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Laboratory Test Campaign Aimed at the Analysis of an Uncommon Wear Phenomenon in a Marble Quarry

Alfio Di Giovanni [1], Carmine Todaro [2], Marilena Cardu [1,2,*], Stefano Bianchini [3] and Brunello Forfori [4]

1 DIATI Politecnico di Torino, 10129 Torino, Italy; alfio.digiovanni@polito.it
2 IGG-CNR, 10129 Torino, Italy; carmine.todaro@polito.it
3 Marmotest Srl, 54033 Carrara, Italy; s.bianchini@marmotest.com
4 Luana Marmi Srl, 55030 Vagli Sotto, Italy; studio.forfori@gmail.com
* Correspondence: marilena.cardu@polito.it; Tel.: +39-0110907655

Featured Application: This paper presents a laboratory test campaign focused on the reduction of the wear phenomenon related to a material extracted from a marble quarry. The aim of the work is to propose a potential solution for the wear reduction pertaining to chainsaw cutting machine tools.

Abstract: The use of ornamental stones has a historical value that makes them strategically precious in Italy; marble can offer high performance in architectural applications, even though the variability of the rock mass requires detailed studies to optimize the exploitation techniques and reduce waste. Italy is world famous for its marble, which is extracted mainly through chainsaw cutting machines, which are currently used intensively due to their high-safety working conditions compared to alternative techniques and for their great versatility, especially in underground applications. Although this cutting technique is well-rooted, an uncommon problem of tool wear was found in the quarry under study, which strongly affected productivity. A series of laboratory test were carried out to estimate the wear potential of the rock and the suitability of the tools. The Cerchar abrasivity test highlighted a mean wear potential for the marble of 2.77, while microhardness outcomes pointed out the presence of quartz veins in the tested material (values over 10,000 MPa). Finally, additives typically used in the conditioning process of EPB machines in tunneling were tested with the purpose of reducing the extent of wear. A reduction of about 50% in the wear (in terms of weight lost) was obtained for a moisture content of 9%.

Keywords: chainsaw cutting machine; dimension stone exploitation; tool wear; rock–tool interaction; Cerchar abrasivity test; microhardness; wear reduction

Citation: Di Giovanni, A.; Todaro, C.; Cardu, M.; Bianchini, S.; Forfori, B. Laboratory Test Campaign Aimed at the Analysis of an Uncommon Wear Phenomenon in a Marble Quarry. *Appl. Sci.* **2022**, *12*, 2264. https://doi.org/10.3390/app12042264

Academic Editor: Dibyendu Sarkar

Received: 18 January 2022
Accepted: 19 February 2022
Published: 21 February 2022

1. Introduction

The exploitation of ornamental stone and marble requires the extraction of intact blocks that can be sawed into slabs and tiles. Therefore, the need to extract intact blocks leads to requirements different from those for, e.g., the extraction of aggregates, and has led to the development of specific exploration and extraction techniques [1–3]. The world of dimension stones, and especially the marble market, is expected to grow, reaching a production value of USD 64 billion in 2023. Italy, mostly the Apuan Alps region, is in the top ten quality-marble-producing countries [4]. The marble quarry under study is located in the geographical context of the Apuan Alps, in the Garfagnana area [5]. The quarry area develops, throughout the project, between the altitudes of 920 and 800 m a.s.l. and has an overall development along the N–S axis, widening towards the west in the northern part. The structural conditions are good, the production area being characterized by a limited number of discontinuities with an average spacing above 1 m, a condition that allows for the obtainment of blocks of good quality [6]. In more detail, according to the surveys in the area being exploited, a geomechanical classification of the site was carried out according to the authors of [7] (RMR) and Hoek and Brown [8] (GSI), obtaining an RMR equal to 62 (Class. N. 2—Good) and a GSI close to 60.

At 869 m a.s.l., where the development was planned for the expansion of the underground exploitation, the presence of grey-white marble with flint nodules was noticed. In this area, during the works started in 2018, a "sheath fold" emerged, with a siliceous marble core in entrochi, characterized by a trend of about 350°, immersion at NW of about 10°, and boudinage. Initially, this structure seemed to close quickly, while in a short space corresponding to the execution of about three development advances in the tunnel, for about 9 m in total, the core opened into a boudinage, and the structure progressed towards the inside of the cluster. The core of this structure proved impossible to cut, due to the fast wear of the tools. The machine used in marble cutting operations is the chain cutting saw (Figure 1), which has the great advantage of not requiring preliminary cutting operations. The arm operates easily, even in the presence of only one free surface. In all cases where it is necessary to perform blind cuts, the chainsaw, alone or in cooperation with the diamond wire saw, is frequently used. At the quarry, the excavation works are carried out with a chainsaw on which a 3.5 m long cutting blade is installed, equipped with guides, where a single-mesh metal chain runs (74 mm pitch, 42 mm cutting width), equipped with polycrystalline diamond plate tools. Seven sets of tool-holders are installed on the cutting chain; each series includes 12 tool holders with different cutting configurations. The tool has a diameter of 8.0 mm, a diamond layer thickness of 1.5 mm, and a tungsten carbide (WC) layer thickness of 6.6 mm, for a total height of 8.1 mm. The WC area is welded directly on the tool holder and does not contribute to the cut (made expressly from polycrystalline diamond) but represents an intermediate support between the diamond and the tool holder. Figure 2 shows a detail of the tools adopted.

Figure 1. The chain cutting machine adopted in the quarry. The machine is engaged in a series of horizontal cuts to widen the underground opening (link https://www.fantinispa.it/en/gu70rxc-tunnel-chain-saw-machine/, accessed on 2 October 2021).

In this field, many studies have been conducted to improve the performance of the tools: the complexity of the cutting unit, which includes dozens of devices mounted at different angles, means that the inspection and replacement times are hours instead of minutes, and the environment in which research necessarily develops is a site much less equipped and comfortable than a mechanical workshop.

(a) (b)

Figure 2. Detail of the tools and their tool holder: (**a**) front view of the arrangement of the tools in the execution of the cut with a thickness of 40.82 mm, (**b**) cutting chain front view.

As far as the design of marble cutting tools is concerned, it is assumed to be enough to evaluate the medium hardness value (HK, Knoop hardness; or HV, Vickers hardness) for marble characterization. Tool materials should be tested separately for both hardness and toughness [1].

A PCD tool is represented in Figure 3: a new tool is shown above, where the diamond layer and WC are clearly recognizable, and a tool worn out after 0.24 h/m^2 is depicted below. The almost total lack of the polycrystalline diamond plate tool can be noticed; in other words, the tool is irreparably damaged, and is characterized by severe wear which has completely consumed the diamond layer.

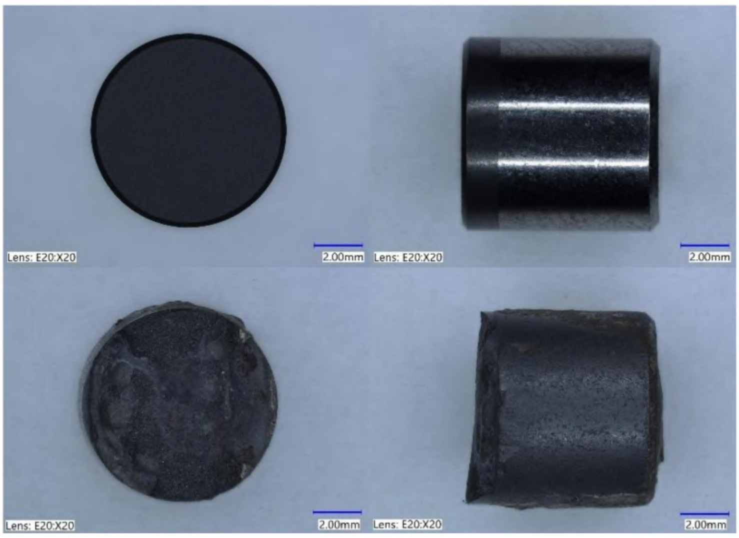


Figure 3. Typical tool used in the chainsaw cutting machine. The front and side views are shown on the left and right of the image, respectively. A new tool is shown above: the color difference between polycrystalline diamond (shorter area) and tungsten carbide (longer area) is clearly recognizable from the top right image. Below is shown a tool after 0.24 h/m^2 of work: the almost complete absence of the polycrystalline diamond layer is evident.

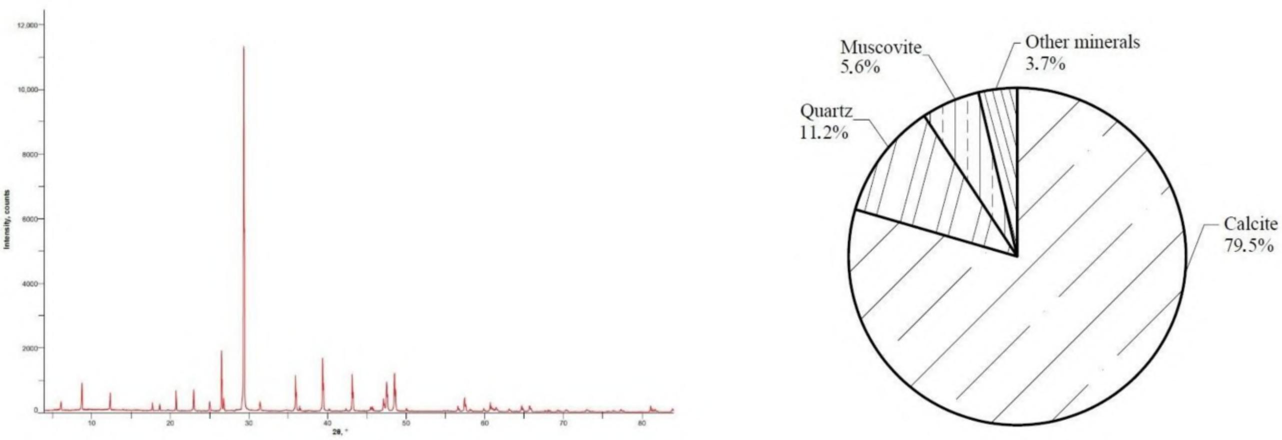
Currently, the information available in scientific literature on chainsaw cutting machines in carbonate rock applications pertains mainly to studies focused on performance prediction models [9–15], but the potential wear and the quartz content have not been studied in depth. In the context of heavy wear (quite rare for a marble quarry), this research was planned to better understand the phenomenon and try to find a solution capable of reducing the wear. A series of laboratory tests were carried out to characterize and study the characteristics of the marble. By comparing the microhardness results obtained for the quarried material with the typical values of the marbles, two different checks were made. On the one hand, it was verified whether minerals harder than calcite were present in the material tested. On the other hand, by comparing the microhardness of the marble measured with that of the tools, the choice of the quarry managers to use certain tools rather than others was verified. Subsequently, by means of XRD (X-ray diffraction), the presence of these impurities was confirmed and their univocal recognition was carried out. Finally, the Cerchar abrasivity index (CAI) provided an order of magnitude of the wear potential, while the wear test (performed using the soil abrasion test apparatus—SATA) allowed us to find the dependence of the wear phenomenon on the content of humidity, as well as to test the contribution of several types of additives.

2. Laboratory Tests and Results

The tests performed are described below and the results obtained are presented. It should be noted that for each test campaign (apart from the microhardness tests), the marble samples were carefully chosen, selecting the material in order to obtain a representative sample of the rock studied. The tests carried out can be sorted into two groups: if the analysis with XRD, microhardness and CAI were programmed to understand the reason for the strong wear of the cutting tools, the wear test was carried out with the aim of proposing a solution able to reduce the wear phenomenon. In addition, it should be noted that unlike the other tests, the wear test performed by SATA is not standardized, although several test campaigns and publications are now available in the literature.

2.1. XRD—X-ray Diffraction Analysis

XRD is a versatile, nondestructive analytical technique that provides information on the crystallographic structure, chemical composition, and physical properties of materials. This technique is based on the observation of the scattered intensity of an X-ray beam, which strikes a sample as a function of the incident and scattered angle, of the polarization, and of the wavelength or energy [16]. The analysis was carried out in the laboratory of the Politecnico di Torino, with an XRD—Rigaku SmartLab SE. The selected marble sample was previously ground to a fine powder in order to obtain an almost infinite number of fine crystallites in random orientations. The incidence angles ranged from 4° (start angle) to 84° (stop angle), with a scan speed of 0.1°/s thanks to the continuous scan mode. The output of the analysis was an intensity vs. incidence angle chart, from which the minerals and their abundance could be identified, as each mineral has a specific angle of incidence. The intensity of the peaks, evaluated with the appropriate Rietveld model [17,18], reflects the abundance of each element. The results are shown in Figure 4.



(a) (b)

Figure 4. Intensity vs. incidence angle chart (**a**) and mineralogical abundance (**b**).

The associated minerals identified were 79.5% Calcite, 11.2% Quartz, 5.6% Muscovite, and 3.7% other minerals.

2.2. Vickers Microhardness Test

Hardness is the measure of the strength to resist localized plastic deformation induced by the mechanical impression due to a given applied load [19] and is obtained by measuring the permanent depth of the impression. The Vickers hardness test method is used for small objects, as well as polished thin sections. Due to the small indentation in a Vickers test, it can test small areas, the surface of a part, or individual microstructures [20]. It can also determine the depth of hardening by dissecting it and creating a series of indentations to find the change in hardness [21]. This method can evaluate almost any type of material, such as ceramics, metals, and rocks. The Vickers microdurometer uses devices developed by the authors of [22], i.e., a pyramid shape is created by a diamond indenter tool (opening of 136°, as shown in Figure 5). By measuring the diagonals of the footprint (d in Figure 5, performed optically as described by the authors of [23]), its surface can be obtained and, consequently, the hardness can be computed as the ratio between the applied load and this area. When the applied load is less than 1 kg, it is common to refer to this test as microhardness. The Vickers test is easy to perform, as the required calculations are independent of the indenter size [24] and the indenter can be used for all types of materials, regardless of hardness. For these reasons, Vickers microhardness tests were chosen for the analysis. The tests were performed according to the authors of [25]. Unlike the standard, the dwell time was slightly longer, close to 40–45 s.

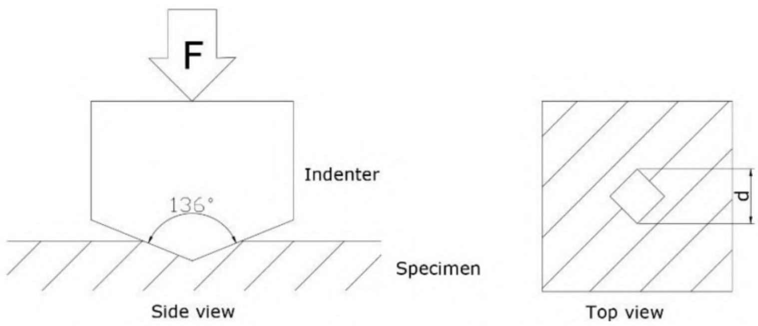


Figure 5. Indentation scheme [23]. F is the applied force, while d is the diagonal of the left footprint.

The marble specimens, 50 × 30 × 15 mm in size, had a perfectly polished upper surface. The dimensions were chosen in order to maximize the available surface, compatible with the constraints of the instrument. Four different samples were prepared, taking care to select material with different mineralogy. Considering the grey veins embedded in the calcite matrix (white color of the background of the samples), the patterns were selected by choosing marble pieces with different presences of impurities (grey veins), as shown in Figure 6. For each sample, 80 microhardness measurements were performed by applying a load of 200 g (1.96 N). On average, the distance between two successive footprints was 100 µm. Regarding the outcome analysis, the microhardness values for each sample were sorted and, subsequently, the values in terms of cumulative frequency were displayed, giving a characteristic curve. Figure 7 shows the microhardness characteristic curves obtained.

(**a**) (**b**) (**c**) (**d**)

Figure 6. Samples analyzed. The grey veins are marginally present in sample 3 (**c**), while in samples 1 and 2 (**a**,**b**), the presence of impurities is greater. Sample 4 (**d**) is almost entirely composed of grey material.

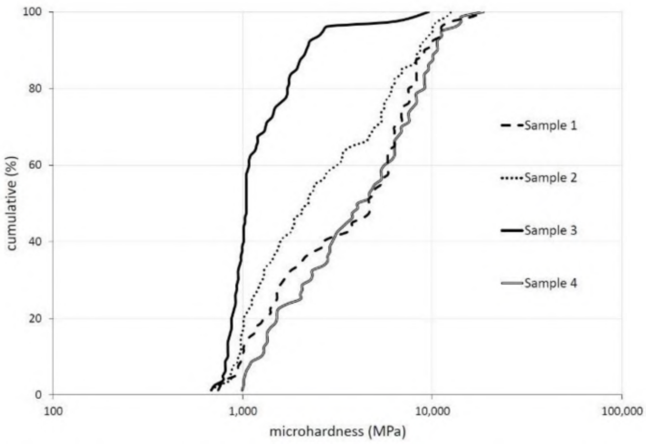


Figure 7. Cumulative frequency curves of microhardness (microhardness characteristic curves).

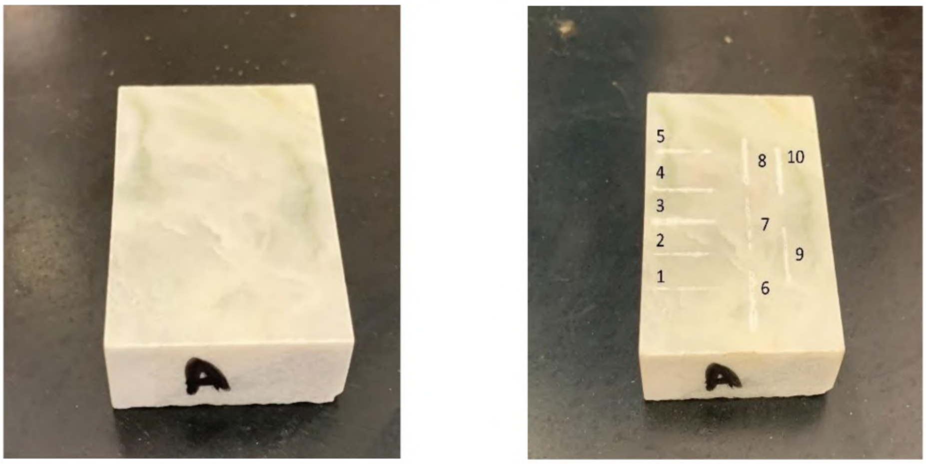
2.3. CAI—Cerchar Abrasivity Index

The Cerchar abrasivity test is one of the most common procedures for laboratory measurement of the abrasiveness of rocks [26–32]. An order of magnitude of the wear potential of the rock can be obtained by evaluating this index, which is a tested material's aptitude for wearing steel tools [33,34]. As described in [35], a stylus (composed of HRC 55 steel) loaded with 70 N is scratched for 10 mm on the rock sample at a rate of 1 mm/s. The CAI is evaluated by measuring the wear surfaces experienced by the stylus [36–38]. In this work, Cerchar tests were performed according to [35]. The selected sample had a size of 50 × 30 × 15 mm, Figure 8a, and 10 different tests were performed. In accordance with the reference, five scratches were carried out horizontally and another five vertically (tests 1–5 and tests 6–10, respectively, Figure 8b).

The highlighted CAI values ranged from 2.08 to 3.30, with a mean value of 2.77 (standard deviation = 0.50). The mean CAI value corresponds to the average wear potential.

2.4. SATA—Soil Abrasion Testing Apparatus

Wear tests on conditioned material are commonly performed to verify the ability of conditioning agents to prevent or reduce tool wear in tunnelling applications [39,40]. These types of test have been developed for cohesionless soils or crashed rocks but, to the authors' knowledge, have never been applied for quarry applications. In any case, we planned to use the soil abrasion testing apparatus (SATA, an equipment designed and developed at the Politecnico di Torino) on the marble, in order to understand firstly the wear potential of the studied material and secondly the desirable effect potentially obtained by using conditioning agents (water and other additives). By providing more details, the wear test we performed provided insight into the wear potential by evaluating the weight loss. The evaluation of the wear potential by estimating the weight lost is common in scientific literature [40–43]. An aluminum disk rotates around its axis at a constant speed inside a cylindrical tank (Figure 9), embedded with granular material [44]. The rotational speed is kept constant, equal to 160 rpm, for a time span of 10 min. The difference in disk weight before and after the test is the weight loss. As for the aluminum disk, it is characterized by Vickers hardness values of 116 MPa [45]. A normal confining pressure of about 2 kPa is applied to ensure continuous contact between the disk and the soil.



(a) (b)

Figure 8. Sample before the test (**a**) and after the test (**b**).

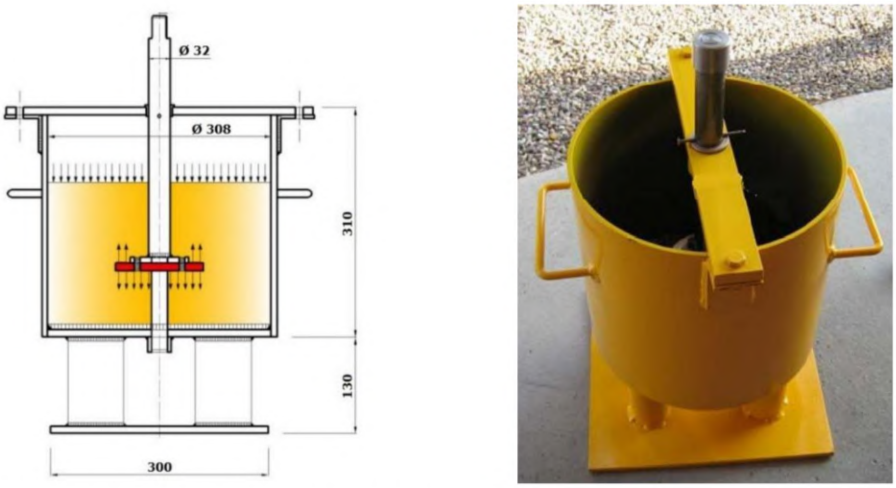


Figure 9. Soil abrasion testing apparatus. Image modified from [45].

In this work, wear tests were performed according to [45,46]. Marble was previously crushed, obtaining powdered rock and chips with a maximum size of 20 mm. The particle size distribution is shown in Figure 10.

The first step of wear testing focused on studying the wear bell, while the second phase focused on testing the conditioning additives. The wear bell is a chart with a typical bell shape that shows in the x and y axes the moisture content and weight loss of the tested material [41,42]. This type of curve is very important, since each material exhibits a different curve (depending on the particle size distribution, mineralogy, and grain shape) and by taking a typical wear bell of a highly wearable material as a reference for comparison, the wear potential of the material studied can be deduced. The results for the tests performed with conditioning agents are also shown on the same chart. Once the conditioning amounts were chosen and the weight loss was obtained thanks to the wear test, the moisture content was calculated by considering the water used for producing the foam or activating polymers; then, the representative test point could be drawn on the chart.

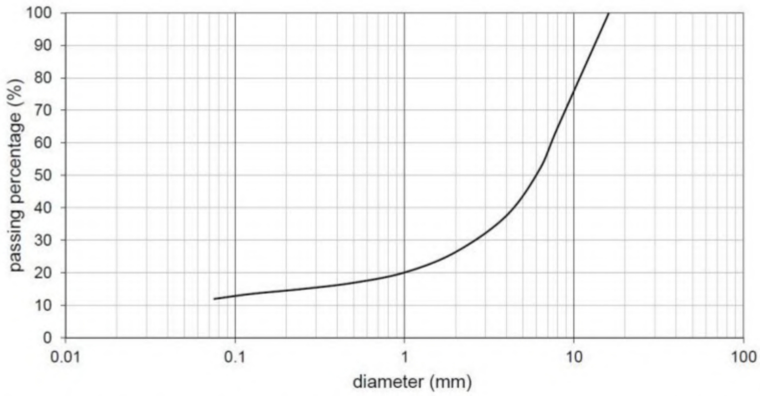


Figure 10. Particle size distribution of the crushed marble used in the wear test performed with the SATA.

2.4.1. The Wear Bell

After a preliminary analysis, we planned to draw the marble wear bell by testing the moisture contents between 1% and 9%. Three tests were performed for each moisture content and the average was calculated [47–49]. The outcomes of the testing campaign are shown in Figure 11, where, for comparison, the wear bell related to a pure quartzite (98% quartz) is also shown [45].

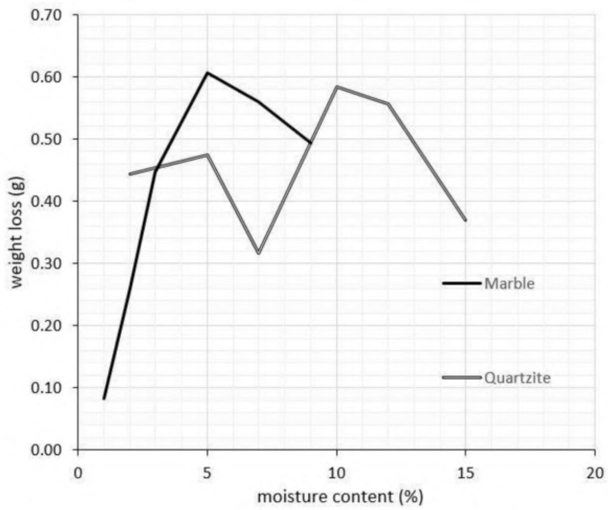


Figure 11. Wear bells related to marble and quartzite.

2.4.2. Wear Test with Conditioning Agents

In the second phase of the study, the moisture content corresponding to 4% (the average value of the material studied) and 9% (the highest water content analyzed) was considered for testing the additives. Two different products were used: a high-performance liquid foaming agent (Product A) and a natural polymer (Product B) that was commercially available as a dry powder. Due to the lack of representative marble material available, the tests with the highest moisture content were performed with Product B only, the latter having a lower environmental impact and a shorter biodegradation time. For Product A, a water solution (4% by volume of the foaming agent) was prepared, while regarding Product B, a slurry (1% by weight) was produced by activating the polymer through a mixing process in water for 5 min (adding the polymer in the first minute of the mixing process), performed with a concrete mixer. Once both water solutions had been prepared, the appropriate amount of conditioning able to achieve the selected moisture content (4% or 9%) was collected and added to the marble sample. Wear tests were performed following the same procedure used previously. The results are shown in Figure 12.

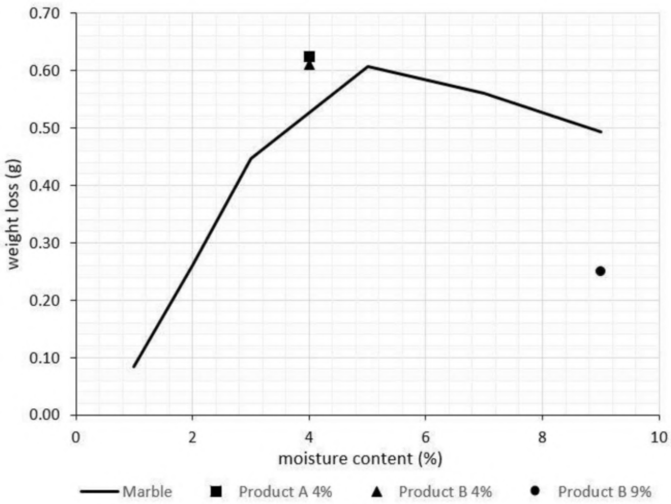


Figure 12. Marble wear bell and wear conditioning tests (4% and 9% moisture content).

3. Discussion

Taking into account the results obtained from XRD, calcite was the predominant component, even though more than 20% of the marble was made up of other elements. The presence of quartz cannot be neglected, with a percentage of 11.2%. The presence of impurities also strongly influenced the campaign of the microhardness tests. In fact, the results achieved confirmed relatively high microhardness values when compared with the range of marble, typically from 1500 MPa to 3000 MPa [50]. Considering the upper limit of the range, the hardness was below 3000 MPa for 40%, 50%, and 40% of the cumulative curves for samples one, two, and four, respectively. In contrast, in sample three, only 8% of the determinations gave a hardness greater than 3000 MPa. This result was expected: in fact, sample three was characterized by only a tiny vein of grey intrusion. However, the microhardness results justify the company's choice of tool material. The choice to discard tungsten carbide tools in the chainsaw was correct, since the microhardness values of this compound ranged between 10,000 MPa and 14,000 MPa, values that were often exceeded during testing. Consequently, the company's choice to use polycrystalline diamond tools can be considered correct, since this material is characterized by a Vickers hardness of about 55,000 MPa [51].

As for the CAI test campaign, the studied marble was recognized as an average abrasive material, the average CAI value being equal to 2.77. This result highlighted the abrasive potential of the impurities present in the marble and previously recognized by XRD; in fact, the CAI was higher than that of pure marble (between 0.60 and 1.00, as suggested by the Colorado School of Mines). In particular, the sample which had areas where the CAI was higher than 3 could be due to the presence of flinty marble (signifying a highly abrasive material).

Regarding the wear, it should be remarked that tool wear is determined by complex laws [52]. Pertaining to the test performed using the SATA, the tested sample was characterized by a wear bell with a peak at 5% water content. From the results, it was confirmed that the water content deeply affected the weight loss of the test disk, as discussed by the authors of [41,42,46]. Starting from a soil moisture percentage equal to the natural condition (1%), increasing the water content did not provide a beneficial effect until a percentage of 5% was reached. After this value, a further increase in water content resulted in a decrease in weight loss. However, comparing the wear bell of marble with that of quartzite, it was evident that the wear potential was similar, the peaks being of the same order of magnitude (close to 0.6 g). The wear tests with conditioning agents revealed interesting aspects, namely that the additives need a certain dosage to work properly. Tests carried out with Products A and B in solution, dosed and added to the marble sample to achieve 4% moister content, showed no reduction in weight loss, while tests performed with a conditioning agent capable of achieving 9% moisture content provided a reduction in weight loss of 50%. It can be stated that a reduction in the wear was observed when the additive used surpassed a certain threshold. The mechanism of wear reduction is certainly a function of the amount of the additive (9% moisture content provides the lowest wear). Anyway, it should be noticed that additives, in order to work properly, need to be conveyed homogeneously in the conditioned soils. In conclusion, it can be hypothesized that there exists a critical moisture content, recognizable in this case as between 4% and 9%, which, once reached, allows the added product to properly exert its anti-wear action.

4. Concluding Remarks

This work was conceived with the aim of deepening the study into the phenomenon of the tool wear of the chain cutting machines used for the exploitation of marble in the quarry studied. The research was planned to optimize the economic and productive sources of the construction site. The tests showed the presence of impurities in the marble that give the material unusual values of microhardness and a high potential for wear. Although the quarry managers adopt polycrystalline diamond and tungsten carbide tools, the study carried out shows that the wear phenomenon cannot be addressed without the addition of conditioning agents during cutting operation. According to the preliminary results obtained on a laboratory scale, conditioning agents appear to be ineffective unless a certain moisture content of the tested material is guaranteed. On the other hand, the polymer added in the form of slurry (1% by weight concentration in water) seems to be strongly effective against wear when used in amounts of 9% of the moisture content of the marble. However, these tests were performed on a laboratory scale, and only by carrying out a test campaign at the real scale can the results can be confirmed. In addition, it should be noted that the cutting operation performed in the quarry is characterized by a different mode of execution and that the tool material is different to that used in the laboratory. However, further tests and an onsite experimental campaign are planned in order to verify the efficiency of the conditioning agents, considering that, to date, quarry activity at the site under study has been interrupted due to the ineffectiveness of the chain cutting machine.

Author Contributions: Conceptualization, A.D.G., C.T. and M.C.; methodology, A.D.G., C.T. and M.C.; investigation, A.D.G., C.T. and M.C.; resources, M.C., S.B. and B.F.; data curation, A.D.G.; writing—original draft preparation, A.D.G. and C.T.; writing—review and editing, A.D.G., C.T. and M.C.; supervision, M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to A. Boscaro and E. Barbero (Mapei UTT Company) for providing the additives and for their technical and logistical support in carrying out this research.

Conflicts of Interest: The authors declare no conflict of interest.

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