 30 degrees pitch angle on Silica sand samples. Figure 6-25, 6-26 and 6-27 summarize the results of testing. By increasing the pitch angle, the applied torque to the sample increases as well (Figure 6-25). The comparison between the effect of rotational speed and pitch angle on torque can be found in Figure 6-26 and Figure 6-22. Once again the results confirm that
the 10° pitch angle and 60 rpm set-up is the best choice for the final testing set-up in case of torque consistency during the test.

Figure 6-24. Measured torque on dry clay by using 10° pitch angle propeller with (a) 60 and 180 rpm in 5 minutes (b) 60 rpm in 5 and 15 minutes time steps (c) 180 rpm in 5 and 15 minutes time steps and (d) Rotational speed of propeller versus torque and weight loss after 15 minutes of testing

Figure 6-27 shows that despite the increase in torque at higher pitch angles, the weight loss of the covers decreases in both 60 and 180 rpm tests. Furthermore, the effect of water content on torque is studied by performing a set of tests at 12.5% and 22.5% water content Silica sand and Limestone sand by using 10° pitch angle propellers and 60 rpm rotational speed. The result of this study is summarized in Figure 6-28 and Figure 6-29.
Figure 6-25. Measured torque on dry Silica sand with different propeller pitch angles by using (a) 60 rpm and (b) 180 rpm set-up.

Figure 6-26. Measured torque on dry Silica sand by using (a) 60 rpm and 20° pitch set-up (b) 180 rpm and 20° pitch set-up (c) 60 rpm and 30° pitch set-up (d) 180 rpm and 30° pitch set-up.
As it was discussed earlier in this Chapter, water content plays a significant role on abrasion and wear. As one can see in Figure 6-28 the water contents close to dry of optimum in compaction test (W=12.5%), cause much higher torque compared to dry and saturated (W=22.5%) conditions. It should be noted that due to a very high amount of torque applied to the Limestone sand sample, when testing at 12.5% water content, the safety shear pin was cut off and the test stopped. It is interesting to consider that the amount of applied torque at 12.5% water content test was much higher in Limestone sand as compared to Silica sand, but the amount of weight loss of covers is much higher in Silica sand samples. This shows that high torque values individually cannot be used as a measure of abrasion and a combination of different variables such as mineral content, sphericity and roundness, etc. should be considered in the wear analysis.
Figure 6-28. Effect of water content on torque in (a) Silica sand, W=12.5\%  (b) Silica sand, W=22.5\% , (c) Limestone sand, W=12.5\% , (d) Limestone sand, W=22.5\%  (e) Comparison of torque with different water contents in Silica sand (f) Comparison of torque with different water contents in Limestone sand
Figure 6-29. (a) Effect of water content on torque and weight loss in Silica sand (b) Relationship between torque and weight loss in Silica sand at different water contents (c) Effect of water content on torque and weight loss in Limestone sand (d) Relationship between torque and weight loss in Limestone sand at different water contents (The reported weight loss is for 15 minutes of testing)

**Consistency and Repeatability of Testing Results**

For many test configurations investigated in this study, three tests were performed to investigate the repeatability of the proposed testing system and procedure. For example, three tests with 17 HRC steel covers in Silica sand samples at $W = 10\%$ yielded 23.64, 22.07, and 23.22 g of weight loss after 10 minutes of testing and three similar tests at $W = 22.5\%$ yielded 3.65, 3.48, and 3.46 g of weight loss after 60 minutes of testing (Figure 6-30). These results are within $\pm 4\%$ of the average values; therefore, the test repeatability is considered to be acceptable.
Figure 6-30. Consistency analysis of the testing results by using 17 HRC covers in Silica sand samples (a) $W = 10\%$ (b) $W = 22.5\%$
Chapter 7

Development of Penn State Soil Abrasion Index (PSAI)

Standard Setting for the Testing System

The standard setting for the testing device is obtained based on the parametric study on different parameters that are discussed in Chapter 6. This setting includes the rotational speed of 60 rpm, propeller pitch angle of 10°, and cover hardness of 17 HRC. The test will be performed at various moisture contents including a dry sample, soil with water content dry of optimum compaction, and saturated soil.

Penn State Soil Abrasion Index

The Penn State soil abrasion index (PSAI) which is introduced in this study is the result of wear measurements using a standard test setting on the developed soil abrasion testing device. The observations during testing at various conditions show that at wear rates of above 20 gram, the blade covers do experience some losses in the surface area towards the lower side of the propeller around the outer edge. This means that the propeller blades will get exposed to highly abrasive soils and will wear and incur permanent damage if the tests continue beyond this point. In other words, there are cases that the testing has to be stopped within a few minutes to avoid permanent damage to the propeller or the equipment. In addition, the accuracy of the testing results is in danger since instead of weight loss being registered on the covers; it would be registered on the propeller blades. This is while in some other cases, the covers hardly show any sign of wear even after 60 minutes of testing. Therefore, there was a need to develop a procedure to allow for comparing the weight loss of covers in different soil types based on the same testing
time. This could allow for comparing the weight loss of the covers under the same testing conditions and for the same point in time to define a standard abrasion index.

To achieve this goal, the test results for various test durations will be combined in a graph and a best-fit curve will be developed to estimate the characteristics of the soil. Given the shape of the wear curves when plotted against time, a power function seems to offer the best fit. Thus the variation of the wear on the cover as a function of time can be expressed as follows:

\[ W = AT^b \]  \hspace{1cm} (6)

Where \( W \) is wear (gram), \( T \) is time (minutes), and \( A \) and \( b \) are constants defining the shape of the curve. With the use of \( A \) and \( b \) in this study, one can extrapolate the measured wear on the covers for shorter tests. This facilitates estimation of the anticipated wear for a given time frame. For example, with only two measurement of wear within the first 5-10 minutes and using the origin \((0,0)\) as a starting point, a best-fit curve can be developed for the available data to estimate the anticipated wear at 30 and 60 minutes. The measured or calculated wear at 60 minutes (from the formula) is defined as the Soil Abrasion Index or “PSAI”. Moisture content can be noted with the subscript to indicate the testing conditions. As such \( \text{PSAI}_D \), \( \text{PSAI}_S \), \( \text{PSAI}_{10\%} \) would represent the abrasion index in Dry, Saturated, and at 10% water contents, respectively. Table 7-1 is the summary of measured PSAI for various soil samples along with the other two characteristic parameters of the curve, \( A \) and \( b \).

This approach allows for expansion of the application of the soil abrasion index. While \( A \) signifies the magnitude and intensity of wear, the power \( b \) shows the long-term effect of continued testing. “\( b \)” values of over one shows the increasingly aggressive abrasion while values below one show somewhat slower wear as the testing continues.
Table 7-1. Summary of Soil Abrasion Index (PSAI) testing results for various soil types and testing conditions

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Soil type</th>
<th>Moisture content</th>
<th>Test time (min)</th>
<th>Weight loss of cover (g)</th>
<th>A</th>
<th>b</th>
<th>PSAI or Weight Loss in 60 min based on $W = A.T^b$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>mixture of clay, silt, sand</td>
<td>dry</td>
<td>60</td>
<td>0.31</td>
<td>0.0271</td>
<td>0.6035</td>
<td>0.32</td>
</tr>
<tr>
<td>2</td>
<td>mixture of clay, silt, sand</td>
<td>dry</td>
<td>60</td>
<td>0.39</td>
<td>0.1751</td>
<td>0.2101</td>
<td>0.41</td>
</tr>
<tr>
<td>3</td>
<td>ASTM Graded Sand</td>
<td>dry</td>
<td>60</td>
<td>0.48</td>
<td>0.1027</td>
<td>0.3601</td>
<td>0.45</td>
</tr>
<tr>
<td>4</td>
<td>mixture of clay, silt, sand</td>
<td>dry</td>
<td>60</td>
<td>0.53</td>
<td>0.0981</td>
<td>0.4234</td>
<td>0.56</td>
</tr>
<tr>
<td>5</td>
<td>non-glacial till</td>
<td>dry</td>
<td>60</td>
<td>0.59</td>
<td>0.2099</td>
<td>0.2620</td>
<td>0.61</td>
</tr>
<tr>
<td>6</td>
<td>Silty sand (Northern Virginia)</td>
<td>dry</td>
<td>60</td>
<td>0.66</td>
<td>0.0274</td>
<td>0.7985</td>
<td>0.72</td>
</tr>
<tr>
<td>7</td>
<td>glacial till</td>
<td>dry</td>
<td>60</td>
<td>0.66</td>
<td>0.0447</td>
<td>0.6798</td>
<td>0.72</td>
</tr>
<tr>
<td>8</td>
<td>Silty sand (Northern Virginia)</td>
<td>dry</td>
<td>60</td>
<td>0.68</td>
<td>0.0410</td>
<td>0.6981</td>
<td>0.71</td>
</tr>
<tr>
<td>9</td>
<td>Silica sand</td>
<td>dry</td>
<td>60</td>
<td>1.37</td>
<td>0.1066</td>
<td>0.6474</td>
<td>1.51</td>
</tr>
<tr>
<td>10</td>
<td>Silica sand</td>
<td>dry</td>
<td>60</td>
<td>22.55</td>
<td>1.1262</td>
<td>0.7482</td>
<td>24.10</td>
</tr>
<tr>
<td>11</td>
<td>Silica sand (75%)-Limestone sand (25%)</td>
<td>dry</td>
<td>60</td>
<td>19.61</td>
<td>0.9844</td>
<td>0.7413</td>
<td>20.48</td>
</tr>
<tr>
<td>12</td>
<td>Silica sand (50%)-Limestone sand (50%)</td>
<td>dry</td>
<td>60</td>
<td>14.88</td>
<td>0.7661</td>
<td>0.7337</td>
<td>15.50</td>
</tr>
<tr>
<td>13</td>
<td>Silica sand (25%)-Limestone sand (75%)</td>
<td>dry</td>
<td>60</td>
<td>6.96</td>
<td>0.3294</td>
<td>0.7595</td>
<td>7.38</td>
</tr>
<tr>
<td>14</td>
<td>Limestone sand</td>
<td>dry</td>
<td>60</td>
<td>1.27</td>
<td>0.1942</td>
<td>0.4849</td>
<td>1.41</td>
</tr>
<tr>
<td>15</td>
<td>Silica sand</td>
<td>sat (W=22.5%)</td>
<td>60</td>
<td>3.52</td>
<td>0.6940</td>
<td>0.4214</td>
<td>3.74</td>
</tr>
<tr>
<td>16</td>
<td>Silica sand (75%)-Limestone sand (25%)</td>
<td>sat (W=22.5%)</td>
<td>60</td>
<td>4.84</td>
<td>0.9340</td>
<td>0.4190</td>
<td>5.19</td>
</tr>
<tr>
<td>17</td>
<td>Silica sand (50%)-Limestone sand (50%)</td>
<td>sat (W=22.5%)</td>
<td>60</td>
<td>6.13</td>
<td>0.8055</td>
<td>0.5153</td>
<td>6.66</td>
</tr>
<tr>
<td>18</td>
<td>Silica sand (25%)-Limestone sand (75%)</td>
<td>sat (W=22.5%)</td>
<td>60</td>
<td>7.30</td>
<td>0.5549</td>
<td>0.6460</td>
<td>7.92</td>
</tr>
<tr>
<td>19</td>
<td>Limestone sand</td>
<td>sat (W=22.5%)</td>
<td>60</td>
<td>9.12</td>
<td>0.4249</td>
<td>0.7467</td>
<td>9.04</td>
</tr>
<tr>
<td>20</td>
<td>Silica sand</td>
<td>moist (W=15%)</td>
<td>60</td>
<td>20.02</td>
<td>4.7953</td>
<td>0.3546</td>
<td>20.48</td>
</tr>
<tr>
<td>21</td>
<td>Silica sand (75%)-Limestone sand (25%)</td>
<td>moist (W=15%)</td>
<td>60</td>
<td>14.13</td>
<td>4.4916</td>
<td>0.2719</td>
<td>13.67</td>
</tr>
<tr>
<td>22</td>
<td>Silica sand (50%)-Limestone sand (50%)</td>
<td>moist (W=15%)</td>
<td>60</td>
<td>13.55</td>
<td>1.3326</td>
<td>0.5713</td>
<td>13.82</td>
</tr>
<tr>
<td>23</td>
<td>Silica sand (25%)-Limestone sand (75%)</td>
<td>moist (W=15%)</td>
<td>60</td>
<td>12.18</td>
<td>2.3854</td>
<td>0.3780</td>
<td>11.21</td>
</tr>
<tr>
<td>24</td>
<td>Limestone sand</td>
<td>moist (W=15%)</td>
<td>60</td>
<td>11.94</td>
<td>4.3079</td>
<td>0.2450</td>
<td>11.75</td>
</tr>
<tr>
<td>25</td>
<td>Silty sand (Northern Virginia)</td>
<td>moist (W=45%)</td>
<td>60</td>
<td>0.22</td>
<td>0.0323</td>
<td>0.4628</td>
<td>0.21</td>
</tr>
<tr>
<td>26</td>
<td>mixture of clay, silt, sand</td>
<td>moist</td>
<td>60</td>
<td>0.23</td>
<td>0.0508</td>
<td>0.3552</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Figure 7-1 shows the measured weight loss of the covers versus the calculated weight loss based on the PSAI in dry, 15% water content, and saturated conditions for various mixtures of Silica and Limestone sands. The first observation is that measured weight loss during the actual test and calculated weight loss based on PSAI have a good correlation. Secondly, although the trend in parts (a) and (b) of Figure 7-1 suggests that by increasing the percent quartz in the mixture in dry and moist conditions, weight loss increases, the relationship between percent quartz and weight loss is reverse in a saturated condition. The observed phenomenon could be explained by the lubrication effect of water as discussed before. Meanwhile, the lubricating factor seems to be more effective in quartzitic sand as compared to Limestone sand, perhaps due to surface chemistry of the grains. The preliminary results indicate the complex relationship between the wear and water content of the soil samples that cannot be captured in other abrasion testing and surely not by mere comparison of mineral hardness.

<table>
<thead>
<tr>
<th></th>
<th>Silty sand (Northern Virginia)</th>
<th>(W=34.8%) moist (W=60%)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>mixture of clay, silt, sand</td>
<td>moist (W=38.8%)</td>
<td>60</td>
<td>0.29</td>
<td>0.0667</td>
</tr>
<tr>
<td>28</td>
<td>mixture of clay, silt, sand</td>
<td>moist (W=34.8%)</td>
<td>60</td>
<td>0.39</td>
<td>0.0377</td>
</tr>
<tr>
<td>29</td>
<td>mixture of clay, silt, sand</td>
<td>moist (W=27.7%)</td>
<td>60</td>
<td>0.48</td>
<td>0.0778</td>
</tr>
<tr>
<td>30</td>
<td>mixture of clay, silt, sand</td>
<td>moist (W=30.2%)</td>
<td>60</td>
<td>0.15</td>
<td>0.0472</td>
</tr>
</tbody>
</table>
Figure 7-1. Soil abrasion index (PSAI) versus the actual weight loss in (a) Dry, (b) W=15%, and (c) Saturated condition in mixture of Silica and Limestone sand

Figure 7-2 shows the measured weight loss of the covers versus constant $A$ in the PSAI index formula that signifies the magnitude and intensity of wear. As it is shown in parts (a) and (b) of Figure 7-2, by increasing the weight loss constant $A$ increases as well. Part (c) of Figure 7-2 shows the relationship between $A$ and weight loss in a saturated condition. By increasing the weight loss the magnitude of $A$ decreases. The conducted tests to date do not demonstrate the complex tribological behavior of sand mixtures of different minerals in a saturated condition and more study is required to understand the trend.
Figure 7-2. Measured weight loss versus the constant A in (a) Dry, (b) W=15%, and (c) Saturated condition in mixture of Silica and Limestone sand.

Figure 7-3 shows the measured weight loss of the covers versus power b that represents the long-term effect of wear in the PSAI index formula. As it is shown in parts (a) and (b) and (c) of Figure 7-3, by increasing the weight loss the power b increases as well. One should notice that in dry and 15% water content by increasing the quartz content in the mixture the weight loss increases but in a saturated condition the trend is reverse.
Figure 7-3. Measured weight loss versus parameter b in (a) Dry, (b) W=15%, and (c) Saturated condition in mixture of Silica and Limestone sand

Classification of Soil Based on PSAI Testing System

Given the ability to measure the soil abrasion index using the new testing device at Penn State University, a preliminary classification has been developed to offer a qualitative description of abrasivity of different soil types. Table 7-2 shows the suggested soil abrasion classification based on the PSAI soil abrasion index. This is an introductory classification and will be subject to future modification based on comparison of the measured index and the wear on various machine components observed in the field.
Table 7-2. Criteria for the PSAI soil abrasion index

<table>
<thead>
<tr>
<th>Classification</th>
<th>Weight Loss (g) after 60 minutes based on $W=AT^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non to Very low abrasivity</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Low abrasivity</td>
<td>2-5</td>
</tr>
<tr>
<td>Medium abrasivity</td>
<td>5-10</td>
</tr>
<tr>
<td>High abrasivity</td>
<td>10-15</td>
</tr>
<tr>
<td>Extremely high abrasivity</td>
<td>&gt;15</td>
</tr>
</tbody>
</table>

The preliminary classification for soil abrasion based on the PASI index offered in this Chapter can be used for classification of different soil types for selection of cutting tools and hard facing as well as quantification of wear on various machine components. This requires comparison of field data with measured PSAI values and regression analysis of the results to obtain a correlation between these parameters. One should also note that wear on the cutterhead of tunneling machines is an operational parameter and cannot be simply estimated by using this or any other index. This is to say that while PSAI can offer a measure of soil abrasion in different conditions, in the real-life application, the soil is modified by using various soil conditioners to reduce its abrasivity and required cutterhead torque. Therefore, the actual primary and secondary wear of the cutterhead and machine components are in fact a function of these operational parameters that are different from site to site, and at various times in the same tunneling operation. This includes using the same machine in the same soil, but changing soil conditioners or various foam injection or expansion ratios (FIR, FER), face pressure, or advance rates.
Chapter 8

Study of the Effect of Relative Hardness on Soil Abrasion

Introduction

There are a few key parameters that need to be addressed in the design of any type of wear test for soils to represent wear mechanisms that happen in the field. For this reason, it is necessary to look at the common wear mechanisms that have been observed on various tunneling machines. The damage to the cutterhead and cutters of soft-ground mechanized TBMs can be categorized into three different categories as displayed in Figure 8-1:

1- Plastic deformation, that is the deformation in the shape of the cutters beyond acceptable limits without any wear,

2- Breakage of part of a cutter due to weakening by wear or excessive forces, and

3- Abrasion wear.

This study is restricted to abrasion wear. Zum Gahr (1987) has classified the wear based on motion to rolling, sliding, oscillating, impact, and flowing. The wear in soil cutting tools in mechanized tunneling is mainly caused by sliding motion. From a practical and observational viewpoint, the main mechanisms of wear can be classified as Adhesive, Corrosive, Erosive, Fatigue, Delimitation, Fretting, Fretting Fatigue, and abrasive wear.
Abrasive wear refers to the case where a harder surface abrades a softer surface, i.e. two-body wear, or hard particles that are present at the interface abrade one or both surfaces, i.e. three-body wear. In general, abrasion is the removal of material from a softer surface by asperities of a harder material for both two- and three-body abrasion. There are several micro-phenomena (plowing, cutting, cracking, etc.) that count as the micro-mechanism of abrasive wear. However, it is very hard to single out one of these micro-phenomena as the dominant one in a particular application.

The main mechanism of wear in soft-ground mechanized tunneling is abrasive wear. Therefore the testing system that is developed in this study mainly focuses on abrasive wear.

For the TBM manufacturers, the hardness and type of the cutters and steel that are used in the TBM cutterhead are very crucial. This refers to the selection of the right type of steel with proper hardness to avoid excessive wear. Steel types with higher hardness are typically more
expensive due to the need for additional work and heat treating, while they are more difficult to work with for repair and maintenance purposes. Also additional handling of the steel at the site, i.e. welding and cutting, can compromise the target hardness and result in lower than desired hardness. Thus, the study of the relative tool-soil hardness is very important and has decisive implications for the manufacturers.

As it is shown in Chapter 6, Figure 6-7, by increasing the hardness from 17 HRC to 60 HRC the weight loss of the covers in a dry condition decreased from 22.55 g to 18.70 g. In contrast to a dry condition, by increasing the hardness of the covers, the weight loss increased in Silica sand with 10% water content and also in saturated conditions, as illustrated in Figures 6-8 and 6-9. The exception to this observation was the tests in fine-grained soil where the increased hardness had a positive impact on wear characteristics of the soil, as discussed earlier in Chapter 6.

To better understand the wear phenomenon in this process and the related behavior of the testing system, a study of tribology of the tool-soil contact is performed as will be discussed in the following sections.

**Tool Wear and Relative Hardness**

**Weighted-Average Mohs Hardness and Equivalent Quartz Content**

One of the most important parameters that determine the abrasion behavior of the soil is the type and abrasiveness/hardness of its constituent minerals. To study this parameter, a series of tests were performed using various combinations of Silica sand (abrasive) and Limestone sand (non-abrasive) in a dry condition and with 15% water content. Tables 8-1 and 8-2 show the mixing ratio of these two types of sands and also the weighted-average Mohs hardness and
equivalent quartz content of these mixtures, and also the measured weight loss of performed tests in dry and 15% water content conditions by using 17 and 31 HRC covers.

Table 8-1. Weight loss (g) of 17 and 31 HRC (231 and 310 Vickers hardness, HV) covers in dry condition in different mixing ratios of Silica and Limestone sands with their representative EQC and weighted-average Mohs hardness

<table>
<thead>
<tr>
<th>Limestone Sand (%)</th>
<th>Silica sand (%)</th>
<th>EQC (%)</th>
<th>Weighted-avg. Mohs hardness</th>
<th>17 HRC/231 HV</th>
<th>31 HRC/310 HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>97.126</td>
<td>6.852</td>
<td>22.554</td>
<td>23.942</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>73.782</td>
<td>5.889</td>
<td>19.609</td>
<td>19.383</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>50.438</td>
<td>4.926</td>
<td>14.882</td>
<td>14.168</td>
</tr>
<tr>
<td>75</td>
<td>25</td>
<td>27.094</td>
<td>3.963</td>
<td>6.958</td>
<td>7.890</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>3.750</td>
<td>3.000</td>
<td>1.269</td>
<td>1.378</td>
</tr>
</tbody>
</table>

* Equivalent Quartz Content (EQC) from Roziwal hardness based on Thuro (1997)

Table 8-2. Weight loss (g) of 17 and 31 HRC (231 and 310 HV) covers in sample with 15% water content and different mixing ratios of Silica and Limestone sands with their representative EQC and weighted-average Mohs hardness

<table>
<thead>
<tr>
<th>Limestone Sand (%)</th>
<th>Silica sand (%)</th>
<th>EQC (%)</th>
<th>Weighted-avg. Mohs hardness</th>
<th>17 HRC/231 HV</th>
<th>31 HRC/310 HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>97.126</td>
<td>6.852</td>
<td>20.0221</td>
<td>22.4735</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>73.782</td>
<td>5.889</td>
<td>14.1316</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>50.438</td>
<td>4.926</td>
<td>13.5547</td>
<td>14.2783</td>
</tr>
<tr>
<td>75</td>
<td>25</td>
<td>27.094</td>
<td>3.963</td>
<td>12.1835</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>3.750</td>
<td>3.000</td>
<td>11.9403</td>
<td>12.0947</td>
</tr>
</tbody>
</table>

* Equivalent Quartz Content (EQC) from Roziwal hardness based on Thuro (1997)

Figures 8-2 and 8-3 show the weight loss of 17 and 31 HRC covers after one hour of testing as a function of the percentage of the Limestone and Silica sand in the mixture in a dry condition and with 15% water content, respectively. As it is clear from these Figures, by increasing the percentage of Silica sand in the mixture the amount of weight loss increases. However, the rate of change in moist conditions is much less than dry conditions.
Figure 8-2. Weight loss of (a) 17 HRC and (b) 31 HRC covers after 1 hour of testing in dry condition with respect to the percentage of Limestone sand and Silica sand in the mixture.

Figure 8-3. Weight loss of (a) 17 HRC and (b) 31 HRC covers after 1 hour of testing in 15% water content condition with respect to the percentage of Limestone sand and Silica sand in the mixture.

Figures 8-4 and 8-5 show the weight loss of the 17 and 31 HRC covers after 1 hour of testing as a function of the weighted-average Mohs hardness and equivalent quartz content of the soil mixture in dry and 15% water content condition, respectively. As it can be seen, equivalent quartz content shows a better distribution as compared to weighted-average Mohs hardness.
The tests results suggest that increasing the average hardness of the sample will increase the abrasion wear. In these tests, the increased hardness of the covers did not change the wear characteristics of the tool/soil combination and 17 and 31 HRC tools behaved more or less the same in various soils. Obviously, the shape of the curves could vary by the material hardness and their surface properties as reflected in the tribological behavior of individual mineral grains and the friction between various minerals and the tools.
Vickers Hardness

Due to the importance of the relative hardness and the promising results that are obtained in the earlier testing, it was decided to address the issue of relative hardness in a more systematic way. The overall hardness of soil mixtures and composites with homogeneously distributed particles has been related to their constituents’ properties through different models including shear-lag theory, finite element method (FEM), and self-consistent variation methods (Dong and Schmauder, 1996; Lesle et al., 1998; Nardone and Prewo, 1986). A simple and intuitive method for estimation of the effective hardness in terms of constituents is the rule of mixtures (ROM). In utilizing the ROM approach, both the equal strain (iso-strain) and the equal stress (iso-stress) assumptions have been widely considered. However, for mixtures with a high volume fraction of the hard particle, it has been suggested that the iso-strain assumption which predicts an upper bound for the hardness value yields more accurate results (Kim, 2000).

For calculating the hardness of the soil samples, Vickers hardness of the soil mixture \( H_V \) was calculated based on the following formula:

\[
H_V = \sum_{i=1}^{n} HVA_i \times Q_i 
\]  

(7)

Where \( H_V \) is the Vickers hardness of the minerals in the mixture and \( Q \) is the percentage of the mineral in the mixture. The tool to mineral hardness ratio was obtained by dividing the measured Vickers hardness of the steel covers by the Vickers hardness of the mixed soil. Table 8-3 displays the developed test matrix for the relative hardness study including soil mixtures, their Vickers hardness, and the tool to mineral hardness ratio for each combination of the cover and mixture. As one can see in this Table, different tool to soil hardness ratios ranging from 0.21 to 2.75 were obtained by changing the percentages of soil constituents, i.e. quartzitic and Limestone sand, as well as using blade covers of different hardness.
Table 8-3. Test matrix for sand mixtures and their representative hardness ratio (tool/mineral)

<table>
<thead>
<tr>
<th>Silica Sand (%)</th>
<th>Limestone Sand (%)</th>
<th>Weighted-avg. HV of Sand Mixture</th>
<th>Hardness Ratio (Tool/Mineral)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>17 HRC (231 HV)</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>1113</td>
<td>0.21</td>
</tr>
<tr>
<td>75</td>
<td>25</td>
<td>898</td>
<td>0.26</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>683</td>
<td>0.34</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>468</td>
<td>0.49</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>253</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Figure 8-6 shows the measured weight loss of the covers versus the hardness ratio (tool/mineral) in dry sand mixtures after one hour of testing. Figure 8-6 demonstrates that an increase in hardness ratio, corresponding to an increase in tool hardness and/or a decrease in mineral hardness, results in a reduction in tool wear. This trend is consistent with the mechanisms of abrasive wear in a two-body wear system, where the removal of material from a softer surface is caused by asperities of a harder material. In the cases of low hardness ratios, the relatively soft covers are easily abraded by the relatively hard minerals in the sand mixture. As the tool/soil hardness ratio increases, the ability of the minerals to abrade the covers decreases. A similar trend is observed among the covers with 17 HRC, 31 HRC, 51 HRC, and 60 HRC. It is also interesting to note that to produce the same weight loss, a higher hardness ratio is needed for harder covers.

In practice, the hardness of cutting tools in tunneling applications falls in a narrow range, and the expected S-shape band occurs within a small range, which helps in the design of the cutting tools and selection of materials for inner components of the cutting chamber. The wear mass data shown in Figure 8-6 forms an inverted S-band bounded by curves of highest and lowest tool hardness. The S-curve implies that when the relative hardness ratio of the tool/mineral is low, high wear is experienced but changes are very limited as the ratio increases till this ratio approaches 0.8-1.2 area, a sharp drop is observed and beyond this range, the variation is again relatively limited and less sensitive to an increase in the ratio. As the tool hardness increases, the
wear curve shifts lower and to the right. This is consistent with the fact that a harder tool can be abraded by a harder soil mixture.

The transition from a high-wear to a low-wear regime is shifting to the right in Figure 8-6 as the hardness of the cover increases. Theoretically, the transition is expected to occur at a hardness ratio of 1. Wear of covers with 51 and 60 HRC exhibit such a behavior. The covers with a lower hardness exhibited premature transitions. For these covers, the higher tool to soil hardness ratios were mainly obtained by significantly reducing the quartzitic sand content of the soil, which was the dominant abrasive constituents. Therefore, the covers experienced a low wear regime. In the real soil excavation applications, the tool hardness is typically higher than 50HRC and the transition in the wear band resembles the findings of this study.

![Figure 8-6. Weight loss of covers versus hardness ratio (tool/mineral) in dry sand mixtures](image)

**Water Content and Relative Hardness**

To investigate the effect of water content on the relationship of weight loss versus hardness ratio, sand mixtures at water content W=15% and W= 22.5% were tested using the covers with 51 HRC hardness. Figure 8-7 compares the results of these tests with those performed in a dry condition as shown in Figure 8-6. Figure 8-7 demonstrates that the effect of water content
on the relationship of weight loss versus hardness ratio is complex. Between the water contents of $W=0\%$ (i.e., dry condition) and $W=15\%$, an increase in water content may increase or decrease weight loss depending on the hardness ratio. Between these two water contents, weight loss decreases as hardness ratio increases and this trend is monotonic. For sand mixtures at $W=22.5\%$, although the trend is generally valid, it is not monotonic as the weight loss initially increases with relative hardness.

Figures 6-7 through 6-10 in addition to Figure 8-7 underscore the importance of water content on the tool wear and abrasive characteristics of granular soils. Most of the previous tribological tests on this topic have been on a single grain and in a dry condition, but the developed new testing device provides sufficient means to investigate the effect of relative tool/mineral hardness of a mixture of particles in dry/moist conditions on tool wear.

![Graph](image)

**Figure 8-7.** Weight loss of covers (51 HRC) versus hardness ratio (tool/mineral) in sand mixtures with different water contents

In addition, a series of tests using different hardness of covers in soil mixture samples with 15% and 22.5% water content was performed. The results of the relationship between tool to mineral hardness ratio (based on Vickers hardness) and weight loss are displayed in Figures 8-8 and 8-9 for $W=15\%$ and $22.5\%$, respectively. As it can be seen in these Figures, in hardness ratios below 0.4 in $W=15\%$ and below 0.5 in $W=22.5\%$, increasing the hardness ratio resulted in
increasing weight loss which is completely opposite of the expected behavior of hardened material in abrasive wear and also the behavior of the tools in a dry condition. In these Figures, the complex effect of water content on the relationship of weight loss versus hardness ratio in two- or multiple-body wear phenomena is evident.

Figure 8-8. Cumulative weight loss of the covers after 1 hour of testing in soil mixture with 15% water content vs. the tool to mineral hardness ratio by using Vickers hardness

Figure 8-9. Cumulative weight loss of the covers after 1 hour of testing in soil mixture in saturated condition vs. the tool to mineral hardness ratio by using Vickers hardness
Increasing the Hardness Ratio by Using Chromium Carbide Covers

One of the main benefits of the PSU soil abrasion testing system is the capability to compare and investigate the tool life of different types of materials used for cutting purposes. This can lead to development of longer-lasting excavation tools, which could reduce the overall cost of construction in soft-ground tunneling.

As it was mentioned in Chapter 6, steel covers with different hardness including 17, 31, 43, 51, and 60 HRC were used for testing. As it is shown in Figure 6-7, by increasing the hardness of steel covers from 17 HRC to 60 HRC in dry Silica sand samples the weight loss of covers slightly decreased from 22.55 g to 18.70 g.

In order to investigate the effect of other types of materials on the wear, chromium carbide covers manufactured by JEDCO Company were used in the testing system. Two sets of tests in dry Silica sand samples and 10% water content Silica sand samples were performed by using these covers. Figure 8-10 shows the results of testing in a dry condition compared to the results of testing with steel covers.

![Figure 8-10. Weight loss of chromium carbide covers compared to different hardened-steel covers with respect to time in dry Silica sand samples](image-url)
As it can be seen in Figure 8-10, significant improvement in the weight loss is achieved by using the chromium carbide covers. The weight loss of covers is decreased after 60 minutes of testing from 18.7 g in 60 HRC steel covers to 6.2 g in chromium carbide covers.

The same scenario was repeated in Silica sand samples with 10% water content (Figure 8-11). As it can be seen in Figure 8-11, significant improvement in the weight loss is achieved by using the chromium carbide covers and the weight loss of covers is decreased after 10 minutes of testing from 26.6 g in 51 HRC covers to 8.8 g in chromium carbide covers. Figure 8-12 shows the chromium carbide covers and the wear pattern after 10 minutes of testing in 10% water content Silica sand samples. This shows the great potential of the developed testing device and its capability to compare different cutting tools in the case of wear and life, and it can be used widely by the TBM manufacturers and cutting-tool manufacturers.

![Figure 8-11. Weight loss of chromium carbide covers compared to different hardened-steel covers with respect to time in W=10% Silica sand samples](image-url)
Figure 8-12. Pictures of chromium carbide covers after 10 minutes of testing in 10% water content Silica sand samples and their wear pattern.
Chapter 9

Study of the Effect of Soil Conditioning on Soil Abrasion

Introduction

Soil conditioning is one of the main factors in EPB Tunneling which involves changing the characteristics of the ground in order to make it suitable for the tunneling process. Soil conditioning is usually applied at different points throughout the tunneling process such as at the face of the tunnel, within the cutting chamber, inside the screw conveyor, etc. Milligan (2000) summarized the advantages of using soil conditioning as follows:

- Increasing the stability of the tunnel face
- Improving the flowability of material
- Reducing the friction and therefore reducing the driving torque
- Changing the excavated material into a uniform plastic soil which leads to:
  - Better control of pressure inside the cutting chamber
  - Better control of groundwater inflow
  - Better control of flow of soil in the screw conveyor
  - Reducing the clogging in the chamber
  - Better handling of excavated soil
- Improving the safety of the personnel, especially during the maintenance of the cutters/cutterhead
- Maintaining the above conditions during tunneling operations and maintenance stops, and
- Finally, reduction of wear and tear of the cutters, cutterhead, and other wear parts

Soil conditioning is done by injecting foam, polymer, water, and filler (bentonite) into the tunnel face, pressure chamber and screw conveyor. Selection of the type of foam and
polymer mainly depends on soil type, geological condition (groundwater and soil permeability), and properties of the tunnel boring machine (injection points, open or closed cutter head, type of foam generator, etc). The most important soil conditioners are foam and polymer. However, in some cases due to existing conditions, some other additives like anti-clogging or anti-wear material are also added to the soil conditioning agents.

In order to look at the subject of soil conditioning in EPB tunneling in a more-detailed manner, there are several definitions that need to be addressed:

- Foam: defined as a product generated by the combination of a foaming solution and air,
- Foaming solution: basically a mixture made from water and a surfactant,
- Foam Expansion Ratio (FER): the ratio between the volume of foam at working pressure and the volume of the solution. EFNARC (2005) has specified the range of FER between 5-30.
- Foam Injection Ratio (FIR): the ratio between the injected volume of foam at working pressure and the banked volume of ground. EFNARC (2005) has specified the range of FIR between 10-80%.

A detailed discussion about the history of soil conditioning and calculation formulas for the foam injection ratios and foam expansion ratios can be found in Williamson et al. (1999). As it was mentioned earlier foam and conditioned soil should have specific properties during the tunneling operation. In order to understand and control these properties several laboratory tests have been developed that are briefly introduced in the next section.
Characterization of Foam and Conditioned Soil

Characterization of Foam

In order to characterize the foam used for tunneling purposes, simple laboratory tests are developed (Quesbed et al., 1998):

- Generation test: to study the relationship between pressure generation and fluid flow in the generator and foam flow rate
- Consistency test: to quantify the foam quality (bubbles size)
- Half-time test: to measure the necessary time for foam to lose half of its solution used originally for its generation
- Compressibility test: to understand the foam behavior in a confined environment and under changing pressure

It must be noted that in the tests mentioned above, foam is tested separately; however, in tunneling operations using EPB machines, foam is mixed with soil. Despite the usefulness of these tests, for better and more-detailed qualification of foam properties and its behavior during the tunneling operation, it is better to evaluate the conditioned soil.

Characterization of Conditioned Soil

To evaluate conditioned soil there is no universally accepted test but some methods are used for qualification of conditioned soil that have been adapted from concrete or geotechnical tests. Some of these tests are as follows:

- Foam Penetration Test: the purpose of this test is evaluation of foam penetration into soil (tunnel face). In this test pressurized foam is pushed into the soil. If foam penetration is high, then foam consumption is increased and the produced pressure may be insufficient.
On the other hand, if foam penetration is low, control of groundwater is difficult during the operation.

- Mixing Test: in this test, soil and foam are mixed together and the variation of the electric motor power, necessary time to obtain a homogeneous mixture and the quality and behavior of the conditioned soil are evaluated.

- Slump Test: in this test (ASTM C143, 2012), soil with a certain amount of water and foam are poured into a concrete mixer and after mixing, poured into the mold. The mold is carefully lifted vertically upwards in such a way that it does not disturb the conditioned soil cone. The amount of subsidence of the top surface of the mixture as the cone is removed is measured and called the slump value. The overall behavior of conditioned soil is evaluated and classified based on reference shapes (Figure 9-1).

Figure 9-1. Reference shapes for classification of conditioned soil based on Slump test (Borio et al., 2007)
The slump test has been widely used to evaluate the behavior of conditioned soil (Peron and Marcheselli, 1994; Quebaud et al., 1998; Jancsecz et al., 1999; Williamson et al., 1999; Langmaack, 2000; Viani et al., 2007). This test is simple, fast, and low cost. This test provides an overall index on the rheological behavior of the conditioned soil. The suggested value of slump is in the range of 120-250 mm.

- Permeability Test: to evaluate the permeability of the conditioned soil, some methods like Constant Head Test (for coarse-grained soils) or Hydraulic Compression Cell (for fine-grained soils) can be used. In general, conditioned soil is less permeable than ordinary soil.

- Compressibility Test: in this test, the compressibility of conditioned soil is evaluated. This test can be done using an apparatus similar to that used for a permeability test and the effects of pressure variation on compressibility of conditioned soil can be measured.

- Adhesion Test: this test is used for evaluation of adhesion between the conditioned soil and a metallic surface. In this test, adhesion of conditioned soil is measured by measuring the friction angle of the soil. Measurement of the friction angle can be achieved by using a sloping stainless-steel surface (Quebaud et al., 1998), a shear box (Jancesecz et al., 1999) or a ring shear apparatus (Milligan, 2000).

- Cone Penetration Test: in this test, the effect of a foam-solution type on clay soils is determined. For this purpose, a metallic cone falls down into the conditioned soil sample from a specific height and the penetration depth is measured.

Study of the Effect of Conditioned Soil on Reducing the Wear

As discussed in the previous section, a variety of tests have been developed that look into different properties of the foam and conditioned soil for application in EPB tunneling. However,
the effect of conditioned soil in reducing the wear of cutters or abrasivity of soil is absent in the literature. One of the major advantages of soil conditioners in EPB tunneling is to reduce the wear of the cutters and other components of the machine. The main theory behind the wear reduction phenomenon is that the high surface area of foam constrains the fine particles in the soil and therefore the friction between soil particles and the soil and tool reduces. In 2012, two groups of researchers at the Norwegian Institute of Science and Technology (Jakobsen at al., 2012) and Politecnico di Torino (Peila et al., 2012) in Italy started to look into this research study. In the next section a brief summary of these two testing systems are provided.

**Proposed Testing System by NTNU**

The Norwegian University of Science and Technology together with SINTEF and BASF Construction Chemicals Company developed a new testing system. The proposed testing system consists of a hyperbaric chamber 150×300 mm in size. In this testing system, soil samples are compacted in four layers in which all layers are compacted by applying 10 strokes of a Proctor hammer (with a diameter of 50 mm and a load of 2.5 kg). Four steel spokes (with the hardness of around 17 HRC) drills into the soil to a depth of 200 mm with a rotational speed of 90 rpm and a penetration rate of 56 mm/min. In order to mix the foam with the soil in a better way, the tests are performed stepwise to depths of 50, 100, 150, and 200 mm. The tests can be performed on samples with grain size up to 12 mm, different moisture contents, different soil compactions, different pressures up to 6 bars, and with different uses of chemicals such as foams and bentonites. Figure 9-2 displays the drilling tool in addition to the hyperbaric test chamber.
In their preliminary studies, they performed several tests on two sets of samples containing 44% and 34% quartz (SAT values of 26 and 23.5, respectively). The recorded weight loss of covers in their testing ranged from 0.02 to 0.1 g. This weight loss sounds very low with respect to the quartz content of the samples since the SAT values are high and the materials have high quartz contents. In addition, the result of testing by using foam confirms that conditioned soil leads to a reduction in weight loss (Jakobsen et al., 2012).

**Proposed Testing System by Politecnico of Torino**

The tunneling and underground space center and laboratory of the Politecnico of Torino have developed a new testing system with the aim of looking into the effect of soil conditioning on wear of an EPB TBM during the preliminary stages of design. The proposed testing system consists of an aluminum disk (with a tensile strength of 440 MPa and elastic modulus of 3.3 GPa) that rotates inside a tank filled with soil with a constant speed of 320 rpm. During the test, a
A confinement pressure of 2 KPa is applied on the soil in order to provide a continuous interaction between the soil and the disk. Figure 9-3 displays the proposed testing system.

![Figure 9-3. Cross section and picture of the aluminum disk and the proposed testing device by Politecnico of Torino (Peila et al., 2012)](image)

Torque is measured during the test as well and the results are expressed in terms of weight loss of the aluminum disk divided by the disk area in (g/m²) with respect to the ratio of the average applied torque during the test and the surface area of the aluminum disk in (N/m). The results of their testing confirmed that by using the correct conditioning (which is measured by using the slump test), wear and torque are greatly reduced (Peila et al., 2012).

One of the shortcomings of the proposed testing system by Politecnico of Torino is the high rotational speed of the aluminum disk inside the soil (320 rpm), which can potentially change the properties of the tested soil such as grain size and shape during the test. In addition the wear mechanism of the proposed testing system is friction caused by high impact, which is in contrast to the actual working condition of the TBMs in the field. Furthermore, the use of an
aluminum disk instead of actual wear material that is used in the cutters (steel, tungsten carbide, or chromium carbide) is one of the other shortcomings of their proposed testing system.

**Penn State Testing System**

The developed soil abrasion testing system at Penn State has the capability of examining the effect of soil conditioners on abrasion. A foam generator designed and fabricated by BASF Chemicals Company (Figure 9-4) was used to generate the foam. By using this foam generator, different agents/additives with selected properties such as an agent to water ratio, and foam expansion ratios (FER) could be generated. The generated foam was mixed with the soil with different foam injection ratios (FIR) and the effect of the soil conditioner in reducing the wear can be studied.

Figure 9-4. Foam generator device
Study of the Effect of Soil Conditioners on Wear

In order to study the effect of soil conditioners on abrasion, several tests were performed on three different materials by using selected soil-conditioning agents. The soil types that were used for this study included Silica sand samples, a crushed rock sample from the Washington Suburban Sanitary Commission (WSSC) tunnel project, and a crushed rock sample from the Indianapolis Deep Rock Tunnel Project. The rock samples were crushed to less than 4.75 mm in size for testing.

Soil Conditioning Tests on Silica Sand

A set of preliminary tests were conducted on Silica sand samples. This sample was selected due to its high quartz content as an abrasive testing material and since there was sufficient soil abrasion testing data available by testing this sample at various conditions. Table 9-1 summarizes different performed tests on the Silica sand samples.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Moisture Content (%)</th>
<th>Testing Time (min)</th>
<th>Weight Loss (g)</th>
<th>Conditioning Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica sand</td>
<td>0-Dry</td>
<td>30</td>
<td>12.9313</td>
<td>-</td>
</tr>
<tr>
<td>Silica sand</td>
<td>10</td>
<td>10</td>
<td>22.0670</td>
<td>-</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15</td>
<td>10</td>
<td>10.4559</td>
<td>-</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15</td>
<td>30</td>
<td>0.6453</td>
<td>3% Conc. Meyco SLF 47, FIR=25%, FER=17</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15</td>
<td>30</td>
<td>3.9132</td>
<td>3% Conc. ABR5, FIR=25%, FER=17</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15</td>
<td>30</td>
<td>2.9787</td>
<td>1% Conc. AQF-2, FIR=30%, FER=17</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15</td>
<td>10</td>
<td>13.3139</td>
<td>0.125% Quik Mud D-50 mixed with water and mixed with dry sand</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15</td>
<td>30</td>
<td>2.9530</td>
<td>0.125% Quik Mud D-50 mixed with water and mixed with dry sand +1% Conc. AQF-2, FIR=28%, FER=14</td>
</tr>
</tbody>
</table>
As can be seen in this Table, a total of 8 tests were conducted with different moisture contents, and with our without soil conditioning. Prior to each test, a slump test was performed to capture the optimal conditioning parameters based on Peila et al. (2009). Figure 9-5 displays the results of performed Slump tests on some of the performed tests on Silica sand samples. Figure 9-6 shows the samples at the end of testing in the soil abrasion testing device.

Figure 9-5. Pictures of (a) Mixing soil with the conditioner (b) Slump test on W=15% Silica sand sample (c) Slump test on W=15% Silica sand sample conditioned with 3% concentration ABR 5, 25% FIR and FER of 17 (d) Slump test on W=15% Silica sand sample conditioned with 3% concentration Meyco SLF 47, 25% FIR and FER of 17

Figure 9-6. Pictures of (a) 15% water content Silica sand sample conditioned with 3% concentration ABR 5, 25% FIR and FER of 17 (b) 15% water content Silica sand sample conditioned with 3% concentration Meyco SLF 47, 25% FIR and FER of 17 after 30 minutes of abrasion testing
Figure 9-7 displays the results of soil abrasion tests on the selected sample with different moisture contents and soil-conditioning combinations. This Figure clearly shows that by using the soil abrasion testing device, impacts of different conditioned soils on soil abrasion can be quantified. The comparison between conditioned soil and unconditioned soil shows that adding soil conditioner results in a substantial reduction in soil abrasivity.

![Graph showing weight loss over time for different soil samples](image)

Figure 9-7. Results of testing with soil conditioner on Silica sand samples

**Soil Conditioning Tests on WSSC Sample**

A set of three tests (Table 9-2) were performed on samples of crushed rock from a hard-rock tunneling project in Montgomery county, Maryland (WSSC water main project) to compare the difference in abrasive properties of the muck with and without conditioner. Prior to testing, the samples are crushed to less than 4.75 mm in size.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Moisture Content (%)</th>
<th>Testing Time (min)</th>
<th>Weight Loss (g)</th>
<th>Conditioning Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSSC</td>
<td>0-Dry</td>
<td>30</td>
<td>8.8929</td>
<td>-</td>
</tr>
<tr>
<td>WSSC</td>
<td>10</td>
<td>5.5</td>
<td>41.5526</td>
<td>-</td>
</tr>
<tr>
<td>WSSC</td>
<td>10</td>
<td>30</td>
<td>1.0902</td>
<td>3% Conc. Meyco SLF 47, FIR=50%, FER=10</td>
</tr>
</tbody>
</table>

Table 9-2. Soil conditioning tests performed on WSSC samples
Figure 9-8 displays the performed Slump tests on the samples as well as the condition of the sample after performing the abrasion test. Figure 9-9 shows the compacted samples at the bottom of the chamber after 5.5 minutes of abrasion testing with W=10% as well as the wear on the covers. A large amount of weight loss (41.5526 g) was observed during this test. The aggressive wear on the covers and degree of loss of the edges on the covers is shown in Figure 9-9. The remnant sample at the bottom of the chamber was fully compacted and had to be chiseled out of the chamber. The compaction of the moist sample had caused such high torque that it tripped the protection circuits of the drill press and the unit was shut down.

Figure 9-8. Slump and soil abrasion tests on WSSC sample with (a) W=10% (b) W=10% conditioned with 3% concentration Meyco SLF 47, 50% FIR and FER of 10
Figure 9-9. (a) Compacted material after 5.5 minutes abrasion testing on WSSC sample with W= 10% (b) Comparison between the original cover and one of the covers after 5.5 minutes abrasion testing on WSSC sample with W= 10%

Figure 9-10. Results of testing with soil conditioner on WSSC samples

Figure 9-10 displays the results of soil abrasion testing on the WSSC sample. As shown in this Figure, the addition of a conditioner to the sample reduces the weight loss of the covers significantly. This result points to reduction of the soil abrasion by a factor of about 250 times, if the initial test of the sample at 10% water content was to be projected to 30 minutes of testing.
Soil Conditioning Tests on Samples of Crushed Rock from Indianapolis Deep Rock (IDR) Tunnel Project

A set of five tests (Table 9-3) were performed on IDR samples in order to compare the difference in abrasive properties of the sample with and without conditioner. In addition, since torque plays a significant role in EPB tunneling, torque was measured during each of these tests and comparisons were made between the conditioned and unconditioned samples to see the potential for torque reduction. Prior to testing, the samples were crushed to less than 4.75 mm in size. Table 9-3 summarizes the results of performed tests on this sample.

Table 9-3. Soil conditioning tests performed on IDR samples

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>Average Torque (N.m)</th>
<th>Weight Loss in 60 min (g)</th>
<th>Conditioning Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDR 0-Dry</td>
<td>214.5</td>
<td>2.005</td>
<td>-</td>
</tr>
<tr>
<td>IDR’ 7.5</td>
<td>1476.48</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IDR’ 11</td>
<td>755.12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IDR 15</td>
<td>81.4</td>
<td>3.331</td>
<td>-</td>
</tr>
<tr>
<td>IDR 15</td>
<td>42.7</td>
<td>1.448</td>
<td>2% Conc. ABR 5,FIR=20%, FER=15</td>
</tr>
</tbody>
</table>

No abrasion results are available due to high amount of torque

Figure 9-11 shows the tested samples in different conditions after abrasion testing. Due to the high amount of torque in tests with 7.5% and 11% water content, the shear pin which connects the propeller to the shaft inside the testing chamber was sheared. The pin was primarily used to protect the testing device against a high amount of torque that could potentially damage the motor and gear box of the testing system. The weight loss of the covers was not reported because the tests halted by the failure of the shear pin within the first 5 seconds.
As one can see in Table 9-3, the IDR material was not very abrasive but the main issue with this material was cementation. Figure 9-11 part (b) displays the material at the bottom of the chamber after performing the test on the IDR sample with 11% water content for less than 5 seconds. Due to a high amount of torque (T=755.12 N.m) the shear pin was sheared and the test was stopped. Figure 9-12 displays the measured torque during the test for 5 other testing conditions.
Figure 9-12. Measured applied torque during the abrasion testing for IDR samples in (a) Dry condition (b) W= 7.5% (c) W=11% (d) W= 15% (e) W=15% conditioned with 2% concentration ABR 5, FIR of 20% and FER of 15

As it is displayed in Figure 9-12 parts (a) and (b), adding soil conditioners to the IDR sample with 15% water content reduced the applied torque to almost half (from 81.4 N.m to 41.7 N.m). In addition, it should be noted that the weight loss of covers was reduced from 3.331 g to 1.448 g, respectively.
Chapter 10

Comparison between SAT Test and Penn State Soil Abrasion Test

Introduction

This Chapter discusses the comparison between the results of soil abrasion testing using the Penn State system and the SAT test developed by SINTEF/NTNU. The NTNU SAT testing procedure as well as its advantages and disadvantages were described in Chapter 2. The reason for this comparison is because the SAT test has been used by the tunneling industry in a few projects in the past years. Obtaining any relationship or correlation between the PSAI and the SAT will allow the use of some of the machine performance databases where SAT tests were performed to evaluate the ability of PSAI in predicting the wear on these machines. The study of SAT has been conducted on the testing device at Penn State University and provides for evaluating the sensitivity of the SAT testing system to some of the controlling parameters.

Selected Samples for Comparison

Five sets of samples are used for the comparison of these two tests. The samples are Silica sand, Limestone sand, ASTM 20/30 sand, ASTM Graded sand, and Silty sand. The properties of these soil samples were provided in Table 6-1.

SAT Testing Parameters

A duplicate of the SAT testing system was built at Penn State University based on the descriptions by Bruland (1998) and interactions with the laboratory personnel at NTNU in
Trondheim, Norway. However, in general description, there are several testing parameters such as flow rate, grain size distribution of soil samples, roughness and hardness of the rotating steel disk, and the hardness of the steel wear pieces unclear. The impacts of these controlling parameters on the test results needed to be checked.

For example, a low flow rate causes the steel wear piece to run against the body of the turn table and that can change the SAT values significantly. An excessive flow rate causes plugging of the sample groove and passing of the sample on the sides of the wear piece. In the test manual offered by Bruland (1998), a flow rate of 80 g/min is reported only as a guideline and it should be adjusted for each soil sample prior to performing the test. No specification is provided on how this adjustment should be performed.

The roughness of the rotating steel is another important factor and based on the communication with the NTNU staff, the surface of the track should be slightly roughened by running the crushed quartz on the track as the test material or alternatively sand blasting the surface. Finally, the hardness of wear pieces is important since generally harder material tends to abrade less.

In order to study some of these parameters, it was decided to perform a set of parametric studies to understand the procedure of the SAT test in a systematic manner. Different flow rates from 80 g/min to 560 g/min were used in the testing matrix to capture the sensitivity and importance of the flow rate. Also, different steel hardness ranging from 20-60 HRC were used in order to examine the importance of the pin hardness in the testing results. It should be noted that the test results on the SAT testing machine at the Penn State rock mechanics laboratory is the value of weight loss on the wear piece and is shown by SAT∗. The term SAT, as it is reported by NTNU and used in the industry, represents a standard test setting at NTNU and is copyrighted by SINTEF/NTNU, and what is reported here is the interchangeable use of the measured amount of wear on the wear piece using equipment similar to the NTNU device. The actual values of SAT
are only the ones that were conducted by NTNU staff at their facility and they will be identified as such in this Chapter.

Review and Discussion of SAT\textsuperscript{*} Test Results

Silica sand Samples

Figure 10-1 displays the results of SAT\textsuperscript{*} testing on Silica sand samples. As shown in this Figure, flow rates of 80, 100, 120, 420 g/min were used for testing and the tests were performed on 20, 36, and 60 HRC steel pins. The general trend is that by increasing the flow rate the SAT\textsuperscript{*} value increases. Figure 10-2 displays the medians of the performed individual tests in each setting. It is interesting to note that by increasing the hardness from 20 to 36 HRC, the SAT\textsuperscript{*} values are slightly increased or remained in the same range. This trend is in agreement with the result of Penn State soil abrasion testing where increasing the hardness of covers from 17 to 43 HRC caused little change in the weight loss of the covers in a dry condition.
Figure 10-2. Median of three performed SAT tests on Silica sand samples for different flow rate settings

In addition, based on the results of performed SAT tests, it can be concluded that the 120 g/min flow rate is a reasonable set-up for this sample. As it is displayed in Figure 10-2, from 80 to 100 g/min flow rate, the SAT value decreases. This can be due to reduced steel-against-steel abrasion as the flow rate increases. In the mean time, there appears to be no significant difference between the results of tests at 100 g/min and 120 g/min flow rates. This shows the reduction of the influence of the flow rate on the testing results and the possibility of getting more-consistent results that are somewhat independent of the feed/flow rate. The 420 g/min flow rate represents a flow rate at which the surface of the rotating steel disk is completely covered by the Silica sand material (Figure 10-3). It should also be noted that the flow rate in g/min represents a volumetric description if the density of the samples are the same. If the dry density of a sample were to be higher, it was reasonable to assume that the increased rate would be required to achieve a certain area coverage on the track of the testing device.
Figure 10-3. Picture of 420 g/min flow rate set-up for Silica sand sample during SAT* test

**Limestone Sand Samples**

Figure 10-4 and 10-5 display the results of SAT* testing on Limestone sand samples. As it is displayed in these Figures, flow rates of 80, 100, 120, 360 g/min are used for testing and tests are performed on 20, 36, and 60 HRC steel pins.
Figure 10-4. Individual results of SAT* test on Limestone sand samples for different flow rate settings

Figure 10-5. Median of three performed SAT* tests on Limestone sand samples for different flow rate settings

As it is shown in Figures 10-4 and 10-5, the SAT* values are very low for Limestone sand samples. The variation of testing results at the 80 g/min flow rate is very high as compared to 100, 120, and 360 g/min. At 100 and 120 g/min flow rates the SAT* values are zero. As shown in Figure 10-5, by increasing the hardness from 20 to 60 HRC at the 80 g/min flow rate setting, the SAT* value decreases to zero. This can be explained by the fact that since the hardness of the turn table is around 60 HRC, steel-against-steel abrasion has a higher impact on 20 and 36 HRC wear pieces as compared to 60 HRC wear pieces. Based on the results of flow rate analysis, the
120 g/min flow rate is selected as a representative flow rate for Limestone sand. It should be noted that the wear mechanism for the SAT test is three-body abrasion; therefore, the SAT values in this case are lower than the Penn State soil abrasion testing set-up which represents a two-body abrasion test.

Since the Limestone sand is very soft, a layer of ground material tends to cover the surface of the turn table (Figure 10-6). The existence of this layer reduces the wear piece-on-disk set-up contact and therefore does not cause much wear on the tool. In addition, in contrast to Silica sand samples, when using the 360 g/min flow rate setting test (where the surface of the turn table is covered with the Limestone sand) the SAT values were higher.

Figure 10-6. Pictures of (a) 360 g/min flow rate set-up for Limestone sand before test (b) A layer of ground Limestone sand has covered the turn table after the test
ASTM 20/30 Sand Samples

Figures 10-7 and 10-8 display the results of SAT* testing on ASTM 20/30 sand samples. As it is displayed in these Figures, flow rates of 80, 100, 120, 140, 160, 180, 560 g/min were used for testing and the tests were performed on 20, 36, and 60 HRC steel pins. In contrast to Limestone sand and Silica sand samples, the grains of the ASTM 20/30 sand samples are categorized as round.

Figure 10-7. Individual results of SAT* test on ASTM 20/30 sand samples for different flow rate settings

Figure 10-8. Median of three performed SAT* tests on ASTM 20/30 sand samples for different flow rate settings
As shown in Figures 10-7 and 10-8, 60 HRC steel wear pieces show a much better trend and less variation in comparison to 20 and 36 HRC steel pins. This can be explained by the fact that since the turn table is made of 60 HRC hardness steel, the effect of steel-against-steel abrasion is minimized compared to the other two hardened pins (i.e., 20, 36 HRC). The 560 g/min flow rate represents a flow rate which the surface of the rotating steel disk was completely covered by the ASTM 20/30 sand material.

During the SAT\* tests at a low flow rate, it was observed that the rounded sand grains tend to bounce off of the turn table as soon as they contacted the steel pin and by increasing the flow rate, this trend was reduced. This is a factor that can impact the results of this test since the material needs to be forced under the wear piece in order to abrade it, and in samples with round particles this issue can significantly affect the results of testing.

![Figure 10-9](image)

Figure 10-9. Pictures of (a) 100 g/min flow rate set-up for ASTM 20/30 sand (b) 560 g/min flow rate set-up for ASTM 20/30 sand

In addition, as it was discussed in Chapter 6, sphericity and roundness are major parameters that influence the abrasive properties of the soil. In the proposed Penn State soil abrasion testing system, wear caused by the angular particle Silica sand sample after 1 hour of testing was much higher than the wear caused by round ASTM 20/30 sand samples (i.e., 23.2936 g, 0.4564 g). In contrast to PSAI testing results, the SAT\* tests show higher measured abrasion values since the wear piece crushes the material and, consequently, ASTM 20/30 with round
grains and Silica sand samples with angular grains result in much closer SAT\(^*\) values. Based on the results of the flow rate analysis, a 140 g/min flow rate was selected as a representative flow rate for ASTM 20/30 sand for SAT\(^*\) testing.

**ASTM Graded Sand Samples**

Figures 10-10 and 10-11 display the results of SAT\(^*\) testing on ASTM Graded sand samples. As shown in these Figures, flow rates of 80, 100, 120, and 240 g/min were used for testing and the tests were performed on 20, 36, and 60 HRC steel wear pieces. Similar to the ASTM 20/30 sand, ASTM Graded sand is categorized as round grains but contains a narrower (and smaller) grain size distribution as can be seen in Figure 6-1.

Figure 10-10. Individual results of SAT\(^*\) test on ASTM Graded sand samples for different flow rate settings
Figure 10-11. Median of three performed SAT\textsuperscript{*} tests on ASTM Graded sand samples for different flow rate settings

Based on the obtained test results, one can conclude that 60 HRC pins caused less variation as compared to 20 and 36 HRC wear pieces. In addition, since the grain size distribution of ASTM Graded sand is smaller than ASTM 20/30 sand, less bouncing of the grains was observed. Furthermore, the variation of individual testing results was smaller compared to the tests performed on ASTM 20/30 sand. It should be noted that despite the fact that the grain size distribution of ASTM Graded sand is smaller compared to ASTM 20/30 sand, the SAT\textsuperscript{*} testing results for ASTM Graded sand are higher.

The 240 g/min flow rate represents a flow rate where the surface of the rotating steel disk was completely covered by the ASTM Graded sand material. Based on the results of flow rate analysis, the 120 g/min flow rate was deemed the appropriate flow rate for ASTM Graded sand.

**Silty Sand Samples**

Figures 10-12 and 10-13 display the results of SAT\textsuperscript{*} testing on Silty sand samples. These Figures illustrate flow rates of 80, 100, 120, and 240 g/min for testing using 20, 36, and 60 HRC...
steel wear pieces. The 240 g/min flow rate represents a flow rate where the surface of the rotating steel disk was completely covered by the Silty sand material (Figure 10-14b).

Figure 10-12. Individual results of SAT* test on Silty sand samples for different flow rate settings

Figure 10-13. Median of three performed SAT* tests on Silty sand samples for different flow rate settings

Figures 10-12 and 10-13 indicate that 60 HRC wear pieces show less variation as compare to 20 and 36 HRC steel pieces. In addition, at the 80 g/min flow rate, the effect of steel-against-steel abrasion was visible (Figures 10-13 and 10-14a). Based on the measurements made on these samples, the 120 g/min rate was selected as the representative flow rate for Silty sand samples.
Steel-against-Steel Abrasion

In order to study the effect of steel-against-steel abrasion a set of tests were performed using 20, 36, and 60 HRC wear pieces run on the empty track. These tests were run to measure weight loss of the wear piece after 1 minute of testing at a rotational speed of 20 rpm. Figure 10-15 displays the results of steel-on-steel abrasion on 20, 36, and 60 HRC wear pieces. As it was
discussed in the previous sections of this Chapter, 20 and 36 HRC wear pieces wear as they are rubbed against a higher-strength (60 HRC) turn table. Figure 10-16 shows the picture of 20, 36, and 60 HRC wear pieces after the steel-against-steel tests. As can be seen, the amount of abrasion is reduced as the hardness increased.

Figure 10-15. Median of three performed steel-against-steel SAT\textsuperscript{*} tests on different hardened pins

Figure 10-16. Pictures of 20, 36, and 60 HRC pins after the performed steel-against-steel SAT\textsuperscript{*} test
Summary

The sensitivity of the SAT testing system was examined for a variety of factors in this Chapter. The performed test results indicate that the representative flow rate for Silica sand, Limestone sand, ASTM 20/30 sand, ASTM Graded sand, and Silty sand are 120, 120, 140, 120, and 120 g/min, respectively. These flow rates were selected based on the results of parametric studies on the flow rate for each of these samples, and they represent the range where the slight changes in flow rate does not change the SAT\(^*\) results. It should be noted that several tests with different flow rates should be performed for each sample in order to select a representative flow rate. Steel-against-steel abrasion should be minimized during the SAT\(^*\) test. The results of performed SAT\(^*\) tests showed that 60 HRC wear pieces were more resistant to steel-against-steel abrasion compared to 20 and 36 HRC pins. As it was mentioned earlier, the hardness of steel pins and the round table in addition to the roughness of the turn table are not specified in the available descriptions in the NTNU publications. Furthermore, the SAT test is sensitive to grain size distribution as well as sphericity and roundness of particles. The SAT test is modified from the AV/AVS abrasion test that was originally designed for rock. In the AV/AVS test, the rock is crushed to less than 1 mm in size for testing. There is no problem for the samples with less than 1 mm in size to be crushed by the pins, but as it was observed in performed SAT\(^*\) tests in this study, most of the larger particles (between 2-4 mm in size) tend to avoid getting under the wear piece and the grains generally escape from the sides without any contact with the wear piece.

In addition, round particles in general (large or small particles) tend to bounce off of the turn table. This can cause a major issue in the SAT test results. Finally, the consistency and repeatability of the testing results should be closely controlled in the SAT test. Despite the precise control of the testing conditions, the variability of test results could be high (up to 100% higher SAT\(^*\) values are recorded in some tests).
Figure 10-17 shows the results of SAT* by using 60 HRC steel pieces and flow rates of 120, 120, 140, 120, 120 g/min for Silica sand, Limestone sand, ASTM 20/30 sand, ASTM Graded sand, and Silty sand respectively versus the PSAI values by using 17 HRC covers.

In the case of comparison between SAT* test results and the proposed soil abrasion testing system introduced by Penn State University, the Penn State testing system is more reliable in quantifying the wear for non-abrasive material such as Limestone sand (1.269 g) compared to SAT* test (zero). This can be explained due to nature of the SAT test and the impact of steel-to-steel wear on the turn table. A two-body wear system can register higher abrasion as compared to a three-body abrasion system. In addition, since the SAT test changes the abrasive properties of the testing material during the test, it cannot quantify the effect of sphericity and roundness of particles on abrasion. For example, the SAT* value for Silica sand (angular and highly abrasive) ASTM 20/30 and ASTM Graded sand (both round and highly abrasive) are 41.94, 32.1 and 30.25, respectively, as compared to the results of Penn State testing system (i.e., 22.5539, 0.4564, and 0.3437 respectively). Despite the fact that these three types of sand are highly abrasive, in the PSAI testing system, due to the higher sphericity and roundness of ASTM 20/30 and ASTM Graded sand, they result in much lower weight loss compared to Silica sand (angular) obtained.
from crushed rock. This factor cannot be accurately characterized in the SAT test, since the sample containing larger grains will be crushed to less than 4 mm in size, meaning a change in the grain shape, and thus abrasion behavior. Similarly, if the soil sample contains rounded grains but smaller than 4 mm, they will be fed to the turn table, and these grains will be crushed during the SAT test, thus changing the abrasion behavior of the samples.
Chapter 11

Conclusions and Recommendations

Findings of This Study

The issue of soil abrasion and its impact on machine performance and wear of the cutters and other machine components is very important. This issue is increasingly becoming a major contractual issue in tunneling projects. Prediction of the wear rate on the cutters has not been very successful due to lack of a standard testing method for measurement of soil abrasion. To address this issue, a new soil abrasion testing method has been developed at Penn State University that is based on the anticipated interaction between the soil and various components of a shielded tunneling machine. The results of testing by using the proposed soil abrasion testing apparatus at Penn State University shows a great potential for making relevant measurements of soil abrasion characteristics in a setting that closely simulates the working conditions of the mechanized soft-ground tunneling. The setting allows for the simulation of the soil flow pattern, high contact stresses, moisture content, various ambient pressures, and preserving original soil composition. The results of this study confirmed the capability of the proposed testing system in distinguishing between various soil types and their impact on tool wear. Major findings of this study are summarized in the following sections:

General Observation on Soil Abrasion Testing

- The study of the available soil abrasion testing techniques showed that the existing testing methods were unable to provide testing conditions similar to those in the tunneling operations using pressurized face shielded machines. This includes alteration
of the original grain size distribution, deviation from the nature of the contact stresses between the tool and the soil, inability to incorporate moisture content and elevated ambient pressures, and ignoring the impact of soil conditioning on tool wear that is a standard practice in soft ground tunneling.

- The developed soil abrasion testing system at Penn State is a close simulation of the nature of the contact and wear in soft-ground tunneling. It allows for inflicting measurable wear in a short period of time while preserving the soil grain distribution. By using this testing system, the effect of water content and ambient pressure on wear can be investigated. In addition, the system allows for observation of changing operational parameters on soil abrasion and wear of various machine parts.

- The testing system does not cause major changes in soil grain size distribution and shape in terms of sphericity and roundness. This was evident in several tests where the grain size distribution and shapes were studied before and after testing.

- Wear of tools showed to be a function of time, thus tests were performed at certain time intervals to track the tool wear versus time during the testing.

- The testing system was used to develop a soil abrasion index (PSAI) and the results have been proven to be repeatable and consistent. The PSAI index is based on the measured wear on special wear parts made of steel of known hardness and represent the abrasivity of the given soil under prescribed testing conditions.

- Various soil types have been tested to evaluate the impact of grain size distribution, gain shape, mineral content and mineral hardness, moisture content, ambient pressures, and other testing parameters on wear. The soils tested include Silica sand, limestone sand, ASTM standard sands (ASTM 20/30 and ASTM Graded), and quartz rich Silty sand, in addition to soil samples from some tunneling projects in the US.
Effect of Soil Overburden on Soil Abrasion

- The study of the amount of soil used in testing or alternatively height of the soil in the testing chamber showed a good relationship with the amount of wear on the special wear plates. The relationship seemed to be almost linear when testing crushed Silica sands.
- Based on the parametric study on the required amount of material for each test, 40 kg (~90 lbs) of material was selected as a baseline for all performed tests and for standard PSAI testing.

Effect of Pitch Angle of the propeller on Soil Abrasion

- The impact of contact stresses as measured by the pitch angle of the propeller was very important and the propeller with a $10^\circ$ pitch angle created the highest contact stress and compaction in the soil. This was concluded by testing a range of pitch angles from 10-30° and the maximum wear occurred at $10^\circ$ pitch angle. Increasing the pitch angle from 10 to 30 degrees caused higher torque and lower weight loss.

Effect of Tool Material Hardness on Soil Abrasion

- The results of parametric study showed that the tool wear is not as sensitive to tool hardness as it was initially assumed. In other words, the wear does not drop proportional to increase in hardness as measured by Rockwell Hardness scale (HRC). In many tests the wear on the harder covers were similar to the wear effects on the covers with lower hardness. In general, the increased hardness of the blades (tools) will impact the wear but does not reduce the wear by a proportional rate in dry soil.
The testing included tool hardness ranging from 17 to 60 HRC and the difference in measured wear when tested in Silica sand was small. The variations and trend in moist and saturated samples did not show a consistent pattern.

The wear characteristics of the chromium carbide are much superior to the hardened steel despite the closeness of hardness of the two materials. This could be due to the increased relative hardness of tool/soil but it is consistent in both moist and dry soils, as opposed to the observed behavior of steel even when it is hardened to 60 HRC.

Effect of Moisture Content on Soil Abrasion

The effect of moisture content is very significant and the presence of water in the soil medium can change its behavior drastically and increase the soil abrasivity, especially at the moisture content in dry of the optimum water content for maximum compaction in which the soil samples get densely compacted under the propeller.

The increased strength of the soil through dynamic compaction of the soil by propeller blade can have a notable impact on tool wear and increase the tool wear by a high percentage.

Apparent soil abrasion decreases with increased moisture content beyond the above-noted optimum percentage, to the point that the abrasivity of the saturated soil sample is less than it is for dry soil. In crushed Silica sand the amount of wear was measured to be around 22 g in a 60 minutes test in dry condition, as opposed to around 25 g in a 10 minutes test when the soil was moist (~10% water content), and the wear dropped to less than 4 g in 60 minutes in saturated conditions.

Moist samples (W=12.5%) caused higher torque compared to dry and saturated samples (W=22.5%) in Silica sand. The amount of torque in Limestone sand was much higher
than the amount of torque in the Silica sand sample in moist conditions (W=12.5%). Despite the higher amount of torque in Limestone sand, the weight loss is much less than the weight loss for Silica sand.

**Effect of Ambient Pressure on Soil Abrasion**

- The result of testing the Silica sand in saturated condition under atmospheric pressure as well as 310 and 620 kPa (45 and 90 psi) pressures showed that increased ambient pressure will increase the wear by a small increment. This confirms the actual phenomena that happens in the field and has been observed by various machine manufacturers and operators.

**Effect of Grain Size and Shape on Wear**

- Angularity of the particles plays a significant role on abrasion. Despite the high quartz content in Silica sand, ASTM 20/30, and ASTM Graded sand, the amount of weight loss of covers in round samples (ASTM 20/30 and ASTM Graded sand) was significantly lower than for angular samples (Silica sand from crushed rock).
- The finer-grained soil shows lower abrasion, even at relatively high quartz content. In other words, while the Silty sand sample contained substantial amount of fine particles of quartz, it showed much lower abrasion compared to the Silica sand.
- The impact of tool hardness was more significant in the Silty sand sample and could be a very important factor in increasing tool life in fine-grain soil.
Effect of Rotational Speed of Propeller on Wear

- Increasing the rotational speed resulted in higher torque and higher weight loss of covers in sand-size samples.
- Tests performed at 60 rpm show consistent torque during the test. In contrast to 60 rpm testing set-up, performed tests at 105 and 180 rpm showed torque reduction during the test.
- The higher flow speed and the dynamic impact of soil movement resulted in lower wear and lower torque for Silty sand material.

Consistency and Repeatability of the Testing Results

- The testing system’s repeatability and consistency of the results is within ±4% of the average values. This indicates that the tests are reliable and reproducible.
- The comparative testing of the samples by different operators showed that the proposed new soil abrasion testing system is not operator sensitive.

Penn State Soil Abrasion Index (PSAI)

- Based on the performed parametric study, the rotational speed of 60 rpm, a propeller pitch angle of 10°, and a cover hardness of 17 HRC were selected as the standard testing set-up. The standard test could be performed at various moisture contents including a dry sample, a soil with water content slightly lower than optimum for compaction, and a saturated soil.
A formula was introduced to estimate the anticipated wear at 60 minutes of testing and this value will be used as the PSAI for given soil under various testing conditions. This is to allow for shorter tests in moist/abrasive samples to be extrapolated to 60 minutes and therefore the impact of time on tool wear can be eliminated.

The standard testing set-up will be used to measure the soil abrasion index (PSAI) which is introduced as the result of this study. Moreover, a preliminary soil classification is provided based on the results of performed tests and measured PSAI Indexes during this study.

**Effect of Relative Hardness on Soil Abrasion**

- Percent quartz or, in general, weighted-average Mohs hardness (equivalent quartz content) of the minerals has an impact on wear characteristics of the soil as anticipated.
- The testing of the samples with various relative hardness which was prepared by using controlled proportions of silica and limestone sands (crushed stone) showed that the anticipated inverted S-curve that is well-known in tribology studies can be generated when the tool hardness is kept constant and material hardness is changed by changing the mixing ratio of abrasive and non- abrasive soils.
- The change in tool hardness will shift the inverted S-curve, meaning that the absolute value of the relative hardness is not the determining factor for wear.
- The behavior of the tribological system and wear of tools in various soil mixtures will change at the presence of water. The trends are not monotonic.
Effect of Soil Conditioning on Abrasion

- The application of foam and other soil-conditioning agents can reduce the wear and torque significantly; the initial tests on three different types of material showed that the use of soil conditioner could reduce the wear at least by two orders of magnitude.

Comparison between SAT Test and Penn State Soil Abrasion Test

- SAT or soil abrasion test which has been recently developed by NTNU in Norway and used in some projects is compared to the PSAI index. The comparison showed the benefits of the PSAI system in several characteristics, such as quantifying the abrasivity of the fine and non-abrasive material, quantifying the abrasivity of different soils by considering the sphericity and roundness of the particles, repeatability and consistency of the performed test results, combination of two- and three-body abrasion as a main wear method, ability to perform tests with different moisture contents and by applying different ambient pressures, and no need for change in grain size and shape of the soil samples during the sample preparation.

Recommended Follow-up Study

The development of the testing device has opened the door to a variety of research opportunities in this field. The response of the tunneling industry towards this study has been very strong and positive. There have been some indications and pledges for support and collaboration by the industry in future efforts. These pledges will be pursued to expand the use of this index in geotechnical site investigations and for prediction of wear on various soft-ground
tunneling machines in the future. The following is a list of research topics that can be considered for future studies on soil abrasion by using the new test device:

**Laboratory Work**

- Study of the soil physical and index properties such as grain size distribution, sphericity and roundness, uniaxial compressive strength, shear strength, cohesion and friction angle, hardness, etc on various soil samples in addition to measuring the abrasive properties by using the developed testing system at Penn State. This will pave the way to examine the relationship between soil properties and PSAI.

- Extending the measurements of the torque and axial forces to use the new testing device as a rheometer for various soil types and moisture conditions. Understanding the rheological properties of the soil can lead to understanding of soil movement inside the pressurized chamber and screw conveyor of the TBMs, which can pave the way toward the understanding of the wear phenomena in the cutterhead, pressurized chamber and screw conveyor of the TBMs.

- Study of the tribological parameters of the soil and variation of the relative hardness in dry and moist conditions to see the possibility of reducing the wear on various machine components using materials with different hardness.

- Surface characterization of the worn material to identify the mode of failure in the tools and thus develop a better understanding of the wear mechanism. This could be performed by using the Scanning Electron microscope (SEM) to analyze the surface of the worn material and, if needed, perform high-definition profilometry of the worn surface.
Study of various tool materials and improvements and optimization of the hardness for anticipated working conditions. This could include increasing or decreasing the tool hardness to reduce the anticipated cost of manufacturing while improving tool wear.

Field Work

Measurement of the actual wear in the field followed by an effort to predict the wear. A representative wear prediction model can be developed by the use of the developed soil abrasion test during the design phase of the tunnel, validating the abrasivity of different soil types during the excavation, monitoring the operational parameters of the TBM, tracking the actual wear during the excavation in different soil types, and creating a database for different soil types. The predictive model can then be obtained from the statistical analysis of wear data against soil properties and machine operational parameters.

Comparison of the effect of soil conditioners and their impact on tool wear and torque between laboratory studies and field studies. This would allow for optimization of soil conditioner settings in the field for various soil types to reduce machine wear and torque. In addition, this study will help in understanding the effect of operational parameters of the TBM such as foam injection and expansion ratios (FIR and FER), and agent to water ratio that can be used for developing wear prediction models.
REFERENCES


ASTM D1557, 2012. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft$^3$ (2,700 kN-m/m$^3$)), ASTM Standards.


TWI Ltd Web <http://www.twi.co.uk/home/> (visited 14 Nov 2012).


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• 2nd rank in graduate student poster contest with the poster “Impact of Abrasion in Soft Ground Excavation Machinery and Development of a Reliable Soil Abrasivity Index”, SME Conference, 2011, Denver, CO
• 2nd rank in student paper competition with the paper “Tool Wear Issue in soft Ground Tunneling, Developing a Reliable Abrasivity Index”, North American Tunneling Conference, June 2010, Portland, OR
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PUBLICATIONS

• More than 30 journal and conference papers related to the field of tunneling and geomechanics