The phenomenon of tools' wear in a marble quarry: laboratory tests to evaluate the performance of conditioning as a wear preventer

Alfio Di Giovanni, Carmine Todaro, Simone Saltarin, Marilena Cardu
Politecnico di Torino, Department of Environment, Land and Infrastructure Engineering, Torino, Italy

ABSTRACT: Exploitation with a chain saw cutting machine has been the ordinary industrial practice in marble excavation for over thirty years, due to its ability to adapt to difficult environments and to guarantee a high level of safety during the cutting phase. Nevertheless, the presence of impurities in the calcite matrix, e.g. quartz, leads to the problem of rapid and unusual wear on cutting tools.
In this study, two laboratory tests were selected and carried out to estimate the rock's wear potential: the CERCHAR Abrasivity test and the Soil Abrasion Test Apparatus (SATA).
The results highlight a high degree of abrasivity in dry conditions, which was satisfactorily reduced by using water and additives. This mixture, typically used in tunnelling applications, is intended to decrease the wear from rock excavation and a significant reduction of this phenomenon has been noticed.

Keywords: dimension stone exploitation, tool wear, Soil Abrasion Test Apparatus, CERCHAR Abrasivity test, wear reduction.

1. INTRODUCTION

The exploitation of Carrara marble is an ancient practice that has taken place since Roman times, and is a significant part of the region's economy even today. Over the centuries, Carrara marble has been used in some of the world's most iconic monuments and buildings, including the Pantheon, the Taj Mahal, and the British Museum. Commonly, the wear phenomenon linked to the Carrara marble exploitation process is negligible, since the commonly used technologies, such as the chainsaw and the diamond wire are capable of easily cutting blocks of marble, mainly composed of calcite (3rd degree of the Mohs scale). However, in recent years, the wear issue has become more topical in the Carrara quarries, since in several areas the required productivity was not guaranteed due to the strong abrasiveness of the marble, which can hide (and in extreme cases completely block) the chainsaw cutting machine.

Wear is a critical issue affecting mining and quarrying, as it directly impacts efficiency and operating costs (Ellecosta et al. 2019). Many different factors have to be considered when investigating the wear process, such as the excavated material proprieties, the water content, the

relative quartz content, the excavation technique, the characteristics of the cutting tools, etc. (Alber 2008, Rauch et al. 2018 and Di Giovanni et al. 2023). Between marble and tools, during the cutting process, a mutual destruction takes place, which is wanted on the rock side but is suffered on the side of the tool (Mancini & Cardu 2001). Therefore, to minimize these effects, the shape and composition of the tools must be properly designed.

Currently, the literature on chainsaw exploitation in carbonate rock pertains to performance prediction models (Çopur et al. 2010, Çopur et al. 2011 and Tumac et al. 2013) although the problem of wear linked to the possible presence of quartz or other abrasive minerals has not been investigated in depth. In the context of the intense wear phenomenon found in a specific area of Carrara quarries, this research was developed. The wear phenomenon has been studied following two different approaches: on one end, the standard CHERCAR Abrasivity Index (CAI) has allowed an evaluation of the wear potential considering the marble as a rock. Alternatively, the marble has been crushed and the Soil Abrasion Test Apparatus (SATA) allowed the material to be studied as soil. This second approach was chosen to try to better simulate the wear caused by the rock already destroyed by the tools of the chainsaw, along the path dictated by the saw. Furthermore, a specific test campaign was planned with the aim of evaluating the potential reduction in terms of the extent of wear obtainable by using a specific additive commonly adopted for tunnelling applications, hereinafter referred to as an anti-wear agent. The results highlight the influence of the water content on wear (confirming the results reported by Abu Bakar et al. 2016) but the important innovation presented and discussed concerns the strong wear reduction obtained from the anti-wear agent used.

2. LABORATORY TEST

2.1 Testing material

The material to be tested comes from a marble quarry in the Apuan Alps, where the problem of wear occurs. The exploitation extends underground, according to the room and pillar mining method.

The marble was mineralogically characterized thanks to an X-Ray Diffraction analysis, which is based on the constructive interference of monochromatic X-Rays and the crystalline sample (Bunaciu et al. 2015). The analysis was carried out in the laboratory of the Politecnico di Torino with an XRD-Rigaku SmartLab SE. The marble sample was ground into a fine powder to obtain an infinite number of randomly oriented fine crystallites. The incidence angles ranged from 4° (initial angle) to 84° (final angle), with 0.1°/s as the scan speed. The result of the test was a chart of the angle of intensity versus incidence, from which it was possible to identify the minerals and their abundance. The amplitude of the peaks, correlated with the appropriate Rietveld model (Young 1993 and Gualtieri 2000), corresponds to the abundance of each relative element.

As for the CERCHAR Abrasivity test, specimens with dimensions of 125x85x4 mm were prepared, as shown in Figure 1. As for the SATA, instead, the material was previously crushed to ensure that the dimensions of the marble pieces were less than 30 mm. Figure 2 shows a sample of the material used for SATA (left) and its particle size distribution (right).
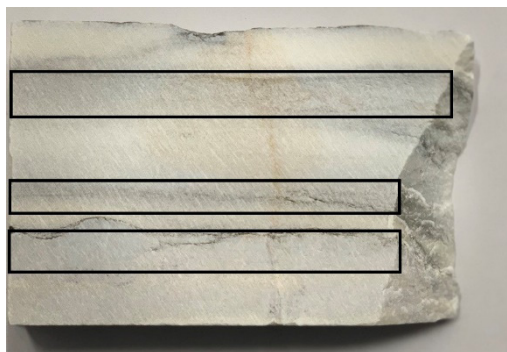

Figure 1. Sample used for the CHERCAR Abrasivity test. Area 1 is characterized by a predominance of calcite (the main part of the sample), while area 2 is rich in quartz (black boxes).
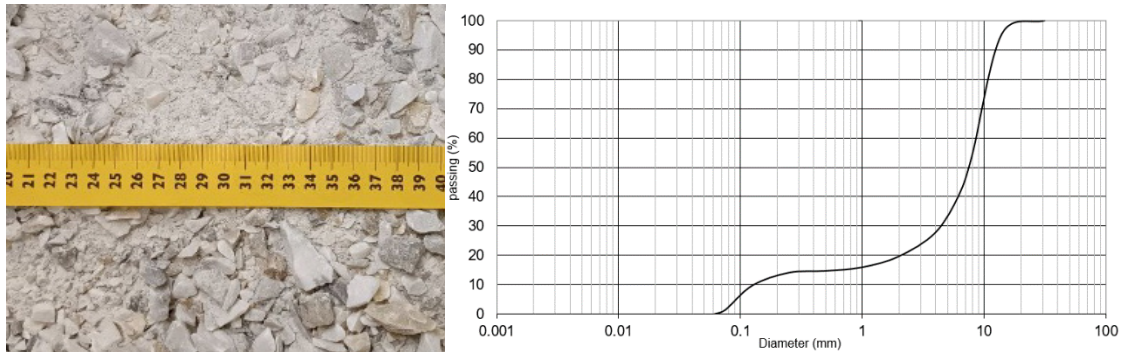
Figure 2. Crushed material used for SATA test (left) and its particle size distribution (right).

2.2 CHERCAR Abrasivity Test

The CHERCAR Abrasivity test is one of the most important laboratory tests aimed at the assessment of rock abrasivity (Hamzaban et al. 2018). As described in Alber et al. (2014), a steel stylus (HRC 55) scratches for a 10 mm path on the sample surface with a feed speed of 1 mm/s, loaded with 70 N. The CHERCAR abrasivity index (CAI) is evaluated by measuring the wear surface of the stylus tip. In this work, CHERCAR tests were performed according to Alber et al. (2014) with the test apparatus designed by West.

The samples were analyzed taking into account two different areas of the sample, i.e. the area characterized by a clear predominance of calcite (area 1 in Figure 1) and an area characterized by a clear predominance of quartz (vein recognized in area 2 in Figure 1). As a result, two different CAIs were calculated: a series of tests were performed in area 1, and other scratches crossing the quartz-rich area of area 2 were also performed. In addition, the CAIs were evaluated by testing different conditioning circumstances. As regards the CHERCAR test, the different conditionings turn into different conditions of the tested surface, while, for the SATA, the conditioning is instead understood as for tunneling applications (Peila et al. 2019). The tested conditions were: dry, wet (saturated condition for CAI, different water content for SATA), slurry with 1% by weight of polymer, and slurry with 2% by weight of polymer. The two slurries were water solutions. Slurries were produced by activating the polymer through a mixing process in water for 5 minutes. The proper amount of additives was weighed and added to the water (previously set in motion by the impeller) in the first minute, according to the procedure described in Di Giovanni et al. (2022). A concrete mixer was used to produce a homogenous slurry. The polymer used was a natural polymer for drilling fluid and slurry with anti-wear properties provided by MAPEI UTT.

The results are given in Table 1. The CAI values reported are the average of the tests performed (at least 5), while SD is the standard deviation. The classification of the wear potential was drawn up considering the CAI values, according to Alber et al. 2014.

Table 1. CHERCAR Abrasivity test results.

Surface condition	Area 1			Area 2		
	CAI	SD	Classification	CAI	SD	Classification
Dry	1.02	0.09	Low	3.62	0.07	High
Wet	0.42	0.07	Extremely low	2.71	0.17	Medium
Slurry 1%	0.39	0.12	Extremely low	2.67	0.03	Medium
Slurry 2%	0.34	0.12	Extremely low	1.77	0.05	Low

From the results obtained, the dry specimen was classified as a low abrasive material for area 1 and a high abrasive for area 2. The wet specimen and the sample conditioned with the two slurries were classified as an extremely low abrasive material for area 1, whereas, in area 2, the CAI classification varied from medium to low abrasive potential.

2.3 Soil Abrasion Test Apparatus – SATA Wear Test

Wear tests on conditioned soil are routinely performed to confirm the ability of conditioning agents to prevent or reduce tool wear in tunneling projects (Salazar et al. 2018 and Peila et al. 2019). The selected test (SATA) belongs to a family of not-standardized tests used to estimate the wear potential by assessing the weight loss of a tool subjected to the action of the material to be tested (Rostami et al. 2012, Jakobsen et al. 2013, Salazar et al. 2016a and Todaro et al. 2022). These tests have been developed for cohesion-less soils or crushed rocks, although studies relating to applications in quarries have also recently been developed (Di Giovanni et al. 2022).

In SATA, an aluminum disk (Vickers hardness 116 MPa) rotates around its axis at 160 rpm for 10 minutes. The disk rotates inside a cylindrical tank (Figure 3), embedded in the crushed marble (material used around 20 kg). To ensure constant contact between the tool and the soil, a confining pressure of 2 kPa is applied to the top of the sample. The disk weight difference calculated before and after the scheduled testing time is the weight loss due to friction with the soil and is the main output of the test. The greater the weight loss, the more abrasive the material under the specific conditioning conditions tested. According to the literature references mentioned above, SATA was used by first assessing the dependence of the water content on wear, where the slurries were then added for specific water contents in order to verify the potential reduction obtainable.
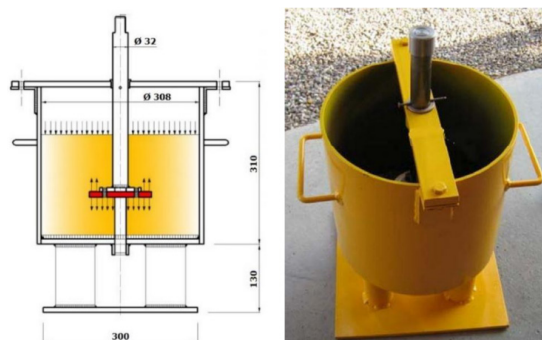

Figure 3. Soil Abrasion Testing Apparatus device. Image modified from (Salazar et al. 2016a).

The range of water content was selected between 0% and 12% using the 2% step. 12% was expressly selected above the saturation water content (close to 6%) to better simulate the cutting action of the chainsaw, where a stream of water is commonly used to control the cutting temperature and help the removal of the cutting debris. At least three tests were performed for each moisture content and the average was calculated.

In the second phase of the study, the moisture contents corresponding to 8% and 12% (recognized as the highest values of the wear bell) were considered for testing the additives. The two slurries (1% by weight - 2% by weight in water solution) were added to the dry crushed marble samples with a suitable dosage for reaching the selected moisture contents. Results are shown in Figure 4.
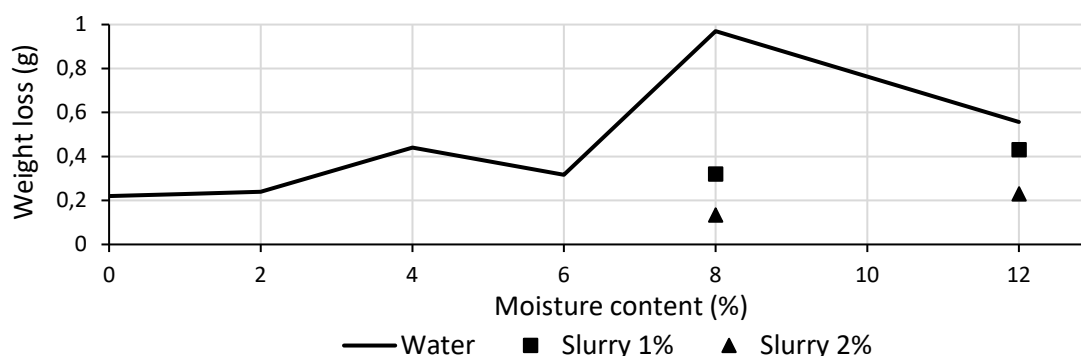

Figure 4. Marble wear bell (continuous line) and weight loss due to slurry conditioning tests (singular points).

3. DISCUSSION

Considering the results obtained from XRD-SEM analysis, calcite was the predominant element, with 79% of the weight fraction, even though more than 20% of the sample was composed of other elements. The presence of quartz cannot be overlooked, with a percentage of 11%.

The results obtained with the CHERCAR Abrasivity test highlight a High - Low abrasive potential, with a CAI value of 3.62 and 1.02 respectively for areas 2 and 1 for the dry surface condition. This strong discrepancy (more than 2.5 points) is due to the presence of quartz in area 2. In fact, even if the global quartz content of the marble sample is 11%, hypothesized that the presence of quartz is mainly concentrated in area 2. Medium - Extremely Low abrasive potential (CAI equal to 2.71 and 0.42) was computed for the wet condition respectively for area 2 and area 1. The same classification was obtained for the slurry test with 1% polymer. As already mentioned, the difference in abrasiveness of about 2.3 CAI points for both cases between areas 1 and 2 is due to the high presence of quartz in area 2. A Low - Extremely Low abrasive potential was recorded for the sample conditioned with 2% by weight of polymer (CAI equal to 1.77 and 0.34 for areas 2 and 1).

As regards the influence of conditioning agents on the CAI, it can be stated that regardless of the type of conditioning agent (water, 1% slurry, 2% slurry) a decrease in the wear potential was obtained compared to the dry condition. The best wear reduction performance was obtained using the highest concentration of slurry, resulting in a reduction of about 67% and 51% for areas 1 and 2 respectively. The 1% polymer slurry works well in area 1, while a smaller reduction in wear is appreciable in area 2 (62% and 26 % respectively). Similar values were obtained for the wet condition (59% and 25% respectively). It can be concluded that even if the reduction in wear seems to be more appreciable for area 1 (all % reduction close to or greater than 60%), the results of area 2 are also strongly important since this area is the most problematic in terms of wear and a reduction of at least 25 % has to be considered a good result. Finally, it is worth noting the strong reduction in wear, close to 50%, which can be obtained in area 2 by using the more concentrated slurry.

Regarding the results obtained with SATA, the tested material was characterised by a wear bell with the main peak at 8% water content and a second peak at 12%. This analysis confirms that moisture content deeply affects tool wear, as claimed by Rostami et al. 2012, Jakobsen et al. 2013 and Salazar et al. 2016b. The tests with conditioning agents show important aspects, also linked to the percentage of polymer present in the slurries. For the two percentages of moisture content tested, the use of more concentrated slurry resulted in a decrease in weight loss calculated over the original peak of 86% and 59% for the main and the second peak respectively. Instead, the use of 1% polymer slurry guaranteed a reduction of 67% and 23% of the lost weight loss, for the main and for the second peak respectively.

According to the results obtained with the CERCHAR Abrasivity test and the Soil Abrasion Test Apparatus, the slurry with a polymer concentration of 2% is the best performing.

4. CONCLUSION

The phenomenon of tool wear is a complex topic, not fully understood currently. In excavation projects, it plays a key role in terms of costs and time consuming. For these reasons, various research studies were performed on this topic, even if a standardized predictive model is not present in the literature yet. Tests performed with the addition of the slurry polymer revealed a significant reduction in wear potential, especially for the more concentrated one. Although these tests were carried out on a laboratory scale, a full-scale test campaign could confirm the results achieved. Future research based on the use of additives could certainly implement the study and provide further data on the phenomenon of wear.

REFERENCES

Abu Bakar, M.Z., Majeed, Y. & Rostami, J. 2016. Effects of rock water content on CERCHAR Abrasivity Index. *Wear* 368–369, pp. 132-145. doi:10.1016/j.wear.2016.09.007

Alber, M. 2008. Stress dependency of the CHERCAR abrasivity index (CAI) and its effects on wear of selected rock cutting tools. *Tunn. Undergr. Space Technol.* 23(4), pp. 351-359. doi.org/10.1016/j.tust.2007.05.008

Alber, M., Yaralı, O., Dahl, F., Bruland, A., Käsling, H., Michalakopoulos, T.N., Cardu, M., Hagan, P., Aydın, H. & Özarslan, A. 2014. ISRM suggested method for determining the abrasivity of rock by the CERCHAR abrasivity test. *Rock Mech. Rock Eng*. 47, pp. 261–266. https://doi.org/10.1007/s00603-013-0518-0

Bunaciu, A.A., Udriştioiu, E.G., & Aboul-Enein, H.Y. 2015. X-Ray Diffraction: Instrumentation and Applications. *Critical Reviews in Analytical Chemistry* 45(4), pp. 289-299. doi.org/10.1080/10408347.2014.949616

Çopur, H. 2010. Linear stone cutting tests with chisel tools for identification of cutting principles and predicting performance of chain saw machines. *Int. J. Rock Mech. Min. Sci.* 47, pp. 104–120. doi.org/10.1016/j.ijrmms.2009.09.006

Çopur, H., Balci, C., Tumac, D. & Bilgin, N. 2011. Field and laboratory studies on natural stones leading to empirical performance prediction of chain saw machines. *Int. J. Rock Mech. Min. Sci.* 48, pp. 269–282. https://doi.org/10.1016/j.ijrmms.2010.11.011

Di Giovanni, A., Todaro, C., Cardu, M., Bianchini, S. & Forfori, B. 2022. Laboratory test campaign aimed at the analysis of an uncommon wear phenomenon in a marble quarry. *Applied Sciences* 12(4), 2264. https://doi.org/10.3390/app12042264

Di Giovanni, A., Todaro, C. & Cardu, M. 2023. A statistical approach for the Correlation between CHERCAR Abrasivity Index and Uniaxial Compressive Strength of rocks. Under review.

Ellecosta, P., Käsling, H. & Thuro, K. 2019. Wear Phenomena in Tunnel Boring Ma-chine (TBM) Hard Rock Drilling-Reasons and Consequences. In book: *IAEG/AEG Annual Meeting Proceedings*.

Gualtieri, A. 2000. Accuracy of XRPD QPA using the combined Rietveld-RIR method. *Journal of applied crystallography* 33, 267–278. https://doi.org/10.1107/S002188989901643X

Hamzaban M.T., Memarian H. & Rostami J. 2018. Determination of scratching energy index for CHERCAR abrasion test. *Journal of Mining & Environment* 9, pp. 73-89. https://doi.org/10.22044/jme.2017.5738.1389

Jakobsen, P.D., Langmaack, L., Dahl, F. & Breivik, T. 2013. Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust. *Tunn. Undergr. Space Technol.* 38, pp. 398–408.

Mancini R. & Cardu M., 2001. Ingegneria degli Scavi. *Politeko Ed.*, Torino, Italy

Peila, D., Martinelli, D., Todaro, C. & Luciani, A. 2019. Soil conditioning in EPB shield tunnelling–An overview of laboratory tests. *Geomech. Tunn*. 12, pp. 491–498. https://doi.org/10.1002/geot.201900021

Rauch, R., Goliasch, R., Käsling, H. et al. 2018. Does the in-situ stress state have an effect on tool wear in deep TBM tunnelling? *Geomechanics and Tunnelling* 11, pp. 169-178. https://doi.org/10.1002/geot.201800001

Rostami, J., Gharahbagh, E.A., Palomino, A.M. & Mosleh, M. 2012. Development of soil abrasivity testing for soft ground tunnelling using shield machines. *Tunn. Undergr. Space Technol*. 28, pp. 245–256.

Salazar, C.G.O., Martinelli, D., Todaro, C., Peila, D. & Boscaro, A. 2016a. Study of wear in conditioned granular soil by using a new test device. In: *Proceedings of the ITA-AITES World Tunnel Congress 2016*, San Francisco, USA, 22–28 April, 2016; 3, pp. 2445–2454.

Salazar, C.G.O., Martinelli, D., Todaro, C., Luciani, A., Boscaro, A. & Peila, D. 2016b. Preliminary study of wear induced by granular soil on metallic parts of EPB tunnelling machines. *GEAM* 148, pp. 67–70.

Salazar, C.G.O., Todaro, C., Bosio, F., Bassini, E., Ugues, D. & Peila, D. 2018. A new test device for the study of metal wear in conditioned granular soil used in EPB shield tunnelling. *Tunn. Undergr. Space Technol*. 73, pp. 212–221. https://doi.org/10.1016/j.tust.2017.12.014

Todaro, C., Di Giovanni, A., Salazar, C.G.O. & Martinelli, D. 2022. The soil abrasion test apparatus: a literature review. *Geoing Ambient. Min*.

Tumac, D., Avunduk, E., Çopur, H., Bilgin, N. & Balci, C. 2013. Estimation of the performance of chain saw machines from shore hardness and the other mechanical properties. ISRM SINOROCK 1, pp. 261–265.

Young, R.A. 1993. The Rietveld Method. *Oxford University Press*: New York, USA.