Design New Products with Natural Stone Waste

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Abstract

Major events in the history of human civilization are often labelled with terms such as Stone Age, Iron Age, Bronze Age, Industrial Revolution, or Information Age. Today, the new era of Re-use, Reduce and Recycling has already started. Those events, so remarkable for the human being, have a common characteristic: the discovery, extraction, processing and use of natural materials from the Earth, many of them giving name to its era. The extractive industry plays a crucial role in the current development of our society, providing key raw materials for the industry. However, the negative impact associated with this activity is evident. The growing demand for non- renewable resources, because of the continuous growth of the world's population, makes it urgent to look for other alternatives, to guarantee the sustainability of the planet. Knowing that the mining industry and particularly in natural stone quarries, the percentage of unused stone material (waste) can reach 70% of the total volume of extracted stone, laying down that new uses for the waste materials is a priority which promotes the new paradigm of circular economy and sustainable development. This work explores the possibility of reuse waste generated by the stone extraction industry, through the production of composite materials formulated with stone particles of different grain size joined together by an epoxy resin. The stones used in this study were obtained from the residues from two quarries of natural stone, a marble quarry located in the south of Portugal and a schist quarry in the north of Portugal. The physical-mechanical properties of the stones used were already known and are published in the Catalogue of Portuguese Ornamental Stones. Subsequently, the physical-mechanical properties of the original rocks were compared with those determined in the produced samples. The manufacture of samples made it possible to evaluate the behaviour of the components of the mixture from the aesthetical point of view, but also in terms of their main features, through testing; the physical and mechanical properties were determined. The results led us to conclude that the composite with the most promising properties does not present enough mechanical resistance for structural applications, like some ornamental rocks do; however, it represents a great opportunity to design decorative artefacts for different industrial sectors. Considering the results obtained, a lamp and a decorative panel were designed and manufactured using shale and marble, taking advantage of the observed contrast between dark and opaque shale grains with translucent and light grains of marble.

Keywords: Waste, Natural Stone, Composite, Design, Epoxy Resin

 ISBN: 978-84-09-16892-7

1.Introduction

Considering the occurrence location of a mineral resource (beneath the ground surface or in deep underground) and its length, in depth, it can be mined with one (or both) of these two mining techniques: underground mining (mines) and open pit mining (quarries). In this simplistic perspective, a quarry is usually an open pit excavation where the extraction focus is the stone itself; it can be removed in the form of single blocks, gravel or sand, depending on the occurrence type and the end use (Schrenk, 2016).

The production and waste amount from the mining activity depends on many factors, including: the nature of the resource, the technological development of mining, the environmental concerns, etc.. For example, in Australia, solid waste from the mining industry makes up 80% of all solid waste generated by that country. per year (Boger, 1998). In South Africa this figure is 72.3% (Maboeta and van Rensburg, 2003) and in China is 70% (Liao et al., 2007). In the case of natural stone quarries, the volume of natural stone waste can reach 75% of the total mined volume. The different heterogeneities in rocky massifs (lithological, chromatic, textural, physical-mechanical, etc.) generate large amount stone fragments and blocks that do not meet the market requirements. The extraction process and subsequent treatments also contribute to an increase in the amount of waste produced (University of Tennessee, 2011).

The vast majority of existing products and that exist nowadays depend upon the raw materials provided by the extractive industries. Common everyday objects such as mobile phones, televisions and computers are made up of dozens of different minerals (Larsen et al., 2018). Although these industries have contributed to humankind evolution, the amount of waste generated in their production is a serious environmental threat to the future of our planet (K-Jr et al., 2016).

Waste causes economic problems (spoilage without economic recovery) and its ongoing deposition in the soil may lead to potential environmental troubles (soil and underground water contaminations due to the presence of polluting chemical elements in the stones). The need to remove the topsoil to reach the mineral resources can sometimes cause changes on landscape and natural vegetation, affecting their aesthetic value, constraining local agriculture and creating limitations on local populations (Castro et al., 2012). Even after rehabilitation of the mined areas, local fauna and floras sometimes experience recovery delays which are aggravated by the natural erosion processes both by the wind and rain, causing a greater impact of the problems above mentioned (Zoran et al., 2010).

Through a design-centric approach, the practical use of waste generated by the mining industry in the manufacture of new products can help to reduce their amount. In this way, the mined and unused mineral resources can be valued by the companies, thus contributing not only to a better economic use of the resources, but also to the reduction of the environmental impact of this industrial waste.

1.1 Reutilization of waste

The classic mining activity can be subdivided into several steps: mining – extraction of any underground mineral resource; mineral processing – physical and / or chemical separation of the ore from the rock that surrounds it; mining-metallurgical extraction – involves fusion of the ore leaving as residue the surrounding rock. Any of the mentioned processes (mining, separation and/or extraction and concentration), or even the removal of the topsoil, always involves the production of waste (Lottermoser, 2010; Dhar and Thakur, 1996).

Natural stone mining begins with the extraction of stone blocks using a variety of equipment and technology, such as diamond wire or sawing machines, which cut this natural resource cleanly and consistently. Usually, a large volume block is first dismantled from the rock massif. It is then cut into smaller blocks (up to 24 tons) to enable loading and transport with a loader to the truck and finally transported to the processing plant. Some quarries are located in remote areas, far from the processing plants; transportation on roads, which sometimes present degraded pavement (due to the permanent circulation of trucks with heavy loads of natural stone) can be an additional problem when using this natural resource. In the processing plant, the blocks are first cut into rough slabs, with the intended thickness. The seen face and the rear face are then treated to give them the desired surface finish. Lastly, the rough slabs are cut to the required plane dimensions for the final product (Bedrosians, 2017) (Figure 1).

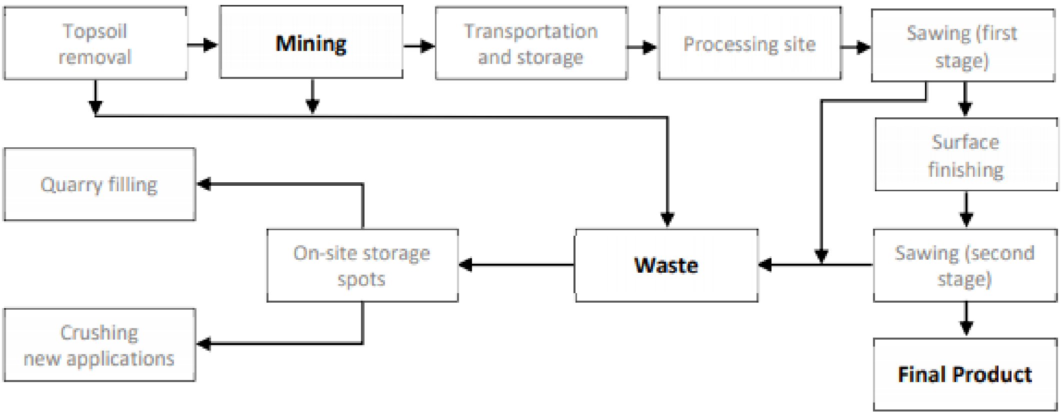

Figure 1. *Diagram of the natural stone mining process, adapted from (*University of Tennessee, 2008).

Besides the adoption of management and planning strategies for mines and mining sites, aiming at waste reduction, the introduction of this waste into the production and manufacture of conventional products (well-defined markets) is already a reality. For instance, the mortar used for the production of some concrete types, in addition to the aggregates, it also includes slag resulting from the smelting of metal ores. This slag is also employed in asphalt and in rock wool used for thermal and acoustic insulation.

There are still other productions where waste from mining rocky massifs is used, such as the production of engineered stone. This manufacture involves moulding a mixture of natural stone waste with mortar, or with epoxy resin, resulting in products with texture similar to some natural stones (Ukcsa, 2017). There are also examples of cut-to-size products for vanity and kitchens and bathrooms tops and products for exterior draining pavements (Figure 2). Natural stone waste is also being used for the production of 3D printing filaments, together with resins, as binder (Cosentino, 2017; TH-PAV, 2016; Saunders, 2017). In all of the above examples, natural stone residues have to undergo a pre-comminution operation to reduce their particle size to the desired calibre.

 ISBN: 978-84-09-16892-7

The obtained aggregates (or powders) are then mixed with different types of binders, which harden and give form to the mixture after moulding.

Figure 2. *Examples of the production of a draining pavement Marmo Drain (left) (TH-PAV, 2016) and a fountain made of engineered stone (right) (Ukcsa, 2017).*

These examples demonstrate that there is a great opportunity for the use of quarry waste.

2.Methods

Experimental work has arisen from the interest of finding a way to utilize an extremely abundant waste, resulting from mining a natural resource, whose is scarcely economically valued. Next, it is described the process of obtaining an engineered stone composite material, consisting of a low particle size stone aggregate which was mixed with a resin, as binder. Samples consisting of test specimens were fabricated and used to carry out the physical and mechanical characterization of the composite.

Although the specimens' mechanical properties depend, in part, on the lithology and original characteristics of the used stone, when the particle size is reduced to 2 mm or less and a binder is added, the resulting engineered stone has its own properties, dependent on that mixture. At this stage, the lithology of the stones used will have a major influence on aspects such as the colour and texture of the engineered stone, which are important aspects to explore in order to bring design value to the project.

A low viscosity epoxy resin was used as a binder, Biresin CR83, with a mass ratio of 100 to 30 of the respective catalyst (Biresin CR83-6). It was intended to maximize the percentage of waste used, however its increase led to greater difficulty in processing the mixing and aggregation of the composite. The amounts of resin used varied according to what was intended to be tested with each sample produced. It was laid down a processability range between 5% and 15% of the total mass of each sample.

Residues of granite, marble, schist, limestone and slate (black schist) were selected. The residues were mixed with the resin in a plastic container with a metal rod until a homogeneous mixture was obtained. After this phase, silicone moulds of adequate size were cast for the manufacture of samples and specimens. Demoulding occurred after 24h of hardening. Figure 3 shows the steps described.
In a first phase, still without scientific rigor, it was intended to master the processing technique of these materials.

This step made it possible to specify the appropriate quantities of the different materials and to understand the relevance of particle size in composite manufacturing.

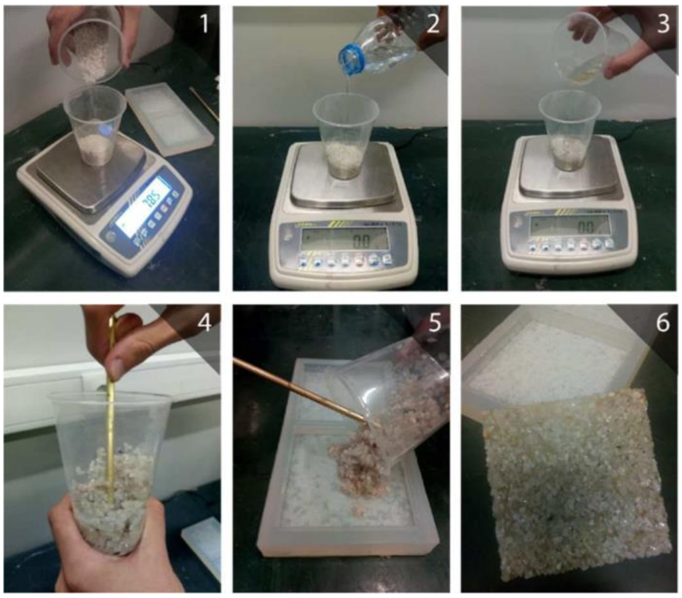

Figure 3. *Samples and specimens manufacturing process steps; 1) waste weighing, 2) resin weighing, 3) catalyst addition, 4) mixing, 5) silicone mould pour, 6) obtained sample.*

The acquired knowledge in the first phase allowed us to start a second phase of experimentation with quantified values and specimen's production, as indicated in Table 1. Particle size distribution was carried out through sieving, using sieves AS200 produced by Retsch (Germany).

Table 1. *Particle size distribution of the stone waste used to prepare the composites.*

	Granite (G)	Marble (M)	Schist (X)	Limestone powder (C)	Slate powder (A)
1st Stage Samples 1 to 12	Not determined	Not used	Not used	Not determined	Not determined
2nd Stage Samples 13 to 24	< 1.18 mm	< 1.18 mm; 1.18 - 2.36 mm; 3.36 - 4.76 mm	< 1.18 mm; 1.18 - 1.70 mm	Not determined	Not used
Specimens	Not used	0.84 - 2.38 mm	Not used	Not used	Not used

The test specimens were produced (Figure 4) in order to be tested according to the following standards: NP EN 14617-15_2010 - Determination of compressive strength;

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NP EN 14617-2_2010 - Determination of flexural strength (bending) (repealed);

NP EN 14617-1_2010 - Determination of apparent density and water absorption (repealed).

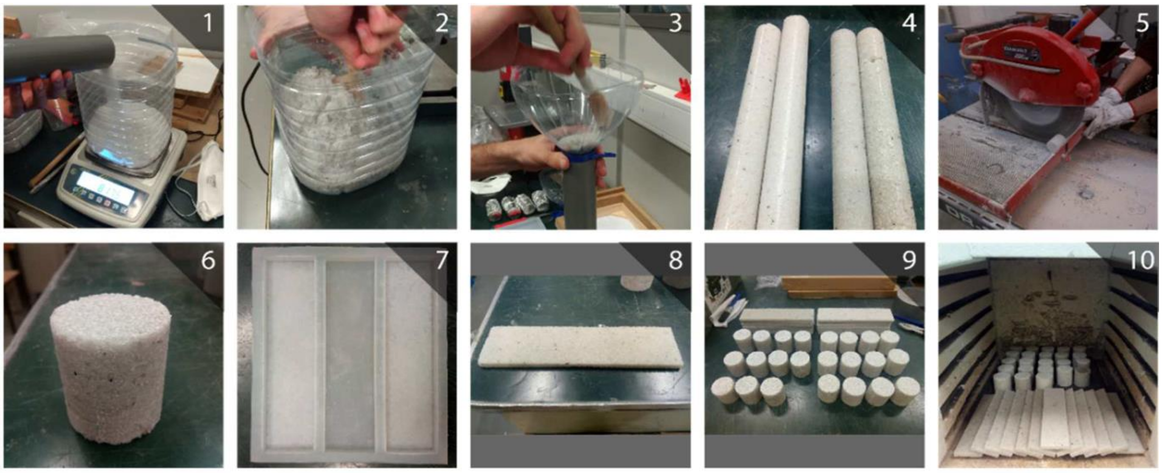

Figure 4. *Specimens manufacture; (1-3) mixture preparation and pouring into the PVC tubes, (4) obtaining the cylindrical composite rods, (5) cutting the specimens, (6) final cylindrical specimen, (7) plates shape specimens manufacture, (8) final plate shape specimen, (9) cylindrical specimens, e (10) drying in oven at 55ºC.*

Specimens of the same grain size were manufactured (0.84 – 2.38 mm), with minimum and maximum values in terms of resin quantity of 5% and 15%, respectively.

For the determination of compressive strength, apparent density and water absorption, European Standards state that specimens shall be 50 mm side cubes or cylinders with 50 mm of both diameter and height. Due to the fact that it is easy to produce cylindrical specimens, PVC tubes of sufficient length were used to obtain six specimens in each tube. Curing time of the composite was dynamic, that is, with a continuous rotation motion of the tubes in a roller drum, at 200 rpm for 24h.

For the flexural strength test, specimens (plate shaped) with the dimensions: 200 mm length, 50 mm wide and 10 mm thickness (this value varies depending on the final application) were manufactured using silicone moulds. After demoulding, the specimens were dried at 55ºC for 48h.

According to the normative procedures, the specimens should be dried at 70ºC for 48h. However, due to the possibility of degradation of resin properties at this temperature, drying was performed at 55° C, which is the post-cure temperature of the resin (Germanischer, 2014).

3.Results and Discussion

Table 2 presents the images of all samples obtained as well as the weight and percentage of resin and the different types of stones used. The codes used are: R (resin), G (granite), M (marble), A (slate powder), C (limestone powder), X (schist).

After performing the physical and mechanical tests on each set of 6 specimens (Figure 5), the properties presented in Table 3 for marble composites made with 5% and 15% of resin were determined. For comparative purposes and for the properties determined in the composites, the table also presents the mean values for Portuguese: sedimentary stones, metamorphic stones and igneous stones (Laboratório Nacional de Energia e Geologia, 2002).

Table 2. *Samples produced and main parameters (resin %, stone type and %, particle size distribution and weight).*

1 	15% R 85% G (60g)	13 	10% R 90% M M < 1.18 mm (100g)
2 	10% R 90% G (70g)	14 	10% R 90% M 1.18 < M < 2.36 mm (100g)
3 	15% R 85% A (70g)	15 	10% A 90% G G < 1.18 mm (100g)
4 	10% R 90% G (100g)	16 	5% R 95% G G < 1.18 mm (100g)
5 	20% R 80% A (100g)	17 	10% R 90% M 3.36 < M < 4.76 mm (100g)
6 	15% R 85% C (80g)	18 	5% R 95% X 1.18 < X < 1.70 mm (100g)
7 	10% R 90% G (100g)	19 	10% R 90% X 1.18 < X < 1.70 mm (50g) 10% R 90% M 1.18 < M < 2.36 mm (50g)

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8 	10% R 90% C (100g)	20 	7% R 93% C (50g) 7% R 93% M M < 1.18 mm (50g)
9 	15% R 85% A (80g)	21 	5% R / 95% M / M < 1.18 mm (25g) 5% R / 95% C (25g) 5% R / 95% G / G < 1.18 mm (25g) 5% R / 95% X / X < 1.18 mm (25g)
10 	15% R 42.5% G + 42.5% A (100g)	22 	5% R / 95% M / 3.36 < M < 4.76 mm (33.3g) 5% R / 95% M / 1.18 < M < 2.36 mm (33.3g) 5% R / 95% M / M < 1.18 mm (33.3g)
11 	15% R 42.5% G + 42.5% C (100g)	23 	10% R 90% M M < 1.18 mm (100g) Food colouring
12 	15% R 42.5% A + 42.5% C (80g)	24 	10% R 90% M M < 1.18 mm (100g) Food colouring

***Figure 5**. Tests carried out; (1) apparent density and water absorption, (2) flexural strength (bending) and (3) compressive strength.*

From the table analysis it can be concluded that any of the composites manufactured have both physical and mechanical properties less favourable to their application (lower: - apparent density, - flexural strength, - compressive strength; higher: - water absorption), than those presented by any of the natural stones lithologies. The 15% resin composite has better properties than the 5% resin composite. This finding was already expected, since the larger amount of low viscosity resin, that was used, contributed to a better filling of the voids left between the stone particles. This fact is corroborated when comparing the water absorption percentages:

specimens made with only 5% resin absorbed much more water.

Table 3. *Mean values (of apparent density, water absorption, flexural and compressive strengths rounded according with the respective European standards), for the marble composite manufacture. Comparison with bibliographic data [19] for sedimentary, metamorphic and igneous stones.*

	Composite 5%	**Composite 15%**	**Sedimentary stones**	**Metamorphic stones**	**Igneous stones**
Apparent density (kg/m^3)	1710	1990	2600	2720	2670
Water absorption (%)	13.9	0.1	1.3	0.1	0.3
Flexural strength (MPa)	3.8	15.4	16.8	23.2	17.7
Compressive strength (MPa)	10	43*	104	87	138

***** Mean value calculated only with results obtained in four specimens, due to problems with the remaining specimens.

The density of the resin — 1150 kg/m3 [18] — together with the pore content of the composite are responsible for its lower apparent density than natural stones, which may be an advantage when developing decorative products.

4.Proposal for implementation

The design proposals for new products with the developed composite took into account a methodology developed by the Design Engineering Department of the Technological University of Delft, Netherlands and by the Design department of the Polytechnic of Milan, Italy – Material Driven Design (MDD), which presents 4 steps to reach conclusions based on the available material and in its technical and experimental characteristics.

This methodology was specifically designed to conduct the entire design process with new materials, based on experimental results and questionnaires made to design students. The result was a set of images and sensory scales relative to the intended terms for the final product: “modern” and “tempting”, as well as visualizations of those same terms (Figure 7). These questionnaires helped to conclude on what features should be incorporated into the proposals.

Since the mechanical properties of the manufactured composites make it impossible to use them for the manufacture of structural products, the proposals presented are of a decorative nature. Taking into account the translucency characteristics of the marble samples and the questionnaire participants' suggestions, the application of the material will target objects used for illumination.

 ISBN: 978-84-09-16892-7

Inspired by the conical shape of the volcanos, a process of the Nature that generates some stone types — the focus

of this study, one of the proposals is a table lamp made entirely from the mixture of marble grains and resin. It brings together the characteristics that came out from the questionnaire methodology described above, featuring a minimalist look, with the unique and serene colour of marble and a symmetrical geometry, which facilitates the manufacturing and demoulding process (Figure 8).

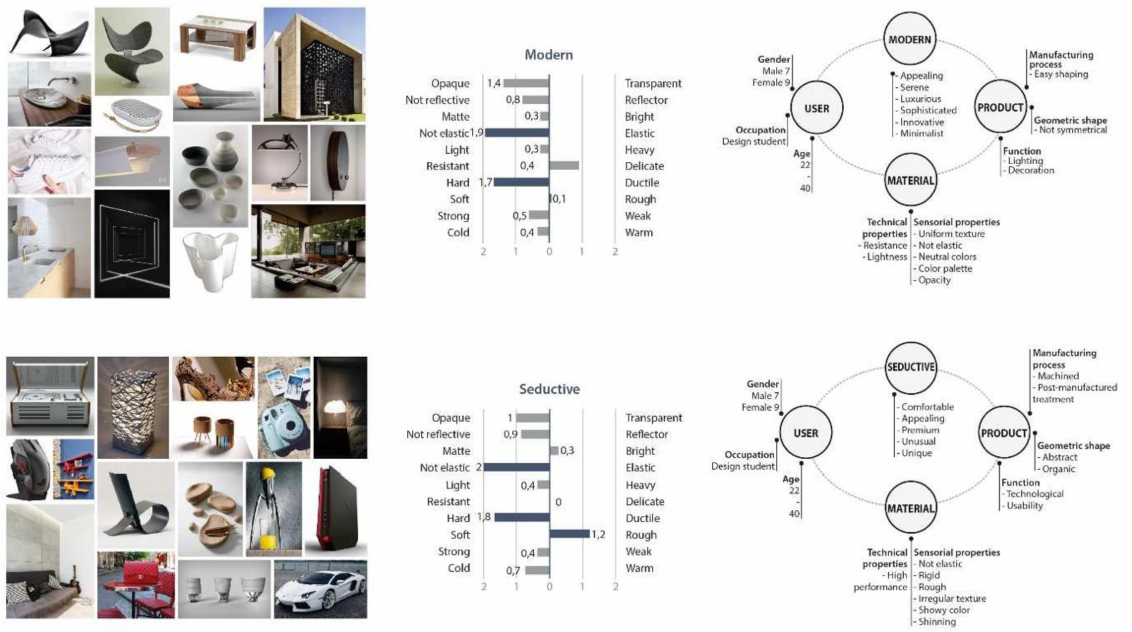

Figure 7. *Mood boards, sensory scales and visualizations for the terms "modern" and "tempting".*

Figure 8. *Application proposal of a table lamp using marble waste.*

The other proposal is based on the concept of joining together different stones, from samples 19 and 20, taking advantage from the contrast between dark and opaque schist grains and translucent and light marble grains (Figure 9); on the back was used a light source that highlights only the marble spots. This concept was tested by manufacturing the acronym of the Faculty of Engineering of the University of Oporto: FEUP, by combining schist and marble composites, manufactured with 10% of resin. It was verified that the light only passes through the marble, thus giving the desired effect. This proposal can be even more complex with the design of a world map (Figure 9).

Figure 9. *Marking and cutting of letters on cardboard (1-2), pouring the mixture around the letters (3-4), card removal and marble pouring after 24h (5-6), end result with light on the back (7) and render from another product in a living room (8).*

It should be noted that the resin used in the experimental phase does not have characteristics suitable for the type of suggested applications, since it changes colour with light and heat exposure. Ideally, a UV and heat resistant resin, such as an acrylic resin, should be used.

5.Conclusions

Mining of natural resources is one of the most important industries for the existence and continuous development of the human beings. As such, it will continue to exist and as the world population continues to increase, it is expected an increase in demand for those resource. As a result, even with continuous improvement of the mining and transformation processes, large amounts of waste will continue to be generated, of which most part will not be used.

The use of residues for incorporation into different products is nowadays a reality. However, utilization rates are still extremely low. This work aimed to develop composites based on different particles of schist, marble, limestone, slate and granite, mixed with epoxy resin. The obtained results, both in terms of physical and mechanical properties, limit their use in the manufacture of structural products (slabs for paving and cladding, Slabs and cut-to-size products for vanity and kitchen tops, etc.). However, it opens the opportunity for the creation of decorative objects. In this sense, two artefact proposals were presented, which took advantage of some stones the translucency, to use them to manufacture illumination objects.

The presented work creates an opportunity for the manufacture of decorative pieces, enhancing the natural stones economic circle. It is a small contribution for the reduction of the environmental impacts caused by

 ISBN: 978-84-09-16892-7

waste generated in the mining and transformation processes of natural resources.

Acknowledgments
Project NORTE-01-0145-FEDER-000022 - SciTech - Science and Technology for Competitive and Sustainable Industries, cofinanced by Programa Operacional Regional do Norte (NORTE2020), through Fundo Europeu de Desenvolvimento Regional (FEDER).

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