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Effects of the water content and grain size on soil-cutting tools interactions: implications of LCPC abrasion test

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ABSTRACT

Increasing demand for the application of mechanical excavation techniques in various civil and mining projects has increased the importance of ground abrasive properties and their mechanized excavatability. The accurate prognosis of cutting tools lifetime has crucial importance in the planning of mechanized tunneling projects. Moreover, the precise estimation of the required cutter number for excavating the determined length of a given section in a specific geotechnical condition is one of the main tasks of the project consultants. The main objective of these estimations is to assess the needed time and cost of cutter replacements in the phase of feasibility studies and to plan a proper maintenance schedule. The LCPC testing procedure is one of the simplest and most common soil abrasivity assessment methods. The purpose of the presented study is to investigate the steel–soil interaction during the LCPC abrasion test. The consumed energy of LCPC tests on different abrasive samples was measured. Based on the recorded energy values, a new parameter of wear-specific energy of the LCPC test (*WSEL*) was introduced. The obtained *WSEL* values showed meaningful correlations with the sample grains size and the sample average hardness. Moreover, the results revealed that the high LCPC abrasion coefficient (*LAC*) values are relevant to the high consumed energy levels recorded during the tests.

Keywords: *Mechanized excavation, TBM, Soil abrasivity, LCPC test, Specific energy*

1. Introduction

At present, mechanized excavation techniques are considered as one of the major tunneling methods in both hard rocks and soft grounds. Despite their efficacious advantages like high safety, great efficiency, and low surface settlements, there are some major drawbacks. Wear and severe damages on cutting tools due to the continuous exposure to the earth materials is one of the most challenging issues. The wear process includes different phenomena of plastic deformations, the appearance, and growth of microcracks, phase transforms due to the high-stress levels and temperatures, and thermal softening [1]. Undetected damages on the cutting tools and the excessive delays on their replacement extend the failures to the other parts of the machine and finally stop its advancement. Any unforeseen stop on the excavation activities not only increases the project construction time but also imposes an enormous cost on the project budget. Hence, in mechanized tunneling projects, designers and contractors always looking for better ways to assess the governing geotechnical conditions and correlate them to the wear potential on the cutting tools.

Various parameters affect the abrasivity of soil and rock. Therefore, different methods have been developed to measure the abrasive properties of earth materials. A large number of the tests are restricted to measuring an average hardness for rock or soil samples. Vickers hardness number of rock (*VHNR*), equivalent quartz content (*EQC*), and abrasive mineral content (*AMC*) are some well-known instances. These are simple and easily available methods. However, they overlook the effect of other important parameters like the size and shape of soil or rock composing grains and the bond strengths between the grains in rock sample texture. In addition to the average hardness describing parameters, there are some plain experimental technics like Los Angeles, Nordic Ball Mill, and Dorry's abrasion tests. However, the major use of these tests is relevant to measuring the abrasive resistance of road pavement materials rather than the abrasivity of earth materials in mechanized excavation applications [2].

Due to the importance of the issue, various testing devices and procedures have been developed in the recent decade to assess the abrasive properties of soil and rock materials. In the soil abrasivity sector, the most noteworthy methods are LCPC abrasion test [3], soil abrasion test (SAT) [4, 5], soft ground abrasion test (SGAT) [6], Penn State abrasion index (PSAI) [2, 7-10], soil abrasion testing chamber (SATC) [11, 12], and RUB tunneling device [13, 14]. The results from different testing methods have revealed that there is a direct correlation between the average diameter of soil grains and the measured wear amount at the end of the test [3, 10, 13, 15-19]. Increasing the pore water pressure in the testing sample decreases the effective stress between the soil particles. The consequence is the decrease in soil abrasivity and lowers wear amounts recorded on wear parts [12]. Moreover, different testing methods have proven that the more the hardness of the testing sample, the greater the wear amounts of metal parts [3, 8. 10-12, 16-22]. The correlation between the sample water content and its abrasive capacity is somewhat challenging. The reported correlations are more or less parabolic [10]. However, some recently published results showed that the compaction theory of soils could be used to describe the behavior in non-cohesive soils [23]. On the soil-steel interaction in mechanized excavation applications, the effect of grain roundness [24] particle size distribution [25], soil strength [26], and the average hardness of soil grains [27] as well as the shape and speed of the cutting tool [28] have been discussed in the literature. Espallargas et al. (2015)

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reported the impact of chemical corrosion on the wear of soil cutting tools [29].

In this research article, the interaction between the abrasive mixture and the wear part of the LCPC testing procedure has been investigated. The effect of water content, as well as the abrasive mixture composition, have been discussed. The results showed that the measured energy consumption during the performed tests could be used as a powerful tool to assess the effect of different factors on the results of LCPC tests.

2. Methodology

In the present studies, the LCPC testing procedure was used to study the interaction between the soil sample and the steel wear part. The central laboratory of bridges and roads in France has developed the test in the 1980s. The recommended procedure of the test has been described in the French standard of P 18-975 [30]. The test was primarily introduced to assess the resistance of rock aggregates against crushing. However, it has been used to measure the wear of steel parts resulting from rock or coarse soil grains, especially in central Europe. The device has a 750-watt electromotor coupled with a steel propeller with a dimension of 5 × 25 × 50 mm. The hardness range of the steel material is between 60-75 Rockwell-B. The steel propeller rotates in a cylindrical chamber containing 500 g of soil sample. The recommended grains size range for the soil sample is 4-6.3 mm. The speed and the time interval of rotation are respectively 4500 rpm and 5 min. To describe the abrasive capacity of the tested soil sample, the LCPC abrasion coefficient (LAC) is calculated as follows:

$$LAC = \frac{m_0 - m}{M} \quad (1)$$

Where m_0 and m are the mass of steel propeller respectively before and after the LCPC test, and M is the mass of soil sample (=0.0005 ton). LAC values are usually expressed as gram per ton of abrasive samples [3].

In the presented studies on the abrasive capacity of soil samples, in addition, to measuring the wear on steel propellers, the consumed power of the driving electromotor was measured and recorded during the performed tests. For this purpose, an electronic power meter was designed and manufactured. It is connected as an auxiliary parallel circuit to the main power supply circuit of the LCPC testing device. The power meter output signal was recorded with a data logger and saved on a PC. Figure 1 shows the general configuration of the testing device along with the auxiliary units to control the testing time duration, set the steel propeller speed, and measure and record the power signal. In Figure 2, an example of a recorded power signal for an LCPC test is plotted. Using the time plots of the power signal, one can calculate the total consumed energy during one LCPC test (E) as follows:

$$E = \int_0^T P(t)dt \quad (2)$$

Where $P(t)$ is the recorded power signal during the reformation of the LCPC test and T is the time interval of the LCPC test (= 5 min). If the E value calculated from equation (2) is divided by the wear amount measured at the end of the LCPC test, the outcome can be considered as the wear-specific energy of the LCPC test ($WSEL$). Therefore, $WSEL$ can be calculated as follows:

$$WSEL = \frac{E}{m_0 - m} = \frac{\int_0^T P(t)dt}{m_0 - m} \quad (3)$$

To facilitate the comparisons, the consumed E values were normalized to the corresponding values at the dry conditions (E_0) using the following equation:

$$Normalized\ E = \frac{E}{E_0} \quad (4)$$

Where E is the consumed energy of each LCPC test under a given water content. The graphs presented in the results and discussion section also include the variations of normalized LAC values calculated as follows:

$$Normalized\ LAC = \frac{LAC}{LAC_0} \quad (5)$$

The experimental studies in the presented research were performed three different types of abrasive grains: coarse and angular silica grains with the size range of 4-6.3 mm (Figure 3-a), micro silica particles finer than 0.5 mm (Figure 3-b), and talc powder (Figure 3-c). The coarse silica particles were mixed separately with the fine silica and talc powder. The applied mixing ratios were 0:100, 20:80, 40:60, 60:40, 80:20, and 100:0. Therefore, six different coarse-fine silica mixtures, as well as six different coarse silica-talc mixtures, were prepared as synthetic abrasive soil samples. Different water contents of zero, 5, 10, 15, 20, 25, and 30 percent were added to each abrasive mixture. Therefore, 84 LCPC tests were performed in the experimental investigation program.

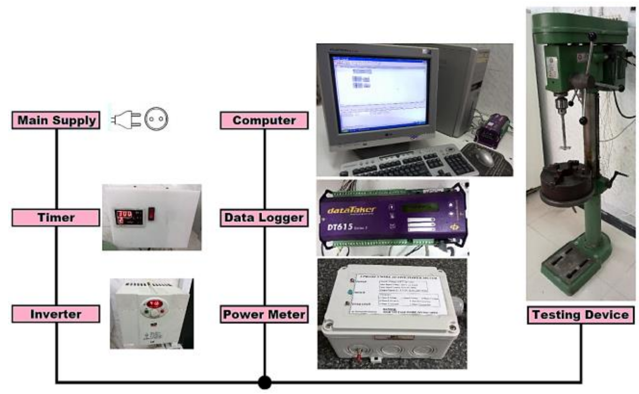

Figure 1. General configuration of the testing device and its auxiliary units [31]

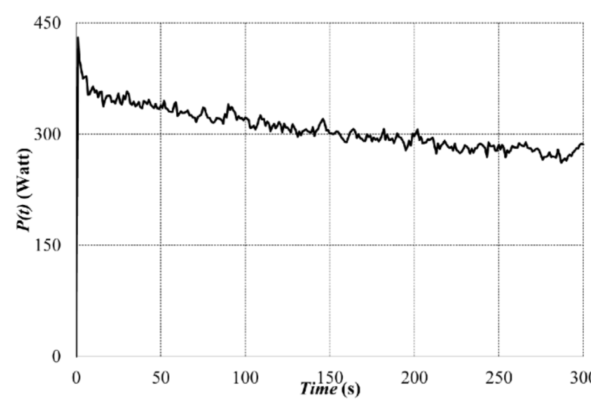

Figure 2. Recorded power signal for a performed LCPC test

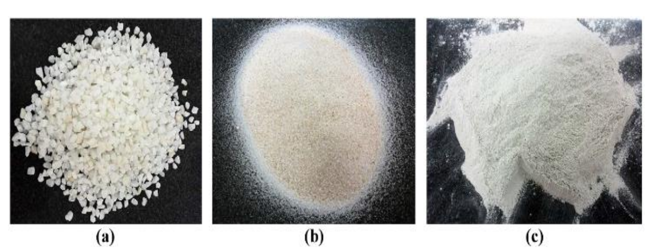

Figure 3. a) Coarse silica grains, b) micro silica, and c) talc powder used in the testing program

3. Results and Discussion

Figure 4 shows the graphs of $WSEL$ changes against the percentage of fine particles (micro-silica or talc) in the abrasive mixtures. The plots of Figures 4-a to 4-g are respectively relevant to the water content values of zero to 30 percent. In each graph, the data of coarse-fine silica and coarse silica-talc results are presented with single bold and double thin lines respectively. The vertical axes have a logarithmic scale and it can be seen that growing the share of coarse silica grains decreases the wear specific energy of steel propeller as a power function. The calculated correlation coefficients are considerable means that the fitted trends are meaningful.

Based on the plotted trend lines in Figure 4, it can be seen that when the fraction of coarse silica grains in the sample mixture increases, the wear on the steel propeller develops much more easily along with the consumption of very low energy. Revealing such trends in the results of coarse-fine silica mixtures is more considerable. In these mixtures, the type and therefore the hardness of the coarse and fine components are the same. Hence, the descending trends fitted on the resulting data reflect mainly the effect of coarse grains content on the abrasivity of testing mixtures. It seems that even though the fine particles in the soil texture may have high hardness values but their presence will considerably decrease the abrasivity of the soil mixture.

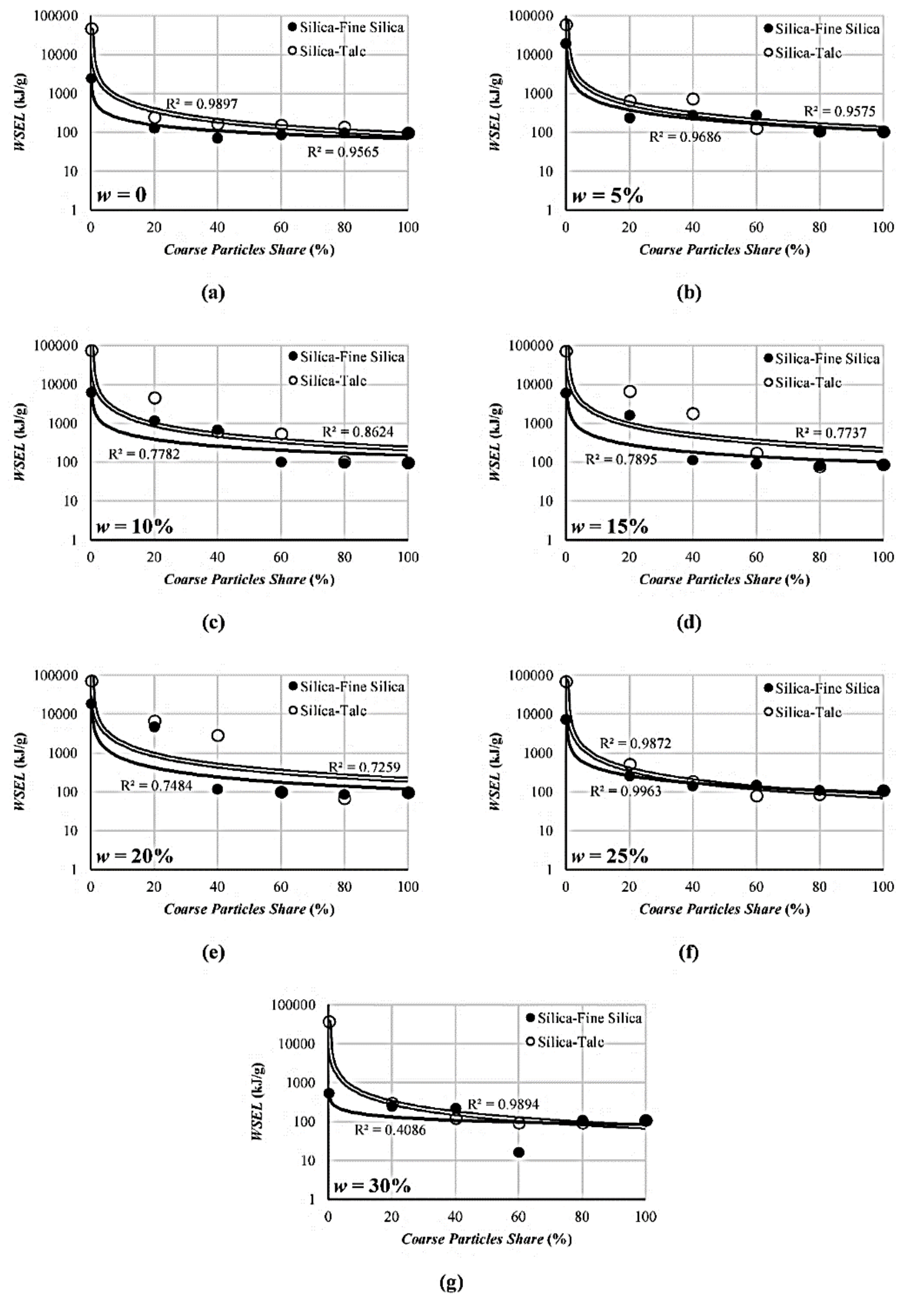

Figure 4. Wear specific energy of LCPC tests (*WSEL*) against the share of coarse silica grains in different coarse-fine silica and coarse silica-talc samples and the moisture contents (*w*) of a) zero, b) 5, c) 10, d) 15, e) 20, f) 25, and g) 30 percent

Comparing the obtained trends for coarse-fine silica mixtures and silica-talc mixtures reveals that the fitted trend lines on the silica-talc data always show higher *WSEL* values at the same coarse silica fractions. Considering the logarithmic scale of the y-axes, the difference between the two sample types is very significant when the majority of samples are composed of fine particles. However, increasing the share of coarse silica grains reduces the distance between two trend lines. The main reason for this behavior is the different hardness values of talc and micro-silica particles. The micro-silica-containing mixtures have higher average hardness values than those having the same share of talc. Therefore, the micro-silica containing mixture is more capable to create wear on steel propellers. This means that although the importance of small particles on the abrasivity of soil samples is smaller than those of coarse ones, however, their hardness is still a determinative factor. Growing the share of coarse silica grains closes the trend lines together. It is clear that when the content of coarse grains increases, the micro-silica, and talc mixes become more similar and the difference between their hardness values reduces.

Using the consumed energy of the testing process (E) one can describe the interaction (in other words, the degree of engagement) between the soil sample and the steel propeller. The higher E values reflect the higher resistance against the rotation of the steel propeller inside the abrasive sample and vice. However, adding water to the mix can result in more sophisticated consequences. In such cases, the comparison of the recorded consumed energy values with the obtained LAC ones will provide more comprehensive insight into the interactional behavior between the abrasive mixture and the rotating wear part. As it will be discussed in the following paragraphs, the measures E values could be used to interpret how the hard particles, which are the major cause of occurred wear, can move in the moist abrasive paste.

Figure 5 shows the consumed energy values of LCPC tests against the sample water content for different coarse fractions. The plots are relevant to coarse-fine silica samples. Figure 6 shows similar graphs for coarse silica-talc mixtures. The graphs relevant to zero coarse silica fraction were not included in both Figures 5 and 6. Because neither micro-silica nor talc alone cannot cause significant wear on steel propellers.

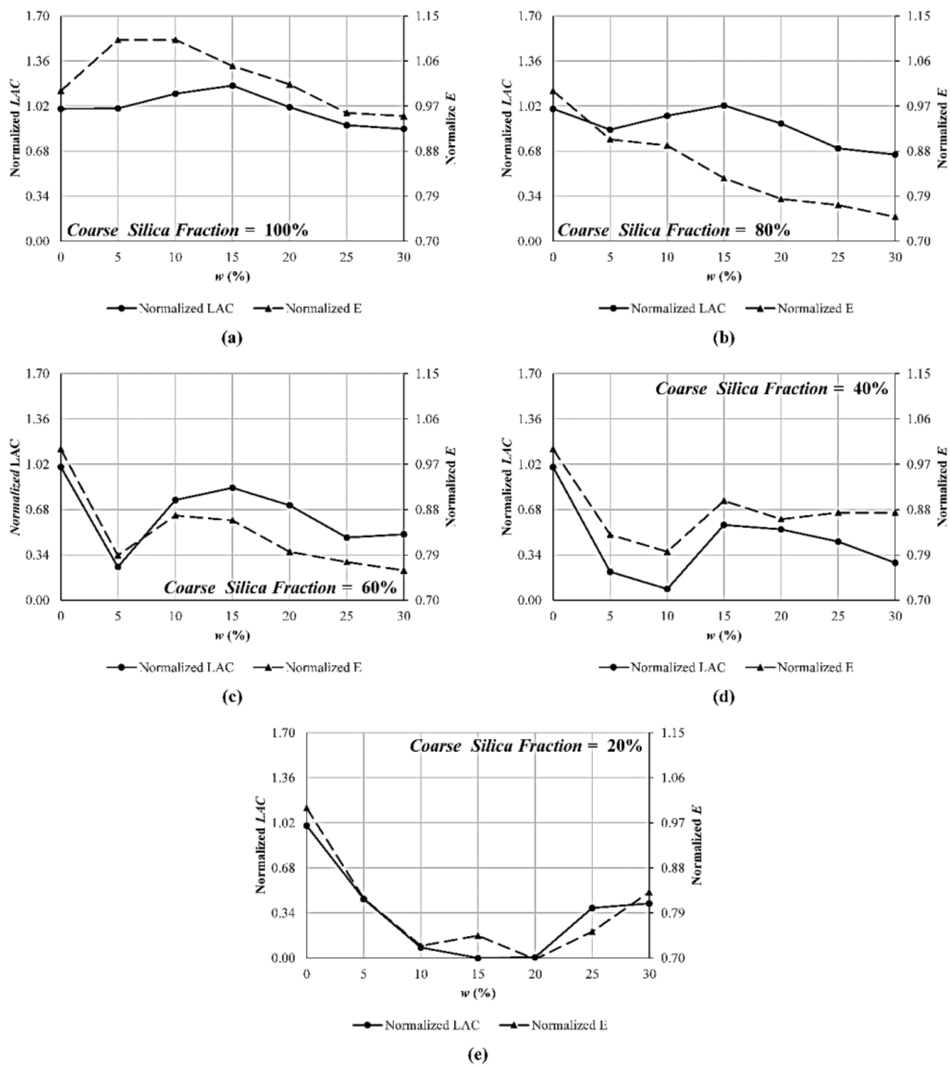

Figure 5. The variations of normalized LCPC Abrasion Coefficient (LAC) and normalized consumed energy (E) against the sample water content for the mixtures with the coarse silica grains fraction of a) 100%, b) 80%, c) 60%, d) 40%, and e) 20% (fine-coarse silica mixtures)

The graphs of Figures 5-a and 6-a are the same. Because both correspond to the 100 percent coarse silica grains. The graphs of Figures 5-b and 6-b also exhibit a great similarity because the share of the fine fraction, which is different in the two groups of samples, is just 20 percent and both groups of mixtures are mainly made of coarse silica grains. Growing the share of fine fractions in the sample mixtures increases the difference of the plots in the next relevant graphs of Figures 5 and 6. However, considering the plots of Figures 5 and 6 the following general conclusions can be made.

In all cases, the range of the variations of the normalized E values is smaller than those of LAC ones. This means that the effect of water content on the created wear on the steel propeller is greater than its effect on the recorded consumed energy values in the performed LCPC tests.

In Figures 5-a and 6-a, which include the results from coarse silica grins alone, increasing water content increases the consumed energy levels at the first step. The larger E values reflect greater resistance against the rotation of the steel propeller inside the moist sample. The higher resistance is likely the consequence of the higher degree of compaction, which developed in the testing sample due to the presence of water [23]. The higher *LAC* values in the water content range of 0-15 percent approve this reasoning. Increasing water content from 10 to 15 percent reduces the consumed *E* level. Nevertheless, the *LAC* trend is still ascending in this range. The higher moisture makes the sample grains move easier and this reduces the required energy for rotating the steel propeller. However, the compaction degree in the abrasive mixture is still high and the easier motion of grains likely causes greater numbers of hits between the abrasive grains and the steel propeller. Therefore, an increase in the measured *LAC* is obtained. In the range of the moisture content higher than 15 percent, more increase in the existing water content decreases both the recorded *E* and measured *LAC* values. It seems that when the water content is higher than 15 percent, the coarse silica grains separate and float in the existing water. The outcome is the lower resistance against the rotation of the propeller and smaller wear amounts on the rotating wear part.

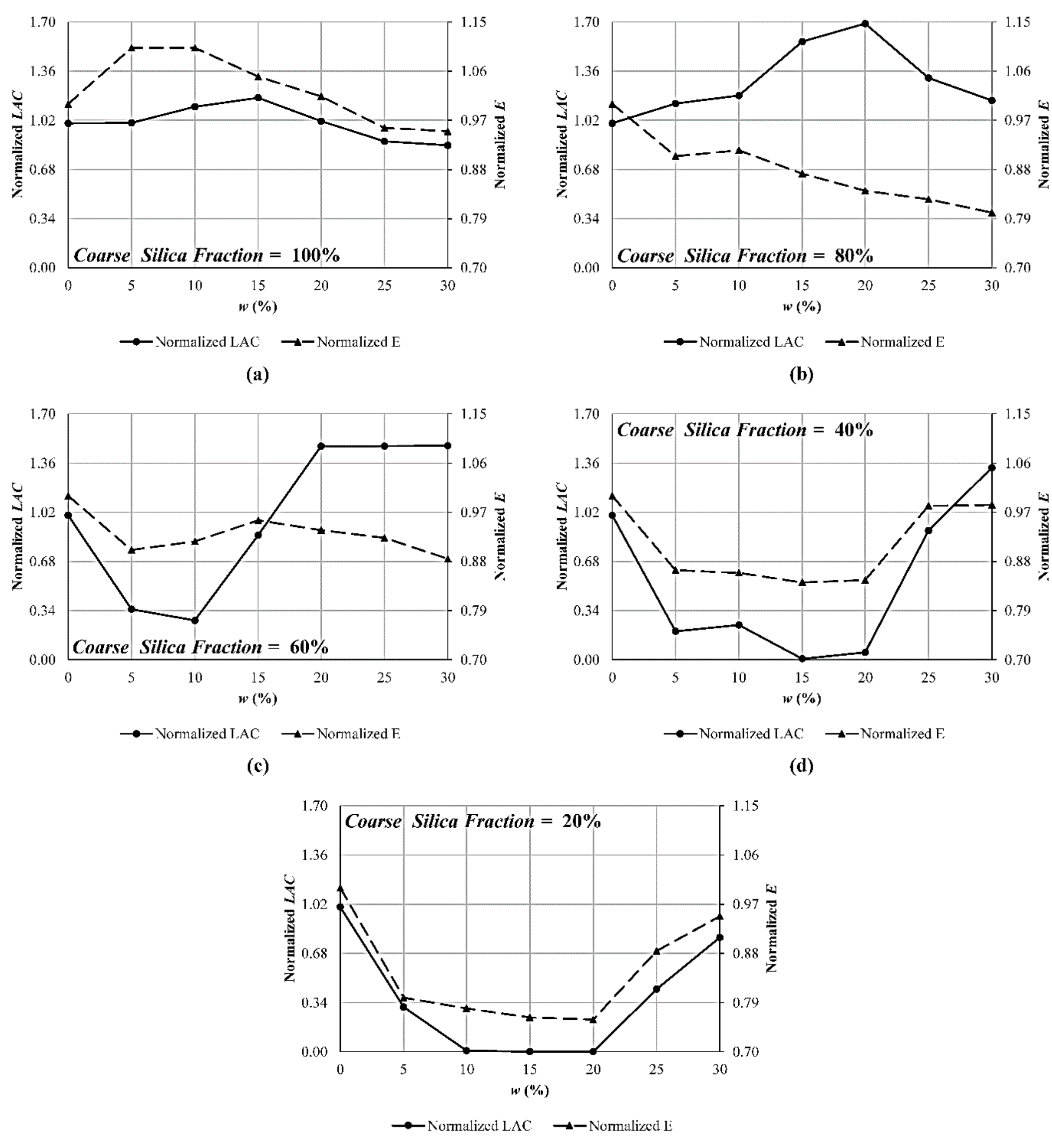

Figure 6. The variations of normalized LCPC Abrasion Coefficient (*LAC*) and normalized consumed energy (*E*) against the sample water content for the mixtures with the coarse silica grains fraction of a) 100%, b) 80%, c) 60%, d) 40%, and e) 20% (talc-coarse silica mixtures)

In Figures 5-b and 6-b, the descending trends of *LAC* and *E* values coincide with each other respectively in the water content ranges of greater than 15 percent and greater than 20 percent. However, in the lower moisture ranges, growing the water content level increases the measured *LAC* values. While the recorded consumed energy trends are descending. The *LAC* trends of Figures 5-a and b, as well as the same trends in Figures 6-a and 6-b, are similar. However, the consumed *E* trend lines exhibit a more or less monotonous descending trend. Considering the similarity of *LAC* trends, it can be said that the governing compaction effect of water content, which has been discussed extensively before [23], does not change so much with the addition of 20 percent fine particles (micro-silica in Figure 5-b and talc in Figure 6-b). However, the existence of this small fraction of fine particles has its effect, which is reflected in *E* values. The effect is the sticking or cohesion of wet fine particles, which will be discussed in the following paragraphs.

A good coincidence between the *LAC* and *E* trends is seen in the graphs of 5-c, 5-d, and 5-e as well as the plots of 6-c, 6-d, and 6-e. In the presence of water, the fine particles create a cohesive paste, which traps the coarse grains and reduces the rate of coarse grains hitting the steel propeller. The recorded E trends approve the reasoning. The low LAC values imply that the steel propeller has rotated in a cohesive mixture. The outcome of the propeller rotation in such a condition is to create a void space inside the testing sample and around the rotating propeller. The rotation in the void space does not need the consumption of considerable energy. From Figures 5-e and 6-e, it can be seen that when the LAC becomes zero due to increasing the moisture content, simultaneously the E values reduce by about 30 percent.

Figure 7 shows the correlation between E and LAC values in a clearer manner. The plot shows that in the results of LCPC tests, there is a good coincidence between the measured wear amounts on the steel propeller and the governing conditions in the soil-propeller interaction. Generally, it is reasonable to imagine that the wear on a special soil cutting tool is the consequence of soil-cutter interaction. Therefore, in the development of a suitable experimental model for the assessment of wear on soil cutters, the critical point is the degree of similarity between the governing mechanisms in the test and the real condition. If one accepts that the wear is the outcome of an interactional mechanism, the mechanisms in the test and real conditions must be the same to produce comparable results. An overall comparison between the LCPC test and the different soil cutters like drag picks, scrapers, chisels, and rippers reveals that there is a considerable difference between the interactional mechanism of a small thin steel part, which rotates at a high speed inside the soil sample, and a large hard steel part, which attacks under a given angle to the soil mass and removes its pieces with a relatively low speed. Moreover, based on the presented results, the presence of water content and fine particles in the testing sample can significantly affect the governing interaction in LCPC tests. Therefore, the difference between the governing experimental and real interactional mechanisms may even become greater in finely graded soils under wet conditions. The general deduction is that the LCPC test is not a proper experimental method to assess the wear on soil cutting tools, especially in fine soils including moisture.

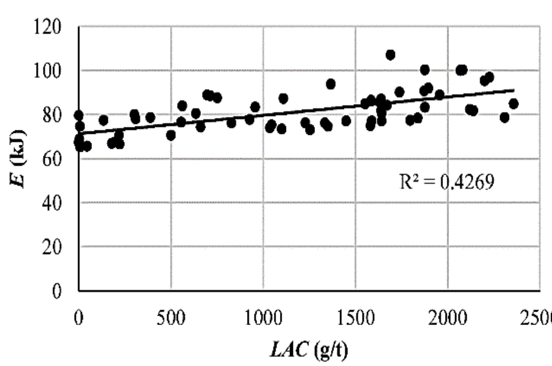

Figure 7. Correlation between LCPC Abrasion Coefficient (LAC) and the consumed energy of LCPC tests

4. Conclusions

In this research article, the interaction between the abrasive mixture and the wear part of the LCPC testing procedure has been investigated. The effect of water content, as well as the abrasive mixture composition, have been discussed. The results of performed LCPC tests showed that the calculated wear-specific energy of the LCPC test ($WSEL$) can clearly describe the effect of soil grains particles and their hardness on the abrasivity of soil samples. The results also showed that there is a good correlation between the changes in measured LAC and recorded E values. When the abrasive mixture turns into a cohesive paste due to the presence of water and fine particles, the rotation of the steel propeller creates a void space inside the testing sample. In these conditions, the LAC value decreases due to the lower engagement of the propeller and abrasive soil grains. Similarly, the rotation of the propeller inside a void space does not need significant energy. Therefore, it can be concluded that the measured wear values at the end of LCPC tests (in term of LAC numbers) highly depends on the state of propeller-soil interaction during the test. Considering the differences between the rotation of a thin rectangular steel piece inside a soil sample and the movement of real cutting tools against the soil mass, it seems that the results of LCPC tests are not so reliable to correlate with the wear data from real cutters, especially under the wet conditions and the presence of fine particles.

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