materials proceedings

Proceeding Paper

Ornamental Stone Cutting Processing and Sludge Production Evaluation with the Goal of Ending Waste †

Lorena Zichella *, Rossana Bellopede and Paola Marini

Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy; rossana.bellopede@polito.it (R.B.); paola.marini@polito.it (P.M.)
* Correspondence: lorena.zichella@polito.it
† Presented at International Conference on Raw Materials and Circular Economy, Athens, Greece, 5–9 September 2021.

Abstract: In the quarry sector, the reduction of landfill material may be obtained not only by finding a suitable recovery of the material as a by-product, but also by identifying the best available cutting technique to be used on the basis of the physical, chemical, and mechanical characteristics of the stones. The choice of the best cutting technique could lead to high efficiency and performance, high quality of the cut surfaces, and a very low environmental impact by reducing energy consumption, decreasing the concentration of heavy metals in the sludge, and producing less waste. In this context, an analysis of the procedures for cutting different types of ornamental stones into slabs together with the evaluation of sludge production for the different cutting methods has been carried out. Two types of analysis were carried out in parallel: evaluation of the stones workability and calculation of the amount of sludge produced in the three different cutting technologies and from the cutting of blocks. A comparison was carried out on the quality of the sludge produced, on type and quantity of metals present, taking into account the different cutting technologies. The performed tests were: chemical analysis, magnetic separation test, and SEM analysis of the metal fraction. The study could provide stone producers with a technological, scientific instrument to identify the best cutting techniques for the processing of their stones, in order to obtain a high-efficiency process, optimize the recovery process, increase the economic advantages, and evaluate the possible reuse of the sludge through a proactive waste management strategy.

Keywords: waste management; end-of-waste policy; sludge characterization; best available technique; ultrasonic pulse velocity; magnetic separation

Citation: Zichella, L.; Bellopede, R.; Marini, P. Ornamental Stone Cutting Processing and Sludge Production Evaluation with the Goal of Ending Waste. *Mater. Proc.* **2021**, *5*, 57. https://doi.org/10.3390/materproc2021005057

Academic Editor: Evangelos Tzamos

Published: 7 December 2021

1. Introduction

The stone industry is seeing continuous innovative development moving towards sustainability and security. The goal, in accordance with European Union strategies, is to promote the circular economy by increasing the ability to carry out production within the European countries' own territories by combining resources efficiently [1]. The tools for the sustainable development of mining activity are good management of production processes and reduction of processing waste. Waste produced by industrial processes during the cutting phase of ornamental stone, such as sludge and powders, constitutes a large quantity of material that—if properly treated—could be recycled and transformed into a secondary raw material in order to produce highly innovative opportunities for companies.

The European Directive 2008/98/EC [2] provides definitions of waste, waste management, recycling, and recovery. Moreover, it provides guidelines to distinguish between waste and by-products, explaining how waste ceases to be waste and becomes a secondary raw material when it has undergone a recovery and recycling process and meets specific criteria (Art. 6 (1) and (2) of the Waste Framework Directive 2008/98/EC end-of-waste criteria).

The mining sector's main aim is to avoid the disposal of the huge amount of waste resulting from stone cutting processes, in accordance with the International EU Conference on mining policy and technologies [3]. At present, most companies send sludge to landfill which leads to higher costs for transport and disposal. The treatment and recovery of these wastes is not yet considered either due to unclear legislation or local authorities' prohibitions. However, the recovery of such material would constitute an economic and environmental advantage.

The Italian stone industry, including the extraction and processing of natural stone, comprises 10,373 companies, of which 9313 deal only with natural stone processing [1]. In Piedmont (Italy north region), 97% of ornamental stones are processed in the districts of Cuneo (CN), Torino (TO), and Verbania (VB).

The amount of sludge produced by the processing of ornamental stones is very high. The plants processing and extracting ornamental stones produce processing waste. The average tons value of stone extracted in Piedmont in the last 5 years amounts to 1009 tons, and the relative sludge production amounts to 37,000 tons. Sixty percent of the sludge production is registered in the province of Verbania (VB).

2. Materials and Methods

The materials considered in this research came from the Piedmont Region, in particular from the districts of Verbania, Cuneo, and Torino (Italy).

The four stones studied are all silicate stones: gneiss and granite with different mineralogical, textural structure. Table 1 shows the main mineralogical composition of the stones.

Table 1. List of the stones studied with their trade names and mineralogical composition.

Trade Name of the Stone	Mineralogical Composition
Luserna Stone	Quartz: 50%; Plagioclase:15%; Alkaline Feldspar: 20%; White mica: 5%; Chlorite: 5%; Epidote: 5%.
White Beola	Quartz: 30%; Plagioclase:15%Alkaline Feldspar: 34%; Biotite: 5%; Muscovite:14%; Accessory: 2%.
Serizzo Antigorio	Quartz: 30%; Plagioclase:25%Ortoclase: 26%; Biotite: 10%; Muscovite: 5%; Epidote: 3%; Accessory: 1%.
Montorfano Granite	Quartz: 40%; Plagioclase:20%Orthoclase:35%Biotite: 5%.

2.1. Stone Characterization

The workability of a rock is closely linked to its structural and textural characteristics and to its mineralogical composition. In 2011, Ozcelik and Yilmazkaya [4] stated that cutting strength decreases with the increase of anisotropy. Korre and Durucan [5] found experimentally that, with the same mineralogical characteristics, foliation plays a fundamental role in the cutting of blocks in slabs. The wear of the diamond tools on isotropic quartz granites is the same in the two cutting orientations, while it varies greatly in the case of gneiss with foliation. Therefore, the texture of the stone is an important factor to consider in the choice of cutting technology. Exploiting the orientation of weakness planes reduces the wear of the cutting tools.

The quality of the cut, and therefore of the slab produced, is an important factor for choosing the best technology to be used in accordance with the type of stone to be cut. In the study of Bellopede et al. [6], a good correlation was found between the ultrasonic pulse velocity (UPV) and the Knoop value which refers to the hardest minerals (HK25). The UPV test highlights the mechanical and physical characteristics of a stone, while the Knoop test considers the micro-hardness of a surface, two characteristics closely related to the workability of a stone.

In order to understand and optimize the cutting technology, it is important to analyze the physical and mechanical characteristics of the stones tested as well as their mineralogical content. All the tests were carried out in accordance with the EN European standards. Table 2 shows the tests carried out with the number of specimens analyzed and the relevant reference standards.

Table 2. Tests carried out with number of specimens for each stone tested and the relative reference standards.

TESTS Carried Out	No. Specimens Tested	Standard References
Compressive strength	10	EN1926:2006
Flexural strength	10	EN 12372:2006
Apparent density	6	EN 1936:2006
Water absorption	6	EN 13755:2008
Knoop microhardness	1*	EN 14205:2004
UPV—Ultrasonic pulse velocity	3*	EN 14579:2004

2.2. Sludge Production Quantification and Characterization

The production of sludge during cutting with different technologies is a function of the thickness of the slabs and of the diamond tools used. Taking into account a block dimension of 1.5 × 2 × 3 m (9 m^3 of block), a specific weight material of 2.7 t/m^3, and considering a slab thickness of 3 cm, the percentage of lost material (sludge) and the number of slabs produced was calculated. The calculation of the cutting width for the gangsaw technology, diamond wire, and diamond blade technologies are based on formulas proposed by Mannella P. [7].

The characterization of sludge, deriving from the cutting of blocks in slabs, is important in order to understand if the cutting method used is efficient, and to understand which treatment is most suitable or necessary to obtain by-products that are re-usable in other processes. Many issues are associated with sawing sludge, which until now has been considered a waste and not a resource. The recovery of this material brings both environmental and economic advantages, as indicated by the International EU Conference on mining policy and technologies. However, unclear national legislation and local authorities do not consider that a simple eco-compatible treatment can turn a waste into a by-product. There are currently many research studies carried out in this field [8–11], but the production of guidelines for the correct recovery of this material is still in progress.

The analyses were carried out on two types of sludge (one specimens for type of sludge), 10 kg each sludge, deriving from two plants: M1 and G1. Table 3 shows the cutting methods used and the stones cut for the different plants.

Table 3. Cutting technologies and type of stones cut in two different plants.

Plants Code	Cutting Technologies	Stones Cut
M1	Frame saw	Serizzo Antigorio
G1	diamond blade—diamond wire	Serizzo Antigorio—Luserna Stone—White Beola—Montorfano Granite

The analyses performed are as follows:

- Particle size distribution, in wet conditions on 1 kg of specimens, using five sieves (0.038 mm, 0.075 mm, 0.106 mm, 0.212 mm, 0.425 mm), in order to obtain six size classes.
- Specific gravity, using the Le Chatelier Flask, suitable for very fine material. The body holds about 250 mL and the bulb in the neck holds 17 mL. Graduations are 0–17 mL below the bulb and 18–24 mL above.
- Chemical analysis, (according to Italian Ministerial Decree 186/2006).
- Magnetic separation in a dry condition, on 5 kg of specimens, in order to separate the metallic fraction with magnetic characteristics from the mineral fraction of the sludge. A simple magnet with magnetic induction of 83 mT was used for this purpose.
- Scanning electron microscope (SEM), for a quality evaluation of the metal content in the different granulometric classes. Analysis performed using a QUANTA INSPECT 200 LV FEI device with ECAX GENESIS energy dispersive X-ray spectroscopy (EDS), and a SUTW detector.

3. Results and Discussion

3.1. Stones' Characterization Results

From Table 4, flexural strength—perpendicular to foliation plane—of Luserna and White Beola is higher than that for the Montorfano granite, due to its isotropic fabric. Among the gneiss, Serizzo Antigorio shows a lower value of flexural strength, probably due to the higher dimension of the grain. The compressive strength is indirectly correlated to the workability classes and to the apparent bulk density; in fact, at high compression, values correspond to low porosity values, measures indirectly by means WA, and low UPV values. According to a study by Almasi et al. [8], the wear of the cutting tools and the production rate is correlated with the compressive strength of the materials; in abrasive stone, the bead wear rate is very high for low production rates.

Table 4. Mechanical characteristics of the rocks tested. The values indicated are average of the values obtained for each sample.

Stone Tradename	Compressive Strength (MPa)	Flexural Strength (MPa)	Apparent Density (kg/m^3)	Water Absorption (%)	UPV 33 (kHz)	Knoop Hardness (HK25) (kgf/mm^2)	Workability Class
Luserna Stone	162.4	21.7	2690	0.31	2154	4358	3
White Beola	192	21	2550	0.34	2321	3521	3
Serizzo Antigorio	141	16	2730	0.36	2295	5093	4
Montorfano Granite	229	14	2570	0.31	1752	2789	2

The mineralogical and petrographic characteristics, the texture, and the fabric of the four considered stones are important aspects in the workability classification. Three of the studied rocks are schistose metamorphic rock; the only rock that does not show evident foliations is the Montorfano Granite. According to previous studies [12–14], the petrographic aspect that most influences the workability of the rocks is the percentage of quartz.

3.2. Sludge Quantification and Characterization Results

Considering a block weight of 24.3 t, 11.2 t of sludge produced has been estimated (using a grit diameter of 0.4 mm) and 11.74 t of sludge (using a grit diameter of 0.8 mm) for the frame saw, 11.93 t of sludge for the diamond wire against 13.54 t of sludge for the diamond blade.

The particle size distribution shows that all the samples are similar to a silt-clay (very fine particle). In Table 5, the percentage of fine particles <0.075 mm and the specific gravity of the two sludges considered are specified.

Table 5. Specific gravity and percentage of finer particles for the two sludge.

Plants Code	Finer Particle < 0.075 (%)	Specific Gravity (g/cm^3)
M1	95.5	2.67
G1	88.08	2.74

M1 plant processes its stone with frame saw technology and its sludge show high concentration of Cr, Ni, and Cu. G1 plant processes its stone with diamond technologies, with tools composed by Co, for this reason the sludge shows high concentration level of Co. Therefore, the results show that the sludge as analyzed would be disposed of in landfills. To avoid this option, it is necessary to proceed through an evaluation of the correct cutting methodologies used based on rock workability.

The quantification results on metal concentration, performed by means of magnetic separation, shown a high value of magnetic fraction for the gangsaw technology (3%), respect a value of 0.9% for the diamond technologies. This difference in percentage between the cutting technologies is due to the type of tools used (made of more resistant metal alloys) and on the presence of metal grit.

In all the distribution size classes in the magnetic fraction, the presence of some minerals, such as Biotite, is found. Biotite is paramagnetic and is captured by magnetic metals. The presence of other minerals like plagioclase is due to the very fine particles of the sludge, which creates the problem of packaging.

4. Conclusions

The choice of the best cutting technology should be made considering the type of stone to be treated. The scientific classification of workability and the sludge characterization could be the proper instruments to identify the best cutting technique. From a comparison between the two cutting technologies, on the basis of this research the following considerations can be made:

- Frame saw technology produces: a higher percentage of metals concentration, present above all in the finer particle size classes;
- Diamond wire and diamond blade produce a lower percentage of metals, present in the particle size classes between 0.212 mm and 0.075 mm.

The following remarks can be made:

- Frame saw cutting is safer as regards the linearity of the slabs produced, but produces sludge with higher metal concentration due to the presence of metallic grit.
- Diamond wire produces approximately the same number of slabs as the frame saw with the same block dimension, but the slabs produced have a smoother surface; however, it produces a quantity of sludge similar to that of the frame saw but with lower metals concentration.
- Diamond blade produces smoother slabs, but presents greater problems of linearity, especially in the case of very hard rocks. It produces more sludge than the other technologies.

The technology with diamond wire seems to be the best, both for slabs productivity and for the low percentage of metals in the sludge that can be recycled as it is. Instead, the sludge produced with the frame saw technology has high percentages of Cr, Ni, and Cu, requiring magnetic separation before its reuse.

The magnetic separation could be part of the 'normal industrial practice', indicated by the legislation, as it does not change the status of the waste, but simply makes a separation. In this way it is possible to obtain two fractions that can be recovered separately. The magnetic fraction includes metals covered by the European Union CRM (Critical Raw Material), so their recovery is essential. For example, taking into account the M1 sludge sample obtained from frame saw cutting, the quantities involved are: of 1800 t of sludge produced in a year, 3% is composed of CRM, corresponding to 54 t a year for only one plant. Taking into account that, in Piedmont alone in the year 2015, there were 29,149 t of stone sludge produced, making the average percentage of metals present 2%, a total of 583 t of CRM metals could be recovered, instead of going to special landfills.

Institutional Review Board Statement: Not applicable, this studies not involves humans or animals.

Informed Consent Statement: Not applicable, this studies not involves humans.

Data Availability Statement: Data sharing not applicable. No new data were created or analyzed in this study.

References

1. Gussoni, M. Stone Sector 2017 Trade and Innovation. Internazionale Marmi e Macchine Carrara S.p.a. 2017. Available online: www.immcarrara.com (accessed on 7 May 2020).
2. Waste Framework Directive 2008/98/EC End-of-Waste Criteria. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098 (accessed on 7 May 2021).

3. European Commission. EU-Advanced Mining Countries RMD Event 2016—Exchange of Best Practices on Mining Policies and Technologies: Challenges in the Current State of the Global Economy. In Proceedings of the 2016 International Conference, Brussels, Belgium, 28–29 June 2016. Specific contract No. 30-CE-0741611/00-19-SI2.715908.
4. Ozcelik, Y.; Yilmazkaya, E. The effect of the rock anisotropy on the efficiency of diamond wire cutting machines. *Int. J. Rock Mech. Min. Sci.* **2011**, *48*, 626–636. [CrossRef]
5. Korre, A.; Durucan, S. The effects of granite microstructure on the sawing performance of diamond wires. *Int. J. Surf. Mining Reclam. Environ.* **2000**, *14*, 87–102. [CrossRef]
6. Bellopede, R.; Marini, P.; Tori, A.; Zichella, L. Proposal of a new methodology for stone classification in diamond wire cutting technology (EASE-R3). In *DIAMANTE*; G&M Associated Sas Milan: Milan, Italy, 2014; Volume 79, pp. 19–26. ISSN 1824-5765.
7. Mannella, P.; Estratto Lame. Estratto Lame. Blades, 1–26. Marmilame S.r.l. 2012. Available online: https://ecitydoc.com/queue/la-lama-che-taglia-il-blocco-in-lastre-e-la-cosa-che-piu_pdf?queue_id=-1 (accessed on 7 May 2020).
8. Almasi, S.N.; Bagherpour, R.; Mikaeil, R.; Ozcelik, Y. Analysis of bead wear in diamond wire sawing considering the rock properties and production rate. *Bull. Int. Assoc. Eng. Geol.* **2017**, *76*, 1593–1607. [CrossRef]
9. 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*, 1–9. [CrossRef]
10. Gencel, O.; Ozel, C.; Koksal, F.; Erdogmus, E.; Martinez-Barrera, G.; Brostow, W. Properties of concrete paving blocks made with waste marble. *J. Clean. Prod.* **2012**, *21*, 62–70. [CrossRef]
11. 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. Int. Assoc. Eng. Geol.* **2012**, *71*, 257–261. [CrossRef]
12. Amaral, P.; Cruz Fernandes, J.; Frisa, A.; Guerra Rosa, J.; Manfredotti, L.; Marini, P. Evaluation of the workability by means of diamond tools of a series of Portuguese commercial granites. In Proceedings of the Convegno su "Le cave di Pietre Ornamentali", Torino, Italy, 28–29 November 2000; pp. 323–329.
13. Aydin, G.; Karakurt, I.; Aydiner, K. Wear Performance of Saw Blades in Processing of Granitic Rocks and Development of Models for Wear Estimation. *Rock Mech. Rock Eng.* **2013**, *46*, 1559–1575. [CrossRef]
14. Zichella, L.; Bellopede, R.; Marini, P.; Tori, A.; Stocco, A. Diamond wire cutting: A methodology to evaluate stone workability. *Mater. Manuf. Process.* **2016**, *32*, 1–7. [CrossRef]