 doi:10.20944/preprints202010.0642.v1

Article

New developments for sustainable exploitation of ornamental stone in Carrara basin

Federico Vagnon [1], Giovanna Antonella Dino [1], Gessica Umili [1], Marilena Cardu [2] and Anna Maria Ferrero [1*]

[1] Department of Earth Sciences, University of Turin; [federico.vagnon; giovanna.dino; gessica.umili; anna.ferrero]@unito.it
[2] Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino; marilena.cardu@polito.it
* Correspondence: anna.ferrero@unito.it; Tel.: +390116705114

Abstract: The use of natural stone has a historical and environmental value that makes it strategically valuable for landscape conservation in Europe. Marble, among others, is widely spread on Earth, and it offers high-performance features in architectural applications. However, the complexity of these formations and the rock variability in different ore bodies require detailed studies of the natural and induced stress state, the fracturing degree, and the influence of external factor (such as temperature and/or chemical agents) on the mechanical properties in order to optimize the exploitation processes by reducing extractive waste. This article shows a series of studies conducted by the authors over the last 20 years aimed at making the exploitation of marble blocks in the Carrara basin safer, more efficient, and, therefore, more sustainable. In particular, studies for increasing the knowledge on the natural and the induced stress state through on-site measurements and numerical modeling, studies to improve the quality of the exploited material through improvements of cutting technologies, studies to improve the knowledge of the mechanical behavior of the material under varying loads and temperature conditions and studies to improve the reuse of water materials and their reduction are reported.

Keywords: Ornamental stone; rock mass state of stress and fracturing; marble exploitation techniques; waste reduction

1. Introduction

According to the Cambridge dictionary, the definition of sustainability is "the idea that goods and services should be produced in ways that do not use resources that cannot be replaced and that do not damage the environment".

For what concerns mineral resources, the primary method of resources extraction is still their excavation. Since it is impossible to replace them, we must reduce the damage to the environment. To date, it appears that the main constraints to sustainability in the mining sector derive from the consumption of resources needed to extract and process and the increasing pollution generated by the extraction process. According to United Nation [1], indications to maximize the development benefits of mining while improving the environmental and social sustainability of the mining sector was first addressed in the Johannesburg Plan of Implementation (JPOI), where three priority areas were identified among which: address the environmental, economic, health and social impacts and benefits of mining throughout their life cycle, including workers' health and safety.

In this paper, the authors' research and strategies to improve the mining cycle in marble exploitation and reduce the impact are reported.

Natural stone has a historical and environmental value that makes it strategically valuable for landscape conservation in Europe. Marble, among others, is much widespread and offers high-performance features in architectural applications worldwide. However, the complexity of these kinds of units, on the one hand, and the rock variability in different ore bodies, on the other hand,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 October 2020 doi:10.20944/preprints202010.0642.v1

determine the need to study these formations to classify the geological level of marble, to optimize the exploitation process, to determine the lithological and deformational features and, finally, to reduce the waste produced during exploitation and processing.

The dimension stone quarrying introduces very peculiar characteristics compared to the other exploitation industries: an international market characterizes it, and, above all, it involves high commercial prices on average, which can balance the high production costs typically faced by the quarrying companies.

In order to achieve that this traditional and important activity will be effectively sustainable, the following issues have to be faced:

- The need of a "planned management" and a good organization of the activity. In practice, starting from a better knowledge of mineral resources, it is essential to plan the use of the land and to manage the productivity target correctly.
- The urgency to reduce the production of quarry waste "at the source", through the adoption of the best available exploitation techniques and the introduction of increasingly "precise" technologies. On the other hand, the need to enhance, through productive reuse, the processing waste.
- The need to guarantee the compatibility and environmental sustainability of the mining activity through an effective evaluation of the quarry planning, the improvement of environmental performance during the activities, and the site's complete rehabilitation at the end.
- The performance depends on the type of machine as well as on rock/rock-mass characteristics. Machine specifications are generally easily known, but the rock/rock-mass characteristics are not readily available. The rock/rock-mass characteristics are of paramount importance, given the fact that the cutting tool directly engages with the rock to be cut. This fact warrants the geotechnical investigation in conjunction with the equipment used in a given site, as there is a direct interaction of the cutting tools with rock/rock-mass in which they are applied to cut.
- To improve the knowledge of the behavior of both the rock mass and the rock material.

An unavoidable starting point for improving marble mining is a high-level knowledge of the deposit and the territory in which it is located. In fact, many aspects concerning the physical-mechanical characterization of marble and its geological and mining properties are not known enough.

The exploitation of ornamental stones and marble requires the extraction of intact blocks that can be sawed to extract slabs and tiles. Therefore, the need to extract intact blocks determines different requirements with respect to shapeless mining, and it has led to the development of various investigation and extraction techniques.

The state of natural acting stress and fracturing of the rock masses is the primary point to define the possibility of extracting sized blocks of adequate volumes. The fabric-related anisotropy is a key control of rock mechanical behavior at different environmental conditions, and the interplay between the fabric of crystal deformation and their brittle mechanical behavior needs to be taken into account properly throughout ad hoc laboratory testing.

This article shows a series of studies conducted by the authors over the last 20 years to make the exploitation of marble blocks in the Carrara basin safer, more efficient, and, therefore, more sustainable.

The authors carried out studies in several fields, which are summarized below in this document:

- Studies for the improvement of the knowledge of the natural stress state and induced by excavations through on-site measurements and numerical modeling [2-6].
- Studies to improve the quality of the exploited material through improvements in cutting technologies [7-16].
- Studies to improve the knowledge of the material's mechanical behavior under varying load and temperature conditions and improve the understanding of the behavior of the material used for ventilated facades [5, 17-21].
- Studies to improve the reuse of water materials and their reduction [22-24].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 October 2020 doi:10.20944/preprints202010.0642.v1

2. Geological setting of the Carrara marble basin

The Carrara marble basin (Figure 1) is located in the northernmost part of Tuscany (Italy) near the municipality of Carrara, within the Apuane Alps (Northern Apennines). It has an extension of about 375 km^2 and it is subdivided into three sub-basins: Torano, Fantiscritti, and Colonnata from NW to SW.

From the geological point of view, the Apuane Alps are divided into four tectonic units [25] (Molli et al., 2002): the Liguride and sub-Liguride systems, the Tuscan Nappe, the Massa Unit, and the Apuane Unit. The Liguride system is characterized by ophiolites, deep-water sediments, and sediments of the ocean-continental transition. Very low-grade and non-metamorphic sedimentary rocks characterized the Tuscan Nappe. The Massa Unit is made up of a Hercynian basement and a sedimentary cover, deformed under higher metamorphic conditions. The same basement, unconformably covered by a sequence of sedimentary rocks metamorphosed in greenschist facies, can be recognized in the Apuane Unit.

The metamorphic Apuane Alps complex was generated by tectonic and metamorphic phases that occurred during the Alpine orogeny. The current structure is derived by a sharp rise, initiated by an isostatic response to the previous doubling of the continental crust. Then the Tuscan and Ligurian coatings were eroded, allowing the outcropping of a tectonic window, in which the Apuane Alps emerged. The latter belongs to the geometrically lower Apuane Unit ("Autochtonous" Auct.), which crops out over a NW-SE trending elongated area ca. 20 x 10 km wide, and the overlying Massa Unit, which occurs as a relatively narrow, elongated belt at the inner border of the Apuane Unit (Figure 1a).

The well-known Carrara Marble derives from the greenschist facies metamorphism of the carbonate Liassic platform deposits (Marmi s.s. Formation) characterized by peak temperatures of 350-450°C at pressures of 0.4-0.8 GPa [25].

The Apuan Unit's structural evolution includes two distinct tectonic-metamorphic events: the main event (D1) where the major structuration takes place within the metamorphic units and the late structuration (D2) in which the metamorphic complex gradually exhumed towards more and more superficial structural levels. The most recent stages of the D2 deformation are connected to a polyphase deformation that caused the development of brittle structures (fault and fracture systems) [26-27].

The Carrara marble has been exploited since the Roman time for heritage and building purposes, and it is currently widely used in building applications all over the world.

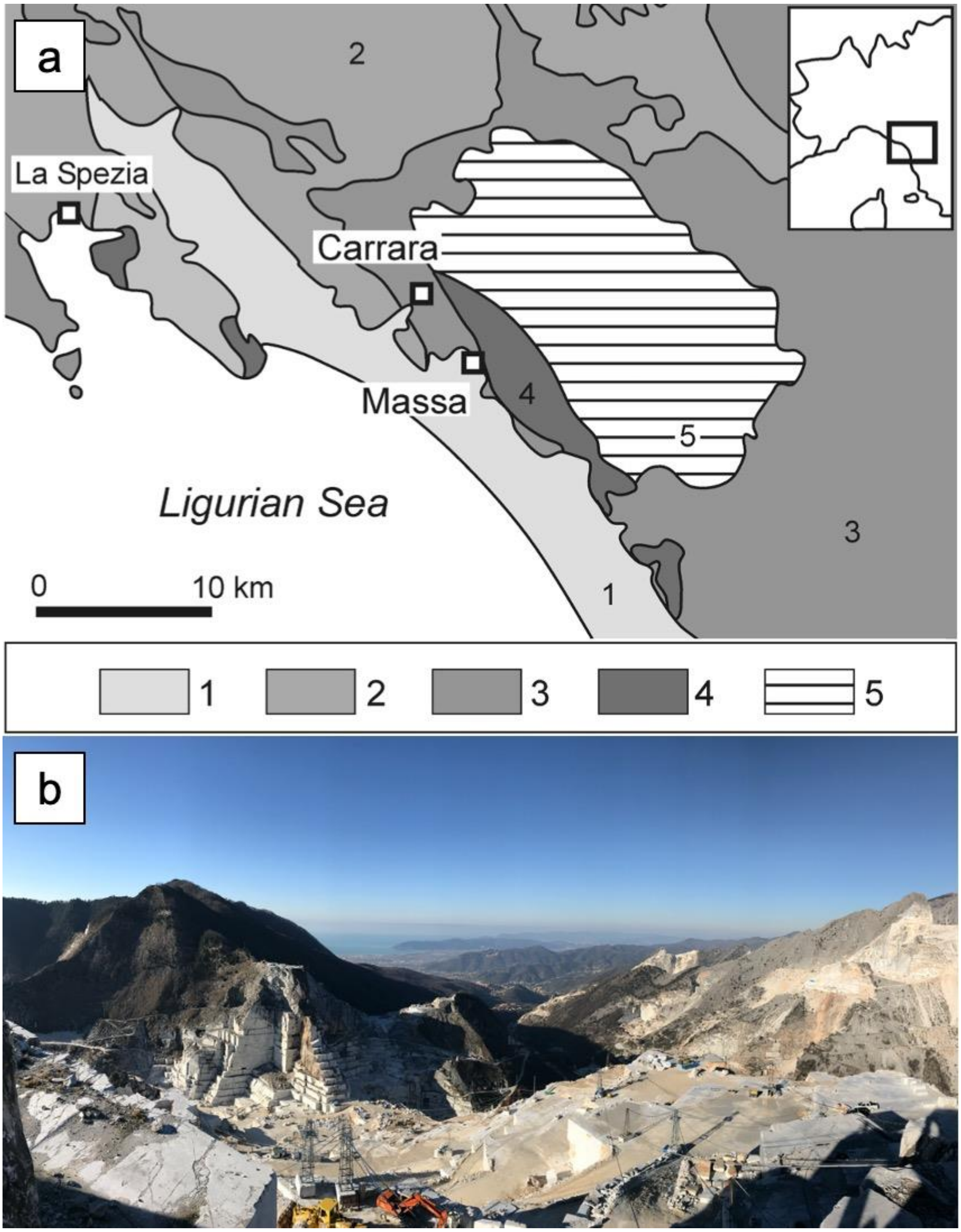

Figure 1. a) Tectonic sketch-map of the Northern Apennines in the Carrara area. 1: Pliocene and Quaternary deposits, 2: Ligurian Units, 3: Tuscan Units, 4: Massa Unit, 5: Apuane Unit ("Autochtonous" auct.). Simplified from [28]. b) Partial view of the Carrara marble basin from the top of the "La Gioia" quarry.

3. Recent developments in the characterization of fracturing state and natural stress state

The fracture characterization and the evaluation of natural and induced stress state and its relationships with extraction operations become essential to achieve sustainability and competitiveness of stone extraction.

The state of stress in an element of rock in the ground subsurface is determined by both the current loading conditions in the rock mass and the stress path defined by its geologic history.

Changes in stress state in a rock mass may be related to temperature changes, thermal stress, and chemical and physicochemical processes such as leaching, precipitation, and constituent minerals' recrystallization. Mechanical processes such as fracture generation, slip on fracture surfaces, and viscoplastic flow throughout the medium can be expected to produce both complex and heterogeneous states of stress [29].

The need for reliable estimates of the pre-mining state of stress has promoted the development of stress measurement devices and procedures. Most methods use a borehole to gain access to the measurement site. The instruments for direct and indirect determination of in situ stresses include photoelastic gauges, USBM borehole deformation gauges, biaxial and triaxial strain cells, flatjacks, and hydraulic fracturing. An alternative method for in situ stress estimation is based on the Kaiser effect and involves acoustic emissions measurement [30].

The study of the geological structures can provide information regarding the regional tectonic events. In fact, the local stress field derives from the far-field tectonic stress, also known as "far-field boundary conditions" [31], and it is an essential parameter for the definition of the geomechanical model. Unfortunately, it is not possible to directly measure past tectonic stress. Still, it can be reconstructed by analyzing regional deformation structures in relation to the tectonic evolution of the area (paleostress) during which the regional stress fields changed in space and time.

Focusing on underground structures, openings, and excavations (e.g., tunnels, quarries, mines, walls, etc.), their design and stability are strictly influenced by the local and regional stress fields in addition to rock mass properties [32]. The natural in situ stresses control the distribution and magnitude of the tensions around underground openings. Stress concentrations in the excavation walls may be large enough to overstress the rock, mobilize the rock mass's strength locally or at a large scale, inducing failure.

Methods of paleostress analysis from faults data (particularly fault-slip data) have been successfully used in the last five decades, considering the basic requirements needed to apply the different methodologies. Faulting is the primary indicator of the stress variation: the regional tectonic stress strongly influences faults and fractures, and this is the reason why most of the studies that aim to characterize the stress system analyze orientation, interaction, and fracture mode (opening, closing, shearing) of faults [33-36].

Moreover, morphology and local geological structures can modify the principal stress tensors' orientation, and they have to be considered both in the planning stage and in monitoring activities. Faults or folds can locally disrupt the regional stress field, and fracture sets connected to those local structures may result in heterogeneous orientations, densities, and fracture modes [31, 37].

In structural geology, a static or dynamic treatment of tectonic evolution is often introduced considering the mechanical forces acting on limited three-dimensional regions that contain the analyzed structure. Therefore, geological and geomechanical surveys are fundamental steps in the work planning, particularly in the case of underground excavations, where both discontinuities and natural stress influence the design requirements and the induced stresses affecting the voids' stability. On this matter, a study of the regional tectonic setting and local structural features is fundamental to combine far-field tectonic stress, local geological structures, and morphology. These elements are necessary for correctly modeling the induced stress during excavation activities, planning in-situ measurements, and monitoring stress variations.

Another major problem is related to a rock mass's fracturing state: a careful study is necessary since small variations in the degree of jointing could have negative consequences for rock exploitation.

This factor is the most important since it controls a massif's ability to provide blocks of suitable dimensions for processing, as there is a geometric limit below which the blocks cannot be commercialized [38].

The genesis of joint- and fracture-systems can be multifaceted and traced back to orogenic, and epeirogenic processes, as well as shrinkage caused by cooling or desiccation. As a discontinuity in a deposit, all surfaces such as faults, joints, cracks, fissures, or bedding planes must be considered [39, 40]. The formation of individual blocks in a compact rock, the so-called in situ blocks [41], is linked to the intersection of these discontinuities.

The model in Figure 2 shows in an exemplary way how changes in a system of orthogonal discontinuities occur when accompanied by rotation in one or both joint system groups. A comparison of the joint spacing distribution leads to the same results in all three cases. Furthermore, an increase in material loss occurs, and that a simultaneous decrease in the average block size can be documented [39].

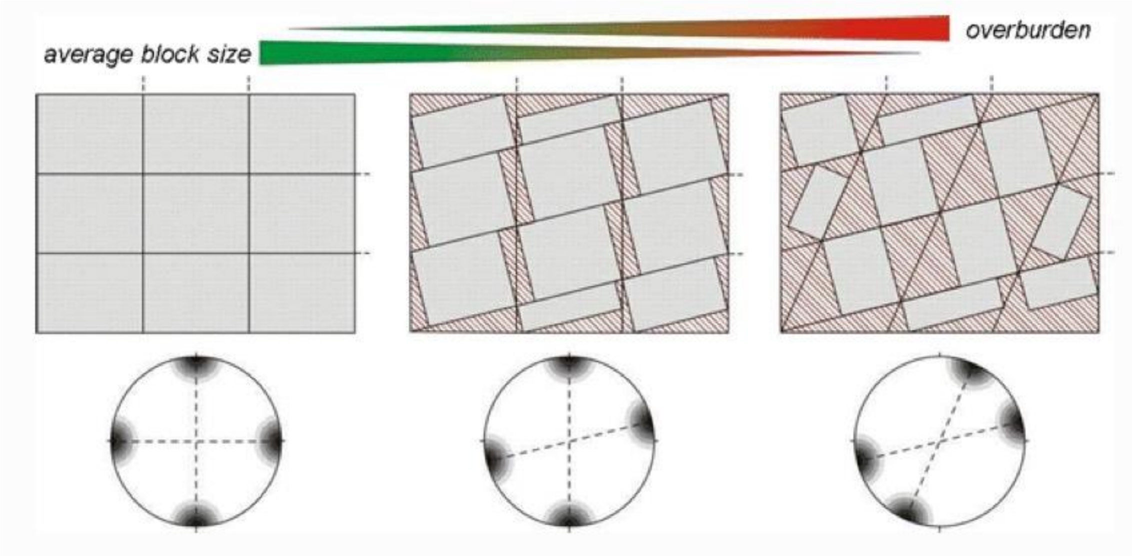

Figure 2. An increase of cutting (overburden) remains with decreasing average block size due to the joint system deviating from orthogonality where the spacing pattern remains equal. The characteristic joint density distributions depict the orientations of each joint pattern (modified from [39])

Moreover, the present fracturing state of a rock mass could be a combination of the induced fracturing effect on the natural fracture system. If the extraction method causes significant fracturing, alternative methods should be considered [42].

Fracture mapping is the fundamental method for forecasting the number of marketable dimension stones [43]. In the last two decades, fracture trace mapping evolved from 2D manual to 3D automatic or semi-automatic methods, based on digital models [44-46]. These methods are particularly effective when the digital model's point density is so high that its surface represents the actual shape of traces. Otherwise, boreholes images and Ground Penetrating Radar (GPR) could represent alternative methods for mapping fractures.

Discontinuity frequency (density) is one of the fundamental measures of the degree of fracturing of the rock mass. Frequency is used as a variable for geostatistical analysis: the fractal method has been applied for studying the fracture network [47-48]. Many studies focused on optimizing the exploitation planning based on multivariate geostatistical methods [49-54]. The results are used to generate a realistic 3D rock mass model, which can be used in different applications, such as rock mass stability analysis, planning the exploitation system, or for sizing the exploitable blocks depending on the project goals [48, 55].

The authors considered, among others, an underground quarry located in the Alpi Apuane marble district (Tuscany, Italy), named Ravaccione. Stress measurements were performed with a CSIRO cell, in correspondence with horizontally drilled boreholes [2, 5]. The results in terms of principal stress, magnitude, and orientation are reported in Table 1.

Table 1. Principal stress components with mean orientation and magnitude measured in Ravaccione quarry and estimated orientation of the paleostress.

	In-situ stress measurements				Paleostress	
Depth of investigation [m]	**Principal stress**	**Magnitude [MPa]**	**Plunge [°]**	**Trend [°]**	**Plunge [°]**	**Trend [°]**
6.9	σ1	16.5	79	242	78	47
	σ2	1.3	10	086	10	263
	σ3	0.5	4	355	6	171
9.65	σ1	16.5	81	293	78	47
	σ2	2.2	9	117	10	263
	σ3	0.6	1	027	6	171

Moreover, a multiscale and multidisciplinary approach was set up to detect and analyze geological structures to define the paleostress orientation. At the regional scale, the lineament extraction was performed employing a semi-automatic method [56] on the Digital Terrain Model of the area of about 10 km^2 in which the quarry is located (resolution of 10x10m). The obtained lineament features (Figure 3) were then associated with the main directions of the natural stress tensor (paleostress, Table 1), inferred from previous studies.

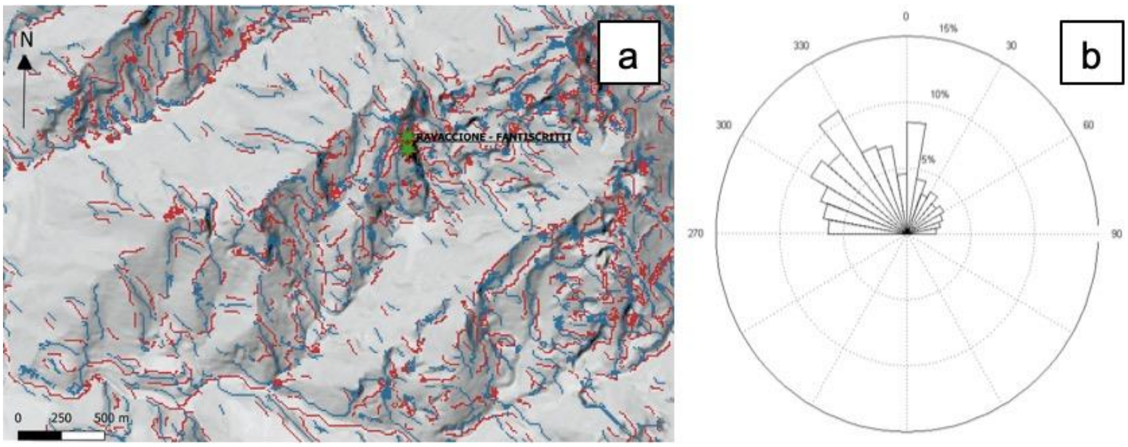

Figure 3. Results of lineament extraction: map of the lineaments (convex in red, concave in blue), rose diagram representing lineament frequency based on the direction respect to North.

In the Ravaccione site (Figure 4), the quarry face is oriented nearly parallel and perpendicular to the maximum and minimum paleostress tensors. After this study, it was possible to define the variations of the local stress produced by the excavation at the time of the measurements: in particular, vertical σ1 stress changed in trend from about N47 to N293, while horizontal σ2 and σ3 rotated of about 180 degrees (Table 1).

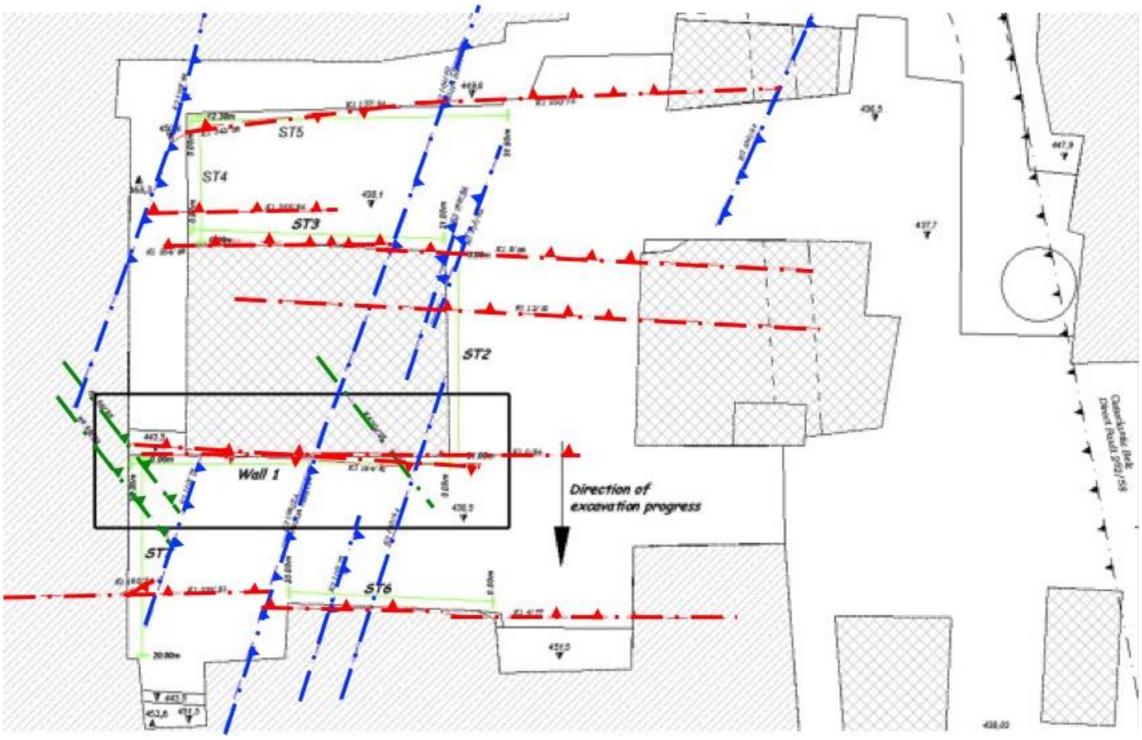

Figure 4. Map of Northwestern chamber of the Ravaccione quarry with the indication of the main surveyed discontinuities (red, blue, and dark green dashed lines); the rectangular shape shows the location of the survey (modified after [5]).

4. Technology improvements

The progressive optimization of extraction techniques and practices is essential to achieve the final sustainability and competitiveness of stone extraction.

In Italy, dimension stones represent a significant economic asset. The stone sector has progressively improved the available technologies, with extensive use of shovels, front loaders, diamond wire saws, chain cutters, hydraulic drilling, and line drilling machines. Italian manufacturers mainly produce consumables and tools.

The technological evolution in the stone sector has led to a progressive increase in marble production in the Carrara basin, reducing excavation times, and ensuring better product quality. One of the most obvious consequences was the drastic reduction in the number of workers: it went from about 9000 to 800 in less than a century; on the other hand, the annual productivity/employee went from about 80 t to over 1000 t [57-58]. Furthermore, analyzing the period 1950-2020, a significant increase in productivity was recorded from 1976: this is due to the spread of diamond wire in the Apuan quarries. To date, over 20% of the material that has been historically excavated was exploited in the last 15 years. The annual production is around 1,400,000 t, representing the most important activity in the dimension stones sector; the density of quarries in that area is 0.33/km^2 (7 quarries/km^2 for the municipality of Carrara only) compared to the national average, which is 0.02/km^2 [57]. These results were achieved thanks to the high performance of the diamond wire cutters, which made it possible to adapt the cuts to the quarries' morphological conditions and guarantee high productivity.

Diamond wire saws have greatly influenced both production speed and efficiency over the years. Despite the many improvements and optimizations over the years, its use is still the cause of injuries, sometimes fatal, following the circuit's opening during cutting, resulting in whiplash and high-speed projection of its components. Recent experimental studies have made it possible to evaluate some of the leading causes of the diamond wire ring opening during cutting, from some already known in the literature [59-60], such as failure due to the slippage of the junction clamp (Figure 5), and/or the breakage of the steel cable close to it, to other less known ones, such as the breakage of the junction clamp [61]. From these tests, it emerged that a knowledge of the materials used and a register showing the specifications of a given cut (i.e., length of the wire, cut surface, and so on) could lead to a more in-depth analysis of the causes of breakage, to induce manufacturers to define diamond wire replacement criteria based on numerical values rather than on visual inspections dictated by the experience of the quarrymen, with the aim to safeguard the health of workers and avoid frequent breakage of the diamond wire.

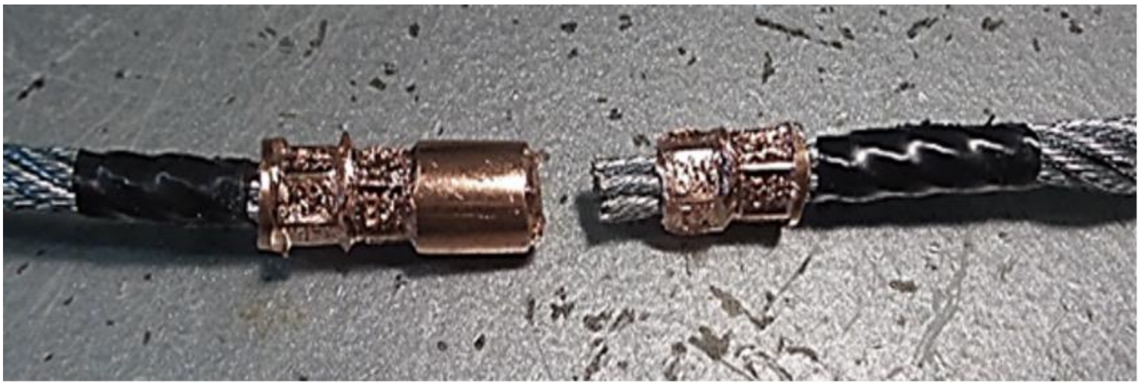

Figure 5. Breakage of the junction clamp, close of the variation of the resistant cross-section.

Another experimental campaign was recently carried out [62] to evaluate the diamond wire's actual load during both the squaring and upstream cuts. The values provided by the measurements show stress on the wire of about 1/10 of its static tensile strength, considering a minimum value of 800 kg imposed by the junction clamp [61]. Therefore, if the cuts were made according to the parameters used during the acquisitions, the wire's tearing should not occur unless a sudden failure of the rock that can block the wire.

Today, the diamond wire cutter is the most versatile system and offers remarkable performances in the dimension stones cutting sector. Thanks to the safety systems that the machines are equipped with, good working conditions could be obtained by respecting the cutting parameters identified during the experimental campaign (even in the case of upstream cutting -Figure 6- the load on the wire is less than the limit imposed by the reference standards). For this reason, the need for a technological evolution arises, to be pursued by implementing the collaboration of electronics and control systems with the mechanics of cutting.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 October 2020 doi:10.20944/preprints202010.0642.v1

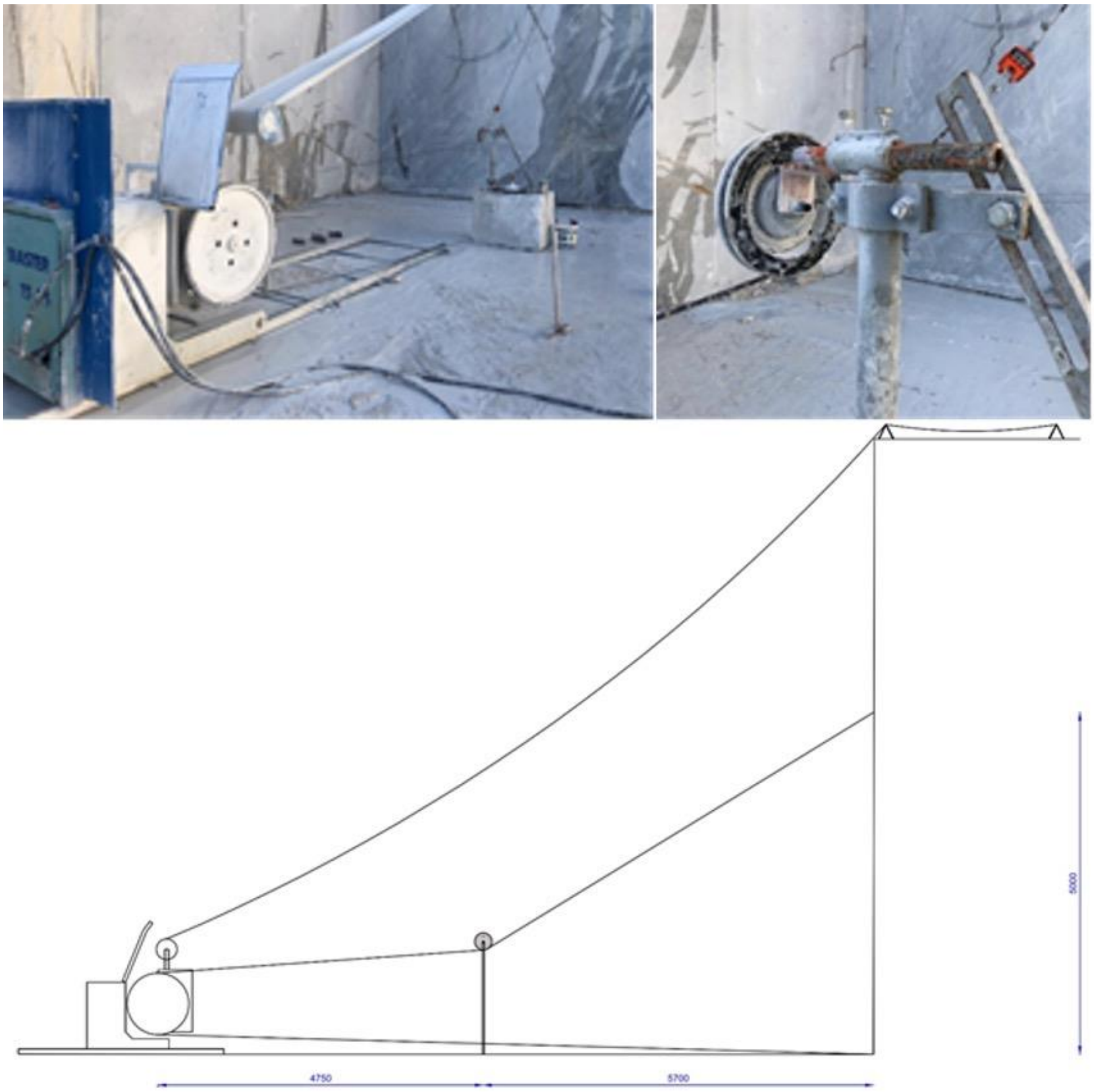

Figure 6. Cutting scheme through the Bfc MASTER TS75 cutting machine: upstream cut calibration, dynamometer on the wire's upper side.

One way could be to install a bearing load cell on the machines, such as the one used for the experimental campaign (Figure 7), combined with a control system more refined than those currently available. Thus, an automatic control system would be obtained, which regulates the withdrawal based on the force acting on the wire, without exceeding the load limit imposed by the standard and increasing the operation's degree of safety.

Using a traction control, as required by UNI EN 15163 [63], which limits the tension to the envisaged threshold, the probability of tool breakage would drastically decrease. However, this device would not prevent whiplash, which is an eventuality since the electric motors cannot stop in such rapid times.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 October 2020 doi:10.20944/preprints202010.0642.v1

Figure 7. a) Positioning of the load cell on the Apuania Corsi MF 5000 machine. b) Placing the draw wire encoder. c) Installing the dynamometer for calibration.

To do this, hydraulic motors would be necessary, controlled in feedback by servo valves to obtain a system with a high dynamic response.

Another machine frequently used in marble cutting operations is the chain cutting saw, which has the great advantage not to require 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 (as in underground construction sites - Figure 8), the chain saw, alone or in cooperation with the diamond wire saw (Figure 9), is frequently used. Its limit is the arm's length, which affects the cuts' extension, but recently very long arms (about 8 m) are being tested, although this may affect the cut's precision.

Figure 8. Chain cutting machine (on the top of the bench) operates in an underground construction site (Lasa quarry) while a diamond wire saw performs a squaring operation.

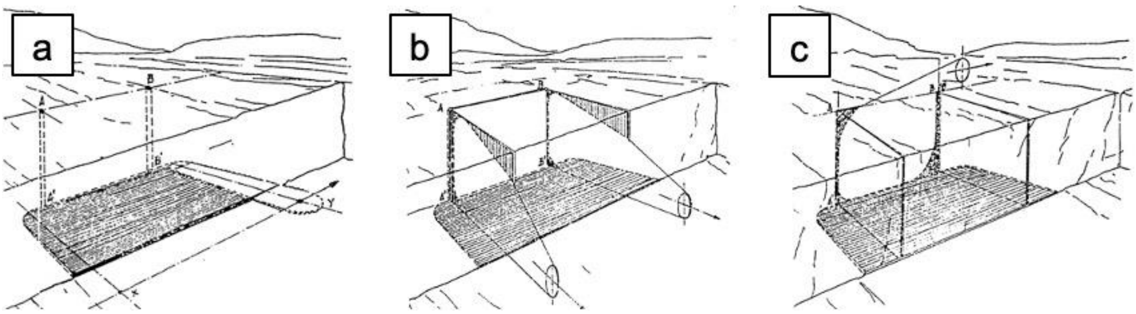

Figure 9. Cooperation between diamond wire cutting machine and chain cutting machine. a) Drilling of the vertical holes for the loop closure of the diamond wire. b) Horizontal cut at the bottom of the bench through a chain saw (thickness of the cut: about 37 mm, enough to allow the passage of the wire circuit. c) Cutting of the side surfaces and the rear surface using a diamond wire cutter.

In this field, studies are underway 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.

If the survey refers only to marbles, it is assumed enough to characterize the material with a strength value (Uniaxial compressive strength) and a medium hardness value (HK, Knoop Hardness, or HW, Vickers Hardness); about tool materials, they should be separately tested for both hardness and toughness. Furthermore, the attack angle can only be changed by modifying the tool holder.

According to tests recently carried out in the laboratory, the bevelling of tools has improved their performance in terms of duration: this fact indirectly proves that small variations in the angle of attack can lead to significant improvements or worsening. Bevelling is equivalent to a local reduction, on a sub-millimeter scale, of the angle of attack; the operator decides the depth of cut. Indeed, for a given series of tools, it depends on the length of the sequence (data on which the operator does not even intervene), on the sliding speed of the chain, and the feeding speed (progression of the machine): the operator adjusts the depth of cut through the speed of the machine, relying mostly on noise. A less subjective criterion would be desirable. Indeed, the operator will tend to increase the speed until the machine begins to vibrate abnormally. Still, the optimal progression speed (which ensures both good cutting speed and useful life of the tools and the machine as a whole) is certainly lower. Further investigation is underway, but it is believed that improved tool performance may lead to greater efficiency of quarry operations.

5. Mechanical behavior of marble in different environmental conditions

In order to enlarge the market and the value of marble products, it is crucial to know how it will behave in different environmental conditions. The physical and mechanical properties of building stones can vary due to various degradation mechanisms caused by temperature and chemical agents. The problem of chemical and thermal weathering on marble rocks is an important issue to consider for designing building façades since it may cause sugaring, bowing, cracking, and spalling. Moreover, accurate comprehension of induced damages is required for restoration and conservation of heritage monument purposes. In a circular economy, a better awareness of the mechanical and physical processes to which marble products may be subject could increase the sustainability of exploitation processes by reducing the waste and the demand for replacing any products found to be faulty (e.g, marble slabs affected by bowing).

For this purpose, the authors conducted many studies for evaluating:

- The effects of temperature on physical and mechanical characteristics.
- The combined effect of thermal and chemical weathering.
- The effect of bowing on marble slabs

The effect of high temperatures as a degrading factor of rock materials has been investigated by [17, 64]: marble samples have been subjected to thermal cycles (ranging from 105° to 600 °C) and to subsequent non-destructive and destructive laboratory tests to evaluate the variation of physical and mechanical properties as a function of temperature variations (Figure 10). The study showed that the increase of crack density with temperature and the consequent porosity increases were the leading causes of degradation of physical and mechanical properties. In general, density, ultrasonic pulse velocity, wet electrical resistivity, uniaxial compressive strength, and Young's moduli decrease as temperature increases. By contrast, peak strain and porosity increase. Correlations between temperature and physical-mechanical properties were proposed together with a damage parameter to quantify mechanical properties' degradation with temperature.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 October 2020 doi:10.20944/preprints202010.0642.v1

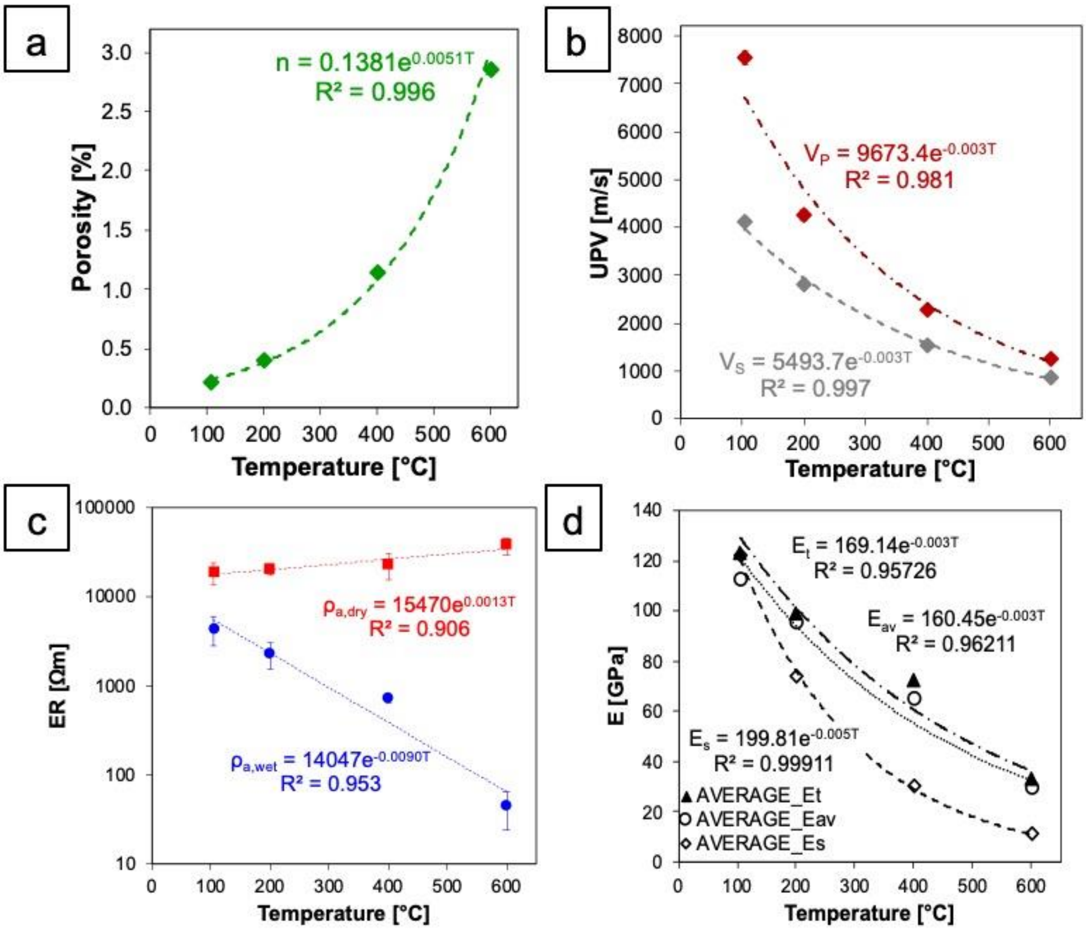

Figure 10. Relationship between a) the average porosity, b) the average P- and S-wave velocity, c) the average dry and wet average electrical resistivities, and d) the average values of Young's moduli of marble samples and target temperature.

In another study, the authors performed non-destructive (ultrasonic pulse velocities) and destructive tests (bending tests) on Carrara marble slabs in natural and after thermal (with target temperatures respectively of 50 and 90°C) and thermo-chemical treatment. Thermo-chemical treatments were performed by soaking the specimens in a 10^{-6} mol/l solution of sulphuric acid at pH=5 to simulate the acid rain behavior, at constant target temperatures, for one week. In general, for each weathering mechanism, progressive degradation of the physical and mechanical properties of marble specimens was observed. In particular, a marked drop in tensile strength, mirrored by a wide variation in P- and S-wave velocity, was found in specimens chemically treated at target temperature equal to 90 °C (Figure 11).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 October 2020 doi:10.20944/preprints202010.0642.v1

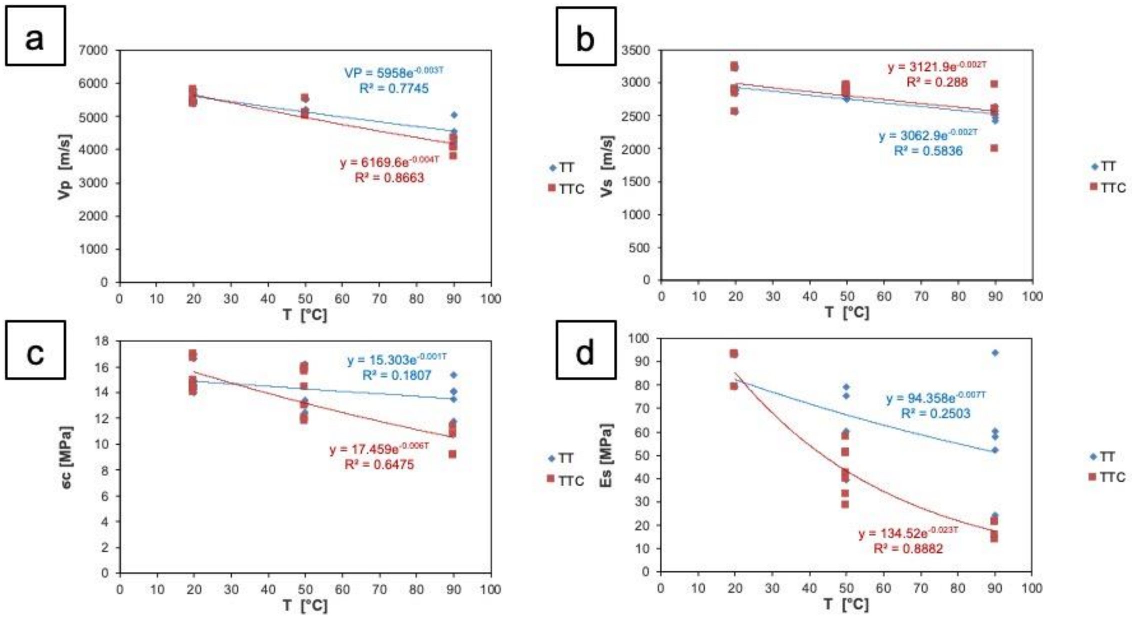

Figure 11. Relationship between a) P-wave velocity, b) S-wave velocity, c) Shear resistance, and d) secant Young's moduli as a function of temperature for Carrara marble sample under thermal (TT) and coupled thermo-chemical treatment (TTC).

The influence of marble degradation is particularly essential when marble slabs are used in ventilated facades, as they cover a large share of the ornamental stone market. The authors have focused on:

- The marble slabs in different environmental conditions, by developing new models for forecasting the slabs' behavior in time and proposing new technologies to improve the strength and durability of the slabs while preserving the aesthetic features of the natural material by using different anchoring systems. New products that can be safer, longer-lasting, and lesser weight can be developed, e.g., by impregnating the thickness of the slabs with resins or designing composite slabs with an internal layer of light material (honeycomb or foam).
- Optimization of tests for the certification of materials, and improving predictive tools for structural design and life cycle analysis, to reduce the distance in terms of quality and reliability between natural and artificial materials.
- Improvement of the durability of the slabs with the aim of expanding the ornamental stone market by including construction sites with more severe environmental conditions (extreme temperature excursions and moisture content in Nordic, hot-humid, and desert environments; solid transport by the wind; frosting).

Figure 12 shows a scheme of the intergranular equivalent cracking considered for computing the bowing effects as a deflection of the slabs as a function of the months of exposition of a marble slab with a different grain density (Figure 13).

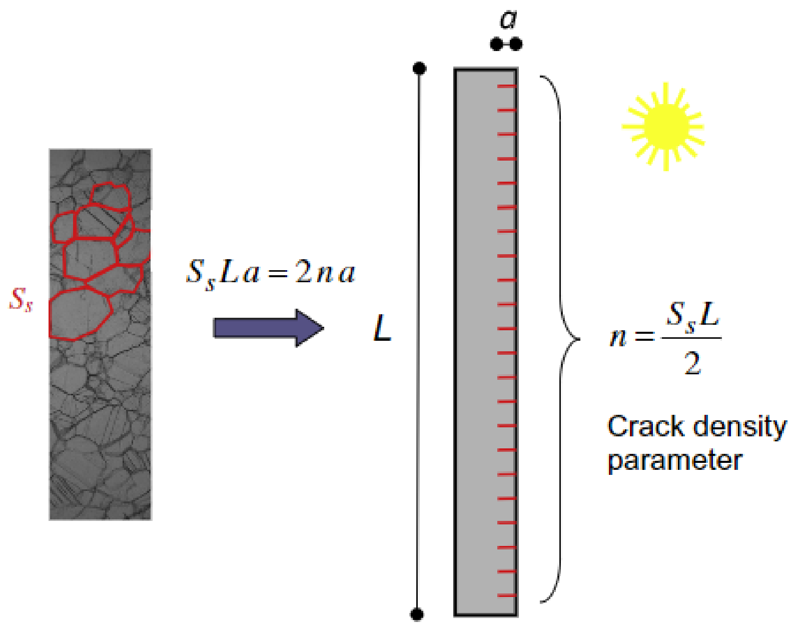

Figure 12. Scheme of the intergranular equivalent cracking (after [18])

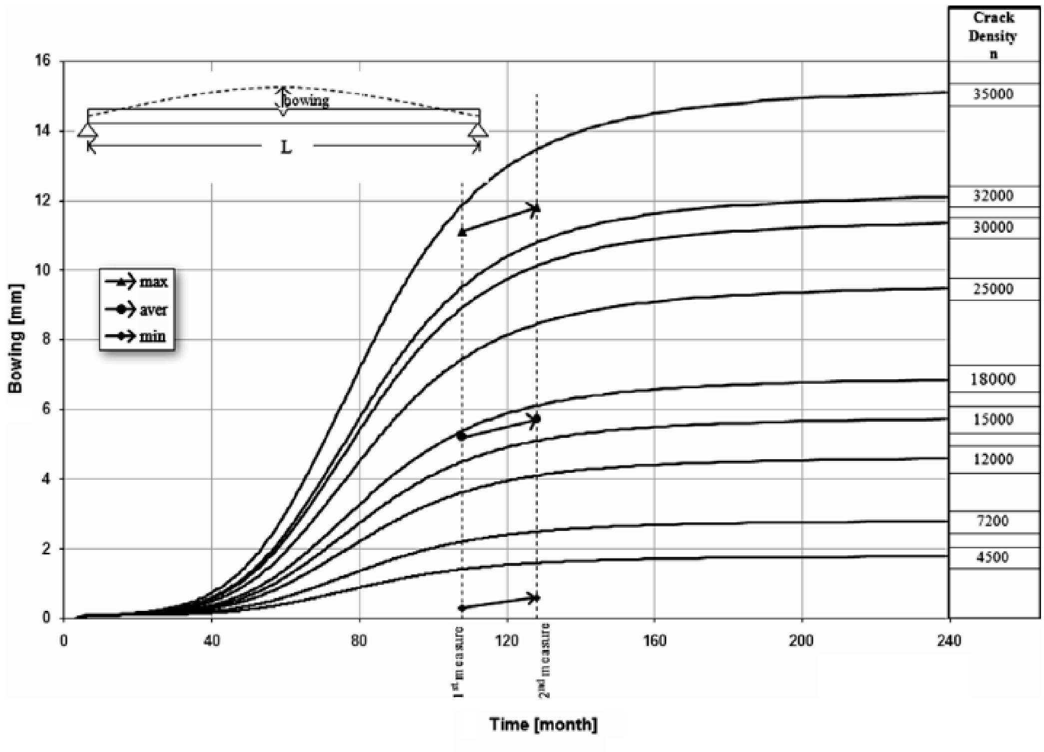

Figure 13. Total (bulk and crack induced) deflection as a function of the number (expressed in months) of thermal cycles for the simply supported slab with different values of crack density n (after [18])

5. Extractive waste management and recovery

In 2016, the mining and quarrying industry represented the second most important sector, at the EU-27 level, in terms of waste production (27.6% or 624 million tons), just after Construction & Demolition Waste (C&DW – 34.8% [65]). The needs to minimize waste production, in order to reduce their impacts on the environment and to save natural resources, and, contemporary, the opportunity for the reuse/recycling of waste materials are in line with the EU policy expressed in the Europe 2020 strategy for smart, sustainable and inclusive growth [66], in EU Sustainable Development Strategy [67-68] and the Paris Agreement document. Indeed, to strive for sustainable and efficient management and recovery of the extractive waste (EW), it is fundamental to guarantee the reduction of the environmental impacts associated with EW management and, contemporary, to ensure the environmental acceptance and the market conditions suitable for the new products (by-products, secondary raw materials – SRM) arising from the EW exploitation. The environmentally sustainable management of EW, which aims at recovering and recycling of both clean and contaminated materials, would therefore help to reduce the pressure on natural resources and potentially to reduce the land take and the environmental and landscape contamination [23]. Territorial environmental agencies form Northern Europe recommend the reuse of recycled products and SRM coming from waste treatment, whenever possible, instead of using natural (non-renewable) resources. In general, sustainable land and resources management is based on the overall organization of materials flows and on the optimization of the recycling activities, including the evaluation of the more suitable and marketable recycled products obtained from EW treatment and recycling activities [69].

At the Italian level, EW management, mainly associated to the dimension stone industry, is still a matter of concern, both for wastes produced in the quarrying areas and for the ones connected to working phases (residual sludge, above all). Such wastes could be profitable and sustainable recovered and recycled as SRM (e.g., industrial minerals, high-value products, aggregates, filler materials, etc.). Still, most of the time, they were disposed of EW facilities. Carrara marble quarrying basin represents a vital case study for the recovery and recycling of EW. Indeed, EW recycling, together with more modern and efficient quarrying techniques and technologies, leads to the aimed sustainable mining of the marble resources.

Carrara quarry basin includes about one hundred quarries for colored and white marble exploitation, exploited from the Roman time. The quarry basin is ideally split into three sub-basins (NW to SW: Torano, Fantiscritti, and Colonnata sub-basins). Marble was exploited with traditional systems up to the 90s of the XX cent.; marble production was originally for national and international customers, characterized by a low-medium production rate and a "not-industrial" approach. Such a kind of quarry management allowed the coexistence of the *Ravaneti* (EW facilities; some historical *Ravaneti* are still visible and renewed) and quarries as natural parts of the landscape, guaranteeing the safety of slope stability and a "green" environmental rehabilitation. From the 90s of XX century, there was a huge increment of marble requests from foreign countries (China, Russia, Emirates above all), causing a fast and intensive quarrying growth. EW volume increased and increased (Figure 14). The blocks' size differed depending on the different working era, quarrying techniques, and technologies applied (e.g., modern cutting systems generate more fine materials).

Figure 14. Carrara marble quarry basin: open pits and *Ravaneti*. Some of the hystorical *Ravaneti* have been used as a base for the internal roads in quarrying areas

At present EW production is about 3 Mm^3/y (fluent waste), other 80 Mm^3 of EW still present in the ravaneti has to be added to the fluent wastes: only 0.5 Mm^3/y of EW is exploited for SRM production [23]. The amount of EW has become larger and larger, generating problems in quarry

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 October 2020 doi:10.20944/preprints202010.0642.v1

management and activities (landslides, flooding roads, and inhabited urban area). In the meantime, big Companies leader in calcium carbonate production, built dressing plants to recycle material present in the *Ravaneti*: from EW to precious industrial products, recovering only the pure under-size calcium carbonate coming from quarries and leaving a great part of the EW (the worst in quality) in the quarries. In the 10s of the XX century a Newco (Carrara Marble Way srl, which groups 40 Carrara and Massa quarry company) decided to invest in EW management and recovery, creating a complete production-line to exploit EW (from the best to the poorest quality). The starting point to evaluate the best potential applications for marble waste (both coarse and fine fractions) was to investigate different researches dealing with the recovery of limestone and marble waste [70-75], including also residual sludge produced during drilling activity and in working plants [24, 76-80].

Carrara marble characteristics are reported in Table 2, while Table 3 resumes specific tests on two different EW typologies present in Carrara quarrying basin (Calocara and Lorano quarrying areas). For each area (Lorano and Calocara) tests have been performed for three different classes: 0.5-4 mm; 0-25 mm, and 0-150 mm.

Table 2. Carrara marble physical-mechanical characteristics (on average).

Physical characteristics	Value
Bulk density	2688 kg/m^3
Simple compression strength	1209 kg/cm^3
Compression strength after freezing	1181 kg/cm^3
Indirect Tensile Strength (Brasilian test)	174 kg/cm^3
Impact strength test	73.8 cm
Moisture absorption (by weight)	0.16%

Table 3. Summary table of the results of the physical tests [23].

Sample Name	Grain size distribution	Atterberg limits		Density (on average)	Los Angeles test %	Freezing and heat test (on average) %	Shape index (%)	Flat index (%)
		Liquid Limit WL %	Plastic Limit WP%					
C 0.5-4	Sand weakly gravelly	-		2.55		-	-	-
C 0-25	Sandy gravel weakly silty	Not plastic		2.59	68	0.8	16.5	27.2
C 0-150	Gravel weakly sandy-silty	Not plastic		1.96	69	0.3	17.4	19.5
L 0.5-4	Sand weakly gravelly	-		2.46		-	-	-
L 0-25	Sandy gravel weakly silty	Not plastic		2.40	43	0.4	21.9	25.7

L 0-150	Gravel weakly sandy-silty	Not plastic	1.98	42	0.3	28.8	29.5

The first results (grain size distribution, Los Angeles test, Freezing, and heat test, and Atterberg limits, Table 3) show an attitude for EW to be recovered as crushed materials for embankments and armor stone.

Sampled materials shows the following geochemical characteristics: SiO_2 (0.32-2.63 wt%); TiO_2 (0.1-0.4 wt%); Al_2O_3 (0.04-0.9 wt%); $Fe_2O_3$to (0.04-0.40 wt%); MnO (<0.1-0.2 wt%); MgO (0.72-2.13 wt%); CaO (52.60-56.10 wt%); Na_2O (<0.01 wt%); K_2O (<0.01-0.21 wt%); P_2O_5 (<0.01-0.04 wt%); Cr_2O_3 (<0.01 wt%); BaO (<0.01 wt%); SrO (0.01 wt%); LOI (42.00-43.00 wt%). From a petrographical point of view Calocara is an extremely pure, relatively coarse-grained marble, showing a granoblastic texture; while Lorano is an almost pure granoblastic marble which is, however, characterized by variable grain size. The EW coarse fractions shows the same characteristics of the original rock, while the EW fine fractions, compared to the primary rock-type (which is a high purity marble), are slightly enriched in quartz (Calocara: <1 vol. %; Lorano: ~1.5 vol. %), white mica (Calocara: <1 vol. %; possibly partially chloritized; Lorano: ~2 vol. %) and Fe oxides/hydroxides (Calocara and Lorano: <0.5 vol.) [23].

Based on geochemical, mineralogical, and petrographic characterization, both Calocara and Lorano EW (coarse and fine fractions), extremely pure in calcium carbonate, may represent high-value products that could be used as filler for paper, rubber, paint, plastic, etc. production [81].

The results obtained from EW characterization (carried out in two of the most important quarrying areas in the Carrara marble quarry basin) were the basis to project and realize a proper treatment plant (selection, crushing, and screening) to exploit the valuable materials disposed in the *Ravaneti*. The treatment plant still treats the EW, even if, due to the recent global market crisis, it is harder to sell the produced SRM and, consequently, the feeding material to the treatment plant is decrementing more and more.

Concluding, at a broader scale, should the extractive industry aims at guaranteeing the systematic and profitable recovery of EW as SRM, a change in quarrying and working activities has to be projected: together with a more efficient extraction, a dedicated disposal area for marble scraps and processing phase is needed. Furthermore, several actions are fundamental to improve the efficiency in EW exploitation:

- the definition of a working protocol which indicates how to manage the EW and which characteristics are needed for each new product (e.g., crushed material for embankments or as armor stone must be separated from the high-quality ones in order not to pollute their quality)
- the cooperation between public authorities and industries to define guidelines and operative protocols for the application of SRM at a broader level (e.g., in public works and infrastructures)
- a market ready to accept New Products obtained from EW treatment. In this case, it is necessary to inform and sensitize the civil society about the necessity to accept and use products from "waste" treatment (End of Waste Criteria). Indeed, SRM exploited from EW facilities represent an important source, integrating the RW coming from virgin deposits. Waste must be considered a future resource, and waste facilities have to be considered "new ore-bodies" to exploit following the mine approach principles [69].

7. Conclusions

The sustainability in the production of natural stones for building purposes, such as tiles and slabs, requires optimizing all phases of the production process, from the exploitation to the final use. The challenge is to produce artifacts that combine ecology and economy, ensuring high production standards in compliance with historical heritage and architectural traditions in which they will be installed and minimizing the production of waste.

The assessment of the characteristics and environmental impacts of building natural stones is the core of sustainable exploitation processes. To reach these goals, studies in all production steps

 doi:10.20944/preprints202010.0642.v1

have been conducted by the authors for improving the knowledge on the state of stress and the rock mass fracturing determination, on the thermo-chemo-mechanical behavior of rocks, on the cutting techniques, and the strategy for waste reduction.

The paper reported the latest advances in all these fields. In particular, non-contact techniques allow the estimation of the main lineaments that can influence the recovery rate and material quality. The studies concerning the rock behavior under different environmental conditions, in terms of temperature and chemical interaction, are at the base of ongoing research devoted to set up processes able to increase the slab quality, making natural products competitive with artificial ones. Waste reuse is a promising way to reduce the environmental impact of disposal and to increase economic income by finding further employment in the industry.

Author Contributions: Conceptualization, A.M.F; methodology, F.V., G.A.D, G.U., M.C and A.M.F; writing—original draft preparation, F.V., G.A.D, G.U., M.C and A.M.F; writing—review and editing, F.V., G.A.D, G.U., M.C and A.M.F; visualization, F.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

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

References

1. United Nation – Sustained Development (https://sustainabledevelopment.un.org/topics/mining)
2. Alejano, L.R.; Castro-Filgueira, U.; Ferrero, A.M.; Migliazza, M.; Vagnon, F. In situ stress measurement near faults and interpretation by means of discrete element modelling. *Acta Geodyn. Geomater.* **2017**, 14, 181–194, doi:10.13168/AGG.2017.0002.
3. Costantini, G.; Comina, C.; Ferrero, A.M.; Umili, G.; Bonetto, S. Underground application of photographic and GPR techniques for discontinuity survey. *Riv. Ital. di Geotec*. **2019**, 37–47.
4. Ferrero, A.M.; Godio, A.; Sambuelli, L.; Voyat, I.H. Geophysical and geomechanical investigations applied to the rock mass characterisation for distinct element modelling. *Rock Mech. Rock Eng.* **2007**, 40, 603–622, doi:10.1007/s00603-006-0092-9.
5. Ferrero, A.M.; Migliazza, M.; Segalini, A.; Gulli, D. In situ stress measurements interpretations in large underground marble quarry by 3D modeling. *Int. J. Rock Mech. Min. Sci*. **2013**, 60, 103–113, doi:10.1016/j.ijrmms.2012.12.008.
6. Godio, A.; Sambuelli, L.; Ferrero, A.M. Geophysical investigation to optimize excavation of an underground marble quarry in Stazzema, Italy. *Lead. Edge (Tulsa, OK)* **2003**, 22, 574–578, doi:10.1190/1.1587682.
7. Cardu, M.; Giraudi, A.; Murthy, V. M. S. R. Evaluation of dimension stone cutting by diamond wire saw in two marble quarries. *Diamond Tooling J.* **2011**, 3, 1-6.
8. Cardu, M.; Lovera, E. Extraction of dimension stone as a co-product of civil engineering works: a case study. *CIM J.* **2011**, 2, 1-6.
9. Cardu, M.; Michelotti, E. Innovative method to recover and recycle the technological materials used in dimension stones processing. *CIM J.* **2010**, 1, 1-4.
10. Cardu, M.; Zoppo, G. Dimension stone exploitation in the Ossola Basin, Italy. *J. of Nepal Geol. Soc.* **2000**, 22, ISSN: 0259-1316
11. Cardu, M. Analysis of the excavation techniques to optimize the productivity in an Italian dimension stone basin. In Proceedings of the 21st International Symposium on Mine Planning and Equipment Selection (MPES); 2012.
12. Cardu, M.; Giraudi, A.; Murthy, V.M.S.R.; Choudhary, B.S.; Shukla, A. Rock characterization and wire performances for dimension stone cutting by diamond wire saw. *J. of Underground Resources* **2014**, 3, 5, 25-37.
13. Michelotti, E., Cardu, M. Innovative method to recover and recycle the technological materials used in dimension stones processing. In Proceedings of the Sixteenth International Symposium on Mine Planning and Equipment Selection (MPES 2007); 2007.
14. Cardu, M.; Patrucco, M.; Lovera, E.; Michelotti, E. Quarrying by explosive and diamond wire in hard dimension stones. In Proceedings of the European Federation of Explosives Engineers; 2005.

15. Cardu, M.; Lovera, E.; Michelotti, E.; Fornato, M. The exploitation of syenite in the Piedmont Alps (Italy): present relevance of the stone and future technological outlook for its sustainable exploitation. In Proceedings of the International Conference on Dimension Stone; 2004.
16. Mancini, R.; Cardu, M.; Garibaldi, L.; Fsana, A. Vibrations and stresses induced in the rock by the detonating cord splitting of dimension stone blocks. In Proceedings of the 7th International Symposium on Rock Fragmentation by Blasting - FRAGBLAST-7; 2002.
17. Vagnon, F.; Colombero, C.; Colombo, F.; Comina, C.; Ferrero, A.M.; Mandrone, G.; Vinciguerra, S.C. Effects of thermal treatment on physical and mechanical properties of Valdieri Marble - NW Italy. *Int. J. Rock Mech. Min. Sci.* **2019**, 116, 75–86, doi:10.1016/j.ijrmms.2019.03.006.
18. Ferrero, A.M.; Migliazza, M.; Spagnoli, A.; Zucali, M. Micromechanics of intergranular cracking due to anisotropic thermal expansion in calcite marbles. *Eng. Fract. Mech.* **2014**, 130, 42–52, doi:10.1016/j.engfracmech.2014.01.004.
19. Spagnoli, A.; Migliazza, M.; Zucali, M.; Ferrero, A.M. Thermal degradation in Carrara marbles as the cause of deformation of cladding slabs. *Frat. ed Integrita Strutt.* **2014**, 30, 145–152, doi:10.3221/IGF-ESIS.30.19.
20. Migliazza, M.; Ferrero, A.M.; Spagnoli, A. Experimental investigation on crack propagation in Carrara marble subjected to cyclic loads. *Int. J. Rock Mech. Min. Sci.* **2011**, 48, 1038–1044, doi:10.1016/j.ijrmms.2011.06.016.
21. Ito, W.H.; Ferrero, A.M.; Vagnon, F.; Migliazza, M.R.; De Queiroz, P.I.B. Thermomechanical numerical analysis of bowing in marble slabs. In Proceedings of the Rock Mechanics for Natural Resources and Infrastructure Development- Proceedings of the 14th International Congress on Rock Mechanics and Rock Engineering, ISRM 2019; 2020; pp. 2649–2657.
22. Dino, G.A.; Borghi, A.; Castelli, D.; Canali, F.; Corbetta, E.; Cooper, B. The candoglia marble and the "veneranda fabbrica del duomo di milano": A renowned georesource to be potentially designed as global heritage stone. *Sustain.* **2019**, 11, doi:10.3390/su11174725.
23. Dino, G.A.; Chiappino, C.; Rossetti, P.; Franchi, A.; Baccioli, G. Extractive waste management: A new territorial and industrial approach in Carrara quarry basin. *Ital. J. Eng. Geol. Environ.* **2017**, 2017, 47–55, doi:10.4408/IJEGE.2017-02.S-05.
24. Careddu, N.; Dino, G.A. Reuse of residual sludge from stone processing: differences and similarities between sludge coming from carbonate and silicate stones—Italian experiences. *Environ. Earth Sci.* **2016**, 75, doi:10.1007/s12665-016-5865-1.
25. Molli, G.; Giorgetti, G.; Meccheri, M. Structural and petrological constraints on the tectono-metamorphic evolution of the Massa unit (Alpi apuane, NW Tuscany, Italy). *Geol. J.* **2000**, 35, 251–264, doi:10.1002/gj.860.
26. Cortopassi, A.; Molli, G.; Ottria, G. Studio della deformazione fragile nel bacino marmifero di Fantiscritti (Alpi Apuane, Carrara) finalizzato alla ricostruzione del campo di paleostress. *Geol. Tec. Amb.* **2006**, 1–2, 27-45.
27. Ottria, G.; Molli, G. Superimposed brittle structures in the late-orogenic extension of the Northern Apennine: results from the Carrara area (Alpi Apuane, NW Tuscany). *Terra Nov.* **2000**, 12, 52–59, doi:10.1111/j.1365-3121.2000.00272.x.
28. Carmignani, L.; Conti, P.; Massa, G.; Vaselli, L.; Mancini, S. Lineamenti geologici delle Alpi Apuane. *Acta apuana Suppl.* **2006**, 5: 9-23.
29. Brady, B.H.G.; Brown, E.T.; Brady, B.H.G.; Brown, E.T. Pre-mining state of stress. In *Rock Mechanics*; 1999; pp. 141–161.
30. Villaescusa, E.; Seto, M.; Baird, G. Stress measurements from oriented core. *Int. J. Rock Mech. Min. Sci.* **2002**, *39*, 603–615, doi:10.1016/S1365-1609(02)00059-X.
31. Maerten, L.; Maerten, F.; Lejri, M.; Gillespie, P. Geomechanical paleostress inversion using fracture data. *J. Struct. Geol.* **2016**, *89*, 197–213, doi:10.1016/j.jsg.2016.06.007.
32. Amadei, B.; Stephansson, O. *Rock Stress and Its Measurement*; 1997;
33. Célérier, B.; Etchecopar, A.; Bergerat, F.; Vergely, P.; Arthaud, F.; Laurent, P. Inferring stress from faulting: From early concepts to inverse methods. *Tectonophysics* **2012**, *581*, 206–219, doi:10.1016/j.tecto.2012.02.009.
34. Lisle, R.; Orife, T.; Arlegui, L. A stress inversion method requiring only fault slip sense. *J. Geophys. Res. Solid Earth* **2001**, *106*, 2281–2289, doi:10.1029/2000jb900353.

35. Lisle, R.J. A critical look at the Wallace-Bott hypothesis in fault-slip analysis. *Bull. la Soc. Geol. Fr.* **2013**, *184*, 299–306, doi:10.2113/gssgfbull.184.4-5.299.
36. Fossen, H.; Fossen, H. Structural geology and structural analysis. In *Structural Geology*; 2010; pp. 1–20.
37. Rawnsley, K.D.; Rives, T.; Petti, J.P.; Hencher, S.R.; Lumsden, A.C. Joint development in perturbed stress fields near faults. *J. Struct. Geol.* **1992**, *14*, 939–951, doi:10.1016/0191-8141(92)90025-R.
38. Sousa, L.M.O.; Oliveira, A.S.; Alves, I.M.C. Influence of fracture system on the exploitation of building stones: the case of the Mondim de Basto granite (north Portugal). *Environ. Earth Sci.* **2016**, *75*, 1–16, doi:10.1007/s12665-015-4824-6.
39. Mosch, S.; Nikolayew, D.; Ewiak, O.; Siegesmund, S. Optimized extraction of dimension stone blocks. *Environ. Earth Sci.* **2011**, *63*, 1911–1924, doi:10.1007/s12665-010-0825-7.
40. Ferrero, A.M.; Umili, G.; Vagnon, F. Analysis of discontinuity data obtained with remote sensing tools to generate input for EC7 design. In Proceedings of the Rock Mechanics and Rock Engineering: From the Past to the Future; 2016; Vol. 2, pp. 1115–1120.
41. Lu, P.; Latham, J.P. Developments in the assessment of in-situ block size distributions of rock masses. *Rock Mech. Rock Eng.* **1999**, *32*, 29–49, doi:10.1007/s006030050042.
42. Loorents, K.J.; Björklund, L.; Stigh, J. Effect of induced fracturing based on a natural fracture system in a dimension stone quarry in the Offerdal Nappe, Sweden. *Bull. Eng. Geol. Environ.* **2000**, *58*, 215–225, doi:10.1007/s100640050077.
43. Mutlutürk, M. Determining the amount of marketable blocks of dimensional stone before actual extraction. *J. Min. Sci.* **2007**, *43*, 67–72, doi:10.1007/s10913-007-0008-4.
44. Umili, G.; Ferrero, A.; Einstein, H.H. A new method for automatic discontinuity traces sampling on rock mass 3D model. *Comput. Geosci.* **2013**, *51*, 182–192, doi:10.1016/j.cageo.2012.07.026.
45. Li, X.; Chen, J.; Zhu, H. A new method for automated discontinuity trace mapping on rock mass 3D surface model. *Comput. Geosci.* **2016**, *89*, 118–131, doi:10.1016/j.cageo.2015.12.010.
46. Cao, T.; Xiao, A.; Wu, L.; Mao, L. Automatic fracture detection based on Terrestrial Laser Scanning data: A new method and case study. *Comput. Geosci.* **2017**, *106*, 209–216, doi:10.1016/j.cageo.2017.04.003.
47. Ehlen, J. Fractal analysis of joint patterns in granite. *Int. J. Rock Mech. Min. Sci.* **2000**, *37*, 909–922, doi:10.1016/S1365-1609(00)00027-7.
48. Rafiee, A.; Vinches, M. Application of geostatistical characteristics of rock mass fracture systems in 3D model generation. *Int. J. Rock Mech. Min. Sci.* **2008**, *45*, 644–652, doi:10.1016/j.ijrmms.2007.09.009.
49. Taboada, J.; Vaamonde, A.; Saavedra, A.; Alejano, L. Application of geostatistical techniques to exploitation planning in slate quarries. *Eng. Geol.* **1997**, *47*, 269–277, doi:10.1016/S0013-7952(97)00024-0.
50. Bastante, F.G.; Taboada, J.; Ordónez, C. Design and planning for slate mining using optimisation algorithms. *Eng. Geol.* **2004**, *73*, 93–103, doi:10.1016/j.enggeo.2003.12.002.
51. Sohrabian, B.; Ozcelik, Y. Determination of exploitable blocks in an andesite quarry using independent component kriging. *Int. J. Rock Mech. Min. Sci.* **2012**, *55*, 71–79, doi:10.1016/j.ijrmms.2012.06.009.
52. Fernández-de Arriba, M.; Díaz-Fernández, M.E.; González-Nicieza, C.; Álvarez-Fernández, M.I.; Álvarez-Vigil, A.E. A computational algorithm for rock cutting optimisation from primary blocks. *Comput. Geotech.* **2013**, *50*, 29–40, doi:10.1016/j.compgeo.2012.11.010.
53. Riquelme, A.J.; Abellán, A.; Tomás, R.; Jaboyedoff, M. A new approach for semi-automatic rock mass joints recognition from 3D point clouds. *Comput. Geosci.* **2014**, *68*, 38–52, doi:10.1016/j.cageo.2014.03.014.
54. Vagnon, F.; Bonetto, S.M.R.; Ferrero, A.M.; Migliazza, M.R.; Umili, G. Rock-Engineering Design and NTC2018: Some Open Questions. In *Lecture Notes in Civil Engineering*; 2020; Vol. 40, pp. 519–528.
55. Umili, G.; Bonetto, S.M.R.; Mosca, P.; Vagnon, F.; Ferrero, A.M. In situ block size distribution aimed at the choice of the design block for rockfall barriers design: A case study along gardesana road. *Geosci.* **2020**, *10*, 1–21, doi:10.3390/geosciences10060223.
56. Bonetto, S.; Facello, A.; Ferrero, A.M.; Umili, G. A tool for semi-automatic linear feature detection based on DTM. *Comput. Geosci.* **2015**, *75*, 1–12, doi:10.1016/j.cageo.2014.10.005.
57. Coli, M.; Pini, G.; Piccibi, L.; et al. Studi Conoscitivi sui Bacini Marmiferi Industriali di Carrara: Un Contributo per la gestione Pianificata dell'Attività. *GEAM, Georisorse e Ambiente* **2002**, XXXIX n.4.
58. Lovera, E. Razionalizzazione e sviluppo di attività estrattive per pietre ornamentali. PhD Thesis, Politecnico di Torino, 2001.

59. Tantussi, G.; Lanzetta, M.; Romoli, V. Diamond Wire Cutting of Marble: state of the Art, Modeling and Experiments with a New Testing Machine. In Proceedings of the 6th Int. Conf. Italian Assoc. Mech. Tech., Ed. L. Carrino, Gaeta (LT), Italy, Sep. 8-10, 2003, 113-126.
60. Auletta, N. Caratterizzazione di laboratorio mirata all'analisi delle prestazioni di fili diamantati per il taglio di materiali carbonatici. MSc. Thesis, Politecnico di Torino, 2019.
61. Tantussi, G. Studio del comportamento del filo diamantato a seguito di rottura. In Atti del Dipartimento di Ingegneria Meccanica, Nucleare e della Produzione, Università di Pisa, 2008.
62. Fresia, P. Valutazione delle prestazioni di tagliatrici a filo diamantato mediante analisi sperimentali in cave di marmo. MSc. Thesis, Politecnico di Torino, 2019.
63. UNI EN 15163. Machines and installations for the exploitation and processing of natural stone - Safety - Requirements for diamond wire saws. 2017.
64. Weydt, L.M.; Bär, K.; Colombero, C.; Comina, C.; Deb, P.; Lepillier, B.; Mandrone, G.; Milsch, H.; Rochelle, C.A.; Vagnon, F.; et al. Outcrop analogue study to determine reservoir properties of the Los Humeros and Acoculco geothermal fields, Mexico. *Adv. Geosci.* **2018**, *45*, 281–287, doi:10.5194/adgeo-45-281-2018.
65. Eurostat Packaging waste statistics. *Eurostat* **2013**, 17.
66. European Commission. Communication from the Commission EUROPE 2020: A strategy for smart, sustainable and inclusive growth. *Com(2010) 2020*, **2010**.
67. European Commission. Communication from the Commission: Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development. *Com(2001)*, **2001**.
68. European Commission. Communication from the Commission to the council and the European parliament draft declaration on guiding principles for sustainable development. *Com(2005)*, **2005**.
69. Dino, G.A.; Rossetti, P.; Biglia, G.; Sapino, M.L.; Di Mauro, F.; Särkkä, H.; Coulon, F.; Gomes, D.; Parejo-Bravo, L.; Aranda, P.Z.; Lopez, A.L.; Lopez, J.; Garamvolgy, E.; Stojanovic, S.; Pizza, A.; de la Feld, M. Smart ground project: A new approach to data accessibility and collection for raw materials and secondary raw materials in Europe. *Environmental Engineering and Management Journal*, **2017**, 16 (8), 1673-1684.
70. André, A.; De Brito, J.; Rosa, A.; Pedro, D. Durability performance of concrete incorporating coarse aggregates from marble industry waste. *J. Clean. Prod.* **2014**, *65*, 389–396, doi:10.1016/j.jclepro.2013.09.037.
71. Careddu, N.; Siotto, G.; Siotto, R.; Tilocca, C. From landfill to water, land and life: The creation of the Centre for stone materials aimed at secondary processing. *Resour. Policy* **2013**, *38*, 258–265, doi:10.1016/j.resourpol.2013.05.001.
72. Felekoglu, B. Utilisation of high volumes of limestone quarry wastes in concrete industry (self-compacting concrete case). *Resour. Conserv. Recycl.* **2007**, *51*, 770–791, doi:10.1016/j.resconrec.2006.12.004.
73. Gencel, O.; Ozel, C.; Koksal, F.; Erdogmus, E.; Martínez-Barrera, G.; Brostow, W. Properties of concrete paving blocks made with waste marble. *J. Clean. Prod.* **2012**, *21*, 62–70, doi:10.1016/j.jclepro.2011.08.023.
74. Galetakis, M.; Alevizos, G.; Leventakis, K. Evaluation of fine limestone quarry by-products, for the production of building elements - An experimental approach. *Constr. Build. Mater.* **2012**, *26*, 122–130, doi:10.1016/j.conbuildmat.2011.05.011.
75. Luodes, H.; Kauppila, P.M.; Luodes, N.; Aatos, S.; Kallioinen, J.; Luukkanen, S.; Aalto, J. Characteristics and the environmental acceptability of the natural stone quarrying waste rocks. *Bull. Eng. Geol. Environ.* **2012**, *71*, 257–261, doi:10.1007/s10064-011-0398-z.
76. Careddu, N.; Marras, G.; Siotto, G. Recovery of sawdust resulting from marble processing plants for future uses in high value-added products. *J. Clean. Prod.* **2014**, *84*, 533–539, doi:10.1016/j.jclepro.2013.11.062.
77. Marras, G.; Careddu, N.; Internicola, C.; Siotto, G. Recovery and Reuse of Marble Powder By-Product. *Glob. Stone Congr.* **2010**, 1–5.
78. Dino, G.A.; Passarella, I.; Ajmone-Marsan, F. Quarry rehabilitation employing treated residual sludge from dimension stone working plant. *Environ. Earth Sci.* **2015**, *73*, 7157–7164, doi:10.1007/s12665-014-3895-0.
79. Dino, G.A.; Rossetti, P.; Perotti, L.; Alberto, W.; Sarkka, H.; Coulon, F.; Wagland, S.; Griffiths, Z.; Rodeghiero, F. Landfill mining from extractive waste facilities: The importance of a correct site

 doi:10.20944/preprints202010.0642.v1

characterisation and evaluation of the potentialities. A case study from Italy. *Resour. Policy* **2018**, *59*, 50–61, doi:10.1016/j.resourpol.2018.04.012.
80. Dino, G.A.; Mehta, N.; Rossetti, P.; Ajmone-Marsan, F.; De Luca, D.A. Sustainable approach towards extractive waste management: Two case studies from Italy. *Resour. Policy* **2018**, *59*, 33–43, doi:10.1016/j.resourpol.2018.07.009.
81. Prescott, P.I.; Pruett, R.J. Graund Calcium carbonate: ore mineralogy, processing and markets. *Mining Engineering*, **1996**, 48(6), 79-84.