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BETWEEN SCARCITY AND CIRCULARITY OF RESOURCES: TECHNOLOGICAL INNOVATION FOR GRANITE SCRAP IN SARDINIA

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ABSTRACT
Throughout the past two centuries, human activities have had a profound impact on Earth, leading to the progressive consumption of natural resources, increasing in waste, pollution and alteration of ecosystems. This has induced a well-known climate change phenomenon with significant consequences for humankind and ecosystems. The growth of cities and improved living conditions will lead to increased consumption of resources, many of which are already expected to run out by the middle of the next decade. It is essential to monitor resource consumption using relevant indicators to drive economic growth toward resources decoupling. Starting from an analysis of the consumption of the four major categories of natural resources, biomass, fossil fuels, non-metallic minerals and metal ores on an international scale, attention is gradually turned to consumption at the Italian level, focusing on the consumption of non-metallic minerals for use in construction. Thus, the focus was on the granite mining district of Buddusò, in Sardinia, the largest producer in Italy. Granite quarries, which have been drastically reduced in recent decades, have generated huge amounts of processing waste, causing profound changes to landscapes and ecosystems. Based on the analysis of disused quarry sites, the types of rock abandoned have been studied in detail, investigating the chemical-physical, mechanical and technological characteristics and experimenting with innovative products and alternative uses for these wastes. The findings indicate that these residues can be utilised as a secondary raw material within the ceramics industry, also as a protective layer for ventilated facades.

1. INTRODUCTION

1.1 The Antropocene's effects

The steam engine triggered the first industrial revolution in the second half of the 17th century, with disruptive effects on textile and metallurgical production.

Around 1870, the advent of electricity, internal combustion engines, and oil as energy source allowed for the second industrial revolution. A century later, information technology and industrial automation fuelled the third industrial revolution, opening the digital age, which is still expanding. Internet of Things (IoT), sophisticated robotics, big data, and artificial intelligence are pushing a radical transition, which has been officially recognized as the fourth industrial revolution at 2011 Hannover Fair.

Exploiting natural resources and, consequently, modifying the natural landscape emerge as a common character of this centuries-old evolution. Technological advancements have increased the opportunities for economic growth, but they have in parallel engendered strong and enduring impacts due to anthropogenic activities.

Scholars have devoted increasing attention in recent years to innovative technologies and their contribution to increasing the anthropogenic alterations of Earth balance (Saqib and Qin, 2024), mostly due to the only maximization of profit and productivity.

The word Anthropocene - which was coined and made popular by biologist Eugene Stormer and chemist Paul Crutzen in 2000 - has become current to characterize the most recent period in Earth's history, when human activity began to exert a substantial impact on the planet's climate and ecosystems (Crutzen and Stoermer, 2000).

This "new geological age" - although not officially recognized as such - is fuelled by two main dynamics: the huge amounts of greenhouse gases (GHG) due to energy production from fossil sources, with the related global warming this causes, and the more and more intense resource

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exploitation, which reduces natural stock and increases waste (Harbel et al., 2020) -. Indeed, the global consumption of raw materials has risen four-fold since 1970 (IRP, 2019) and further expansion is set by 60% by 2060 (IRP, 2019), also due to the urban population increasing (OECD, 2018). What we are recording from the 2020s onward is that Technosphere, namely the totality of human-made products, is bigger than biosphere and this profoundly alters the planet's ecosystems, causing 60% more global heating, 40% air pollution impacts, and 90% water stress, which leads to water cycle perturbation and ocean acidification, increase in extreme meteorological phenomena, disappearance of forests and biodiversity loss.

Furthermore, this scenario is accompanied by significant landscape degradation, diminution of natural resources, local economic failures, increased conflicts, and forced migrations (WEF, 2025), that even intensify climate change and contribute to environmental disasters (WEF, 2023). Additionally, the exploitation of physical resources has become easier and cheaper, especially when mining is carried out by acquiring inexpensive land in developing countries. The only way to enhance our capacity in utilizing natural resources while reducing our environmental footprint is that we must leverage emerging technologies in curbing air pollution, revitalizing degraded soils, conserving natural habitats, and enhancing carbon sequestration.

This means that we must inspire more intensely from the sufficiency approach (Jungell-Michelsson and Heikkurinen, 2022) and take concrete actions accordingly, to preserve and enhance our planet in a more resource-efficient perspective (COM, 2011).

Thanks to this approach, the value of environmental capital is projected to rise by a minimum of 28%, as reported by the COM final "EU Soil Strategy for 2030 Reaping the Benefits of healthy soils for people, food, nature and climate" (COM, 2021).

1.2 Trends in natural resource consumption: the four main categories of material resources extracted

"Material resources are natural assets deliberately extracted and modified by human activity for their utility to create economic value. They can be measured both in physical units (such as tons, joules or area) and monetary terms expressing their economic value" (UNEP, 2011).

Natural resources provide the raw materials which are then processed and transformed to satisfy basic human needs, like food, shelter, water and medicine, to produce energy for industries, homes and mobility; to build roads and buildings. Although they are vital for human survival, the quantification of natural resource consumption is a hard undertaking, due to both the intrinsic complexity of tracking their flows and the multitude of systems and methodologies employed for the purpose across various countries. Many research centres and government institutions (international, national, and regional) collect and publish data concerning the consumption of natural materials, pollution, and waste production, but they are often difficult to understand and compare, due to a lack of common protocols. Furthermore, data are usually aggregated by macro-categories of resources, providing the total amount of each of them entering an economic system, while very few or no information is available allowing to quantify separately the shares of extracted, processed, consumed or wasted resources.

Krausmann et al. (2009) studied variations in four primary categories of extracted materials: biomass, fossil energy carriers, ores and industrial minerals, and construction minerals. Their analysis showed that extraction increased eightfold in average between 1900 and 2000, with a huge peak for the construction minerals, which rose by a factor 34, while ores and industrial minerals experienced a growth index of 27, and fossil energy carriers grew by 12. The 2015 OECD report "Material Resources, Productivity and the Environment" confirmed that the quantities of materials extracted, harvested, and consumed worldwide have grown exponentially over the past century. This amount reached nearly 72 billion tons in 2010, that is twice that in 1980, and ten times more than in the early 1900s.

Over two-thirds of the global extracted in 2010 was for non-renewable resources. According to the 2019 OECD's report on natural resource consumption, the overall resource withdrawal is expected to rise to 168 Gt per year by 2060, of which metals are estimated to rise to 20 Gt (8 Gt in 2011), fossil fuels to 24 Gt (14 Gt in 2011), biomass to 37 Gt (20 Gt in 2011), and non-metallic minerals to 86 Gt (37 Gt in 2011) (OECD, 2019).

The resources withdrawn in 2017 were shared as follows: metal 10%, fossil fuels 17%, biomass 24%, and non-metallic materials 49%, of which 32% were sand, gravel, and crushed rocks. Nevertheless, the real consumption of raw resources and related environmental pressures are difficult to account for. Indeed, the international handbook on economy-wide material flow analysis (EW-MFA), jointly developed in 2023 by the United Nations Environment Programme (UNEP), the European Statistical Office (Eurostat), and the Organisation for Economic Co-operation and Development (OECD), aims at describing the interactions between a domestic economy and the natural environment, by focusing on primary material extraction, physical trade (i.e. imports and exports), waste and emissions, which flows are recorded at the country level through a coordinated method of data collection (UNEP, 2023). The survey outputs can be used to identify environmental pressures, and they are suitable to couple with Life cycle assessment approach (LCA) to compare the impacts and productivity of natural resources on a national economy level. According to the global manual on EW-MFA, indicator as:

- Domestic Extraction (DE), that measures the flows of materials that originate from the environment and that physically enter the economic system;
- Domestic material input (DMI), that measures the direct input of materials used in the economy, i.e. all materials which are of economic value;
- Domestic material consumption (DMC), that measures the total amount of material directly used in an economy;

- Material productivity (MP), that indicates the economic value generated per unit of material consumption, also called resource efficiency;
- Raw material consumption (RMC), namely "material footprint", that measures the primary resources needed to produce a national product,

can be utilised to calculate and describe the physical resources used at various stages of economic activities, including the production of waste and emissions related. Still, when material extracted but unused is considered, the global rate of withdrawn natural resources grows due to unused domestic extraction (UDE) share, which strongly affects resource productivity (Bianchi et al., 2021).

Then, focusing on Europe-27, China and the USA only, and analysing the four main categories of natural resources consumption between 2010 and 2024, as showed in Figure 1, over the past four decades, the overall material (or resources) productivity indicator, measured as GDP/DMC, has increased, while material consumption (Domestic Material Consumption) has decreased. Many scholars attribute this trend to technological innovations introduced in production processes (Fayomi et al., 2019).

1.3 Environmental pressures of non-metallic and construction minerals

In last decades, our economies have changed from biomass-based agrarian metabolism, the largest source of used material (41%), to 33% in 2000 and 26% in 2020. (UNEP, 2024) - toward a mineral-based industrial one. The non-metallic minerals, namely "stone quarries and clay and sand pits; chemical and fertilizer mineral deposits; salt deposits; deposits of quartz, gypsum, natural gemstones, asphalt and bitumen, peat and other non-metallic minerals other than coal and petroleum" (OECD, 2001), are the most extracted natural resources in OECD countries today, with the fastest growth in the last 15 years (OECD, 2019). They are also requested by various economic sectors, including 1) food and nutrition; 2) mobility; 3) the built environment; and 4) energy.

Non-metallic minerals can be difficult to categorise due to their common mixtures and unclear end uses across various sectors, including industry, construction, and agriculture. To address this challenge, the IRP in 2019 proposed a general classification system designed to clarify the distinct characteristics and potential applications of these minerals (Table 1).

The demand for construction minerals is ubiquitous on a global scale. However, their international trade is limited due to the prevalence of domestically available minerals. The economic value of construction minerals per unit of mass is low and their large volume makes it difficult to transport them over long distances. Although construction minerals are considered non-toxic, with low specific impact on the environment compared to other materials such as industrial minerals or metals, they are often transported by road, causing significant CO_2 emissions. Additionally, other indirect emissions are triggered, mainly due to industrial processes fed by those materials, as in cement production (Winnefeld, 2022), or caused by their extraction as land use, air, water, and loss of biodiversity (Xuhui et al., 2024), even in terms of unused extracted material abandoned in quarry sites.

As this consistent rate of construction minerals unused is progressively growing, we should adopt strategies to promote material efficiency, including but not limited to reduced use of materials through design, material substitution, recovery, reuse, production and lifetime extension (Hertwich et al., 2019; Worrell et al., 2016). This can help reduce environmental impacts from natural resource extraction and consumption, addressing scarcity across various fields (UNEP, 2017). It also contributes to enhancing the decoupling of resources and impacts. (UNEP, 2024).

1.3.1 Non-metallic minerals extracted in Italy and related environmental pressures

According to data from the IRP's online database (2019), the main categories of natural resources extracted and consumed in Italy are biomass, fossil fuels, non-metallic minerals and metal ores. In Italy, in 2024, the biomasses extracted (DE) accounted for 123,7 Mt, imported (IMP) for 54 Mt and exported (EXP) for 21 Mt; the fossil fuels extracted for 8,7 Mt, imported for 210,9 Mt, exported for 3,1 Mt; non-metallic minerals extracted for 279,7 Mt, imported for 13,5 Mt, exported for 13,6 Mt; metal-ores extracted for 0,0 Mt, imported for 13,6 Mt and exported for 31,4 Mt. It is evident that, except biomasses and non-metallic minerals, the Italian country depends on imports.

According to IRP classification in 2019, non-metallic minerals are divided into 1) ornamental building stones; 2)

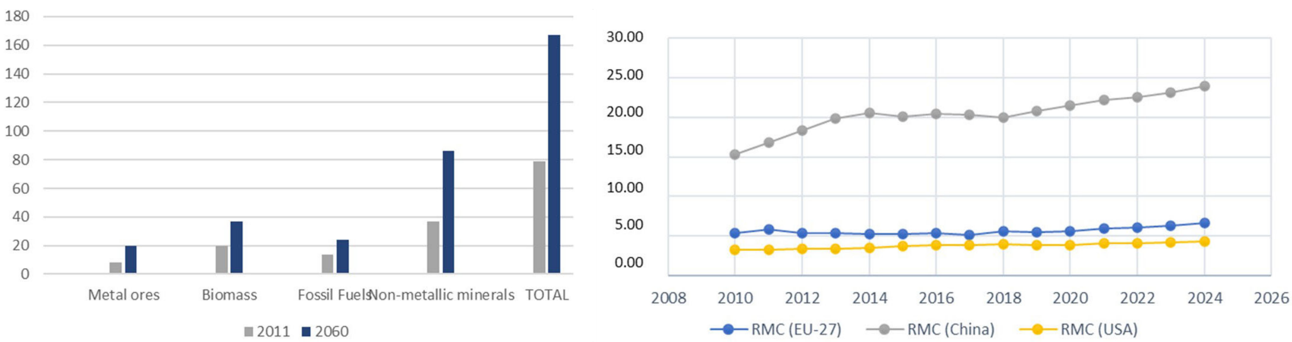

FIGURE 1: a) Consumption rates in 2011 (in Gt) and expected for 2060 (source: authors, based on OECD forecasts); b) Raw material consumption (in Gt) between 2010 and 2024 (source: authors, based on IPR's flow material database).

TABLE 1: IRP's Domestic extraction (DE) classification system of non-metallic minerals (source: IRP, 2019. Adapted by authors).

Category)	First level	Second level
Non-metallic minerals	Ornamental or building stones	
	Carbonate minerals essential in cement	Chalk0
		Dolomite
		Limestone
	Chemical and fertilizer minerals	
	Salt	
	Gypsum	
	Clay	Structural Clay
		Specialty Clay
	Sand and gravel	Industrial sand and gravel
		Sand and gravel for construction
	Other non-metallic minerals	

carbonatic minerals used in cement production; 3) mineral and chemical fertilisers; 4) salts; 5) gypsum; 6) clays for ceramic industries; 7) sands and gravels. By considering only non-metallic minerals for the construction sector, in 2017, according to the available ISTAT data, the total DE accounted for 149,10 Mt. The aggregate's biggest class by weight includes "limestone, travertine, gypsum and sandstone" which accounts for 68.8 Mt; in second place are "sands and gravels", with almost 59 Mt; the extraction of "porphyry, basalt, tuff and other intrusive rocks" amounts to 9.1 Mt, of which 43.9% is basalt (volcanic rock used in building constructions, road works, etc.); still, the extraction of "cement marl" reaches 6.5 Mt (increasing by 8,8%), as well as "ceramic and industrial minerals", mostly feldspar for the glass and ceramics industry, reaches 4.4 Mt. Lastly, the construction stones extracted, such as marble and travertine reaches over 2 Mt and 500,000 tonnes of granite.

The extraction of non-metallic minerals often requires the removal of large rock masses, which can significantly impact the environment and the surrounding areas of the quarry. This process can lead to issues like pollution, waste, and the gradual depletion of increasingly scarce natural resources. Additionally, it poses threats to surface waters, biodiversity, the landscape, territorial integrity, and public health. Modern survey technologies with high spatial and temporal resolution can assist in mapping the territorial impacts related to excavation and tracking their spatial evolution over time. For example, the Italian Higher Institute for Environmental Protection and Research (ISPRA) has developed a GIS-based monitoring system called GEMMA. This system provides up-to-date and detailed information about various quarry sites across the country, using a set of indicators related to thirty-nine thematic categories. Regional governments and companies contribute to the database update through periodic surveys, enabling better monitoring and management of the quarry's environmental pressures. (Fumanti and Di Leginio, 2023).

A total of 3,316 quarry sites were recorded in Italy in 2021, including both active and inactive sites. A total of 2,158 active sites contribute to the overall amount of domestic extraction (DE). This includes 571 sites in the north-west, with 288 located in Lombardy alone; 209 sites in the north-east, of which 146 are in Veneto and 186 in South Tyrol; 456 sites in the central regions, including 224 in Tuscany; and 349 sites in the southern regions, which comprise 141 in Apulia, 178 in Sicily, and 95 in Sardinia. There are also 553 inactive sites, distributed as follows: 102 in the north-west, 94 in the north-east, 135 in the central regions, 169 in continental southern areas, and 53 on the islands. Data is unavailable for the remaining 605 sites.

Various statistical indicators have been developed to monitor the extraction of material resources. Some of these indicators are specifically designed to analyse environmental pressures and to describe and interpret the interactions between the economy, land, and the environment. The National Statistical Authority (ISTAT) releases annual data and calculates the Extraction Intensity (IE) and Density of Active Mining Sites (DSE) for non-metallic mineral resource withdrawals in Italy (Figure 2).

The IE index expresses the quantity of mineral resources extracted per square kilometre, and it is available at a regional scale; the DSE indicator records the ratio between the number of active mining sites per municipality and their surface areas. What emerges from the survey is that in Italy the average extraction intensity (IE index) increased by 20,6% between 2017 and 2021, with some difference among the sub-areas (north +20,4%, centre +13%, continental south +25,6%, Sicily and Sardinia + 28,7%.

Two main issues impact the current situation in Italy and other places. Firstly, there is a need for more effective and environmentally friendly management of active quarries, closely linked to the specific social and territorial contexts of quarries; this emphasizes the importance of reducing and valuing quarry waste using high-efficiency extraction technologies; additionally, it calls for a well-planned and progressive approach to environmental recovery, which should be carried out alongside the exploitation of quarry resources from the very beginning. Secondly, the huge amount of quarry waste, temporarily stored in inactive or abandoned sites, must be addressed first, as it contributes to landscape changes and environmental degradation. This can lead to soil loss, harm to biodiversity,

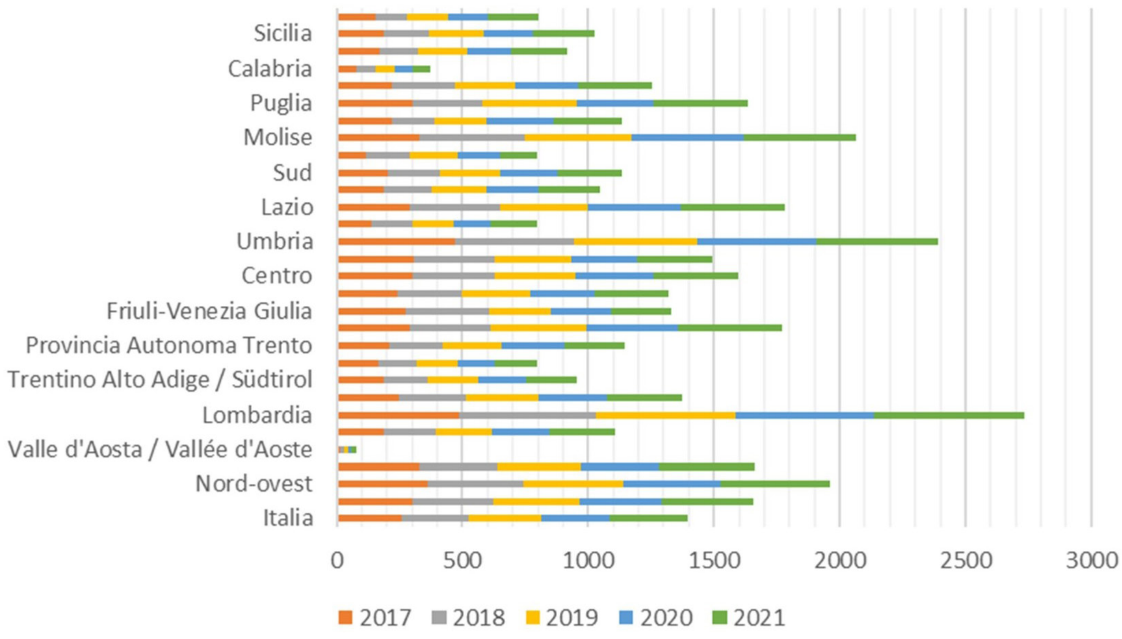

FIGURE 2: Intensity Extraction (IE) in Italy, in m³/km² (Monsù Scolaro A., based on ISTAT's data).

and alterations in underground water, all of which seriously affect the surrounding areas and communities. Waste and scraps can be managed to either reshape the site or be repurposed as secondary raw materials; additionally, these abandoned sites could be transformed into historical parks that hold cultural significance and are open for community use and public enjoyment.

1.4 Granite quarries in Sardinia: a research and development project to valorise abandoned scraps and sites

A comprehensive overview of quarries and mines in Sardinia had been provided by the Regional Plan for Extractive Activities in 2007 (PRAE, 2007), which recorded 397 active quarries, 216 decommissioned (or inactive) ones, and 644 abandoned quarries called "historical" since established before L.R. 30/89. However, as per the most recent ISTAT survey conducted in 2021, the number of active quarries has decreased to 135, of which 95 are productive and 11 not in operation, while the status of the remaining quarries is unknown.

The primary resources extracted in Sardinia are clay, limestone, sand, granite, porphyry, and basalt. From 2017 to 2021, the extraction of non-metallic materials increased by 34%, reaching 134,606 tons in 2021, of which marble 29% to 32%, totalling 2,680 tons; sand 20%, with 1,863 tons; granite 20%, with 1,803 tons; 15% porphyry, totalling 1,395 tons; 13% basalt, with 1,189 tons; and clay, which made up around 2% with 169 tons.

The current regional plan for special waste in Sardinia, in force from 2021 (PRGRS, 2021), highlights significant issues stemming from the production system's insufficient capacity in effectively managing and utilising both before and post-consumption waste materials. The almost total lack of recovery and recycling facilities in the Region is identified as the main cause of this issue. Based on the analysis carried out, the Plan proposes a survey campaign to identify conditions of environmental degradation linked to waste production. This requires collecting and quantifying waste according to its CER code (European Waste Code) to define potential site-specific management and exploitation scenarios at the territorial scale. Also, due to the precious and very sensitive Sardinian natural landscape, extraction activities cause significant environmental alterations, exacerbated by the accumulation of waste, which affects many areas within the regional territory (Figure 3). The recently adopted new building regulations allow the use of scrap to fill voids from any land excavation, even by moving bulky waste from one site to another, if they are geochemically homogeneous and compatible with the ecosystem.

About one-fifth of Sardinia's territory is characterised by a geological substrate of intrusive granitoid rocks known as the "Sardinian-Corsican Batholith." This formation originated during the Hercynian orogeny and has offered significant economic opportunities to the four main quarry basins where it is found (Buddusò and Alà dei Sardi; Calangianus, Priatu and Bassacutena; Arzachena and Luogosanto; Gavoi and Ovodda), which have been extensively mined for resources.

In 1997, a regional decree grouped the first three areas into the "industrial district of Gallura granite", marking it as the largest Italian extraction area by territorial extent. The district once included 114 quarry sites, 30 of which were in Buddusò and Alà dei Sardi municipalities in Sassari County.

The ISTAT data show the relevance of this basin at the national scale: among 3,911 tons of granite excavated in Italy in 2021, about 2,200 tons are of gneiss, while 88.30% of the remaining 1,700 tons of real granite are extracted in Sardinia.

This data must be located within the general trends of Italian whole granite production, which was 2.06 million tons in 2011 but decreased by 93% in 2023, totalling

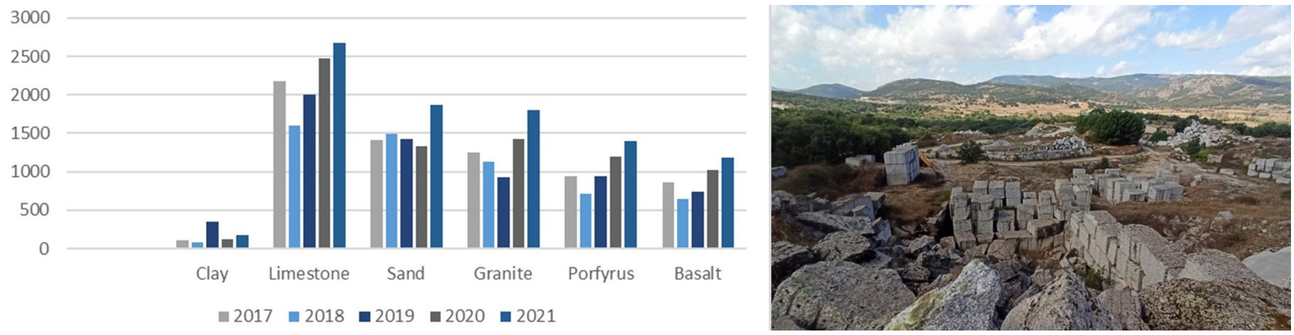

FIGURE 3: a) The non-metallic minerals for construction most extracted (in tons) in Sardinia (Monsù Scolaro A. based on ISTAT's data); b) Landscape alteration by granite quarry activities in Sardinia (Monsù Scolaro A.).

just 143,129 tons. In contrast, the production of blocks and sawn slabs increased by 13%, rising from 474,374 to 534,950 tons during the same period. This growth highlights innovations in extraction processes and a reduction in scrap. The quality in this industry has always relied on the efficiency of the extraction process from the "banks" and quarry faces.

Until the recent past, only 30-40% of the extracted volumes were converted into marketable material, while the remaining became waste, including blocks of various sizes, processing residues, and sludge. Today, diamond wire cutting has gradually replaced the extraction by explosives to help in reducing the waste and its accumulation in mining areas over the years. This reduction is crucial, as the excessive build-up of debris has often strongly limited the productivity of companies by restricting the available space for storing extracted materials while deeply altering landscapes and territories.

1.4.1 Methodological approach

Aiming at finding possible answers to this challenging scenario, the Department of Architecture, Design, and Urban Planning at the University of Sassari carried out a research and development project, entitled "Research for Constructive Solutions for the New Use of Stone Waste and Ceramic Materials for Circular Architecture". This project took place from 2021 to 2023, having been funded by the Italian Ministry for Enterprise and Made in Italy as part of the "Smart Fabric" initiative. Its primary objective was to explore the potential of granite waste as a secondary resource for several sectors, namely the ceramic or the construction industry or other industrial applications, even by depicting possible production chains based on an industrial symbiosis approach. Furthermore, the project focused on identifying potential methods to regenerate and reuse abandoned quarry sites. The methodological approach, which involved various areas of expertise within a multidisciplinary framework, was developed according to the following points:

- map sites by using available technical cartography to differentiate between active, inactive, and dismissed quarries and additionally to identify the quantity of granite scrap and waste in each quarry, along with its condition of access, sourcing and withdrawal;
- laboratory analysis of samples of granite residues to determine their chemical and mineralogic composition to assess their suitability for use as secondary raw materials in the ceramic industry or for other applications;
- laboratory analysis of granite scrap and waste by following common market requests and uses, such as for flat surfaces (sawing machine plans), glossy and rough finishes, to evaluate the modifications of thermal reflectance and absorption after applying nano-paints;
- mechanical analysis of granite thin slabs obtained by cutting granite scraps to find the maximum strength by balancing thickness and planar dimensions, enabling the creation of the largest possible stone slab for designing innovative ventilated facades for smart buildings;
- laboratory analysis to check light flow absorption by previous thin granite slabs.

Additionally, were carried out:

- an analysis of dismissed quarry sites from an ecosystemic point of view for identifying alterations and residual natural characteristics to establish the basis for developing potential methods to regenerate abandoned areas for public use and make them accessible to the community;
- a study of industrial and economic territorial conditions, as industrial areas equipped with technological resources, transportation, storage, and conveying systems, reduced VAT, to explore and enhance strategies for managing scrap and waste through industrial symbiosis approaches.

This last is a crucial step toward activating sustainable and systemic processes to address the challenges presented by abandoned sites, which hold significant untapped potential.

However, the findings of the last two points will be summarised to provide a brief overview of the systemic approache adopted to to address the issue of abandoned quarries and demonstrate how waste can be transformed into local opportunities on a territorial scale.

2. RESULTS AND DISCUSSION

The mapping activity allowed updating the usage status of the quarry sites by using a cartographic survey, comparing the current boundaries of the quarries with the topographical ones already authorized, extracted from the regional plan of mining activities released in 2007 (PRAE, 2007). With the aim of valorizing waste and abandoned sites, eighteen quarries have been selected and classified based on five key logistical criteria:

- Current state of use (active, suspended, decommissioned, or already restored);
- Presence and visual assessment of waste volumes, including any possible lithological variations within the waste;
- Accessibility of waste;
- Availability (on-site or near-site) of suitable machineries for collecting and transporting waste;
- Current conditions of the access route to the quarry and distance from the processing plant (owned by the company EURIT Srl) operating in NE-Sardinia, which carries out pre-treatments (crushing, grinding and deferrization by magnetic separation) of raw materials for ceramics.

The laboratory analysis was conducted on the waste samples collected at each abandoned quarry site, identifying two main lithological varieties. The samples were then crushed, granulated, milled and micronised to perform mineralogical analysis by X-ray diffraction (Rietveld method), chemical analyses (by Inductively Coupled Plasma-Mass Spectrometry), and thermogravimetric (TG) analyses. The classification of the samples according to the Streckeisen QAP diagram is reported in Figure 4 (Cerri et al., n.d.). All samples are monzogranites, except for those that correspond to granodiorites and two which have intermediate compositions.

The chemical composition of the materials was compared with that of conventional quartz-feldspathic fluxes used in the production of porcelain stoneware tiles (de'Gennaro et al., 2003), to evaluate whether and which waste can be used as a component in ceramic bodies. From a technological standpoint, the main issue concerns

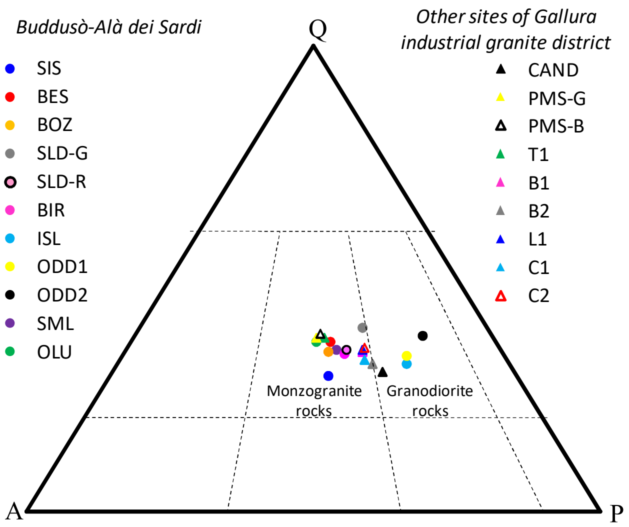

FIGURE 4: Classification of the sampled rocks (Cerri et al., n.d.). Q: quartz; A: sum of Na- and K-feldspar; P: plagioclase.

the iron content, which leads to dark colouration in the fired materials, as observed in the powders of several samples after TG analysis at 950°C (Cerri et al., n.d.). This problem impacts many of the sampled wastes, often compromising their potential reuse in ceramics. Still, lithotypes with favourable chemical and mineralogical characteristics may also require a deferrization treatment.

Considering the logistical aspects assessed for the eighteen quarries and the technological features determined for the twenty waste samples, the investigation focused on three sites: BES, OLU and Senè 1, that is a quarry next OLU containing the same lithotype. The size and abundance of the waste blocks contained in these sites were determined by carrying out a survey using a drone, a satellite system (GPS Top Con Base+Rover) and processing the data with the Meridiana 4.0 software (Geopro.it). In the BES site, 70% of the waste consists of blocks of size ≥ 2 m^3, unlike OLU and Senè 1 where, respectively, 72% and 78% of the blocks have a volume less than 2 m^3 (Figure 5; Cerri et al., n.d.). The volume occupied by waste in the three quarries is estimated to be: BES ≈ 116800 m^3; OLU ≈ 132400 m^3; Senè 1 ≈ 69800 m^3. The tonnages were calculated using an average density for granitoid rocks of 2.7 t/m^3 and assuming a void volume between 15% and 30%. The resulting estimated tonnages are as follows: BES 268-221 kt; OLU 304-250 kt; Senè 1 160-132 kt (Cerri et al., n.d.). Overall, these three sites alone contain at least 0.6 Mt of resources potentially usable as raw materials for ceramics.

Subsequent laboratory analyses were conducted to evaluate the changes in the samples' solar reflectance and thermal absorption. The tests were conducted on a commercially valuable sample of granite known as "pearl grey." After obtaining the reflectance measurements for the three primary colours of the test piece, we formulated three solutions: one that was purely polymeric and two that were hybrids of metal oxide (MO) and polymer at varying concentrations. Preliminary reflectance measurements indicated that the hybrid solutions resulted in a 40% average increase in reflectance while still partially revealing the underlying stone pattern. Subsequently, based on scientific literature, a general coating was chosen to develop a specific coating based on PDMS (polydimethylsiloxane; Sylgard 184) and titania nanoparticles (TiO_2; P25) to optimise the reflective effect of solar radiation and the hydrophobic, self-cleaning and photocatalytic effect of the surface. The coating was characterised by infrared spectroscopy. Being the titania of white colour, several mixing ratios were evaluated with PDMS (transparent) to preserve the pattern of the stone materials without sacrificing the functionality of the coating. The different mixing ratios were applied and tested on the surface of stone materials using an infrared thermometer to evaluate the reflectance of solar rays. Finally, measurements were made with a thermal imager to evaluate the possible variations in the thermal behaviour of the different ratios of the PDMS/TiO_2 coating. The sample was monitored in three different phases to simulate real operating conditions, namely:

- minimum overheating;
- following heating after high sunshine;
- during cooling.

Quarry	Logistica	Technological Aspects	TOTAL
SIS	8.5	8.25	16.75
BES	9.5	8.5	18.00
BOZ	9	8	17.00
SLD-G	5	3.25	8.25
SLD-R	5	5.75	10.75
BIR	7	6	13.00
ISL	8	0.25	8.25
ODD1	8.5	1.25	9.75
ODD2	5	0	5.00
SML	10	7.75	17.75
OLU	9.5	9.25	18.75
CAND	5	3.5	8.50
PMS-G	5.5	9.5	15.00
PMS-B	5	9.5	15.00
T1	4	7.5	11.50
B1	5	6	11.00
B2	9	5	14.00
L1	9	6.75	15.75
C1	5	7.25	12.25
C2	3.5	6	9.50

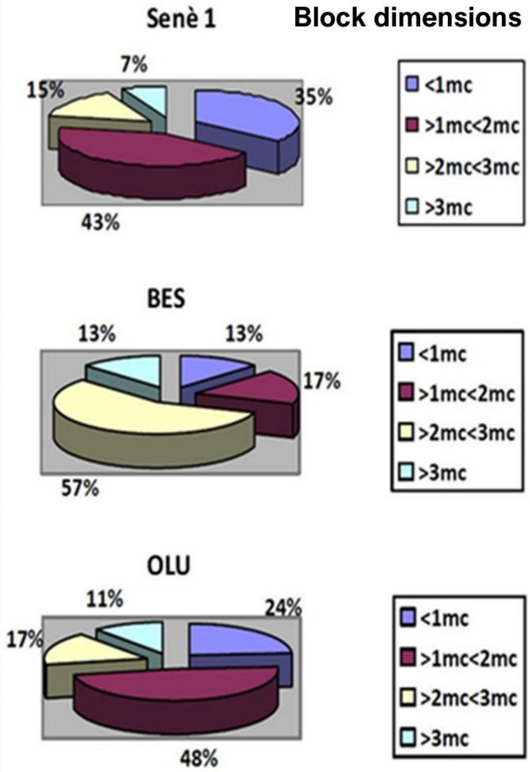

FIGURE 5: a) Final ranking based on the total number of quarries analysed, highlighting (in grey) the three most cost-effective to exploit; b) scrap's dimension of the three quarry most cost-effective (source: Cerri, G. 2023).

The tests were carried out at the end of July to simulate real operational conditions. Finally, in a second thermographic survey, in addition to the PDMS/TiO2 compound, also tested on polystyrene cans, other types of coating were observed on stone waste: 1) TiO2; 2) SiO2; 3) Boric acid; 4) Calcium carbonate (CaCO3). The various samples, numbered 1 to 6, were created by adjusting the mixture ratio of PDMS to TiO2, ranging from 4:1 to 4:0.025. In the minimum overheating phase, a rapid increase in temperature is observed on test piece no. 4 (only PMDS) and, to a lesser extent, n.3. The specimens heat up unevenly, perhaps because of the different thickness of the paint layer, while some specimens heat up more quickly during the higher heating phase as showed in Figure 6.

The PDMS acts as a thermal emitter, accumulating infrared radiation and then releasing it in all directions, thus heating both the underlying stone layer and the external environment. Hence, the need to adopt a double emitter/reflective layer to avoid the transmission of heat to the underlying material without altering the natural stone's layer emerged. A second thermographic survey was carried out comparing the PDMS/TiO_2 mixture with other types of compounds, including calcium carbonate ($CaCO_3$). Scrap coated with two different concentrations of calcium carbonate ($CaCO_3$) showed excellent reflective properties and indeed the lowest surface temperatures of scrap, both at high and low concentrations.

A mechanical analysis was carried out on thin granite slabs to determine their suitability for use as ventilated cladding on buildings. Firstly, the thin plates - 60 cm by 60 cm and 120 cm by 60 cm according to market requirements - were obtained from a waste block of "pearl grey granite", cut with a special machine equipped with ultra-thin diamond wire, with a diameter between 0,35 and 0.6 mm, not existing in Sardinia. To perform the load test, was consulted the norm UNI 11018-1:2023 "Ventilated Facades – Part 1: Performance characteristics and terminology. The slab was supported along its perimeter by a 1 cm wide metal frame. The load was evenly distributed through nine equispaced air pistons (each piston has a thrust area of 12.56 cm^2). The piston thrust area has a thin rubber coating to ensure the uniform application of force. The load application is monitored using a pressure gauge on the compressor and a load cell. Plate failures are measured using a millesimal comparator (displacement sensor) positioned near the center of the plate. The load was applied uniformly until failure occurred at a rate of approximately 40 kg/min. The load was applied by simulating the wind load on a ventilated facade slab. Six load tests were carried out on 60 x 60 cm and 120 x 60 cm slabs; three further tests were carried out by applying the load in the middle of the slab as in Figure 7.

The results obtained are shown in Table 2.

The results show that the maximum strength does not always increase directly as thickness, even when minimal,

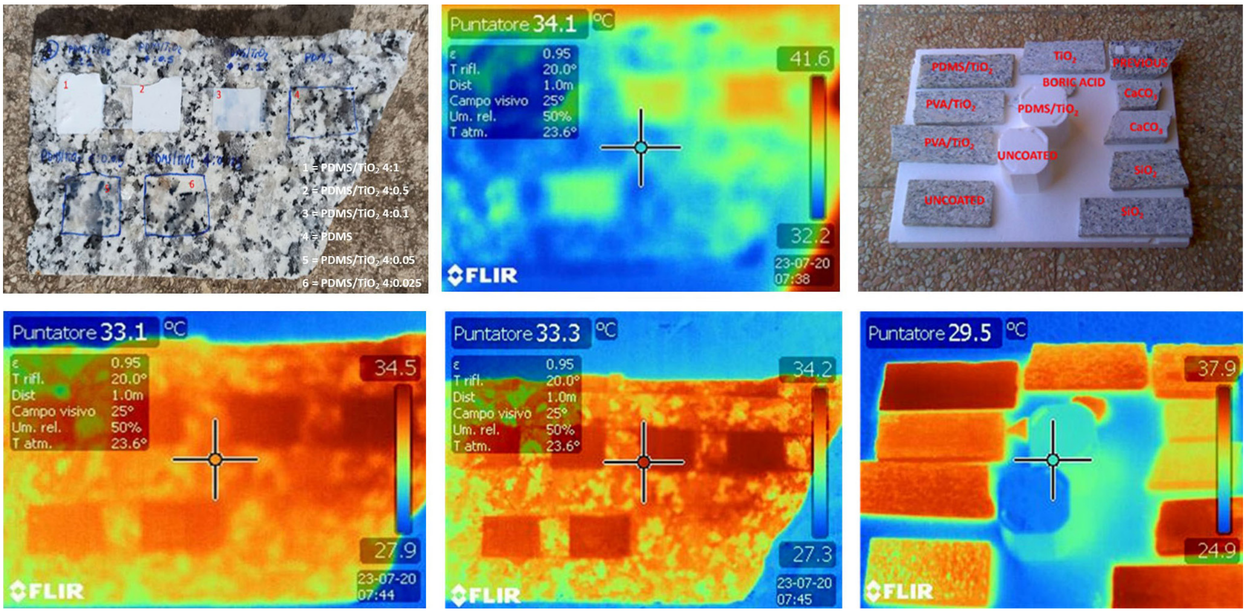

FIGURE 6: top left) the six different coating experimented; top central) minimum overheating; down left) heating after high sunshine; down central) cooling phase. Top right) samples for second thermographic survey and down right) thermal emissivity (source: Malfatti, L. 2023).

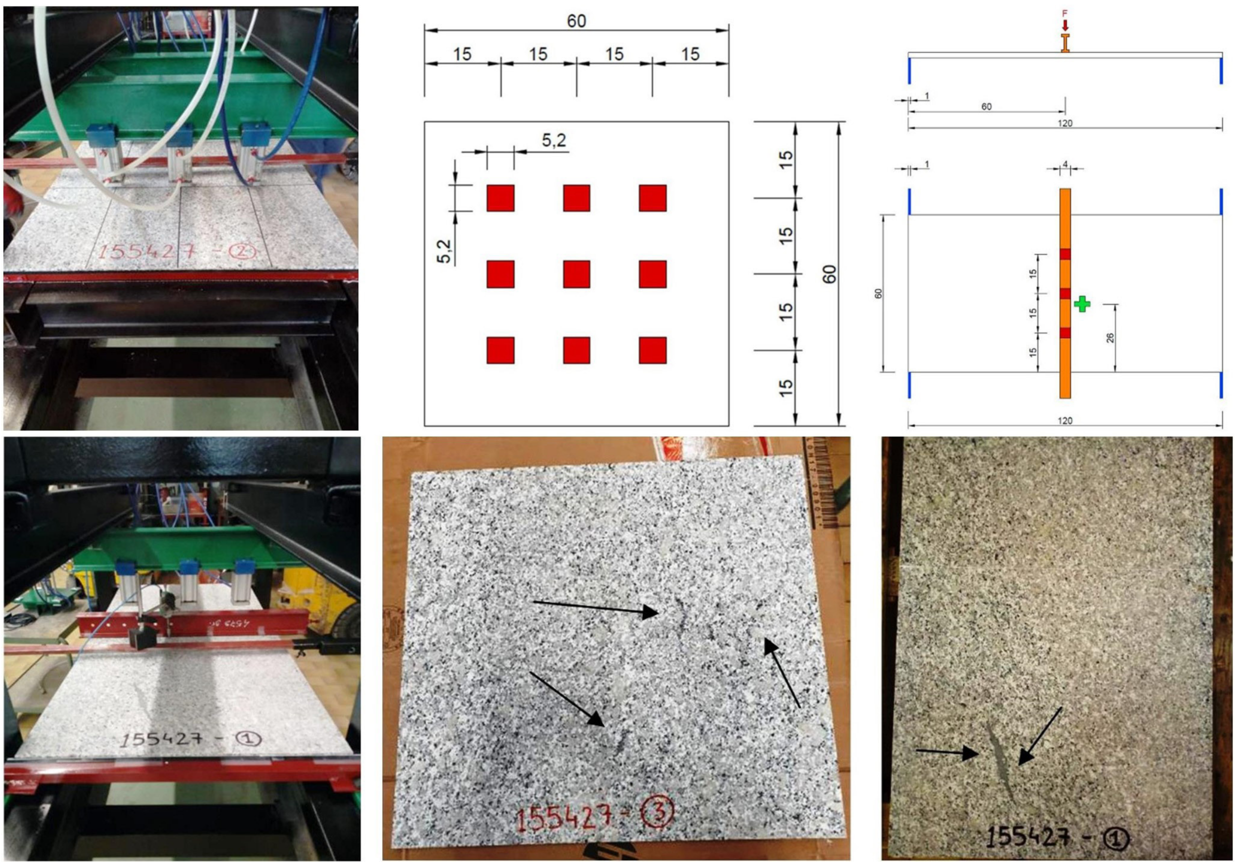

FIGURE 7: top and down, left) three-axle and six-point loading machine; top central) six-point loading scheme on the slab 60x60cm; top right) three-axle loading scheme on the slab 60x60cm; down central and right) arrows indicating defects in the slab (source: Veneta Engineering, 2023).

increases. The 120 x 60 cm slab has the highest breaking load resistance for the lowest thickness, as well as for the 60 x 60 cm slabs. The mechanical behaviour of the slabs, which is not always linear, can be attributed to irregularities and the presence of imperfections in the stone matrix, due to the smallest iron-micaceous portions (see the bottom

TABLE 2: Load test results (source : Veneta Engineering, adapted by authors).

Dimension (cm)	Slab thickness (mm)	Piston (nr.)	Maximum breaking load (Kg)	Maximum Flection (mm)
60 * 60	4,96	9	83,43	7,662
	5,05	9	73,53	6,480
	5,21	9	82,35	7,471
120 * 60	5,72	9	109,53	7,828
	5,73	9	103,05	7,451
	5,76	9	100,53	7,541
120 * 60	5,60	3	11,96	12,240
	5,70	3	9,23	14,358
	5,80	3	11,78	12,478

right side of the Figure 7). Ultimately, the maximum flexion occurs at the smaller thickness, as expected. Furthermore, when a three-piston load is applied, both the breaking strength decreases significantly and the deflection at the mid of the slab increases considerably. The non-linear mechanical behaviour of the slabs was considered due to irregularities and the presence of small imperfections in the stone matrix with the smallest iron-micaceous portions.

Finally, the last test was performed to measure the light flow absorbed by a thin granite slab of "granite grey pearl", dimensions 30 x 30 cm. The test was conducted in a dark room with dimensions of 50 x 30 x 30 cm. Inside the room, slabs of pearl grey granite measuring 300 x 300 x 5 mm were placed (Figure 8). The following equipment was used during the test:

- a LED light measuring 25.5 x 22.9 cm, with a luminous flux of 2,930 lumens.
- a HOBO data logger sensor capable of measuring illuminance in lux.
- a luxmeter (illuminance meter) to measure light levels in lux.
- a plate housing system made of thin black sponge profiles, positioned in the middle of the chamber.

The results in Table 3 show that the medium value of the light density absorbed by the slab, is approximately between 99,66% and 99,78%, but the effect obtained over the slab could be interesting for design scopes.

3. CONCLUSIONS

In the Buddusò's granite district, there are currently only 5 active granite quarries out of the 42 that were operational in the 1970s. Production is focused primarily on the big granite blocks, sold or cut into slabs, depending on market demand. Over the years, the old extraction techniques have caused huge amounts of abandoned granite waste, now significantly altering landscapes and ecosystems. These scraps are generally used to backfill the roadbed or employed as breakwaters, or reduced in size for secondary building applications, like outdoor pedestrian pavements. However, the research has shown that these waste materials hold remarkable residual performance - both mechanical and aesthetic - promising product innovations in line with circular economy approach and decoupling of resources and impacts. If properly sampled, these wastes could be repurposed as secondary resources for the ceramic industry or innovative products in the construction sector. The thin slabs for ventilated facades, obtained from granite blocks, treated with paints to improve thermal behaviour, need further tests in a climatic room or through prototypes, to evaluate the thermal performance in a real

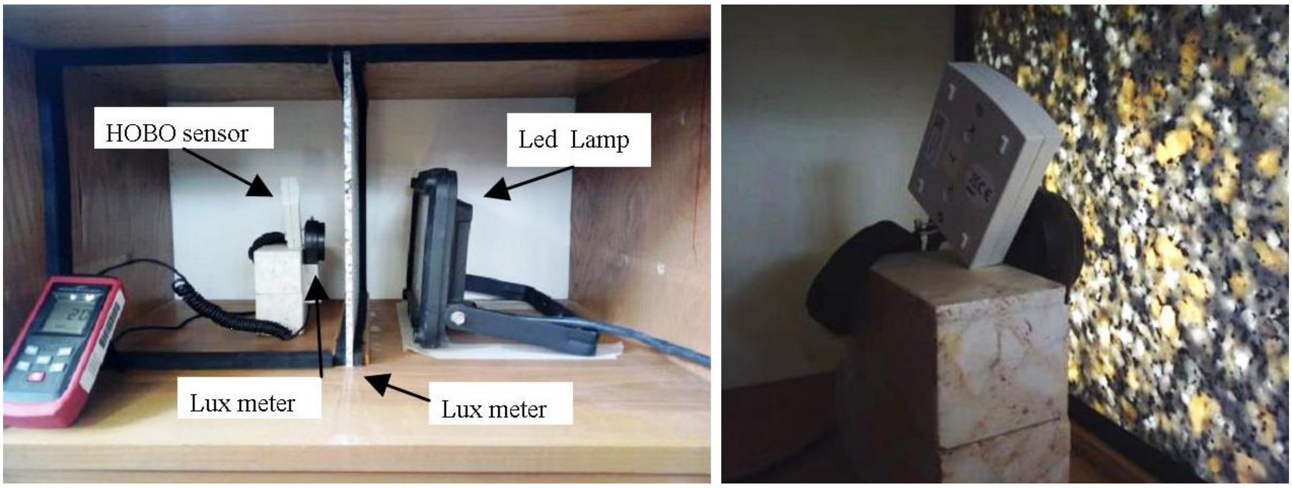

FIGURE 8: Lighting test room (source: Veneta Engineering, 2024).

TABLE 3: Illumination test results (source: Veneta Engineering, adapted by authors).

Test	Illumination without slab (lux)		Illumination with slab (lux)		Light absorbed (lux)		Light absorbed (%)	
	E_{min}	E_{max}	E_{min}	E_{max}	ΔE_{min}	ΔE_{max}	ΔE_{min}	ΔE_{max}
1	22.345,8	26.595,9	59,1	74,9	22.270,9	26.536,8	99,66	99,78
2	22.570	27.620,5	59,1	74,9	22.495,4	27.561,4	99,67	99,79
3	23.245,5	27.400,3	59,1	67,0	23.178,5	27.341,2	99,71	99,78
				Medium value	**22.648,3**	**27.146,5**	**99,68**	**99,78**

environment. The use of the slab without additional reinforcement layers would favour end-of-life reuse.

Furthermore, the existence of equipment, storage facilities, processing machinery, and transportation options, along with favourable logistics and special economic zones, is essential for activating potential production chains in industrial symbiosis. Achieving this goal requires a comprehensive, interdisciplinary approach bearing in mind multiple territorial implications - socio-cultural, economic, and environmental- through an active involvement of local communities, administrations, and economic stakeholders to initiate ecosystem rebalancing and social revitalisation processes. Additionally, this approach should aim to redevelop landscapes and restore soil and natural habitats, enhancing their environmental value (OECD, 2021). In this view, the integration of digital technologies, environmental resilience, and a redefined role for humans in industrial processes could potentially lead to a reduction in waste and environmental impact, concurrently enhancing social justice and sustainability (Mondejar et al., 2021).

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