ABRASIVITY OF ROCK AND SOIL

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ABSTRACT
The abrasivity of rock and soil is a commonly determined property, which is used for the estimation of the wear of excavation tools. Therefore, different laboratory test have been developed over the last decades. Within this work, the often used LCPC- and Cerchar-test are presented. The influence of the steel sample material on the determined abrasivity is analyzed in terms of the tribological system, which describes the components and interactions influencing the wear of the tunneling tools. The problems and inaccuracies in terms of the test methods are discussed and described from the view of materials technology. To determine a sufficient wear-prediction model for excavation tools, laboratory tests like LCPC and Cerchar are useful, but they have to be considered in the tribological context. This means that it is necessary to map as much characteristics as possible from the associated tribological system. The different system components and their interactions have to be taken into account to determine a precise and sufficient wear-prediction model. The mandatory influence of the steel sample material on the results of the presented test methods and thus on the abrasivity of rock and soil has been pointed out.

INTRODUCTION
In recent years, mechanized tunneling and especially tunneling with a TBM has gained in importance. The constantly increasing need for infrastructure and construction sites aroused the intensified interest for underground expansions. The mechanized tunneling with a TBM has become very popular because of some significant advantages. Due to the simultaneously excavation and removal of the ground next to the subsequent tunnel lining, the efficiency of the process is higher compared to other tunneling methods (e.g. blasting or dredging). This increase leads for example to higher advance rates and thus to lower costs caused by shorter project duration. To exploit these advantages, the planning and budgeting of those tunneling projects plays a significant role. Calculations related to the estimated tunneling progress and thus to the overall costs are depending on multiple parameters and influencing factors. One of those parameters can be found in the wear of the tunneling tools, which are mounted on the cutter head. When tunneling tools are subject to excessive wear, penetration and thus the advance rate decreases. The tools have to be replaced during a maintenance interval, which leads to very high costs due to unplanned downtimes. With the help of wear-prediction models, the wear of the tools in dependency of the met geology is investigated. Therefore, actual approaches are based on the abrasivity of the geology and some soil mechanic properties (e.g. equivalent quartz content (EQu) or shear strength). From the view of materials technology, wear has to be considered in the predominant tribological system. This means that it is necessary to take all components, which

have a major influence on the wear of the tools into account (e.g. the tool material, the geology and the interactions in between). This work focusses on these interactions in terms of the tribological system to assess actual used wear-predictions. Thus leading to a better understanding of the wear processes, which in turn is the key to more sufficient wear-prediction models for TBM tools. To illustrate the influence of the tribological system and its components, commonly used testing methods to determine the abrasivity of hard-rock and soil have been performed (LCPC- and Cerchar-Abrasivity-Test). The results are analyzed related to the influence of the used steel sample material to clarify the importance of the TBM tool material on the tribological system and thus on the wear of the tools.

1 EXPERIMENTAL

In the course of the investigations, specimens for the different test methods were made of various materials in accordance with the requirements of the different standards. The materials used, their classification, heat treatment and hardness in Vickers are listed in Table 1. These grades are also used in mining and tunneling for welded steelworks (construction steel), chain links (quenched and tempered steel) or excavation tools (tool steel, cemented carbide). The intention is to investigate the influence of these material groups on the test results in order to derive realistic wear predictions for the wear pairs that occur in real applications. The use of heat-treated steels, tool steels with high carbide content and cemented carbide is intended to widen the scope of application and thus the validity of its statements.

Table 1. Categorization of material groups with regard to the different properties and features, which are picked up in the following chapters. The numbering refers to the diagrams in chapter 2.

Material	Material group	No.	Heat-teatment	Hardness [HV]	Microstructure
C45 (1.0503)	unalloyed quenched and tempered steel	1	soft-annealed	130 ± 15	ferritic/pearlitic
		2	normalized	180 ± 15	ferritic/pearlitic
		3	tempered	320 ± 15	tempered martensite
		4	quenched	440 ± 15	martensitic
S275 (1.0044)	construction steel	5	soft-annealed	120 ± 15	ferritic/pearlitic
		6	normalized	130 ± 15	ferritic/pearlitic
		7	tempered	190 ± 15	ferritic/pearlitic
		8	quenched	250 ± 15	ferritic/pearlitic
34CrNiMo6 (1.6582)	quenched and tempered steel	9	soft-annealed	250 ± 15	ferritic/pearlitic
		10	normalized	320 ± 15	pearlitic/martensitic
		11	quenched and tempered	460 ± 15	tempered martensite
		12	quenched	590 ± 15	martensitic
42CrMo4 (1.7225)	quenched and tempered steel	13	soft-annealed	220 ± 15	ferritic/pearlitic
		14	normalized	310 ± 15	ferritic/pearlitic
		15	quenched and tempered	450 ± 15	tempered martensite
		16	quenched	600 ± 15	martensitic
X40CrMoV5-1 (1.2344)	hot-work tool steel	17	soft-annealed	150 ± 15	ferritic/pearlitic
		18	tempered (SHM)	450 ± 15	tempered martensite
		19	quenched	440 ± 15	martensitic
X210Cr12 (1.2080)	cold-work tool steel	20	soft-annealed	470 ± 15	carbide-rich
		21	quenched	860 ± 15	carbide-rich
		22	tempered at low temp.	780 ± 15	carbide-rich

		23	tempered at high temp.	680 ± 15	carbide-rich
X155CrVMo12-1 (1.2379)	cold-work tool steel	24	soft-annealed	390 ± 15	carbide-rich
		25	quenched	750 ± 15	carbide-rich
		26	tempered at low temp.	870 ± 15	carbide-rich
		27	tempered (SHM)	690 ± 15	carbide-rich
HS6-5-2 (1.3343)	high-speed tool steel	28	soft-annealed	400 ± 15	carbide-rich
		29	quenched	860 ± 15	carbide-rich
		30	tempered (SHM)	890 ± 15	carbide-rich
K40	cemented carbide (medium grain)	31	-	1800 ± 15	90% carbide, 10% matrix

1.1 Heat treatment

In order to create the desired microstructure and the correlating mechanical properties, materials are heat treated according to the manufacturers' instructions (Tab. 1). To keep the article concise, the heat treatment parameters are not listed.

1.2 Hardness measurement

The Vickers (HV 10 and HV 0.05) hardness of the samples was determined according to DIN EN ISO 6507-1 (hardness tester KB-30s; test load 98.7 N). In order to maintain reproducibility, five values were measured for each sample and averaged

1.3 LCPC tests

The LCPC test was performed in accordance with the standard AFNOR P18-579 [1] with sand-blasted impellers of dimensions 50 × 25 × 5 [mm] and air-dried soil samples (500g ± 2g) of grain size 4 to 6.3 mm. The test duration was 5 min. and the rotational speed of the impeller was set to 4,500 rpm. The steel impeller rotates in the soil sample thus leading to wear of the impeller (Fig. 1). LCPC abrasiveness coefficient (LAC) was determined from the mass difference of the impellers according to equation (1), in which m_0 is the mass of the impeller before and m is the mass after the test; M is the mass of abrasive used. Three measurements were performed for each material and averaged. As abrasive, crushed quartz gravel and fused corundum were used, crushed to the required grain size. The used abrasives for all performed tests are listed in table 2.

$$LAC = (m_o - m)/M \text{ [g/t]} \tag{1}$$

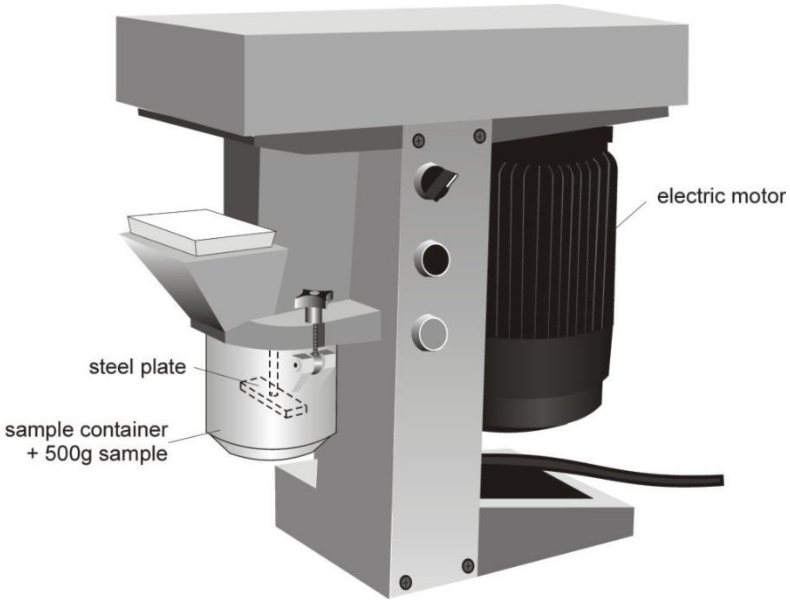

Figure 1. Schematic experimental set-up of the LCPC-test [2].The abrasive is filled in the sample container, which contains the steel impeller/plate. The impeller is driven by an electric motor.

Table 2. Outline of the used abrasives for the investigated test methods. Only for the Cerchar-Tests, the Equivalent-Quartz-Content (EQu), the Uniaxial-Compressive-Strength (UCS) and the Rock-Abrasivity-Index (RAI) were determined [3].

Test-method	Abrasiv	Mohs-hardness	EQu [%]	UCS [MPa]	RAI [-]
LCPC	quartz gravel	6 - 7			
"	fused corundum	9			
Cerchar	Bebertal-sandstone	6 - 7	65	72	46,9
"	Keuper-sandstone	6 - 7	90-95	26	23,4 - 24,7

1.4 Cerchar-Test

The Cerchar-Abrasivity-Test was developed in 1973 by the “Laboratoire du Centre d’Etudes et Recherchers des Charbonnages de France” (CERCHAR), which published the first test specification in 1986 [4]. A steel sample is scratched across a rock surface under an applied static load. The wear of the tip represents the abrasivity of the hard-rock, which is classified with the Cerchar-Abrasivity-Index (CAI). The first test setup was optimized in 1989 [5] (Fig. 2) and additionally characterized in the french specification “NF P 94-430-01” in 2000 [6]. The 90° conical tip of the test body, which is mounted in a socket, is scratched across a predefined freshly broken or sawn rock surface over a distance of 10mm. A static load of 70N is applied on the test body. In terms of the used test body material, only the hardness is defined in the actual specifications. The first specification recommends test bodies with a hardness of 54-56 HRC [3]. WEST (1989) recommends a hardness of 40 HRC for his modified apparatus [5]. The wear of the tip is used to determine the CAI with an optical microscope. Therefore, the diameter of the worn tip *d* [mm] is multiplied with a factor of 10 (Equ. 2).

$$CAI = d_V \cdot 10 \; [-] \quad (2)$$

The Cerchar-tests were performed with test bodies made of different steels and heat-treatments as mentioned in table 1. For every material, at least five values were measured and averaged. Two sandstones with freshly broken and sawn surfaces were used as abrasives (Bebertal and Keuper).

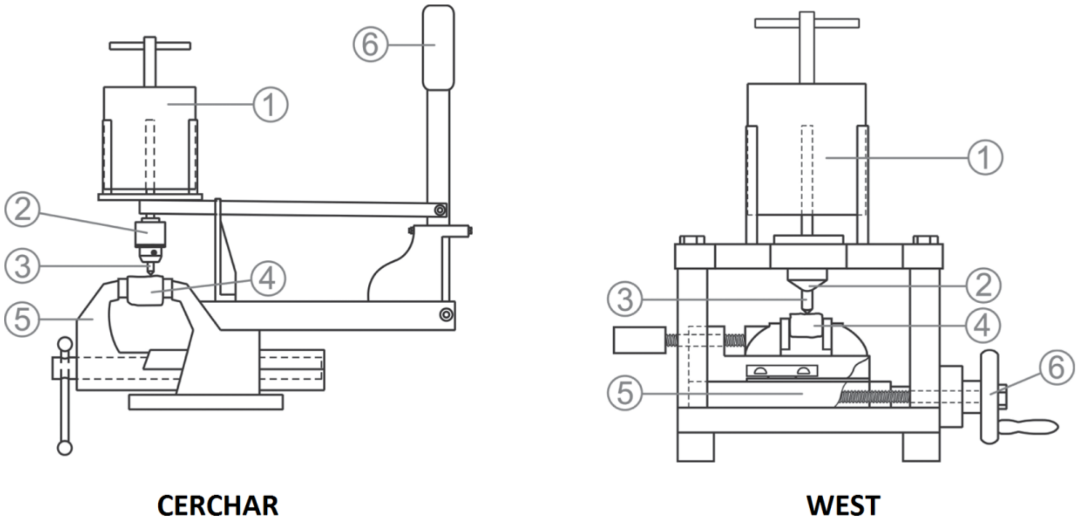

Figure 2. a) Setup after CERCHAR [4]. b) modified setup after WEST [5]. 1-load; 2-sampleholder; 3-test body; 4-rock sample; 5-mounting; 6-crank-handle [7].

2 RESULTS

2.1 LCPC-tests

The results of the performed LCPC-test with the various impeller materials are shown in figure 4 (LAC values for the crushed quartz gravel and the fused corundum against hardness of the impeller in Vickers). The LAC and thus the abrasivity of the abrasive decreases with increasing hardness of the sample. The various specimen materials are categorized in different groups referring to their present microstructure (ferrite/pearlite, bainite/martensite, carbide-rich and cemented carbide). Related to the higher Mohs-hardness of the fused corundum (Tab. 2), the LAC values are higher as for the quartz gravel over the whole hardness range. The LAC seems to decrease linearly with increasing steel impeller hardness. Only for the carbide-rich materials (marked with 21 till 30) the progression of the LAC is not distinct. The LAC increases slightly with increasing hardness. The impeller made of cemented carbide leads to the lowest LAC values for both abrasives.

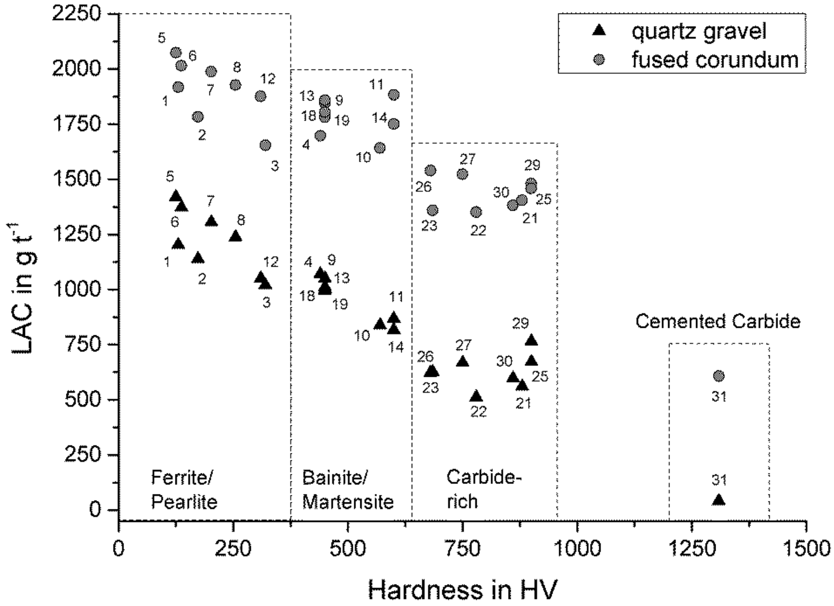

Figure 4. LAC value against hardness of the impeller for the abrasives crushed quartz gravel and fused corundum. The used materials are grouped referring to their microstructure. The numbering denotes the relevant impeller material and heat treatment state (Tab. 1).

2.2 Cerchar-tests

The experiments presented were done with the abrasives Keuper- and Bebertal sandstone in two different surface conditions (sawn and freshly broken). As for the LCPC-test, the sample materials were varied. The results of these tests are shown in figure 5 and 6.

In figure 5a the CAI value for the Keuper-Sandstone with a sawn surface is plotted against the hardness of the used specimen material. The results for the different materials show a high deviation. Furthermore the scattering of the CAI over the entire hardness range is significant high. CAI values from 1 till 7 can be seen for the same abrasive. Figure 5b illustrates the differences in the CAI in dependency of the hard-rock sample surface condition. The determined values on the freshly broken surface (Fig. 5b) are lower over the whole hardness range of the used test body in comparison to the CAI values for the same abrasive on a sawn surface (Fig. 5a).

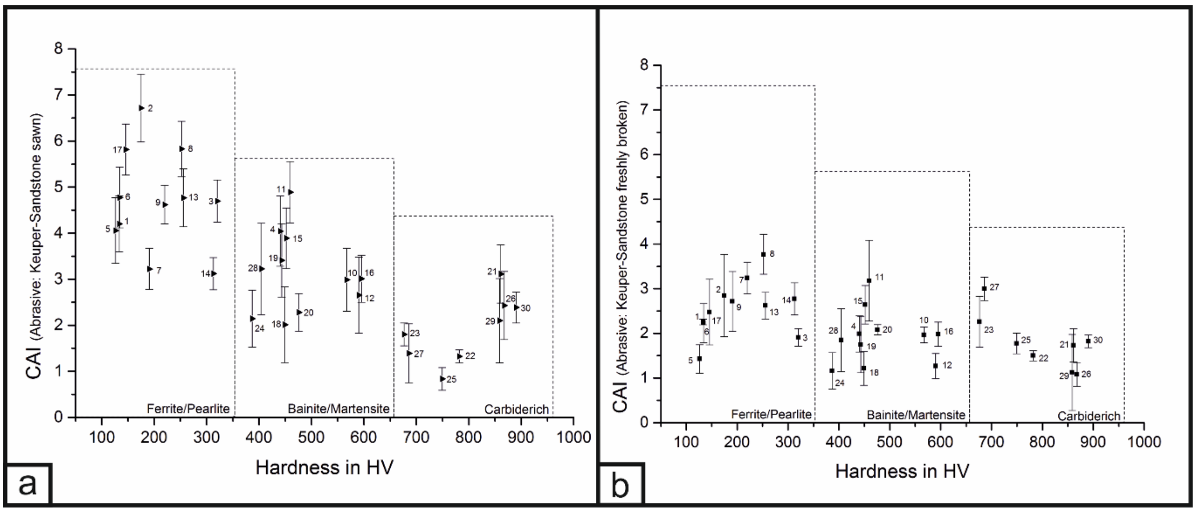

Figure 5. CAI value against hardness of the test body for the abrasive Keuper-sandstone with a) sawn and b) freshly broken surface. The used materials are grouped referring to their microstructure. The numbering denotes the relevant test body material and heat treatment state (Tab. 1).

Figure 6 shows the CAI values for the abrasive Bebertal-sandstone with a sawn (Fig. 6a) and a freshly broken surface (Fig. 6b). As indicated in figure 5, a high deviation in the values over the whole hardness range can be seen. Especially for the carbide-rich sample materials no direct correlation between hardness and resulting CAI-value can be found. This discontinuity can be transferred to all samples, due to the high scattering and irregular progression of the determined CAI values, leading to no distinct correlation between hardness of the sample and CAI of the abrasive. The influence of the surface condition of the abrasive can be seen in both figures (Fig. 5 and 6. For most sample materials, the CAI on a freshly broken surface is lower compared to a sawn surface.

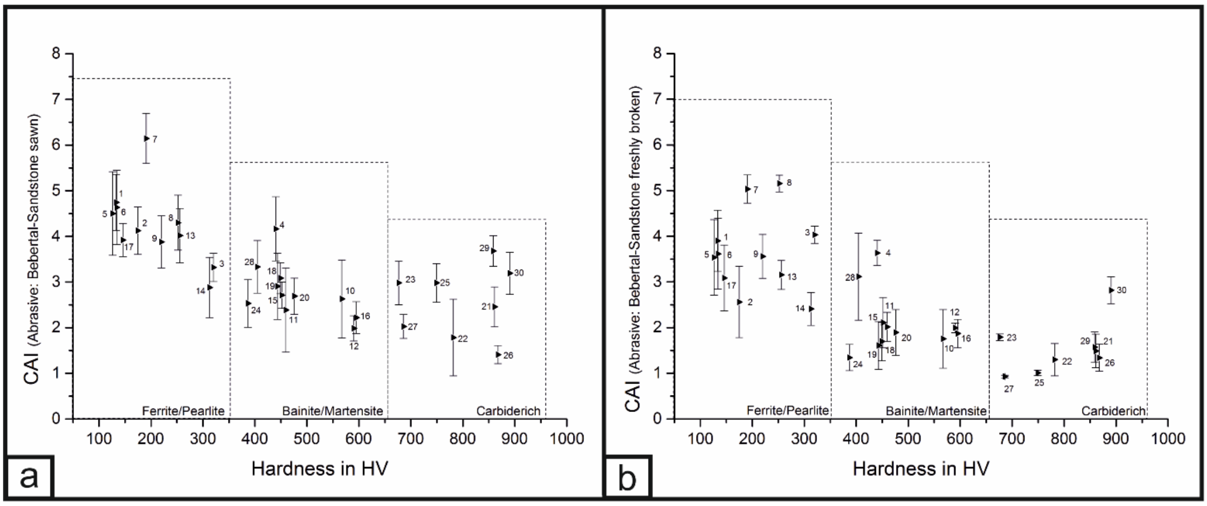

Figure 6. CAI value against hardness of the specimen for the abrasive Bebertal-sandstone with a) sawn and b) freshly broken surface. The used materials are grouped referring to their microstructure. The numbering denotes the relevant test body material and heat treatment state (Tab. 1).

3 DISCUSSION

The presented results of the LCPC- and Cerchar-tests will be discussed in terms of the tribological system. Therefore, tribological system related to a TBM tool is presented and analyzed at first. The tribological system summarizes all components, interactions and influences that have an impact on the stress and thus on the wear of the investigated object [8]. A tribological system always consists of four main system components: base unit, counter body, load spectrum and ambient/intermediate medium [8]. Schematically, figure 7 shows the tribological system “TBM-tool”, which is composed of the tunneling tool (base unit), the working face/geology (counter body) and the load spectrum (contact pressure, advance rate, etc.). The ambient/intermediate medium (e.g. groundwater or bentonite) is not considered in this work.

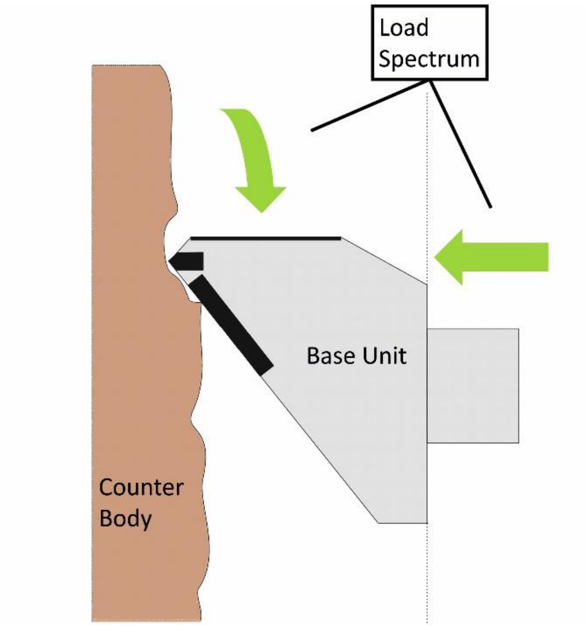

Figure 7. Tribological system for a TBM tool in soil. The tool (base unit) scratches over the tunnel face/geology (counter body) and excavates the soil. This degradation process and the correlated wear of the tool are strongly dependent on the load spectrum of the tunneling process (e.g. advance rate, penetration, rotational speed).

The wear of the TBM tool is dependent on the interactions between these system components. It becomes obvious that if one component is varied, the system is changed thus leading to different wear-mechanisms and wear-rates of the tool. If we transfer this knowledge to the presented laboratory test methods, first problems and inaccuracies occur. In a laboratory scale test set-up, the tribological system cannot be reproduced exactly. The load spectrum of a tunneling process cannot be simulated in wear test in a laboratory scale, thus leading to the first deviations in the investigated tribological system. In the same line, the used base unit and counter body have a mandatory influence on the achieved results. Thus leading to the key question of this work: The influence of the sample material on the investigated test methods to determine the abrasivity of soil and rock.
The results for the LCPC-test presented in figure 4 reveal that the microstructure of the used steel impeller has a significant influence on the LAC. The LAC decreases with increasing macro-hardness of the microstructure from ferrite/pearlite, bainite/martensite, carbide-rich to cemented carbide (Fig.4). The first impression that the regression curve of the LAC values over the hardness of the sample material decreases linearly has to be regarded with suspicion. If the carbide-rich samples (marked with 21-30) are only considered, the LAC slightly increases with increasing hardness. The explanation for this behavior is based on the composition of the microstructure (grain size, hard particle size and distribution, etc.). These correlations are investigated and discussed in [9] and will not be remarked in this work, additionally. The severe influence of the steel impeller material on the abrasivity of the investigated soil becomes obvious. If the focus lies on real tunneling application, a wide range of different steel grades is used in a TBM. For example frameworks or the shield made of ferritic/pearlitic steels, parts of the conveying system made of bainitic/martensitic steel grades and tools made of carbide-rich materials or cemented carbide. Another example would be a composite tool, which consists of a ferritic/pearlitic or bainitic/martensitic substrate, carbide-rich build-up weldments and cemented carbide inlets. These examples in correlation with the results of the LCPC-tests (Fig. 4) illustrate the mandatory influence of the sample material on the tribological system and thus on the wear of the tools.

The results of the Cerchar-tests show an analogous behavior (Fig. 5 and 6). The influence of the different system components in a tribological system on the wear or respectively abrasivity can be demonstrated. Figure 5a illustrates the influence of the sample material on the CAI. As for the LAC, the CAI decreases with increasing hardness although the deviation and scattering of the measurements are high. The previous mentioned discrepancy for the carbide-rich sample materials can be seen in the CAI values too. The abrasivity increases with increasing hardness for the steel grades marked with 21 till 30 (Fig. 5a). By taking figure 5b into account, the influence of the surface condition (counter body in the tribological system) can be seen. The CAI values for the Keuper-sandstone with a freshly broken surface (Fig. 5b) are significantly lower compared to the values on a sawn surface (Fig. 5a). The change in the surface condition leads to a change in the rock mechanical properties (e.g. cohesive forces between grains and particles). The influence of the counter body in the tribological system can be proved additionally with figure 6. The differences in the CAI for the Bebertal-sandstone in dependency of the surface condition can be seen by comparing figure 6a and 6b. The CAI values determined on a freshly broken surface are lower compared to the sawn surface whereby the progression of the values over the sample hardness (Fig. 6b) differentiate from the progression of the CAI of the Keuper-sandstone with a freshly broken surface (Fig. 5b). Although the Keuper- and Bebertal-sandstone have the same Mohs-hardness of 6-7 (Tab. 2), the CAI values and thus the classification of the abrasivity differ. Again the rock mechanical properties of the abrasive reveal a significant influence on the abrasivity and thus on the tribological system (load spectrum of the system is changed). The uniaxial compressive strength (UCS) and the equivalent quartz content (EQu) of the investigated abrasives differ (Tab. 2). Although the EQu of the Bebertal-sandstone (65%) is much lower than the EQu of the Keuper-sandstone (90-95%), the CAI of the Bebertal-sandstone is approximately equal (Fig. 5a and 6a) or even higher (Fig. 5b and 6b). If the UCS of the abrasives is taken into account, the differences in the CAI become more comprehensible. The UCS of the Bebertal-sandstone is more than three times higher than the UCS of the Keuper-sandstone (72 and 26 MPa). PLINNINGER et al. [3] and ROSTAMI et al. [10] have already mentioned that several rock mechanical properties have to be taken into account, if the abrasivity of hard-rock should be determined sufficiently. An example would be the Rock-Abrasivity-Index (RAI) [3], which is determined by the multiplication of the UCS and the EQu. This leads to a RAI for the Bebertal-sandstone of 46, 9 and for the Keuper-sandstone of 23,4 – 24,7 (Tab. 2). The RAI seems to be a more precise approximation for the classification of the abrasivity. In the context of the previous explained tribological system, it becomes obvious that the accuracy of such index values increases with the number of considered rock mechanical properties and influencing factors. So the central statement of these observations is again the mandatory influence of every system component and their interactions in the tribological system.

By transferring these correlations to the need of sufficient wear-prediction models for TBM-tools, the major concerns in terms of the validity become obvious. Models which are based on the abrasivity of the geology determined with the LCPC- or Cerchar-test cannot be precise due to the insufficient mapped tribological system. Improved wear-prediction models have to take the different system components into account. Base unit, counter body, load spectrum and ambient/intermediate medium have to be regarded. Their interactions and thus their influence on the wear have to be described by meaningful parameters, which are directly linked with the associated tunneling project.

4 CONCLUSION

This work deals with the determination of the abrasivity of hard-rock and soil, which is used to generate wear-prediction models for TBM tools. Two test methods were performed with different steel sample materials. The results of the LCPC- and Cerchar-tests illustrate the impact of the used sample material on the classification of the abrasivity of an investigated abrasive. Wear-prediction models, which are based on such laboratory scale index values are very imprecise and show a large scattering. To determine sufficient models, the application-oriented tribological system with all components and interactions has to be taken into account. First approaches in terms of the counter body were done in literature [3, 10], but not for the other system components. This work illustrates the influence of the base unit on the abrasivity of the ground and thus on the tribological system. The abrasivity is strongly dependent on the used sample material. The mentioned correlations lead to the comprehension that it is necessary to map the tribological system with all components to determine precise wear-prediction models.

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