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Experimental study of coarse soil properties influencing soil abrasivity

Diego Sebastiani[a,*], Daniele Passeri[b], Girolamo Belardi[b], Salvatore Miliziano[a]

[a] Dept. of structural and geotechnical engineering - Sapienza University of Rome, via Eudossiana, 18 – 00184 Rome - Italy
[b] Institute for Environmental Geology and Geo-Engineering - National Research Council – P.le Aldo Moro, 7 - 00185 Rome - Italy

Abstract

The paper reports selected results of a study on tool wear for mechanized tunnelling in coarse soil. Several laboratory soil abrasion tests were performed and the results correlated with mineralogical composition, shape and surface roughness of the grains and the grain size curve of the soils. The analysis of the results clearly confirms the well-known correlation between soil abrasivity and quartz content and, for the soils tested, can quantify the relevant influence of grain size and grain roughness. We also report and discuss results useful for quantifying the positive effect of the addition of different chemical agents, injected as foams in a process known as soil conditioning, commonly performed in mechanized tunnel excavation using tunnel boring machines whit earth pressure technology to minimise tool consumption.

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Keywords: Abrasivity; tunneling; mineralogy; tools wear; TBM; conditioning effects

1. Introduction

The ability to predict and control the consumption of excavation tools is one of the decisive aspects for the success of a mechanized excavation. Wearing on cutters of tunnel boring machine equipped with earth pressure balanced technology (TBM-EPB) may be critical in terms of construction duration and costs. To tackle this problem

* Corresponding author. Tel.: +39 0649915335.
E-mail address: ing.diego.sebastiani@gmail.com

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chemical additives are often employed with a lubricant effect when injected and mixed in the soil during the excavation phase.

Tool consumption has to be predicted and consequently substitution designed to avoid the risk of unplanned stops of the TBM. Be able to reach a station, as in the case of a metropolitan line, the overhaul activities of the cutter head could be made easier, safer and faster. On the contrary, to have to replace the cutters without the assurance of the station bulkheads would require injections and other forms of protection for the workers involved in this unsafe activity, somewhat expensive in terms of time and costs.

The wear recorded on the excavation tools and all the different surfaces designed for excavation is widely defined as “primary” [1]. All these elements, in fact, are commonly replaced at appropriate intervals. The wear recorded on all the elements made to support the excavation tools and on the structural elements composing the TBM machines is defined as “secondary”. Usually the wear on these elements is not anticipated by the designers and manufacturers and may become a serious issue in the excavation process.

Primary consumption depends on several factors: soil characteristics, which are the size and shape of particles, such as its mineralogical composition, as well as aspects of the digging tools, such as shape and material, number and geometrical disposition.

This study aims to analyze in detail the effects of each characteristic of a coarse soil and how it influences the primary consumption of the excavation tools. This document will also provide information to help assess and quantify the positive effect of the addition of conditioning agents, injected as foams, in reducing tool consumption. During the last decade a variety of methods for determination and prediction of abrasivity of soil and soft rock has been published [1-4]. Jakobsen [5] proposed an exhaustive summary of several different methods used in Europe to evaluate the abrasiveness of a coarse-grained soil. In our study, a large number of abrasion tests were carried out using the apparatus available in the Geotechnical Laboratory of the Department of Structural and Geotechnical Engineering, Sapienza University of Rome. Samples of coarse soil were used, each differing with regard to mineralogical composition, shape and surface roughness of the grains and grain size distribution. The study also focused on the effectiveness of the injection of chemical foaming agents in the soil, actually performed in mechanized excavation carried out using TBM-EPB. A comparison is made between soil properties before and after treatment as well as between the performance of different foaming agents.

2. Abrasion test and tested soil samples

The equipment employed to perform the abrasion test in this research consists of a metal cylinder with a cover where is placed a rotation axis of a drill press with an aluminum disk inserted.

During the test the disk rotates in the soil at a constant speed and the torque is continuously recorded. At the end of the test, the disk is removed, accurately cleaned and the weight reduction is evaluated. Other detailed information and typical results for this test are presented by Vinai et al. in [4].

a) b) c) d)

Fig.1. a) abrasion test apparatus; b) cylindrical container; c) aluminium disk; d) detail of disk consumption.

The test duration is fixed at 10 minutes. This is a good compromise between the need to have a duration sufficient to produce an appreciable reduction in the disk’s weight, as well as reduce the duration as much as possible considering the implementation of testing of the conditioned soil, where the bubble life is limited [4]. The choice of aluminium as a material for the disk is also a compromise. On the one hand there is the need for a material with relatively low wear resistance to be consumed in a short time interval and, on the other, the need for a sufficiently durable material that would not cause a significant reduction in the size of the disk making the results incomparable.

To study the influence of mineralogy, grading and grain shape, five couples of coarse soil samples very similar for grain size composition were selected (Fig. 2). From grain size distribution, samples C1a and C2a were both composed of about 50% of sand and 50% of gravel, both of which are well graduated (from fine sand to medium gravel). Samples C1a and C2a were sieved differently, creating in laboratory samples C1b and C2b, composed only of sand, and samples C1c and C2c composed essentially of fine sand. Samples C3 and C4 are essentially mono-granular medium sand. Samples C5 and C6 are composed of about 65% of well graded sand and about 35% of fine gravel.

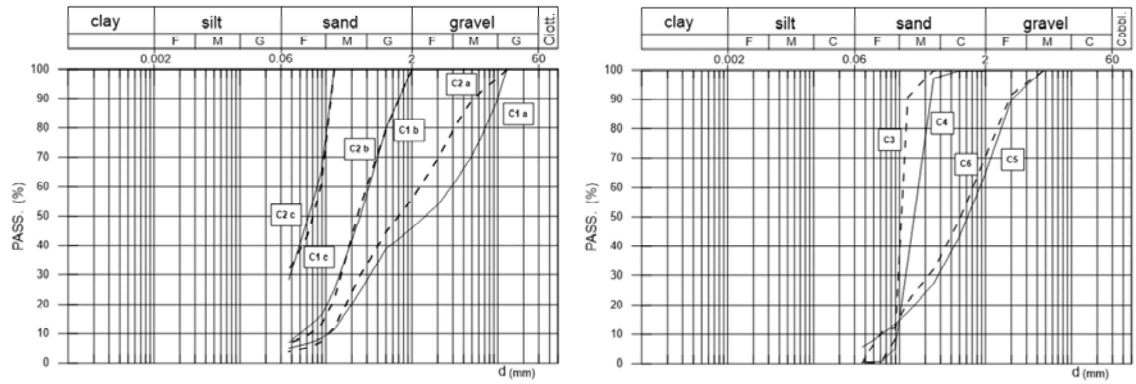
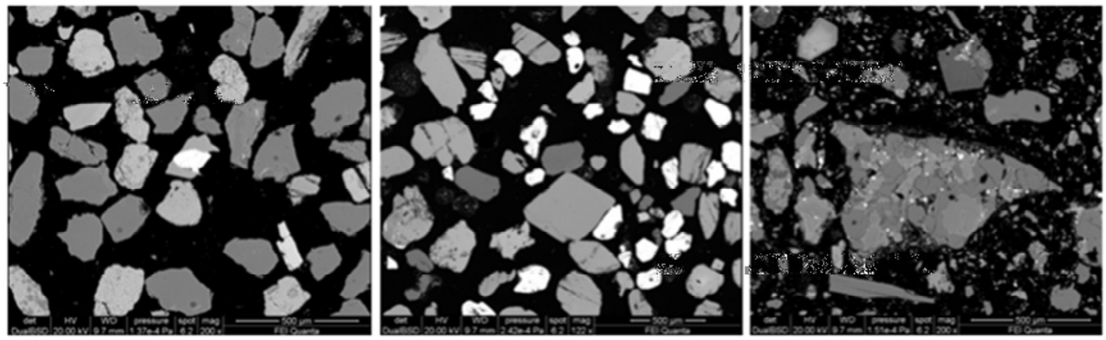


Fig.2. Size distribution of samples tested in laboratory.

Given that the influence of quartz is particularly decisive with respect to sand abrasivity [3,5], the quantitative mineralogical composition of the samples tested was determined by powder x-ray diffraction measurement supported by microscope analysis on representative polished sections. Morphometric characteristics of the grains (shape, aspect ratio, Feret diameter, perimeter, fractal dimension, [6,7]) were measured by processing the images taken from polished sections using scanning electron microscopy with Image-Pro plus 6 software [8] (Fig. 3). Mineralogical composition of the material tested is reported in the Table 1.



a) b) c)

Fig. 3. Examples of Scanning Electron Microscope images of polished section of a) smooth sample (C3); b) rounded grains sample (C4); c) angular grains sample (C6).

3. Performed tests and results

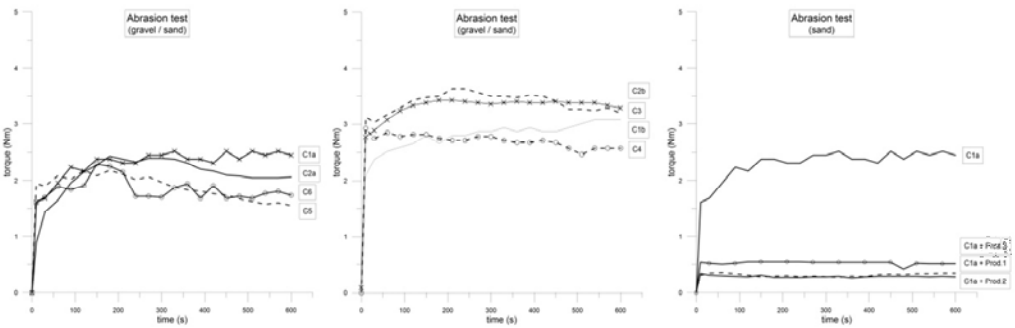
The abrasion test provides information on the expected TBM performances, both on the torque of the cutter head and on the wear of digging tools. These two aspects are described separately.

Average values of the recorded torque during the test are shown in Figure 4 for each sample. The typical trend of the torque value increases almost instantly, reaching the maximum value, while the grains of the soil are rearranged by the rotational movement around the disk. In the second part of the test the torque usually decreases stabilizing around a constant value. For this type of test the registered values of torque are usually in the range between 0 and 5 Nm. As can be seen in Figures 4a and 4b, the torque seems to be mainly linked to particle size. Samples with very different mineralogical composition and grain shapes, but similar grain size curves, yield similar results. This observation applies to both sands (Fig. 4b) and gravelly sands (Fig. 4a). As expected, the average torque increases with decreasing grain size. Number of contacts would appear to be the main factor influencing the torque. The shape of the grains would appear to have no significant effects. Samples C5 and C6, have a similar torque to the samples C1a and C2a, despite their more angular shape and sharp grain surface.

Table 1 - Minerals in the tested samples and percentage of quartz.

Sample	C1a, C1b, C1c	C2a, C2b, C2c	C3	C4	C5	C6
Mineralogical composition (in order of abundance)	Quartz K feldspar Plagioclase Hornblende Muscovite	Quartz Plagioclase K-feldspar Muscovite	Quartz Calcite Plagioclase K-feldspar	Piroxene Ulvospinel Sphene Grossularite K-feldspar Quartz Plagioclase	Calcite Quartz	Leucite Nepheline Pyroxene Ulvospinel K-feldspar Quartz
Quartz content	C1 a = 70 % C1 b = 70 % C1 c = 67 %	C2 a = 83 % C2 b = 80 % C2 c = 76 %	61 %	2.1 %	1.0 %	0.9 %
Source	natural	natural	natural	natural	artificially grinded	artificially grinded
Grain shape	rounded	rounded	rounded	rounded	angular	angular

Figure 4c shows the average values of torque recorded in the tests performed on sample C1a, before and after the treatment, using three different chemical foaming products. The dosage required to properly condition the soil has been evaluated for each product by performing specific preliminary tests. All results show a substantial reduction of the torque associated with the presence of chemical agents. The comparison of the three different products, shows a reduction from an average value of about 3 Nm to around 0.3 Nm for products 1 and 2 (the torque reduction is about 90%), while up to about 0.6 Nm for product 3 (reduction of 80%), As the soil sample and the test procedure is identical for the three cases, these differences may be traced to the effectiveness of the chemical products. Products 1 and 2 are more efficient then product 3 in the reduction of the torque.



a) b) c)

Fig. 4. a) Average torque recorded for a) gravelly sand samples; b) sand samples and c) sample C1a, before and after the mixing with foams generated using three different chemical products.

Regarding disk consumption, the interpretation of the results is somewhat more complex, as particle size, mineralogical composition and shape of the grains all play an important role.

To analyse the effect of the grain size composition, in Figure 5a are showed the recorded consumptions for the gravelly sand sample C1a, the sand sample C1b and the fine sand sample C1c having same mineralogical composition, shape and roughness of the grains. As reported in several studies [3,5], it can be stated that the presence of coarse sand and gravel in a sand sample causes an increase of recorded wear. Similar trend was recorded for samples C2a, C2b and C2c.

The results reported in Figure 5b, were obtained on the two artificially grinded samples having same roughness and grain shape, similarly low quartz content but different mineralogical composition; in detail, sample C5 is composed only by Calcite while the sample C6 is composed by several harder mineral (K-feldspar and pyroxene). The great difference in disk consumption recorded confirms the well-known correlation [3,5] between the mineralogical composition and the wear action of a coarse soil.

Comparing results from graphs in Figure 5a (sample C1a) and Figure 5b, we can also note the higher consumption recorded for sample C6 if compared with sample C1a having similar particle size, an higher content of hard mineral like quartz but a smooth grain surface. These results show how both the shape and the roughness of the surface of the granules play a crucial role and not only the content of hard minerals.

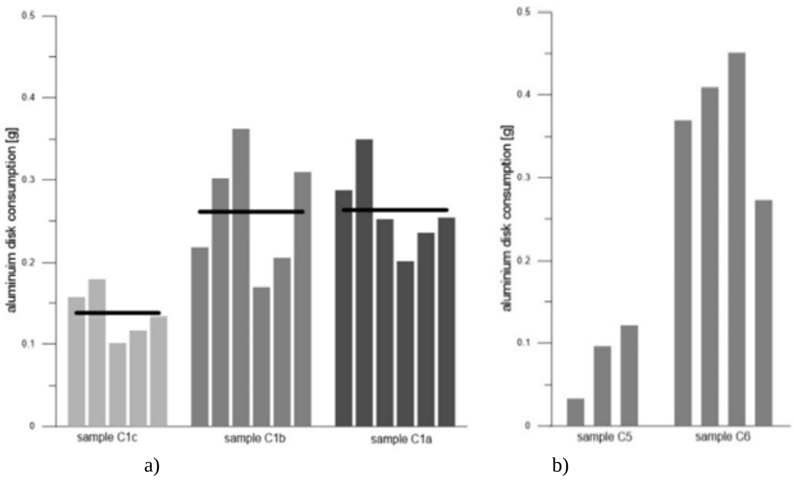


Fig. 5. Effect of a) grain size distribution and b) mineral composition.

Also in the disk consumption the effect of the injection of chemicals in the soil was analysed and the results are presented in Figure 6. For sample C1a, with high quartz content (70%), the values of the recorded consumption before the chemical treatment were higher than 0.250 g while, after the injection of the three different products, were under 0.05 g (reduction higher then 80%); this evaluation provides a quantitative assessment of the benefit obtained from the use of these chemical products. In these three cases, the beneficial effect on consumption is quite similar, however the product 2 is the most performant.

For the evaluation of the chemical product, which provides the most effective lubricant action of the tested coarse soil, it should be considered both the recorded reduction of torque and disk consumption; from this point of view, the product 2 could be considered the best choice for the tested soil.

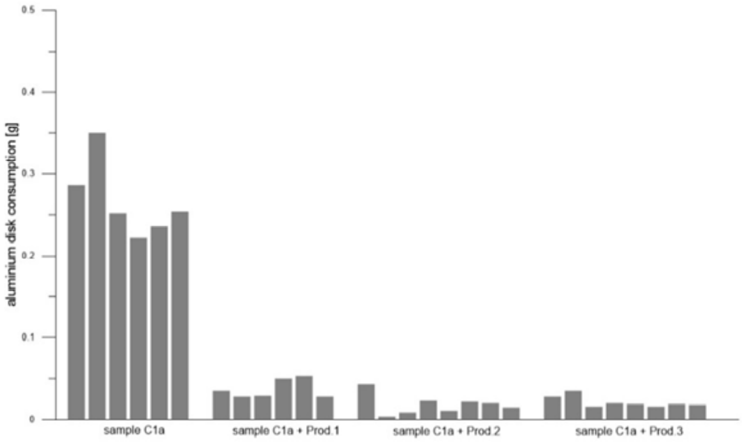


Fig. 6. Effect of injection of three different chemical products (Prod.1, Prod.2 and Prod.3) on disk consumption.

4. Conclusions

The ability to predict and control the consumption of the excavation tools is one of the decisive aspects for the success of a mechanized excavation. Wearing on earth balanced pressure tunnel boring machine cutters may be critical in terms of construction duration and costs.

The adopted abrasion test provides replicable, accurate and reliable results and also can be performed on a sample of coarse soil treated using chemical additives. The experimental results obtained in our study confirm that:

- the abrasivity of a soil is affected by mineralogical composition, shape and surface roughness of the grains and grain size distribution;
- the presence of coarse sand and gravel increases the wear action of the soil on a metallic element;
- the presence of quartz and other hard minerals increases the wear action as well as the roughness and a sharp surface of the grains;
- the torque is mainly related to the number of the contacts of the disk with the soil and then to the size of the soil grains; fine sand samples cause higher torque if compared with samples with coarse sand and gravel.

Finally, the results obtained on a very abrasive gravelly sand soil with high quartz content shoved that the use of appropriate conditioning by mixing the soil with foams generated using chemical products can reduce both the torque and the digging tools consumption more than 80%.

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