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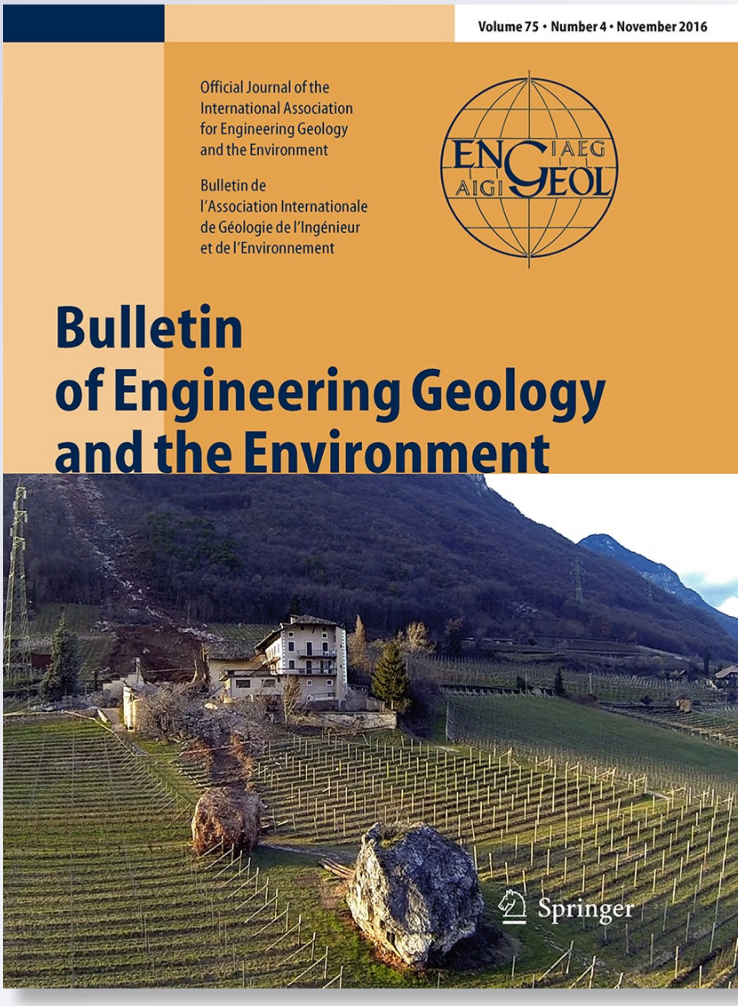

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ORIGINAL PAPER

Impact of some geological parameters on soil abrasiveness

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Abstract A systematic estimation of the amount of tool wear is nearly impossible because there is no universally accepted test for determining soil abrasiveness. Laboratory devices that have been developed in recent years have fewer limitations than older methods, but they are unique and are under development. A new device has been developed and used at the Ferdowsi University of Mashhad, Iran, to evaluate how geological factors affect soil abrasion behavior. Samples with known geological characteristics including hardness (mineralogy), grain size, and grain roundness were prepared and tested using the new abrasion test unit. The results indicate a direct linear relationship between the relative mineral hardness (Mohs scale) and abrasion. Moreover, the results of the abrasion testing showed increasing abrasion with grain size and angularity. Furthermore, the impact of moisture content was also examined, and the amount of measured wear followed an approximately bell shaped curve relative to the water content, as has been reported in similar studies by other research groups. Additional testing of the samples for shear strength showed a good correlation between the shear strengths of the specimens and the abrasivity.

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Keywords Mineral composition of soil · Cutting tool · Soil abrasiveness · Soil physical properties · Moisture content · Shear strength

Introduction

Abrasiveness is the potential of a rock or soil to cause wear on a tool (Plinninger and Restner 2008). Soil abrasion and the resulting tool wear affect machine use, time, and cost of excavation in soft ground tunneling. One of the problematic aspects of working in abrasive grounds is the frequent need for the inspection and replacement of cutting tools, especially in pressurized face tunnel boring machines (TBMs). The risks of excessive primary wear of cutting tools and secondary wear of the other machine components will impose heavy maintenance costs on the project.

Practical experience in mechanized tunneling, especially in abrasive grounds, has proven the importance of the wear of various machine parts that are in contact with the ground. Therefore, the determination of more precise characteristics for abrasion could be a key factor for successful tunneling under such ground conditions. Understanding the abrasive behavior of the ground can help improve tool and cutterhead design, assist in choosing appropriate tunneling technology, and help optimize soil conditioning and the planning of proper construction processes, i.e., logistics, operations, and maintenance. This knowledge can influence machine use, scheduling, and total project cost.

The effect of worn and damaged TBM cutter heads has been documented for numerous tunnel projects around the world. A reliable prognosis of the abrasiveness of soils on a project would be of great benefit for designers, clients, and contractors (Nilsen et al. 2006). Severe primary and secondary wear in the East Central Interceptor Sewer (ECIS) project in Los Angeles and Porto Metro, Portugal, were discussed by Nilsen et al. (2006). The wear of the cutterhead on the 4th Elbe tunnel in Germany was reviewed by Wallis (2000). Moammeri and Tarigh Azali (2010) reported on the impact of high abrasivity on some TBM projects in Iran, including the Esfahan metro line 1, Shiraz metro line 1, Ghomroud water tunnel, and Tabriz metro line 1.

A number of abrasion tests exist for rocks, and some have been proposed for soils; however, none have been successful for properly estimating soil abrasivity and consequently have failed to gained global acceptance. There is no universally accepted or international standard test for soil abrasivity testing (Thuro and Plinninger 2007). Some soil abrasion tests [e.g., NTNU/SINTEF Soil Abrasion Test^{TM} (SAT^{TM}) and Laboratoire Central des Ponts et Chaussées (LCPC)] suffer from important limitations (Alavi Ghrabagh et al. 2013). Additional studies at NTNU on soil abrasion have been underway based on the development of a new device (Jakobson 2014), and work has been undertaken in parallel at the Politecnico de Torino on the same subject (Peila et al. 2013). Rostami et al. (2012) have developed a new system specifically for soil abrasion testing and introduced the Penn State Soil Abrasion Index (PSAI). While the new testing systems have shown promising results, there is an issue of the lack of accessibility to newer tests for other research groups. As a result, a new device has been designed and fabricated at the Engineering Geological Laboratory at Ferdowsi University of Mashhad, Iran. The new apparatus, which is called the Ferdowsi University Abrasion Test (FUAT), has been designed to allow the investigation of the effects of geological parameters on soil abrasivity. This paper will introduce this testing system and the results of preliminary soil abrasion tests that were performed using this unit.

Existing test methods

In recent years there has been a surge in the study of soil abrasion that is pertinent to soft ground tunneling. Alavi Gharehbagh et al. (2011) presented an overview of soil abrasion tests, which can be summarized into the following categories:

1. Methods that are based on measuring geological-geotechnical properties: Mohs Hardness, Vickers Hardness number of the rock (VHNR), Equivalent Quartz Content (EQC), and Abrasive Mineral Content (AMC). These tests consider one aspect of abrasivity phenomenon, namely mineral hardness. Although the measurement of the mineral hardness is necessary, it is not sufficient because these tests cannot capture the impacts of other important factors (e.g., grain size, moisture, and ambient pressure). However, considering important geological-geotechnical properties of soils together are very valuable and is in need of more research. For instance, Köppl et al. (2015) have depicted intrinsic geological-geotechnical parameters, such as hardness of components, grain size, grain shape, and cohesion/friction angle are factors with an influence on the wear to excavation tools in hydro-shield tunnelling in soft ground.
2. Los Angeles test, Nordic Ball Mill test, Dorry's Abrasion test: These tests are designed to determine the abrasion of aggregates for use in road construction. In other words, they measure the resistance of aggregates against impact and rubbing on one another or special metals. Hence, this category isn't suitable for studying the abrasion of wear parts in tunneling.
3. The Cerchar abrasion index (CAI) was introduced for the prediction of drill bit lifetimes in hard rock excavations. During testing, steel pins are scratched against the surface of a rock specimen to determine the abrasiveness by measuring the resulting wear flat on the steel tip (West 1989; Alber et al. 2014).
   The Miller test is used to evaluate the abrasion of a standard steel block that is exposed to a bentonite slurry that contains ground particles (ASTM G75 2001). The test is useful for excavations that are performed using slurry techniques.
   These types of tests are not appropriate to study soil abrasion because they are designed for specific conditions. However, it is possible to use a Cerchar device to measure the abrasivity of coarse grains of soil such as cobbles and boulders, but it does not reflect the behavior of the soil as a whole or other important geological parameters.
4. Devices that are designed and/or developed for the assessment of soil abrasivity: LCPC test (Thuro and Plinninger 2007), SAT^{TM} test (Bruland 1998; Nilsen et al. 2007), Pennsylvania State University soil abrasion testing device (PSU) (Rostami et al. 2012), "TU Vienna Abrasimetre" device (Drucker 2012, 2013), Newly Developed Abrasion Test (NDAT) approach (Barzegari et al. 2013), and the NTNU/SINTEF/BASF Soft Ground Abrasion Test (SGAT) are the most important methods.
   SAT^{TM} and LCPC tests have shortcomings that prevent their effectiveness for representing soil abrasion for tunneling purposes (Rostami et al. 2012). However, Drucker (2012, 2013) introduced a developed form of the LCPC test in order to overcome some of the weaknesses connected with the small sample size and

short sample size spectrum. The PSU method is more complex and can simulate various tunneling conditions (dry, wet, saturated, pressurized, and conditioned soils).The SGAT method makes it possible to evaluate the water content, density/compaction, and use of soil conditioning additives on steel tool life (Jakobsen and Lohne 2013). Generally, the last three approaches (PSAI, NDAT, and SGAT) have fewer limitations, but they are still under development.

The limitations of the methods in categories 1, 2, and 3 and the inaccessibility of the proper devices in category 4 prompted the design of a simple new test to evaluate the effects of various geological factors on soil abrasivity that are pertinent to soft ground tunneling.

FUAT method

The proposed device is illustrated in Fig. 1. The device consists of four M8 steel bolts that are 90 mm in length and have a Vickers Hardness of 179. The four bolts are fastened to a shaft. The vertical distance from the center of one bolt to the center of the next bolt is 20 mm. The lowest bolt is located 25 mm above the bottom of a cylindrical chamber that is 20 cm in diameter. A number of deadweights (5 kg each) are used to provide the desired surcharge loadings. A 1.5 hp drive unit, gear box and inverter are used to rotate the shaft assembly at the desired RPM.

The chamber is filled with approximately 6 kg of soil samples to a specific height of at least 10 cm so that the maximum height of the soil is several centimeters above the top bolt. Subsequently, the planed surcharge loading is placed on top of the soil sample to maintain a positive pressure and to engage the soil with the wear parts or bolts.

The weight of all of the pins before and after the testing is measured precisely to measure the difference and record the weight loss. The sum or overall weight loss is proposed as an index for soil abrasiveness (Fig. 2). The device allows soil samples with grains up to 20 mm in size (fine gravel and finer soils) to be tested. Further improvements in the design, such as improvements in the water tightness of the chamber, are under study to allow for the testing of samples under various ambient pressures.

The results of more than 36 preliminary tests performed on silica sand samples using 15 kg of surcharge loading at 60 RPM for 30 min indicate that the testing is capable of measuring soil abrasion. The preliminary tests were an attempt to examine the relationship between rotation speed, surcharge weight, and test duration and their impacts on soil abrasion. Observations of any alterations of initial sample characteristics, especially grain size distribution and grains angularity, served as an important control. The performed tests showed a negligible change for grain size and roundness. The changes in the plot of grain size distribution (ASTM D6913) for the various testing durations are shown in Fig. 3. Also, Fig. 4 shows the changes in sphericity and roundness after an abrasion test. The grain sphericity (Riley Sphericity) was determined according to Folk (1974), whereas roundness (or angularity) was determined according to Dobkins and Folk (1970). Measurement of diameters of circumscribing and inscribing circles, in the case of sphericity and roundness evaluations, were performed by use of image processing techniques. A comparison of the test characteristics with other soil abrasion tests is presented in Table 1.

The FUAT device was designed to investigate the influences of mineralogy and soil grain on soil abrasion, but to examine the impact of other operational parameters such as soil conditioners and higher pressures in a chamber, some modifications should be implemented. To assess soils with very coarse grains (coarse gravels and cobbles), the size of the device should be increased and a more powerful drive needs to be installed.

Sample preparation

To investigate the influence of geological parameters such as relative hardness, grain size, roundness, and moisture content of soils on the abrasion of tools, a series of tests were performed. The preparation of 6 kg samples from natural soil deposits with controlled characteristics is difficult and time-consuming. Accordingly, three different rock types were selected and crushed to generate silica, orthoclase feldspar and calcite grains, which have Mohs hardness of 7, 6, and 3, respectively. Thus, several boulders from quartz veins of a metamorphic formation (schist and phyllite rocks), blocks of pegmatite zones from a granitic region and pieces of marble were crushed and analyzed for grain size distribution using the standard US sieve series (Fig. 5). This procedure allowed a sufficient volume of samples with consistent mineralogy to be produced as standard soil samples for the testing. The crushed grains were then mixed with additional fines to create samples with different amounts of clay, fine sand, medium and coarse sand, and fine gravel. A Los Angeles testing device was used to obtain samples with various roundness. Therefore, a sufficient number of samples that were manufactured using the stone crushing process were placed in the steel drum without steel spheres, and the drum was rotated for 1–4 and 4–12 h to produce subangular and rounded samples, respectively.

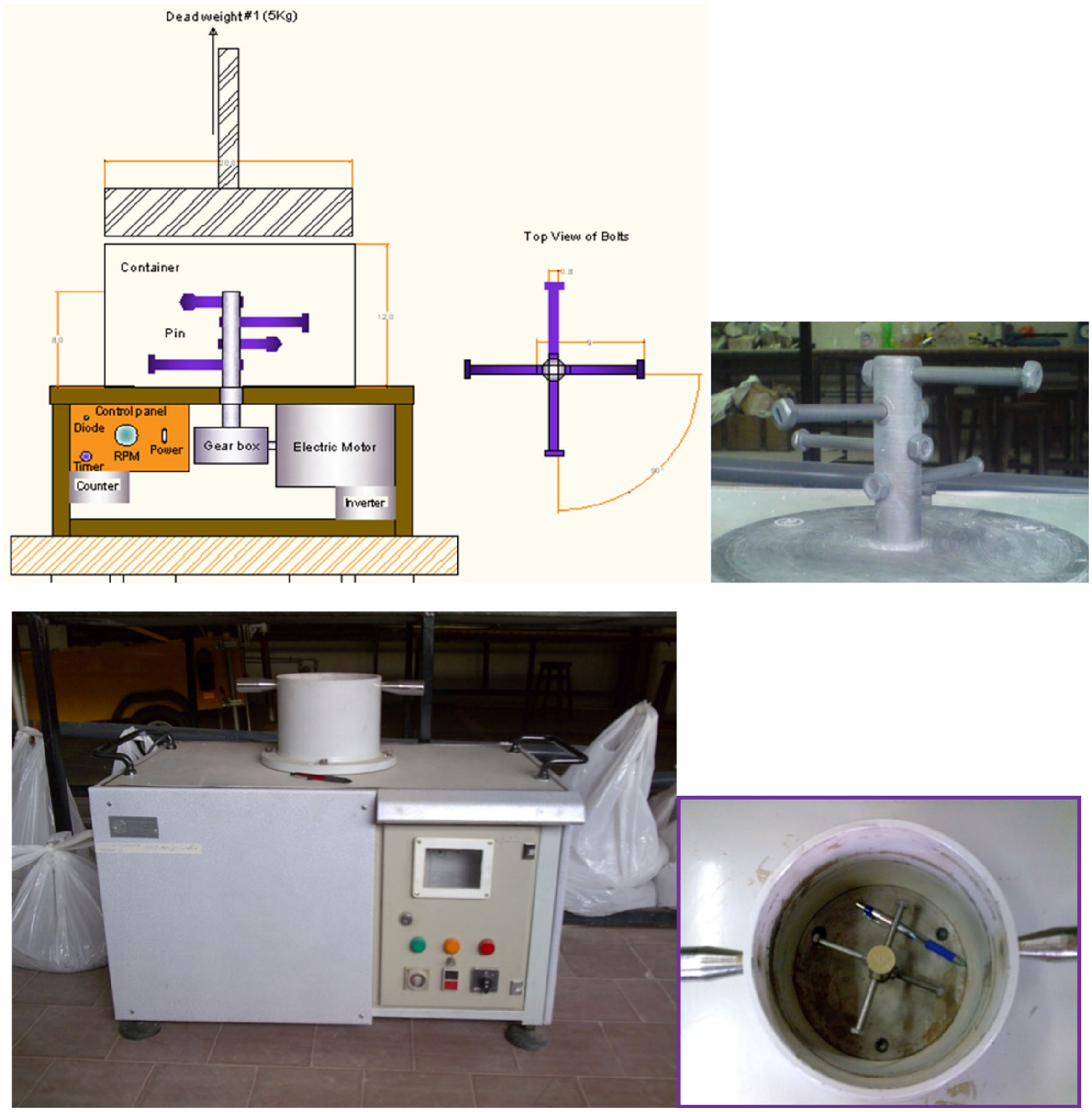

Fig. 1 The FUAT soil abrasion testing device: schematic layout (*upper left*) and its picture in the laboratory; *side view* of the shaft (*upper right*), *front view* (*lower left*), and *top view* (*lower right*)

Results and discussion

Silica sand samples were used to examine wear as a function of changing machine operational parameters. In addition, samples with different minerals were used to study the influence of mineralogical factors on soil abrasiveness.

Effect of surcharge loading, rotation speed, and test duration

A total of 36 tests were carried out on coarse silica sand to measure the effect of surcharge loading, rotation speed and test duration. The results show a direct correlation in the form of a linear relationship between surcharge load and rotation speed versus tool wear. A logarithmic (or power function) relationship was observed between the test duration and tool wear. This coincides with observations by other research groups that are working on soil abrasion testing (Rostami et al. 2012; Alavi Gharabagh et al. 2013)

Effect of relative mineral hardness

As anticipated, a strong relationship between the soil grain hardness and abrasion was observed. Studies by Rostami et al. (2012) and Hashemnejad et al. (2012) concur with the observations in this study. Predetermined mixtures of air-dried fine gravel samples of the three minerals were used in

Fig. 2 Worn (*left*) and original (*right*) wear parts (*standard bolts*)

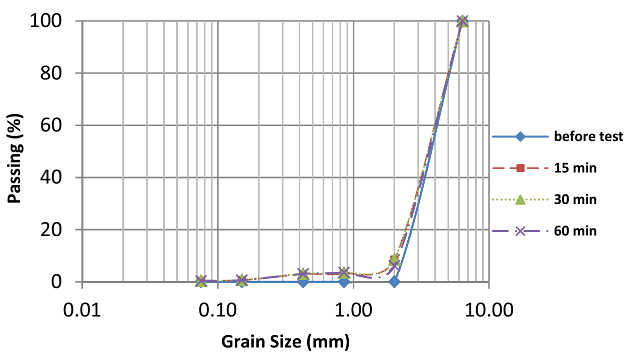

Fig. 3 Changes in grain size distribution during the FUAT test (15 kg surcharge, 60 rpm at 15, 30, and 60 min)

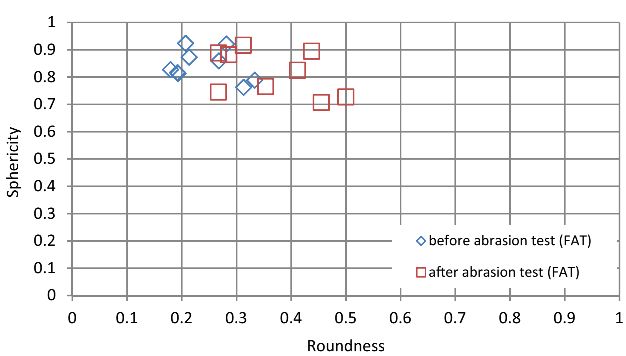

Fig. 4 Changes in grain roundness during the FUAT test (15 kg surcharge, 60 rpm at 30 min)

the testing, with three different angularities (angular, subangular, and rounded). Figure 6 shows the recorded wear as a function of Mohs hardness of the grains in the samples for different grain roundness. The figure shows a direct linear relationship between grain hardness and abrasion. Furthermore, the graph indicates that the weight loss for soils with a grain hardness below 3 (on the Mohs scale) is approximately zero and negligible. This requires additional testing of the tribological system and in-depth study of the relative hardness of the soil/tool, as indicated by Mosleh et al. (2013). Moreover, it can be concluded that there is minimal effect for grain angularity in soils with low hardness; this effect is more pronounced as the mineral hardness increases. In other words, when the relative hardness of the mix is very low, the impacts of grain shape and angularity are insignificant, and as the soil approaches a relative grain/tool hardness near 1, the shape of the grains controls the nature of the contact between the soil grains and the metal surface, and if the grains have pointed edges, there is a higher probability that hard minerals will dig a groove in the metal.

As seen in Fig. 7, a logarithmic relationship is evident for EQC for the same test based on Rosiwal hardness (Thuro 1997).

Effect of grain size distribution and grain angularity

Alavi Gharabagh et al. (2014), Thuro and Plinninger (2007) and Jakobsen et al. (Jakobsen et al. 2013a, b) found that abrasiveness increased as grain size increased. Figure 8 shows the results of the FUAT testing for evaluating the effects of grain size and angularity on soil abrasivity. All of the samples were poorly graded soils. As shown, as the size of the subangular and rounded grains increased, the weight loss increased following a logarithmic function. Non-abrasive samples, which showed no significant change in weight loss as grain size increased, were an exception. A linear relation can be observed for the angular samples. Although a logarithmic trend produced the best regression coefficient, the linear trend shows a high correlation for the subangular and rounded samples. Therefore, a linear relationship was used to show the relationship for the sake of simplicity, but further tests are recommended using different soil abrasion devices to verify this behavior.

The graphs in Fig. 8 show a strong relationship between grain size and soil abrasion, which increased assoil mineral hardness increased. It appears from the graph that the weight loss for the clay-sized samples was negligible, even for abrasive soils. Alavi Gharahbagh et al. (2011) concluded from initial PSU abrasion testing that the presence of a clay material significantly decreased the shear strength of the soil mixture and its abrasive behavior. This may be the main reason for the low abrasivity that was observed in FUAT for the clay-sized quartz. The results confirm testing of a fine grain soil conducted by Alavi Gharahbagh et al. (2011), in which a clay laden soil with 67 % quartz was tested and showed very low abrasivity.

Grain angularity was also evaluated using the FUAT testing device. Figure 9 confirms that the weight loss increased as the grain angularity increased. The magnitude

Table 1 Summary of comparison between FUAT test to the other main soil abrasion testing systems

Soil abrasion testing method	Duration (min)	Rotation speed (RPM)	Surcharge/ chamber pressure	Range of soil grains	Material	Weighing accuracy (g)	Soil Amount per test (kg)
FUAT	30	1–100	0–25 kg	<20 mm	Normal steel (bolt). Vickers hardness 179 (Rockwell hardness of B 88)	0.001	6
SGAT	4	1–100	<6 bars	<10 mm	Standard construction steel. Vickers hardness 227 (HRC 23)	0.001	6.5–8
NDAT	10	20	3 bar	<100 mm	Steel disk (rockwell hardness of B 60–70)	0.001	6
PSU new test	5, 10, 30 and 60	60–180	<10 bar	Up to Large gravel cobble	Steel (17, 31, 43, 51, and 60 rockwell hardness)	0.01	40
LCPC	5	4500	0	<6.3 mm	Soft steel (rockwell hardness of B 60–75)	0.01	0.5
SAT (modified AVS)	1	20	10 kg	<4 mm	Cutter ring steel	0.001	0.08

Fig. 5 Fine gravel samples of calcite (*left*), orthoclase feldspar (*right*), and silica (*down*) in the chamber of the FUAT testing machine

of the increase was influenced by the grain hardness and size. Generally, it can be concluded that grain angularity is a crucial factor in tool wear, particularly in soils with high mineral hardness. As for grain size, the nonabrasive soil mixes showed no sensible effect on abrasivity as the roundness changed.

Effect of moisture content

To examine the changes in tool wear by changing water content, two series of tests were performed: one set on silica sand and another set on silica sand 25 % of microsilica. The silica sand samples had moisture contents of 0, 2.5, 6, 8, and 12 % (saturated condition). The moisture contents of the samples that contained microsilica were 0, 2.5, 5, 7, 8, 11, 12, and 15 % (saturated condition).

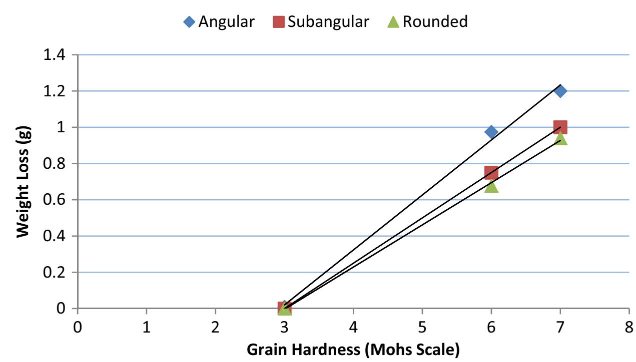

Fig. 6 Relationship between grain hardness and weight loss for samples with different angularity

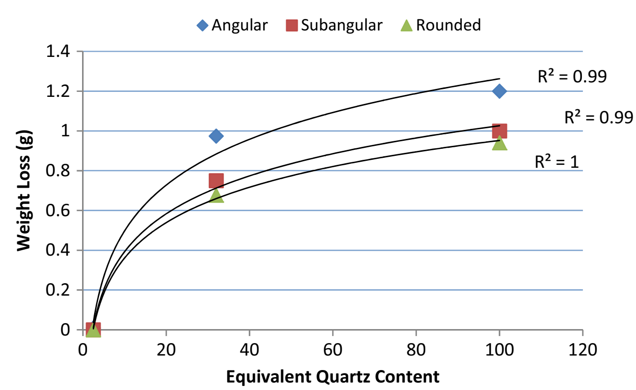

Fig. 7 Correlation between Rosiwal hardness (EQC) of the soil samples and the measured weight loss

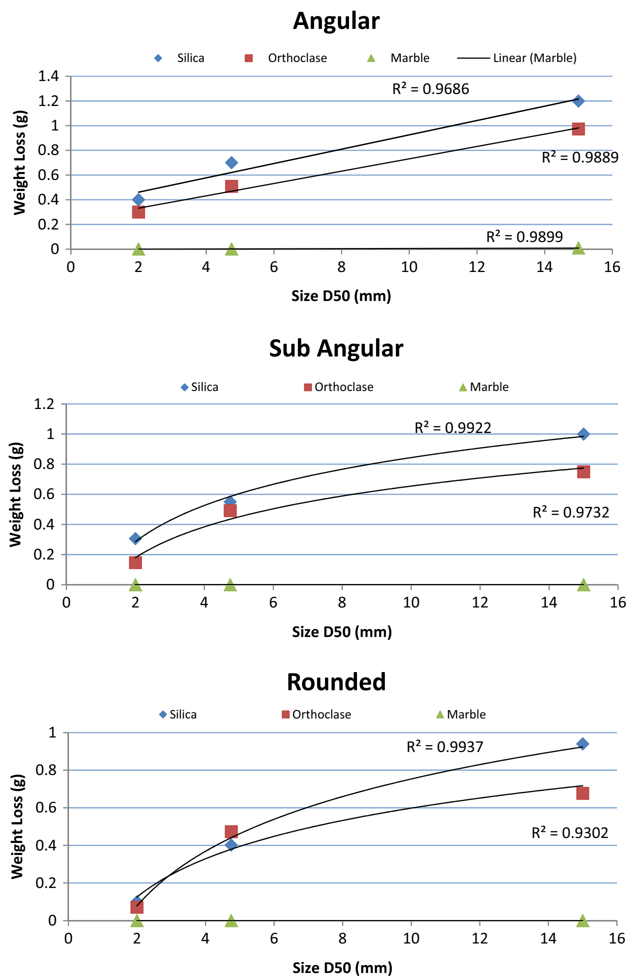

Fig. 8 Variation of weight loss versus grain size of soil samples for angular (*top*), subangular (*middle*), and rounded (*bottom*)

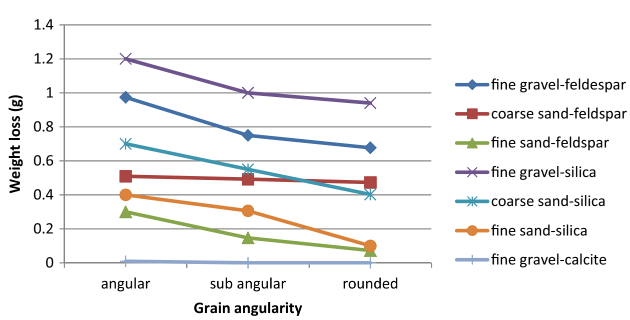

Fig. 9 Weight loss as a function of grain angularity of soil samples with different mineral content

The results verified that an addition of a small amount of water to the sandy soils can cause a drastic change in the abrasive behavior of the mixture. As the moisture content increased, the weight loss increased to a specific point that was slightly less than the optimum moisture in the compaction test. After this peak, the weight loss decreased up to the saturation state.

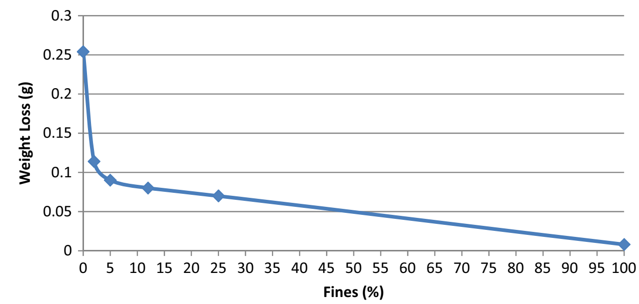

Fig. 10 Influence of different amounts of fine particles in the silica sand samples on the weight loss of the tool in FAUT testing

Obviously, it can be concluded that the water content is a crucial factor in tool wear as well as shear resistance, especially in soils with higher mineral hardness. The findings are useful in tool wear management. More in-depth investigations of the impacts of water and other additives on the abrasive behavior of different soils are essential for future studies.

Effect of fines in silica sand samples

A total of six tests were performed to determine the effect of the presence of fines in the silica sand samples on the abrasive behavior of the soil. This was accomplished by adding various clay-sized particles (microsilica) to the crushed sand samples. The measured weight losses of the tool for these samples are plotted versus the percent fine in Fig. 10.

As seen, the curve has a descending trend with an inflexion point at approximately 2 %. In other words, the addition of the small amount of clay-sized soils to the silica sand drastically decreased its abrasivity. It appears that the effect of the fine particles was two-fold. The first impact was related to the direct contact of the grain with the tools and lower normal stresses, and the second resulted from filling the surface cavities in the coarse grains, which decreased the concentrated contact stresses between the angular grains and the tool surface. In abrasive soils, this finding can be useful for reducing tool wear.

Conclusions

A simple device, FUAT, has been introduced to measure the abrasiveness of soils that have a maximum grain size of 20 mm. The apparatus is still under development, and additional modifications and improvements are expected. The FUAT device provides a reasonable contact between wear parts and soil throughout the soil samples that can simulate the working conditions of tools used in soft ground tunneling applications. The following conclusions were drawn from the preliminary testing of the new device to evaluate the impact of different geological parameters on tool wear:

- There is a high correlation between abrasiveness and the average hardness of the minerals in the soil. A direct linear relationship was observed for the Mohs hardness, and a logarithmic relation was obtained for the Equivalent Quartz Content (EQC) based on the Rosiwal hardness. In addition, the weight losses of the steel tools with a Vickers Hardness of 179 that were measured in samples with hardness values of <3 on the Mohs scale were negligible.
- Logarithmic and linear relationships were established between the grain size of soil samples and abrasion on the tools. The abrasivity of the fine grained soil samples (with a high percentage of clay-sized grains) was negligible regardless of the mineral hardness of the grains.
- The results show that a good relation exists between the abrasiveness of the samples and their grain angularity. In other words, as the grain angularity decreased, the abrasion and resulting weight loss on the tool decreased.
- As the soil moisture content changed, there were large variations in the weight loss. For example, in this study the presence of water increased the weight loss up to 10 times compared to the dry condition.
- As the moisture content increased, the weight loss increased to a specific point that was slightly less than the optimum moisture in the compaction test. After this peak, the weight loss decreased up to the saturation state.
- A substantial decrease of approximately 50 %was observed in the soil sample abrasivity with the addition of even small amounts of fines and clay-sized particles into the abrasive sand sample.

Considering the important role of water, more research is recommended to evaluate its effect on soil abrasivity. This could be complemented by the evaluation of the impacts of various soil conditions on the abrasive behavior of various soils.

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