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Tunnelling and Underground Space Technology 73 (2018) 212–221

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

A new test device for the study of metal wear in conditioned granular soil used in EPB shield tunneling

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A R T I C L E I N F O

Keywords:
Tunnelling
EPB shield
Soil conditioning
Cemented carbides tool
Wear test

A B S T R A C T

The wear phenomenon evaluation in EPB shield tunneling machines is not a simple issue, as a large number of parameters are involved, such as soil and tool material properties, soil conditioning and pressure in the bulk chamber. The evaluation of the influence of these parameters and predicting this influence is a complex task and the research has proposed different test procedures and approaches. In this paper a new procedure for testing wear of tools with an innovative concept and design is presented. The experimental results obtained using conventional steel and hard material tools, tested with natural and conditioned soils, are discussed. The outcomes show the feasibility of the proposed procedure and the quality of the measurements that can be obtained using the proposed wear tool shape.

1. Introduction

Earth Pressure Balanced Shields are currently the most commonly used full face tunneling machines. They use conditioning agents that change the mechanical and hydraulic behavior of the soil forming a plastic paste. In this way, the soil can apply a pressure in the bulk chamber and prevent water inflow when tunneling below the water table. Conditioning is therefore the key point to explain the increasing number of applications of this technology with many different types of soils (Herrenknecht et al., 2011; Thewes et al., 2012; Peila, 2014).

Therefore the conditioned soil should be able to control and homogenize the face pressure in the bulk chamber, to minimize inflow and to create a homogenous flow of the excavated soil from the tunnel face through the cutter head, the bulk chamber and the screw conveyor. Moreover a suitable conditioning makes it possible to minimize the cutter head and the screw conveyor torque, to reduce the friction between metallic parts and the soil and finally to minimize the wear of the tools and the cutter-head (Thewes and Budach, 2010; Vinai et al., 2008). For an optimal management and preliminary design of a tunnel it is necessary to have laboratory devices and procedures that can smoothly compare the positive effects on the soil conditioning on all these parameters. There is extensive research about the soil conditioning tests; the main informations can be found in Maidl (1995), Quebaud et al. (1998), Jancsecz et al. (1999), Milligan (2000), Psomas (2001), Bezuijen and Schaminée (2001), Peña (2003), Merritt and Mair (2008), Rivas et al. (2009), Vinai et al. (2008), Peila et al. (2007, 2009), Thewes and Budach (2010), Borio and Peila (2011), Thewes et al. (2012), Hollmann and Thewes (2013), Todaro (2016), Peila (2014), Martinelli et al. (2017).

The mechanized parts of a machine that are most subject to wear are the tools, the chamber and the screw conveyor. This phenomenon affects the number and the duration of the stops needed for maintenance and tool replacement, and thus it heavily influences construction time and cost. Wear must therefore be assessed at the designed stage.

This paper presents a test procedure and a new device for the study of the effect of conditioning on tool wear. The outcomes of a preliminary test campaign are discussed. The proposed wear tool shape makes it possible to quantify the weight lost and assess the change in shape after each test. Accurately measuring the shape variation, allows the calculation of the worn volume.

1.1. Background

The wear of rock tools (i.e. rolling cutters), used in TBM rock mass excavation, has been widely analyzed and standardized tests have been proposed and accepted in technical literature. The most commonly used laboratory tests are: the Vickers test, the Cerchar test, the LPCP abrasimeter test and the NTNU abrasion test (Blindheim and Bruland, 1998; Ozdemir and Nilsen, 1999; Büchi et al., 1995; Nilsen et al., 2006a, 2006b, 2006c; Abu Bakar et al., 2016). With reference to soil wear, that

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https://doi.org/10.1016/j.tust.2017.12.014
Received 28 July 2017; Received in revised form 25 November 2017; Accepted 13 December 2017

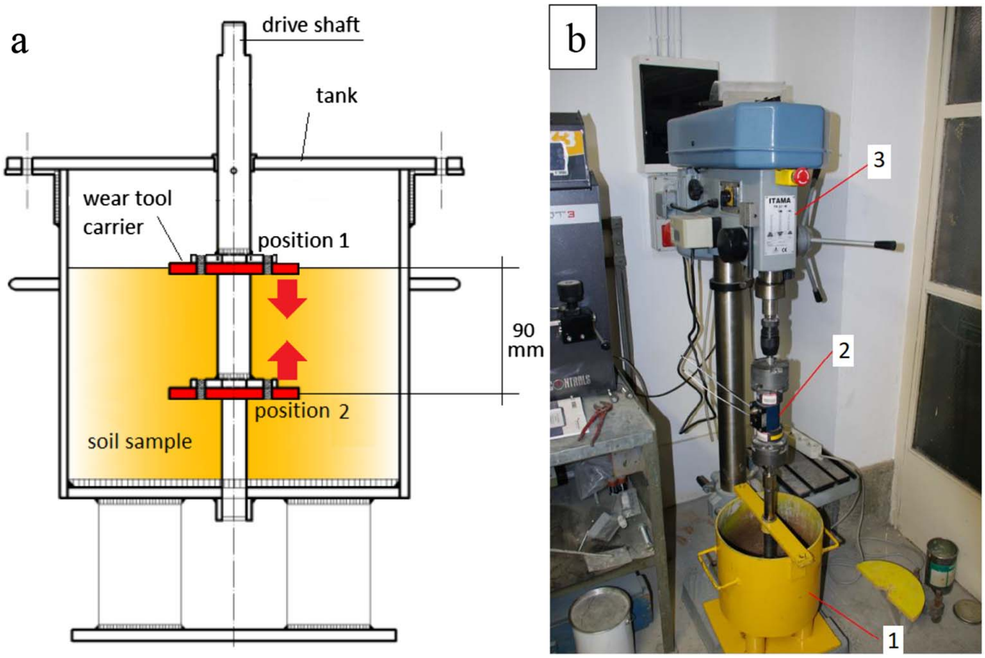

Fig. 1. Schematic drawing of the test tank (a) and a global view of the testing device (b). Key: steel tank (1), power motor (2), digital torque transducer (3).

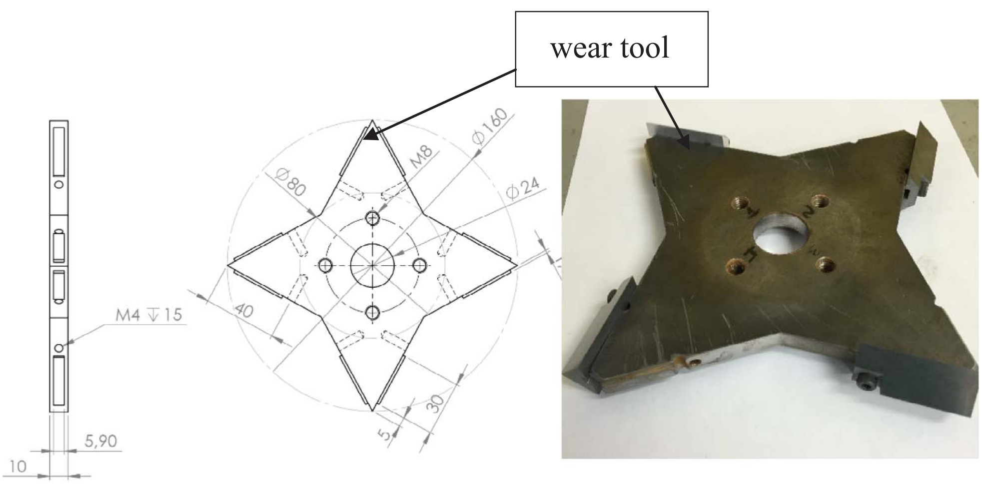

Fig. 2. Technical drawing of the wear tool carrier and photo of the arrangement of the wear tools (measurements in mm).

mainly affects the EPB and Hydroshield TBMs, it is well known that ground abrasiveness is influenced by in situ ground features (homogeneity, density, porosity), sedimentation features (mineralogical composition and grain shape) and the grains mechanical features (mono-axial compressive strength and hard minerals content).

Furthermore, in EPB excavation, conditioning changes completely the wear mode, resulting in a tool working with a plastic paste which embeds the bits and the cutterhead. A correct design of conditioning should be done before starting the excavation when wear problems are expected to be encountered (Köppl et al., 2015). General recognized test procedures for this type of assessment are not yet available and the researches are mainly working to define an index able to link the properties of the soil with the tool life. So far, different laboratory tests have been proposed by various researches and they are generally based on wear elements rotating inside the soil. A reliable and wide discussion of the available tests can be found in Nilsen et al. (2007), Gharahbagh et al. (2011) and in Mosleh et al. (2009). These authors have also carried out tests to better understand the effect of moisture of the soil on the wear. Nilsen et al. (2006a, 2006b, 2006c) proposed to modify the well known NTNU test used for rock masses to be applicable to the soil while Gharahbagh et al. (2011) rotated a propeller made by three inclined blades inside a tank full of soil with or without applied pressure. Rostami et al. (2012), using the same device of Gharahbagh et al. (2011), have found that wear vs. moisture has a bell shape with a maximum of wear ranging around 7–10% of moisture content in the tests soil. These authors studied also the effect of steel hardness and they found that when using natural silica sand the hardest was the tool the less material was abraded, as was expected, and when the soil has a moisture of 10% the results were the opposite.

Similar relationships between moisture and metal wear were obtained by Peila et al. (2012), Hedayatzadeh et al. (2013) and Jakobsen and Lohne (2013), using different test procedures.

The effect of soil conditioning on wear has been studied by few researchers. Jakobsen and Lohne (2013) and Jakobsen et al. (2013) made a good analysis of the existing procedures and proposed a new test device where a cross of prismatic bars is rotated in the soil. Even if the initial results of this research are promising, definitive conclusions have not been obtained. Barbero et al. (2012) and Peila et al. (2012) carried out many tests on different soil types using a simple aluminium disk rotating inside a tank filled of conditioned soil measuring the lost

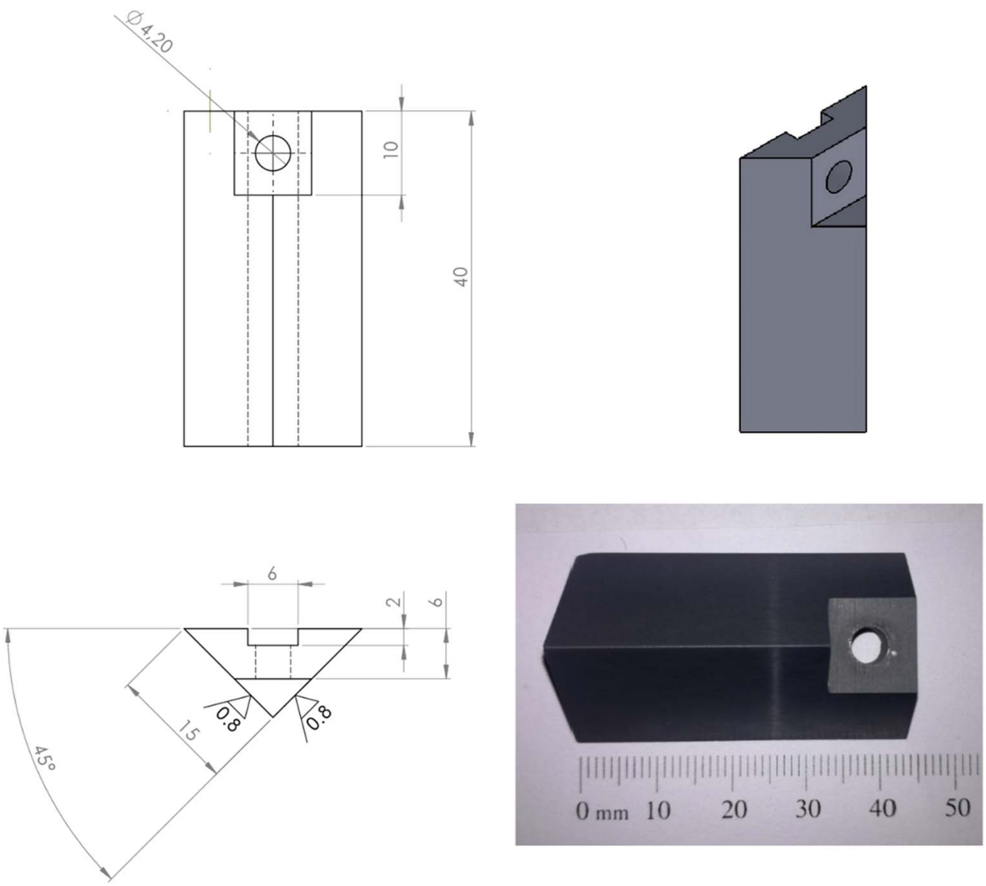

Fig. 3. Technical drawing and picture of the wear tool. Units: dimensions (mm), roughness (μm) (the obtained value is the one of a rectified surface), angle (°).

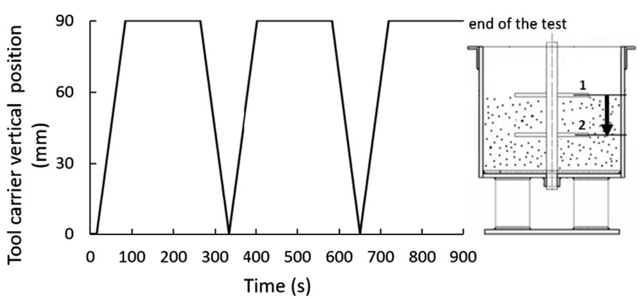

Fig. 4. Scheme of the wear test process. The figure describes the path of the wear tool carrier vs time.

weight and the torque on the disk. In this research the rotational speed of the wear disk has been kept high, to reduce the test time and allow to work with bubbles that are still "alive" in the mix. The tests compared the effects of natural and conditioned soil. The conditioned soil was conditioned at its optimal workability, following the procedure assessed by Peila et al. (2009). An improvement of this test procedure has been developed by Oñate Salazar et al. (2016), reducing the rotational speed and using a steel disk. Hedayatzadeh et al. (2015) studied the effect of pressure and of different sets of conditioning using a more complex wear tool. Gharahbagh et al. (2014) using the device that he previously developed, carried out an experimental study on the influence of foam conditioning of a silica sand. Their results highlighted the importance of foam in reducing wear.

Table 1
Summary of the main data of the carried out tests.

Test #	Water content (% in weigh of the soil)	FIR (% in volume of the soil)	FER (–)	Surfactant concentration (%)	Type of surfactant	Type of tool wear material	Number of wear cycles	Tool path length
#1	2	–	–	–	–	Steel	3	3600
#2	2	–	–	–	–	Cemented carbide M5	3	3600
#3	5	40	10	2	Polyfoamer FP/CC	Steel	3	3600
#4	5	40	10	2	Polyfoamer FP/CC	Cemented carbide M5	3	3600
#5	2	–	–	–	–	Steel	2	2400
#6	2	–	–	–	–	Cemented carbide M5	2	2400
#7	5	40	10	2	Polyfoamer FP/CC	Steel	2	2400
#8	5	40	10	2	Polyfoamer FP/CC	Cemented carbide M5	2	2400
#9	2	–	–	–	–	Steel	1	1200
#10	2	–	–	–	–	Cemented carbide M5	1	1200
#11	5	40	10	2	Polyfoamer FP/CC	Steel	1	1200
#12	5	40	10	2	Polyfoamer FP/CC	Cemented carbide M5	1	1200

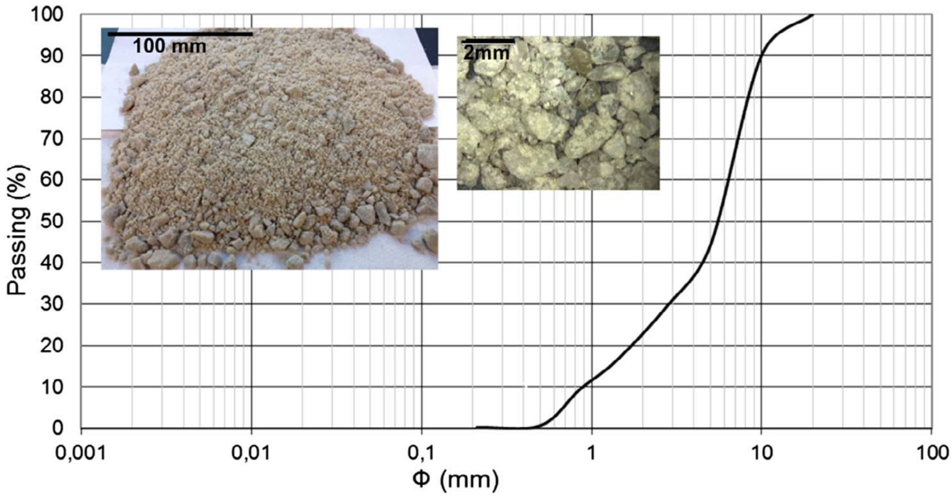

Fig. 5. Grain size distribution of used quartz sand and macroscopic and microscopic pictures. The last one was obtained with a video-microscope LEICA VZ85R (magnification: 40×). The grain size distribution has the following describing parameters: d_{10} (grain size at the percentage of 10%) = 0.9 mm; d_{60} (grain size at the percentage of 60%) = 6.5 mm, Uniformity coefficient = d_{60}/d_{10} = 7.22.

Fig. 6. Phase contrast microscopic analysis pictures of the quartz sand grains. The feldspar grains are visible in the centre of the right picture (magnification: 120×).

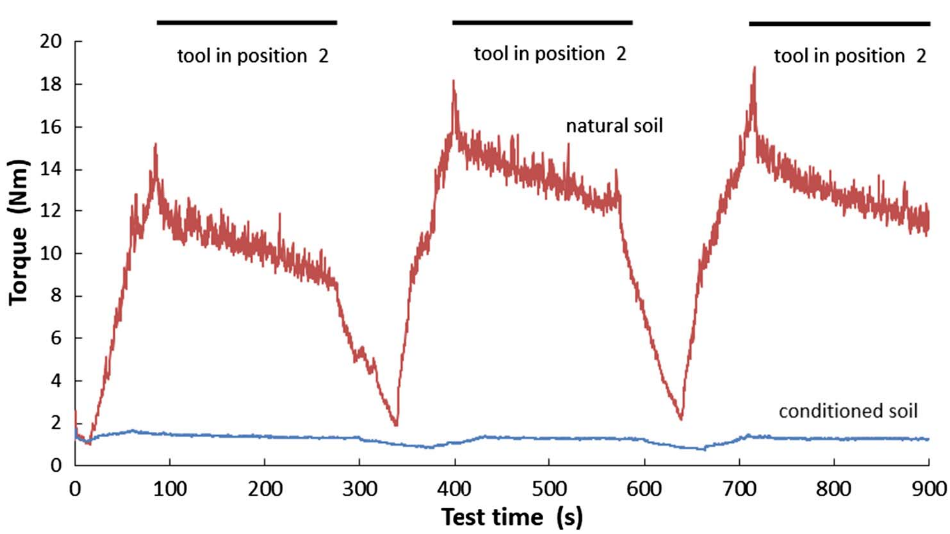

Fig. 7. Reference comparison of the measured torque for natural and conditioned soil when testing M5 cemented carbide wear test.

2. Proposed test method

2.1. Description of the testing device and test procedure

The basic apparatus is similar to the one proposed by Peila et al. (2012) and Bosio et al. (2018). It consists of a steel tank, 300 mm high and with a nominal diameter of 308 mm. The test wear tool carrier is assembled on an electrical motor which produces the rotational torque, with a rotational speed of 160 rpm (Figs. 1 and 2). A digital torque transducer allows the torque measuring on the tool wear carrier shaft. The cylindrical tank is partially filled with soil up to 170 mm from the bottom. The lower position of the wear tool during the test, is in the middle of the tank with 80 mm soil below and 90 mm above.

The test starts with the tool carrier located above the soil and then it is moved up and down with a constant speed inside the soil. The shape of the new proposed wear tools and wear tool carrier is shown in Figs. 3 and 4.

During the test, wear tools change the sharpness of their edges

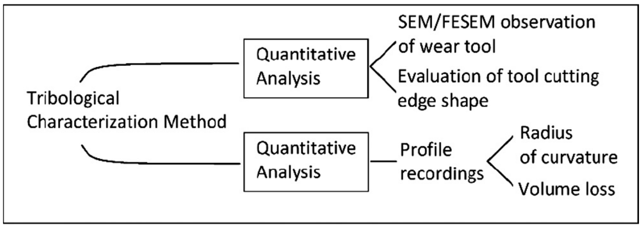

Fig. 8. Schematic of the tribological characterization plan for wear tools.

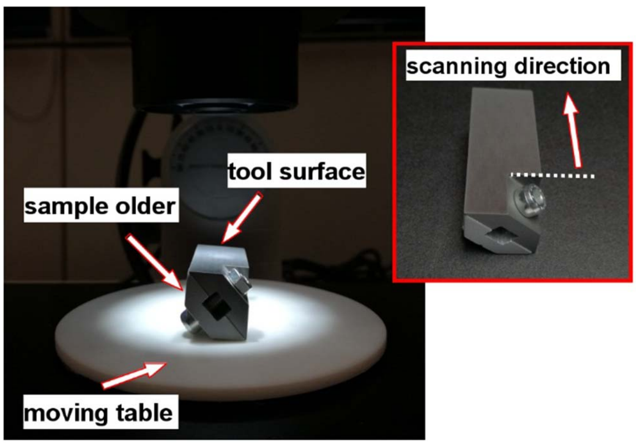

Fig. 9. Sample holder developed for cutting edge observation.

which are abraded. Both these features can be measured as reference parameters.

The proposed test procedure is as follows:

1. a quantity of soil of 25 kg is prepared. If a conditioned soil test is carried out, the conditioning additives and water are added to soil mixing with a concrete bowl mixer (see the procedure described by Peila et al., 2009);
2. the wear tools are weighted before the test and their edge profile is measured along their length;
3. the soil is placed in the mixing device up to 170 mm from the bottom of the tank, then the wear tool carrier is installed on the driving shaft, in contact with the soil;
4. the wear test is carried out rotating the tool carrier in the soil at a rotational speed of 160 rpm. In order to simulate a critical operating condition and to induce an aggressive wear, a regular translational up-and-down movement of the tool carrier is imposed with a vertical movement of ± 90 mm.

The elementary wear test is carried out with the following operational scheme:

(a) the test starts with the tool carrier in the upper position (i.e. laying on the soil – position 1). The tool is then rotated for 15 s in this position;
(b) the tool carrier is moved down, inside the soil to the test lower position (2) with an advance speed of about 1.3 mm/s;
(c) the tool carrier is then kept rotating in the lower position (i.e. at a depth of 90 mm from the surface) for about 180 s;
(d) the tool carrier in moved up to the upper position with an advancement speed of about 1.3 mm/s;
(e) when the tool carrier reaches the surface of the soil, immediately steps b, c and d are repeated for a second round;
(f) after the second round the steps b and c are repeated and then the test is stopped with the tool totally embedded in the soil.

At the end of the test, the tools are removed from the carrier, weighted and scanned along the edge.

Each wear test cycle (Fig. 4) corresponds of a tool path length of about 1200 m (considering the point of the wear tool at the maximum distance from the rotation axis, i.e. the external edge of the test device). The described wear test cycle can be repeated as may time as wanted changing the soil between one test and the other. This operation is important in order to restore homogeneous start conditions. In the present research, three repetitions have been chosen.

2.2. Used soil and conditioning agent

Preliminary tests (Table 1) were used to check the feasibility of the proposed procedure and have been carried out with a quartz sand that comes from an industrial quartzite quarry. This soil is obtained with a mechanical crashing process made directly using the quarry plants. The soil has a natural water content of 2% by weight (hereinafter natural soil). Fig. 5 shows pictures of the quartz sand and the grain size distribution. The mineralogy properties were obtained through phase contrast microscopic analysis using a Leica DMPL microscope (Fig. 6). The results show that quartz is the main mineral with content of 98% while the 2% consist of feldspars and iron impurities.

To assess the optimal conditioning sets, various tests have been carried out on conditioned samples with different contents of water and foam following the procedure defined by Peila et al. (2009). The used conditioning agent is the Polyfoamer FP/CC (Mapei SpA commercial product) and the foam has been produced using the foam generator described by Peila et al. (2007) with a FER (Foam Expansion Ratio) of 10 and a surfactant volumetric concentration in the generation fluid of 2%. The chosen optimal conditioning set is: a water content of 5% (2% natural plus a 3% added water), FIR (Foam Injection Ratio) of 40% and FER of 10.

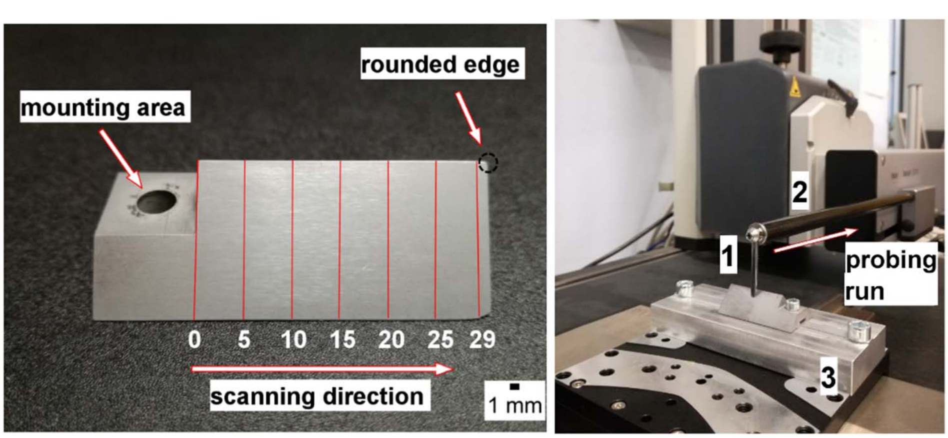

Fig. 10. Locations of the recording linescans along the tool cutting edge and photograph of profilometer MarSurf CD 120 set up used for the measurements. Key: probe (1), tracing arm (2), automated micrometrical sled to position the tool correctly (3).

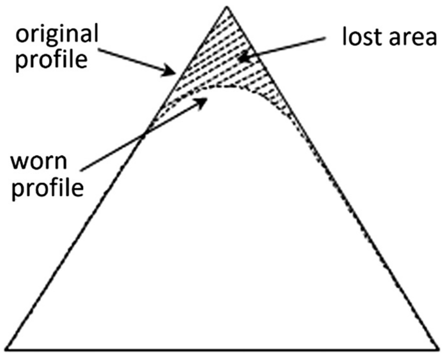

Fig. 11. Examples of two measured profiles of a tool: original and worn ones. The dashed area represents the lost area for the studied cross sections.

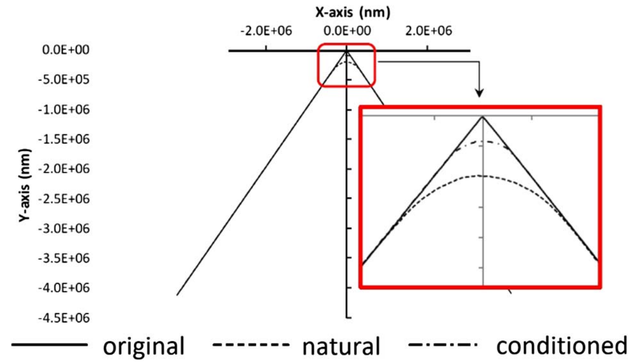

Fig. 13. Example of the measurement of the wear located in the blade of the tool for the cemented carbide tool.

2.3. Materials for wear tool

The used wear test elements were made of cemented carbides, with a WC-Co grade M5 (Upadhyaya, 1998) and of conventional steel, with a Vicker hardness of 160 HV.

3. Torque measurements

The torque on the wear tool carrier has been measured using a torque transducer Lorenz type DR 1221-R installed on the driving shaft. The carried out tests have demonstrated that there is a great difference in torque levels achieved in the conditioned and not conditioned soils. An example of torque measurements is reported in Fig. 7. It shows the great difference between conditioned and not conditions soil. Taking into account the lower position of the carrier (position 2 in Fig. 4), the natural soil torque is ranging between 12 and 16 N m while for conditioned soil torque, values are ranging around 1.5 N m. The conditioning decrease the torque of an order of magnitude.

4. Tribological measurements on the wear tools

The wear tools were characterized after each cycle and the goals of the tribological measurements are:

- to quantify the *volume loss* on the wear tools induced by both natural and conditioned soil;
- to identify the tool position where heaviest wear occurs and to investigate the wear mechanisms;
- to characterize the change of geometry of the tool and to verify if these data can become a representative parameter for assessing the action of the soil wear.

The measured data and the tribological laboratory activities are summarized in Fig. 8. The geometry and the shape of the tool is measured at seven cross sections. The computed curvature radius is a good index of the worn geometry and has the advantage of a simple measurement while the definition of the worn volume requires a more complex measurement. The qualitative analysis of the surface morphology of each worn tool sample was carried out using a Scanning Electron Microscopy (SEM-model *Leo 1450 MP*) and a Field Emission SEM (FESEM) Zeiss Merlin equipped with Gemini column while the evaluation of the tool cutting edge was carried out using a video-microscope LEICA VZ85R (50–400 ×) with a magnification of 200 ×. A specimen sample holder, specifically designed and constructed, was

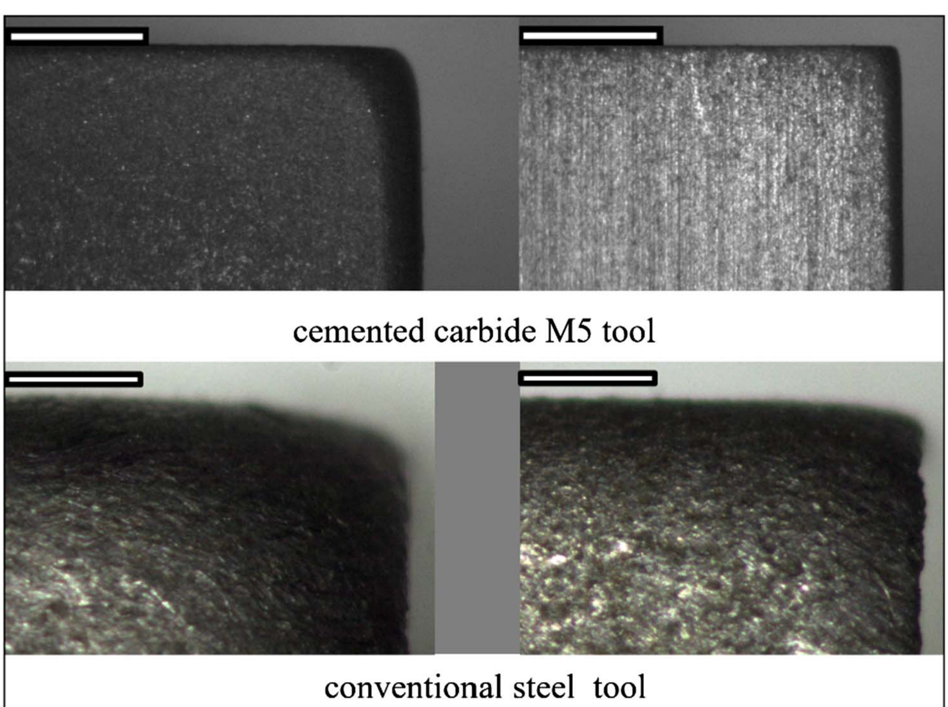

Fig. 12. Tools cutting edge scanned by video-microscope LEICA VZ85R. Natural soil (left) and conditioned soil (right). Magnification: 200 ×. Scale bar: 1 mm.

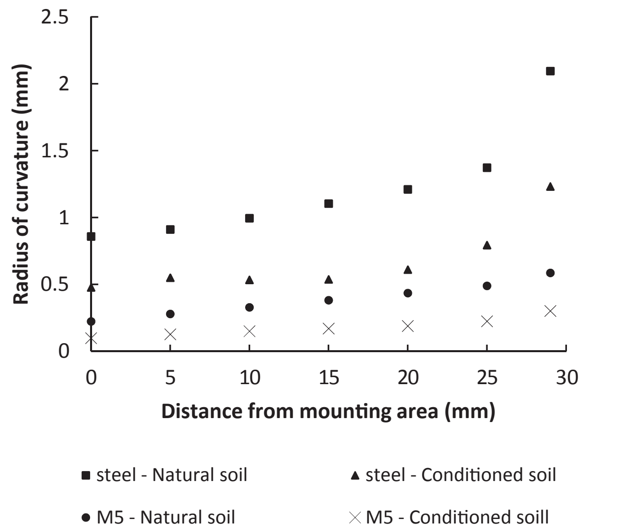

Fig. 14. Curvature radius measured after the three wear cycles *in natural and conditioned soil.*

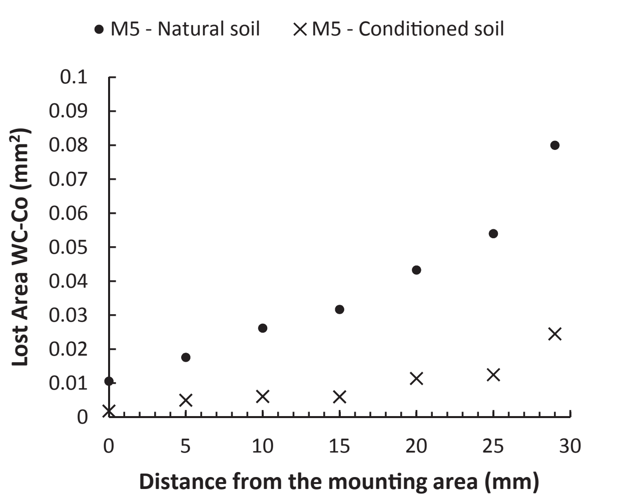

Fig. 15. Area losses according to location of the measurement linescan for the natural and conditioned soil using the cemented carbide tools after three wear cycles.

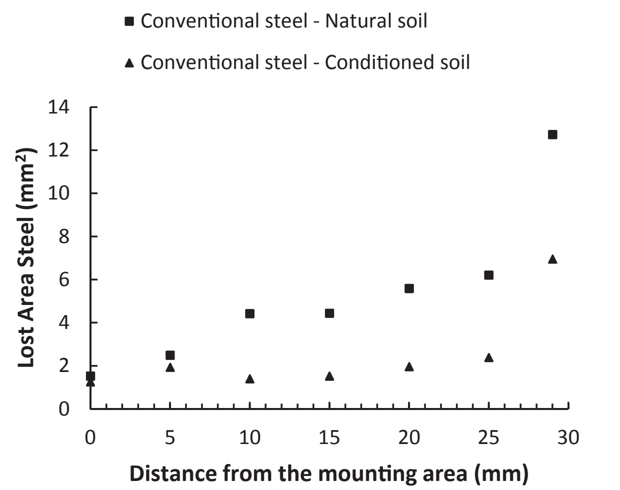

Fig. 16. Area losses according to location of the measurement linescan for the natural and conditioned soil using the conventional steel tools after three wear cycles.

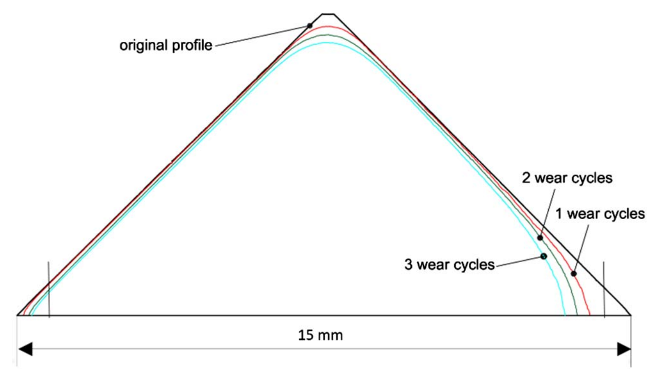

Fig. 17. Measured shape of the tool wear pattern after each wear cycle at the tool edge. The right side is the lower part of the tool when assembled on the carrier.

used to ensure a parallelism between tool surface and the positioning table of the microscope, as shown in Fig. 9.

Quantitative analysis of edge rounding was performed through the measurements of the tool sample profiles, using a profilometer (model *MarSurf CD 120*). All wear tools were tested in seven measuring locations along the cutting edge as shown in Fig. 10. The position of the measuring locations has been chosen to guarantee a complete representation of the worn area along the tool. The radius of curvature of the worn tool is the radius of the osculating circle which best approximates the worn profile at maxima. The volume loss is obtained comparing the original and worn geometries (Fig. 11).

4.1. Experimental results and discussion

The observed images of the tool cutting edge by the video-microscope are presented in Fig. 12 in order to show the change in geometry after three wear cycles. As expected, it is possible to observe that the maximum wear occurs near the tool edge where three wear surfaces are present. From the comparison of the wear morphology for the two tested materials it is possible to see that in M5 cemented carbide tools, the wear is mainly located at the sharp edge of the tool. Only little wear can be detected on the tool lateral sides. On the other hand, conventional steel tools show a stronger wear both on the edge and on the lateral faces where the formation of pitting and of important wear zones can be detected. Furthermore, the use of conditioning agents provided a marked reduction of the wear, as showed for the cemented carbide tools in natural and conditioned soil (Fig. 13).

The tribological action is quantified by the behavior of curvature radius: an increase of the curvature radius value occurs moving towards the external edge, which is subjected to the maximum tangential speed during the wear test (see Fig. 14).

With natural soil, the curvature radius values are ranging between 2.15 mm for conventional steel and 0.585 mm with the M5 cemented carbide. These values are reduced to 1.25 mm (with a reduction of about 45%) and 0.31 mm (with a reduction of about 47%) respectively when using the conditioned soil. These results quantitatively confirm that the conditioning additives effectively reduce the wear as already highlighted by other researches (Hedayatzadeh et al., 2015; Gharahbagh et al., 2014; Peila et al., 2012).

Similar observations can be done considering the values of the lost volumes obtained by the integration of the area loss (Figs. 15 and 16) and the volume loss values at the end of the third wear cycle. The volume loss for the cemented carbide M5 tools ranges from 1.02 mm^3 in natural soil to 0.25 mm^3 (with a reduction of about 75%) in conditioned

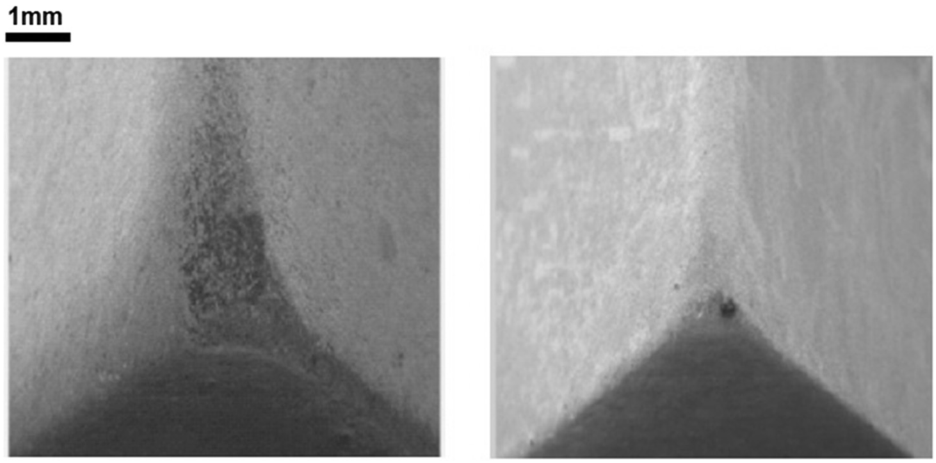

Fig. 18. SEM images focused on the rounded peripheral edge in natural (left) and conditioned (right) tests after three wear cycles with the cemented carbide tool. Acquisition mode: SE. Mag: 50×.

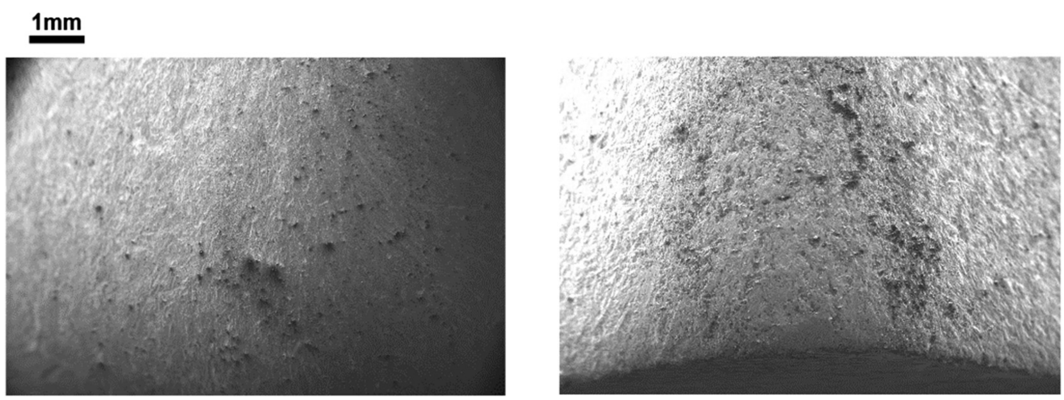

Fig. 19. SEM images focused on the rounded peripheral edge in natural (left) and conditioned (right) tests after three wear cycles in conventional steel. Acquisition mode: Mag: 50×. It is important to highlight that in the natural soil the shape of the tool has been completely worn.

soil while for the conventional steel the volume loss ranges from 148.8 mm^3 to 66.5 mm^3 (with a reduction of about 55%) (see Fig. 17).

Figs. 18 and 19 show the SEM images on the rounded peripheral edge in natural and conditioned soil tests after 3 wear cycles for the M5 cemented carbide and for the conventional steel (acquisition mode: SE. Scale bar: 200 μm. Mag: 50×). It is possible to observe the great difference of wear pattern. In conventional steel, the abrasion wear cuts are evident and some grains of quartz remain embedded in the steel surface. Abrasion occur on the tool blade and also on the face as shown in Fig. 16. The comparison of the wear test with natural soil and the conditioned one, shows an important reduction in the number of these quartz particles on the tool surface (see Fig. 20).

Finally based on the experimental results the following three indexes, able to quantify the wear effect, were defined:

- the curvature radius index (I_{cr}) (mm/km) expresses as the ratio of the mounting area of the wear tool at the tool edge divided the distance carried by the tool (after 3 wear cycles);
- the volume lost after 3 wear cycles (ΔV) (mm^3) expressed by the difference between the shape of the worn tool and the original one. This index takes into account the global wear that can occur both on the sharp angle and along the tool faces and the tool blade;
- the wear index (I_{WeC}) ((mm^3/mm^3)/km)) defined as the slope of the line interpolating the specific volume loss ($\Delta V/V_{Original}$) after each wear cycle (see Figs. 21 and 22).

All the measured results and the computed indexes are summarized in Table 2.

Finally, it should be observed that the used quartzite sand before and after the tests has been checked by the measurements of the grain size distribution. Similarly to results assessed by Gharahbagh et al. (2014) no significant differences were observed by this comparison both for natural sand and conditioned sand. The two grain size distribution lines are completely overlapped. This observation has been confirmed by an analysis of the quartz grains of the sand using a video-microscope, and it was not possible to assess any difference of the grain roundness and shape before and after the test.

5. Conclusion

The wear phenomenon in EPB shield tunneling machine is an important part of the design stage for a new tunneling project. The stops for changing the machine tools, restore a worn cutterhead or a screw conveyor are time consuming processes that can negatively affect tunnel construction. Furthermore, these operations could require working in hyperbaric conditions. For all these reasons, nowadays the study of wear is fundamental, in order to carefully plan construction time, construction cost and the excavation process. Therefore, there is a

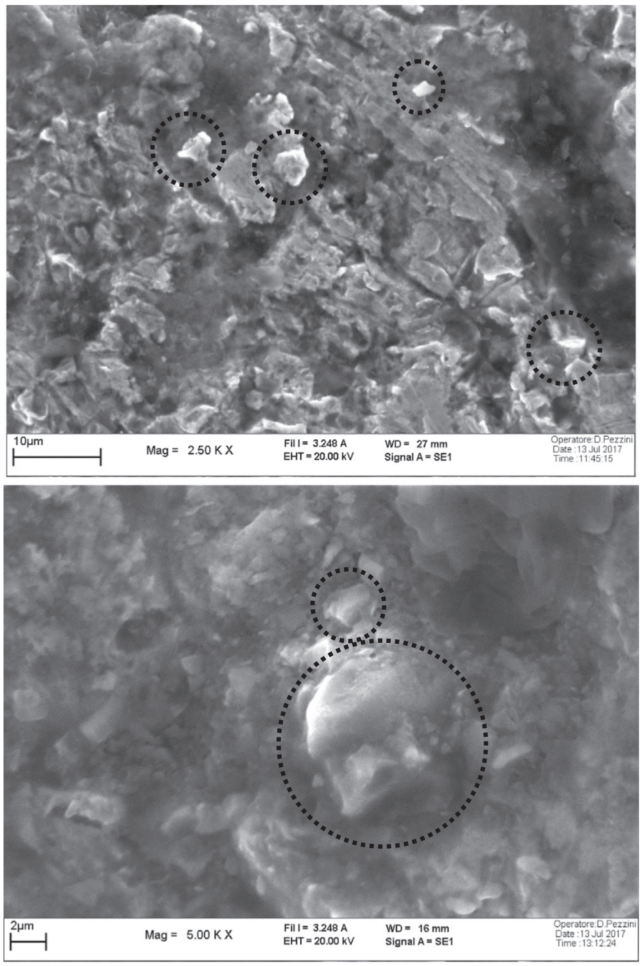

Fig. 20. SEM images focused on the face of the conventional tool surface, at different magnification. The dotted circles highlight the quartz grains embedded in the conventional steel matrix.

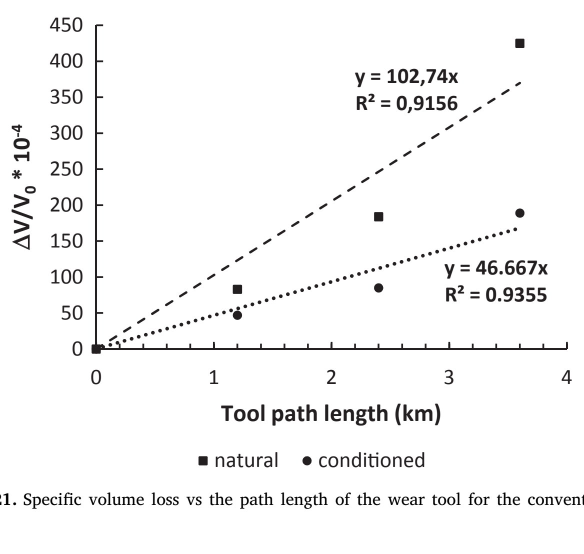

Fig. 21. Specific volume loss vs the path length of the wear tool for the conventional steel.

technical need for tunneling engineers to have feasible and tested laboratory procedures able to provide them with reliable results that can be used for wear prognosis. Many studies have dealt with this topic and

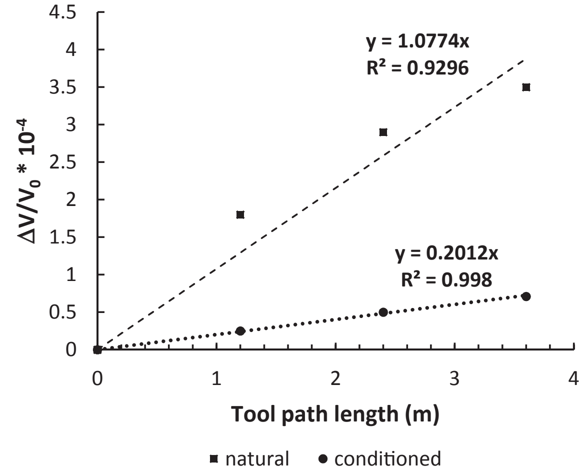

Fig. 22. Specific volume loss vs the path length of the wear tool for the M5 cemented carbide.

different devices and procedures have been proposed and universally recognized tests are not available.

The test procedure presented in this paper is also based on the rotation of the wear tools inside the soil like other tests proposed in scientific literature. The innovation of the methodology are the tool shape and the wear assessment. The tools have been specifically designed to be able to provide reliable results also when carrying out tests in conditioned soil, since they return measurable data even for a short test time. This feature is key for testing since the life of the most used conditioning agents (i.e. foam bubbles) is relatively short. Furthermore, the tool shape makes it possible to obtain measurable data even when studying hard materials, such as the ones used as inserts on the drilling tools, that should not suffer wear in short test time. The designed tools have a sharp shape that allows simple measurements of the torque and the weight lost during and after the test and also a precise geometrical assessment of the worn geometry.

The measurement of the curvature radius at the mounting area of the tool and of the volume lost at the end of the test makes it possible to define a wear index (I_{WeC}): the calculated average slope of the specific volume loss vs. the tool length path. This index globally takes into account the path of the tool during the test inside the soil and the induced wear. All the indexes that this study has identified and proposed can be used to assess and compare the positive effects of different conditioning agents and different conditioning sets, directing the tunnel designer and the conditioning agents producers toward the optimal wear choice in different soils and underground conditions. Therefore, indexes can be linked with the tool behavior in an EPB machine and can be used for wear prognosis at the design stage. Linking the wear that occurs in an EPB machine, working in a specific geological environment, and the laboratory tests is complex: comparing many real tunnel data and laboratory outcomes may allow this link. This process is ongoing.

The description of the proposed device, test method and tribological measurements is a contribution in the issue of wear and can provide a basis for the design of a unified test procedure. The application of the methodology to study the behavior of M5 cemented carbides and conventional steel tools, with and without conditioning allowed to assess the sensitivity of the test method, confirming the great importance of a proper soil conditioning in wear reduction.

Table 2
Summary of the measured data and values of the proposed indexes.

Test	Soil condition	Tool material type	Tool path length (m)	ΔV (mm^3)	R_{cur} (mm)	$\Delta V/V_0 * 10^{-4}$ (–)	I_{cr} (mm/km)	I_{WeC} ((mm^3/mm^3)/km)
#1	Natural	Steel	3600	148.81	2.15	425	0.52	102.7
#2	Natural	Cement carbide M5	3600	1.02	0.585	3.5	0.14	1.07
#3	Conditioned	Steel	3600	66.48	1.25	189	0.30	46.7
#4	Conditioned	Cement carbide M5	3600	0.25	0.31	0.71	0.07	0.20
#5	Natural	Steel	2400	64.40	–	184	–	–
#6	Natural	Cement carbide M5	2400	0.95	–	2.90	–	–
#7	Conditioned	Steel	2400	29.71	–	85	–	–
#8	Conditioned	Cement carbide M5	2400	0.18	–	0.5	–	–
#9	Natural	Steel	1200	29.05	–	83	–	–
#10	Natural	Cement carbide M5	1200	0.62	–	1.8	–	–
#11	Conditioned	Steel	1200	16.45	–	47	–	–
#12	Conditioned	Cement carbide M5	1200	0.09	–	0.25	–	–

Acknowledgements

The financial support of this work has been provided by HM-TUNES Project (264-121) granted by European Structural Founds – PAR FSC 2007/13 and by Politecnico di Torino research founds.

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