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Natural stone waste generation from the perspective of natural stone processing plants: An industrial-scale case study in the province of Bilecik, Turkey

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ABSTRACT

Natural stone has been used for various purposes, such as for building stone, megaliths, ornamental stone, hunting, and grinding, throughout history. Upon the advent of industrial-scale production for natural stone, both quarries and stone processing plants began to generate a high quantity of waste in large bulk. Natural stone waste is a current worldwide environmental problem. It is imperative to use natural stone waste in other industries and to declare the amount of waste generated by users. This study presents an on-site industrial analysis of the natural stone production process for natural stone waste which has not previously been quantitatively and qualitatively examined on an industrial scale. The study was conducted in nineteen natural stone processing plants, generating almost 98% of the marble produced in the province of Bilecik and 11% of that produced in Turkey. The resulting daily amount of waste generated was calculated on a monthly basis based on current production capacity. Following an analysis, the industrial waste was quantified, with the waste generation mechanism being analyzed and the types of waste being classified by size and quality. The results suggest that a natural stone processing plant generates nearly 1044 tons (solid and sludge) of natural stone waste a day. The waste generated was divided in two parts as sludge waste and large-size solid waste, and then analyzed under three categories. In addition, the samples collected from the plants were evaluated via physical-mechanical tests and XRD analyses. According to the figures of the marble processing plants, it can be said that a mid-scale marble processing plant with a monthly production capacity of 10.000 m^2, on average generates a total of 50 tons of waste, comprising 25 tons of solid waste and 25 tons of sludge. It was also observed that natural stone waste was 28% in block cutting and 20% in gangsawing, as a result of cutting operations performed to turn one cubic meter of natural stone into a block. This translates into 756 kg and 540 kg of waste, respectively. Additionally, the storage of natural stone waste dispatched from various plants should be revised, and new categorized landfill areas and storage models should be introduced to individually store solid waste and sludge.

1. Introduction

The production and use of natural stone, production being directly related to various global industries, particularly construction, has followed an upward trend since ancient times. Natural stone is preferred in the form of building and facing stone for its uniqueness in color and design as well as its physical and mechanical qualities. 83.4 million tons of stone material, worth a total of 25 billion USD and 290 USD per ton, was traded around the globe in 2018. There has been an overall increase in processed quantity in almost all countries except for Italy and Spain over the last ten years. The export of stone material was valued at 13.67 billion USD in 2018 (Carli, 2019). In an ever-growing natural stone market, production quantities continue to rise. In any natural stone production process, natural stone waste is generated due to block efficiency, natural discontinuities, color differences, natural defects, and color and design requests of customers at any stage of natural stone production originating from a quarries. The same applies to waste generated for sizing by marble processing plants, due to edge residuals, natural discontinuities in natural stones, production defects and customer demands.

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Turkey has always ranked among top three in the global natural stone market in terms of both reserves and production quantity. Turkey met 17.3% of the need for global stone trade in 2018 (Republic of Turkey Ministry of Trade, 2019) (Table 1).

There are 1717 state-approved stone quarries, almost 2000 small and large scale marble factories and 9000 small-scale workshops in Turkey. (Republic of Turkey Ministry of Energy and Natural Resources, 2019). According to the figures from the Istanbul Minerals and Metals Exporters Association (IMIB), the total production of natural stone in Turkey was around 15.09 million tons in 2018 (Istanbul Minerals and Metals Exporters Association, 2018, 2019). Playing a major role in the global natural stone market, Turkey extracts almost 10% of its marble from the vicinity of Bilecik (Kacır, 2017).

The natural stone quarry yield ranges from 0.5% to 15% on average in Turkey (Sariisik and Sariisik, 2010). The main natural stone formation is highly fractured, because of the North Anatolian Fault Zone in particular. This causes loss and waste at every phase of production. A 10% quarry yield means that 90% of the stone produced in a marble quarry becoming waste. The problem is not only how to reuse waste, but also how to store it. The storage of waste generated by natural stone production operations is an important problem considering environmental factors (Shadrunova et al., 2019). Marble and waste rock fragments is dumped either in nearby empty areas, agricultural fields, or landfills (Ozcelik, 2016). For these reasons, studies on ecological sustainable planning of natural quarrying are extremely important. Careddu and Siotto (2011), investigated environmental factors such as noise, vibration, fumes, and dust caused by natural stone production in the Orosei area of Eastern Sardinia. They also provided suggestions to reduce the impact of these factors on the environment.

It is necessary to understand the waste generation processes in the natural stone industry, find new industries to reuse waste, and most importantly, to find out the share of industrial waste in the total waste of marble production plants (Careddu and Marras, 2015). It is of importance to designate what this can be utilized for. However, it is also of importance to see to what extent the designated utilization can be responsive to waste generated by marble producers. Before addressing how to reuse waste and which industries can reuse it, it is essential to find out how much waste a marble processing plant generates on average.

The reuse of natural stone waste for a sustainable environment starts with gaining insight into all the stages of the waste generation process. Natural stone production plants do not generate one single type of waste (Karaca et al., 2012). This causes waste to have various characteristics. Therefore, it is extremely important to be knowledgeable of the characteristics of natural stone waste. The characteristics to be set out later as a part of the study generate waste in line with its production quantity. This waste may differ in characteristics depending on the production machine, the surface characteristics of the stone and procedures enacted on it. The type of production and characteristics of the waste are designated by a customer's requirements. It is of utmost importance to quantify the waste and to set physical and chemical characteristics.

Various studies over the use of natural stone scraps in various industries may be found in the literature. Stone scraps can be used on a large scale, including the food industry, pharmaceutical industry, construction and the paper industry.

Rai et al. (2011) examined the use of marble powder and granule for mortar or concrete as a part of their study. The mixing ratios were designated as 5%, 10%, 15% and 20%. It has been found out that the thinner marble waste is meaning replacement of fine aggregate by marble scrap, the greater the compressive strength is in proportion to each use. The researchers underlined that the more waste marble there is in the mix, the more flexural the strength is.

In addition, marble powder is also used in mortar and concrete (Corinaldesi et al., 2010). This study analyzes the chemical and physical characteristics of marble powder in an effort to see whether powder generated by marble sawing and shaping can be used for mortar and concrete. The findings of the study suggest that maximum compressive strength is achieved once marble powder is used instead of 10% of sand. The present study and many other research studies reveal that the use of marble powder in mortar and concrete, rather than sand, yields successful outcomes.

Another study emphasizes the impact of marble powder on the mechanical properties of concrete, used samples passed through sieves of 0.25 mm at 0%, 25%, 50% and 100%, and concluded that each rate has a positive effect on the compressive strength figures (Demirel, 2010).

Placing emphasis on how marble waste is exponentially generated in Turkey, another study (Topçu et al., 2009) reveals the utilization of marble scrap dust in self-compacting concrete as a filler material. Based on the results of the study, it is concluded that marble powder should be used at a maximum and optimum extent of 200 kg/m^3 to achieve the optimal performance for both fresh and hardened versions of self-compacting concrete.

In addition, there have been many studies covering the use of marble scrap in asphalt. This is because it is an established fact that more than 95% (in weight) of asphalt paving material consists of aggregates. Various researchers have conducted studies over the use of marble waste as a substitute for aggregates that are used in large quantities. As a part of their study in Afyonkarahisar (Turkey), Akbulut and Gurer examined the use of marble and andesite quarry waste in city asphalt paving between Afyonkarahisar and Iscehisar. They performed Los Angeles abrasion, aggregate impact value, freezing and thawing, flakiness index and Marshall stability flow tests on waste samples. As a result, they found that it was possible to use waste as light-to-medium trafficked asphalt paving binder

Table 1
Global natural stone export and market share by countries (Carli, 2019; Republic of Turkey Ministry of Trade, 2019).

	2015		2016		2017		2018	
	Quantity (Thousand tons)	%	Quantity (Thousand tons)	%	Quantity (Thousand tons)	%	Quantity (Thousand tons)	%
India	7830.3	19.9	10513.7	25.0	10903.5	23.8	11000.0	25.6
China	10740.4	27.1	10138.7	24.1	9475.4	20.7	8609.2	20.1
Turkey	6447.5	16.3	6454.8	15.4	7909.2	17.3	7410.0	17.3
Italy	2661.2	6.7	2465.6	5.9	2652.7	5.8	2409.5	5.6
Brasil	2153.7	5.4	2275.4	5.4	2177.5	4.8	2013.3	4.7
Iranian	694.3	1.8	989.6	2.4	1413.5	3.1	1495.5	3.5
Spain	1798.3	4.5	1661.5	3.9	1625.7	3.5	1495.2	3.5
Greece	825.2	2.1	838.2	2.0	1158.1	2.5	1125.3	2.6
Norway	846.1	2.1	586.5	1.4	753.1	1.7	1059.0	2.5
Portugal	841.2	2.1	649.4	1.6	746.1	1.6	837.6	1.9

layers (Akbulut and Gürer, 2007).

Studies on the use of marble waste as aggregate in concrete or its substitute for sand can be found in the literature. Almeida et al. (2007) attempted to use natural stone slurry in concrete mixtures instead of fine aggregate. They concluded that natural stone slurry can be used in fine aggregate and/or micro filler in concrete mixtures. In their study, they compared blends with and without natural stone slurry. According to the results obtained, they emphasize that compressive strength, splitting tensile strength, and modulus of elasticity values gives better results in mixtures using natural stone slurry. Similar have been conducted using natural stone slurry. Ghezal and Khayat (2002) in their study to reduce costs in self-compacting concrete, emphasize that replacing 100 kg/m^3 of cement with a finely ground limestone filler enhances deformability and stability without affecting one-day compressive strength. The use of natural stone waste not only in construction but also in other industries has always been the subject of studies. Such studies usually make use of sludge samples but not large-sized solid waste. Ahmed et al. (2013) conducted a study on grind sludge to the extent that it would get through a sieve aperture of 10 μm, and mixed it with processed rice hull, another type of waste, and natural rubber for utilization. It was concluded in their study that the mixture enhances all the physical-mechanical characteristics of the end product.

Natural stone waste is used in construction for various purposes (Bilgin et al., 2012), performed a study over the potential utilization of marble powder waste for the brick industry. Waste materials at various ratios were mixed with industrial brick mortar, for 0%–80% in weight, and the mechanical characteristics of the brick as an end product were analyzed. This study suggests that the quantity of marble powder admixture has a positive impact on the physical, chemical and mechanical resistance of industrial bricks.

Munir et al. (2018) conducted a study where they analyzed the utilization of marble sludge for mud brick production at an industrial scale for heat insulation based on the need to construct energy-efficient buildings in today's world. They used marble sludge waste at a ratio of 5%, 10%, 15%, 20% and 25% in weight to mitigate production costs. Based on the findings of the study, burnt clay bricks containing up to 15% waste marble sludge in weight, led to almost a 16% decrease in heat conductivity. Accordingly, 15% of waste marble sludge has been considered optimum in weight for burnt clay brick production leading to sustainable, affordable, environmentally friendly and energy-saving buildings.

In addition, there have been studies that have analyzed the use of marble waste for composite material production (Çınar and Kar, 2018). As a part of their study, Çınar and Kar made use of both PET (polyethylene terephthalate) and marble waste for composite production in order to mitigate the cost and reduce environmental pollution. In this case, the incombustibility of marble powder is billed as a factor. They found that the greater the marble waste ratio is in the mix, the greater the Vickers hardness is for composite material.

In addition, it is a fact that the production of paper, rubber and tires, paints and pharmaceuticals as a filler require micronized calcite of high quantity in whiting and purity (Prescott and Pruett, 1996). Careddu et al. (2014) concluded that the standard requirements of $CaCO_3$, used for the production of paper, rubber and tires, can be met by marble waste. They reiterate that marble in Orosei (Sardinia, Italy), which is home to limestone deposits with high quantity calcium and a processing plant for limestone produced out of these ore deposits, generates waste suitable for micronized calcite production. Another study investigated the usability of micronized calcium carbonate in the building industry and the tire industry. As a result of this study, it was emphasized that micronized calcium carbonate has a high economic value and is an important material for sustainable development (Marras et al., 2017b).

Rubber is another line of business using marble waste (Agrawal et al., 2004a, 2004b) utilized natural stone waste generated out of block cuts through a gangsaw machine at natural stone processing plants in the north of India. The reason why this specific waste was chosen is that marble waste is cheaper than other fillers and can be of use as a filler in half through chemical enrichment of slurry waste and poses no environmental threat, unlike other fillers. The study concludes that marble powder can be use as a filler which is cheaper than other commercial fillers, such as whiting. In addition, the chemical treatment of marble powder does not yield any significant improvement. The researchers conclude, as a part of the study, that marble powder can substitute for carbon black in various rubber-made items. In a similar study, Marras and Careddu (2018) investigated the usability of marble slurry waste in the tire industry. In this study, the structural effect of calcium carbonate particles on tire mixtures is examined and it is concluded that waste can be used as a filler material in the tire industry.

Marble waste is used in many industries, and is also preferred in the ceramics industry as a raw material (Bilgin et al., 2012; Gupta et al., 2009) and as a decorative item. Yeşilay et al. (2017) analyzed, as a part of their study, the use of marble waste out of Afyon-Iscehisar (Turkey) for stoneware transparent glaze. Their study suggests that marble out of Afyonkarahisar-Iscehisar can be of use for its contribution to color diversity in colored transparent stoneware glaze, and that it causes no problem at the production phase.

In terms of quantity, the cement industry is one of the top lines of business for the use of waste generated by natural stone quarries and natural stone processing plants. The production of a ton of cement takes almost a ton of limestone. Cement plants, which require a massive quantity of $CaCO_3$, and consume a great deal of limestone, can use over 1000 tons of marble waste in a day. The most important parameter herein is the shipment cost to transport marble waste from quarries or plants to locations where it is to be reused. Yurdakul and Akdaş (2017) analyzed as a part of their study, whether marble quarry waste, which is generated in Bilecik-Sogut (Turkey), can be of use as a raw material in the cement industry. In their study, they put large-sized marble waste, larger than 50 cm, through a crusher in a quarry and carried out a project to transport 600 tons per shift (8 h) to a cement plant situated almost 25 km away. The project helped to recover 350,000 tons of marble waste which was used in the cement industry.

Soil amendment is another way to make use of marble waste. Soil pH is one of the most important factors for plant growth. In their study (Tozsin et al., 2014), analyze the use of marble waste for the neutralization of soil acidity. This study makes use of both marble quarry waste and marble cutting waste. Based on the findings of the study, both quarry and cutting waste cause soil pH to rise from 4.71 to 6.36 and 6.84 respectively. The study also suggests that both quarry and plant marble waste can be useful for soil amendments. There are other studies over the use of marble waste for soil rehabilitation. Babu and Mary Rebekah Sharmila (2017), report that the marble powder obtained by cutting and polishing marble contains high amounts of calcium, silica and alumina, and when 3–15% marble powder is added to the soil, the soil properties are improved especially in terms of Atterberg limits.

Marble waste is also a material which can be turned into original marble again. Barani and Esmaili (2016) conducted a study regarding the production of artificial stone slabs out of marble sludge, and using 50% of stone sludge, 12% of ground quartz, 25% of waste glass and 13% of resin. Based on the slabs they produced as a result, they made a comparison with natural stone for its density, water absorption and flexure, compressive and tensile strength. In conclusion, they underline that artificial stone slabs are perfect for covering walls or paving floors. In a similar study, Silva et al. (2018) managed to produce artificial stone out of 80% wt marble particles and 20% wt epoxy resin. They highlight the fact that the artificial stone they produce can be of use for civil construction applications from the perspective of physical and mechanical qualities.

While marble waste is scarce in quantity, it is used in manure, paper and water-based paint industries (El-Haggar et al., 2017). As shown by the results of their study and others, marble waste is utilized in relatively low quantities for such production.

In addition to these studies, another subject in the literature is the residual sludge emanating from stone work activities. Careddu and Dino show that this waste is an economic and environmental problem for the natural stone industry and for the community at large (Careddu and Dino, 2016). In this study, the researchers categorize sludge waste according to its origin and evaluate the waste from carbonate rocks and silicate rocks separately.

A good understanding of waste generation processes in all processes related to natural stone, is one of the most important stages for waste reuse or waste disposal. In his study, Buyuksagis examines the waste generation processes and the benefits to be obtained through changes in these productions (Buyuksagis, 2009).

Studies in which marble waste is evaluated regionally are also included in the literature (Marras et al., 2010). These researchers studied on natural stone by-products from the quarries and marble processing facilities in the Orosei district (North east Sardinia). As a result of this study, they concluded that micronized calcium carbonate can be used in the paper, plastic and rubber industries.

There have been several studies on what quantity of marble waste would reduce the waste generated by the huge marble industry and what conditions it would take for waste to be reused and this can be found in the literature. However, the literature offers a number of studies regarding how to use waste for the construction, agricultural and chemical industries whereas there have been few studies investigating what quantity (tones or %) of waste could be of use for various industries. In the literature, there are no studies published on the determination of the amount of monthly waste produced in a natural stone processing plant, or its regional distribution. As a part of this study, solid and sludge waste generated in a day, in line with monthly production capacity, was quantified on site at nineteen natural stone processing plants. The study also analyzes the monthly quantity of natural stone waste and how it is generated. In addition, an on-site analysis was performed on waste generation mechanisms inside the plants, and waste generated by block cuts and slab block sizing was quantified. Quantitative classification of waste is another important course of action. As a part of the study, a methodology was adopted for the classification of waste, based upon on-site observations at plants. It is thought that further insight into waste disposal could be achieved once it is quantified.

The entire natural stone production process is extremely important in terms of a sustainable environment and sustainable production. Natural stone waste can be used in many different areas of industry. Converting waste into a resource in another production process, besides its economic benefits, also promotes sustainability (Marras et al., 2017a).

The natural stone production process that needs to be evaluated together with many environmental factors and the storage of waste arising from natural stone production processes are also regulated by law, especially in the European Union (European Commission, 2018). Turkey's accession process to the European Union will also be required to comply with set legal requirements. The EU's raw material policy envisages the maximum use of secondary raw material in manufactured goods (Korobiichuk et al., 2017). Mining and marble quarrying should be performed in a sustainable way. This is the same for all manufacturing industries. As mining is the consumption of non-renewable resources, the concept of sustainability becomes even more important (Careddu et al., 2018). One of the aims of this study is to draw attention to sustainable production, environmental problems and the storage of stone waste in Bilecik.

2. Materials and method

This study was designed to cover natural stone/marble processing plants that currently operate in the city of Bilecik that meets almost 11% of marble production needs in Turkey. Firstly, the natural stone processing plants were designated based on the records of Bilecik Chamber of Commerce and Industry (phase of access to records and situational analysis). One of the criteria to select the plants in question was to make sure that each had a monthly production for 5000 m^2. The plants are production plants with industrial operations. Secondly, an on-site visit was paid to the natural stone plants, which were previously designated in the city and districts of Bilecik, and a number of preliminary interviews and studies were conducted. Thirdly, the solid waste generated by the natural stone processing plants was quantified as a part of the study. At this stage, hourly, daily and monthly measurements were performed at the designated plants. At the fourth phase, physical-mechanical and chemical characteristics (uniaxial compressive strength, intensity, porosity, and Schmidt hammer hardness index) as well as mineralogical and petrographic characteristics of waste were determined. In the final phase, the data collected from the third and fourth phases was analyzed.

2.1. Data collection

As a part of the study, all of the natural stone processing plants in the city of Bilecik affiliated to the Organized Industrial Zone of Bilecik were selected as the population. The study made use of the storage capacity of waste storage containers and a visual analysis of shipment trucks for waste shipped from each plant and of official tonnage records. The waste storage containers are situated near a machine at the plants and dumped into a truck by the end of each shift. Each plant keeps records of official documents for trucks dispatched to waste landfill sites. The type of material processed, monthly production volume, co-operation attitude of operators, their data on waste generation and whether they were in the possession of production figures were taken into account in the selection of nineteen marble processing plants. All of the plants are situated within the confines of the city of Bilecik. The plants usually process stone from marble quarries across Bilecik. However, the blocks produced in marble quarries based in Bilecik are not only processed in Bilecik, but are also exported to various countries around the world as a raw material. All of the plants mostly produce items of 30 × 60 cm, 60 × 60 cm and 40 × 40 cm in size and 2 cm and 3 cm in thickness. The plants are located in downtown Bilecik and in the districts that are at most, 40 km from Bilecik. In large capacity natural stone processing plants, orders are generally not affected by seasonal conditions. In particular, in businesses that supply stone to large warehouses abroad and those which work on ordering projects, the amount of production generally does not vary greatly for months. However, it should not be forgotten that the data obtained in this study was collected between March and August, due to the large number of enterprises and the spread of geography covering a whole city. As marble waste also comprises the production figures of the plants, the data is expressed in numbers, without the individual plants being identified.

Inspections made at the natural stone processing plants show that three different types of marble from the Bilecik region have been processed at all of the facilities in question. These three different types of stone are shown in Fig. 2.

These three stone examples, given in Fig. 1 represent the main characteristic structure of the entire region. The remaining stone does not vary considerably in terms of color and structural properties. There are different shades of these three types of stone. The detailed physical and mechanical properties of these three stone types are given in Table 2.

Within the scope of this study, a measurement form was created to collect demographic information of the companies as well as data on the production capacity and the amount of waste, in order to determine the total amount of waste. The measurement form included company information, organizational information, employee information, production information, and the waste information of each plant. After the draft form was prepared, measurements were made at three processing plants for trial purposes, and the data measurement form was re-edited and finalized in accordance with information from the companies concerned. After the final measurement form was created, measurements were made at each processing plant to determine the amount of waste and to classify the waste, with samples being taken for these measurements. The samples were taken from both sludge waste and solid waste. At each company, the amount of waste was measured on both an hourly and a daily basis. In addition, the waste formation mechanism was also examined.

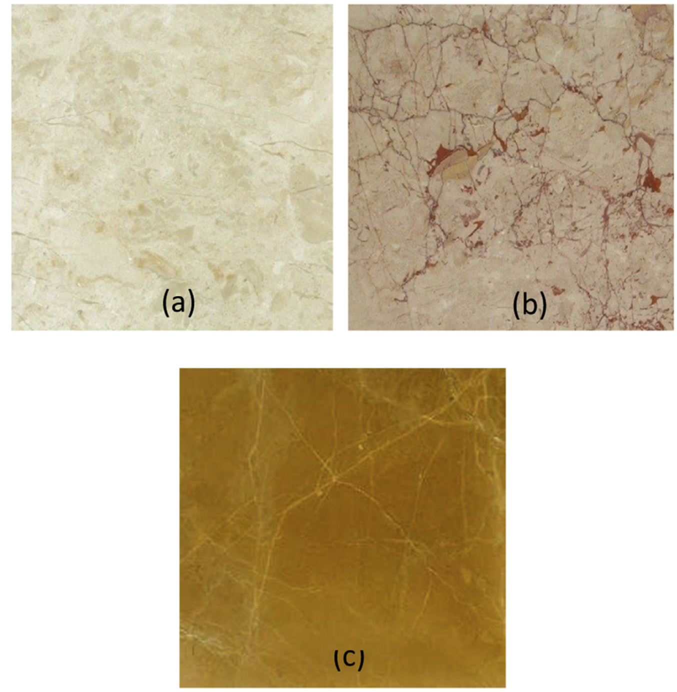

Fig. 2. The characteristic stone of the Bilecik region includes (a) Crema Nouva, (b) Bilecik Rosalia, (c) Golden Tobacco.

2.2. Analyses and materials description

2.2.1. Physical-mechanical properties of marble waste

The physical and chemical properties of waste are very important in terms of determining the area of use for natural stone waste. In this study, solid samples from marble processing plants were classified. The solid samples of three natural stone types, that representing all the samples were subjected to uniaxial compressive strength testing (according to TS EN 1926), bending strength test (according to TS EN 12372), a Shore hardness test (according to ISRM), water absorption (TS EN 13755), apparent density and open porosity (TS EN 1936) testing.

The physical-mechanical properties of the solid waste samples collected from all of the companies located at three different regions, are given in Table 2.

The samples generally display all the characteristics of limestone.

2.2.2. XRD analysis

An X-Ray powder diffraction (XRD) analysis was performed on the dewatered slurry from the plants. Since the samples from the natural stone processing plants had similar characteristics, the XRD results of only three stone types are given in Fig. 2 to prevent complexity in manuscript. The stone types given in Fig. 3 are of the samples in Fig. 2. The scans were collected within a range of 10–80° (2Θ). Diffractograms of each sample were prepared using X'pert Highscore and ICDD 2003 databases.

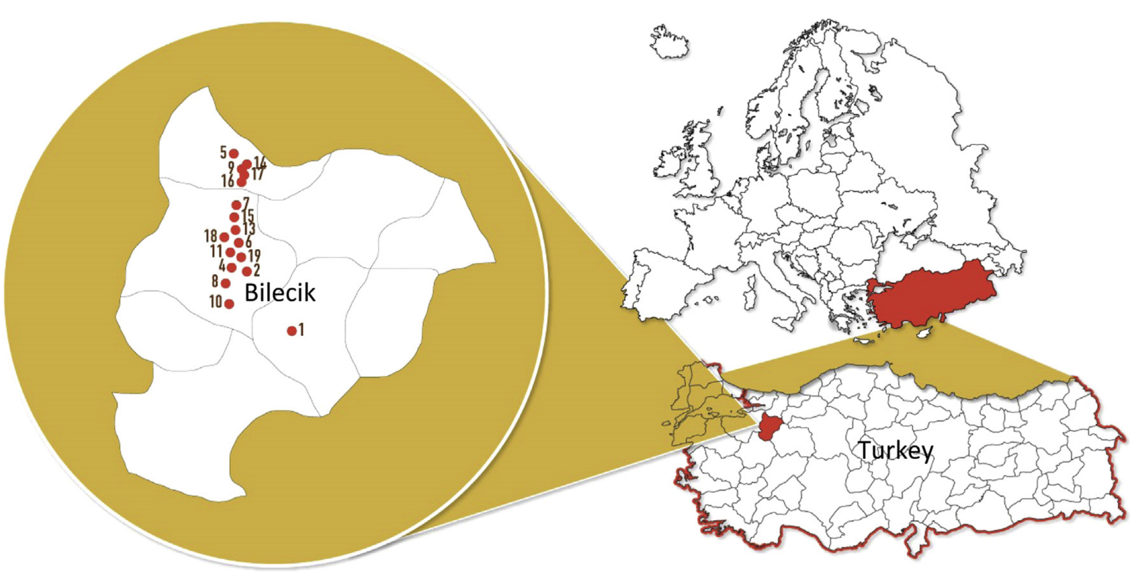

Fig. 1. Geographic location of Bilecik and natural stone processing plants.

Table 2
Physical-mechanical properties of Crema Nouva (a), Bilecik Rosalia (b), Golden Tobacco (c).

Sample	σ_c (MPa)	BS (MPa)	SH (MPa)	A_b (%)	ρ_b(g/mm^3)	ρ_0(%)
a	130.03 (±23.25	11.59 (±1.18)	46.15 (±4.70)	1.64 (±0.78)	2.57 (±0.076)	3.84 (±1.69)
b	109.69 (±25.95	12.54 (±1.70)	60.55 (±3.73)	0.04 (±0.01)	2.70 (±0.004)	0.11 (±0.04)
c	144.48 (±22.96)	15.43 (±4.08)	59.17 (±2.65)	0.64 (±0.10)	2.65 (±0.011)	1.85 (±0.24)
Test Standart	TS EN 1926	TS EN 12372	ISRM	TS EN 13755	TS EN 1936	TS EN 1936

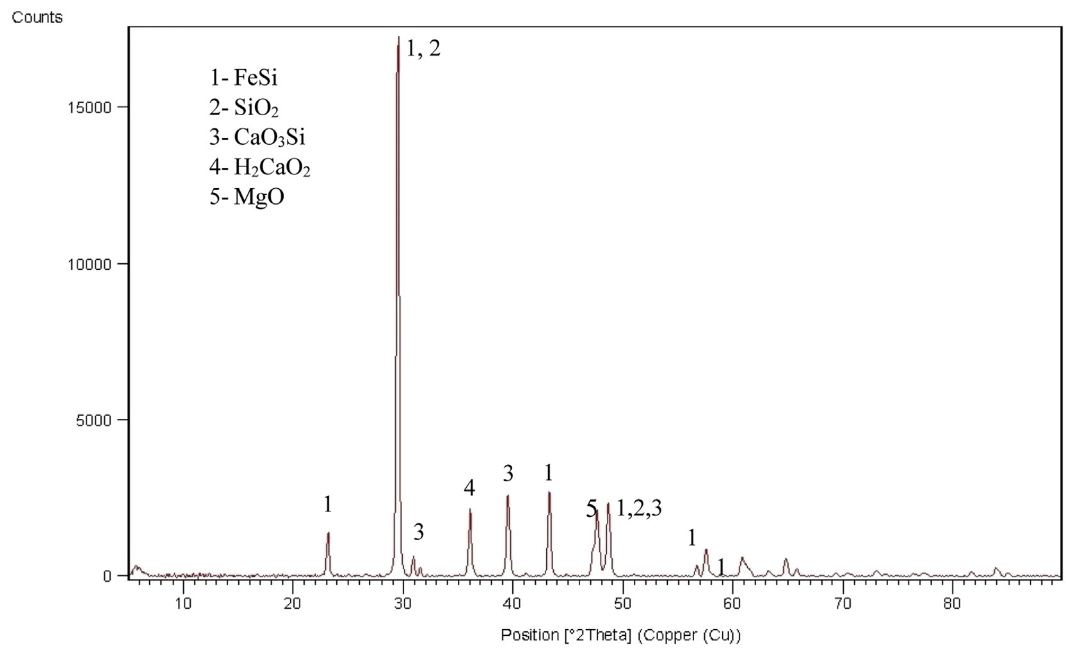

Fig. 3. XRD analysis of sample (a) Bilecik Beige.

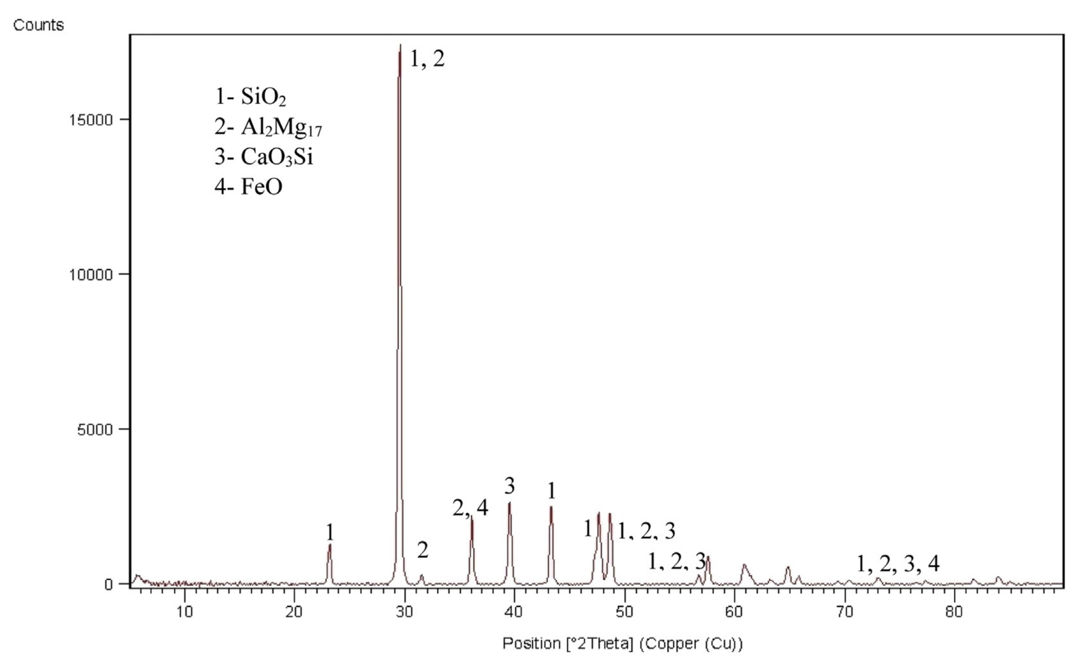

Fig. 4. XRD analysis of sample (b) Bilecik Rosalia.

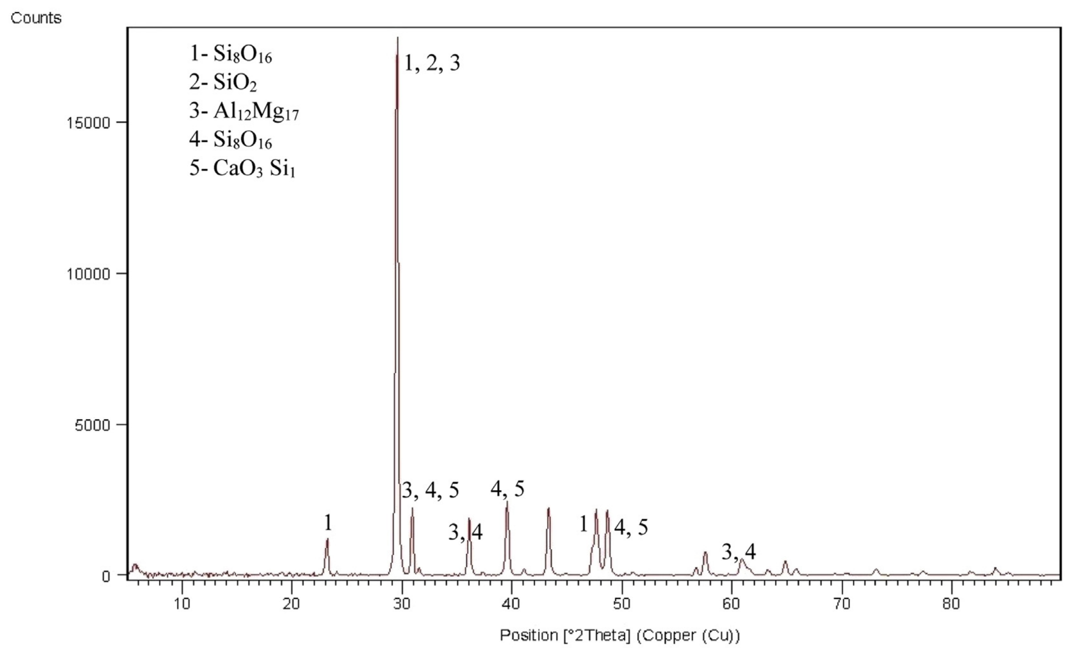

Fig. 5. XRD analysis of sample (c) Golden Tobacco

The Analysis results for samples a, b and c are shown in Figs. 3–5, respectively.

3. Results and discussion

3.1. Monthly amount of waste generated by natural stone processing plants

In this study covering the Bilecik province, where the most important marble sites are located, the data obtained from natural stone processing plants was evaluated. In marble production from natural stone, a large amount of waste is generated due both to quarrying activities and natural stone processing activities. In this study, focusing on waste generated in the natural stone industry, the aims is to determine the amount and quality of waste specifically generated in the Bilecik province. The daily amount of waste generated was measured for one month to determine the amount of generated waste. Data relating to processing capacity and details of the daily amount of waste generated are given in Table 3.

When the natural stone waste in the Bilecik province is examined, it can be said that there is a statistically significant relationship between production capacity and the amount of waste generated ($R^2 = 0.86$) (Fig. 6). The amount of waste can be directly associated with the monthly production capacity. Furthermore, there are also other important factors that can affect the amount of waste; for example, cutters used in natural stone processing; the physical and mechanical properties of natural stone to be processed; whether epoxy is used or not; the skills of personnel (i.e. operators) involved in the natural stone cutting process; and dimensions requested by customer and dimension-related waste. In certain cases, although the amount produced is low, the amount of waste may be higher with the same production process (Processing

Table 3
Average daily amount of marble waste generated in the Bilecik province.

Processing Plant	Establishment year	Closed Area	Block Cutter	Gangsaw Machine	Production Amount (m^2/month)	Solid waste (tones/day)	Sludge Waste (tones/day)
1	1988	6500	4	2	22,000	47	39
2	2008	4500	3	2	6700	21	20
3	1998	10,000	4	3	25,000	51	44
4	2014	2700	1	2	7000	17	16
5	1998	20,000	2	1	9000	27	23
6	2006	2970	3	1	18,000	34	31
7	2015	1200	3	1	13,500	31	35
8	2015	1500	4	1	12,000	28	32
9	1995	3000	3	1	8000	24	30
10	2007	1800	3	3	12,000	34	32
11	2009	1200	2	1	7000	24	25
12	2004	2000	2	1	12,000	26	27
13	2003	1300	2	1	10,000	23	20
14	1994	3000	2	2	17,000	33	35
15	2002	3910	2	1	12,000	27	23
16	1988	10,000	4	3	10,000	26	26
17	2011	800	2	1	9000	20	18
18	2012	1676	2	1	8000	18	15
19	2012	2100	2	1	8000	22	20
					Total	**533**	**511**

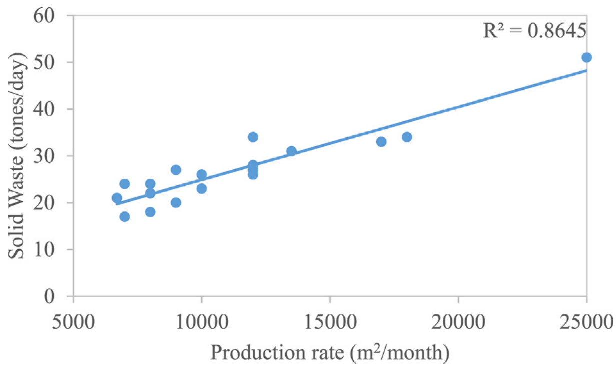

Fig. 6. The relationship between production amount and solid waste amount.

Plant No: 9, 18, 19).

In almost all processing plants (except for Processing Plants No 7, 8, 9, 11, 12 and 14), the amount of solid waste was higher than the amount of sludge waste. This could be due to the fact that the amount of waste generated from block shaving, plate/slab trimming, selection and miss-shaping was higher than the amount of waste from cutting losses. If the amount of sludge waste is higher than the amount of solid waste in a natural stone processing plant, this could be due to the fact that the blocks in that particular plant are more smoothly-shaped and that the stone cut has better physical-mechanical properties and no fractures.

It has been noted that the highest amount of waste was generated by Plant No. 1, with monthly production capacity of 22,000 m^2 generating 47 tones solid waste and 39 tones sludge waste per day. As a result of the on-site observations made in the natural stone processing plants, it was also found that the plants where block cutters were heavily used (Plans 1, 3, 8 and 16) generated more waste compared to other plants. This can be explained by the fact that the plants using block cutters (ST) cut boulders, that the blocks were of small-size and the loss amount was high.

Moreover, cutting tool (gangsaw blade, circular saw blade and suchlike) thickness can be considered as the most important parameter affecting the amount of waste. Since a block cutter has a relatively higher cutting tool thickness than a gangsaw machine, the plants using only block cutters generate more waste, leading to a decrease in production efficiency.

It should be noted that approximately 1044 tons of marble waste is generated daily in Bilecik. The generated waste is stored at an inert waste site in Bilecik (Fig. 8). However, reuse of these waste becomes difficult after being sent to the waste site because the waste from the natural stone processing plants is mixed in waste transportation trucks and dumped at the waste site without being sorted (Figs. 7–8).

This waste, which has different chemical and physical properties, should be sorted for reuse in specific fields. However, since the $CaCO_3$ ratio, as the most basic property of natural stone is considered by some industries, such as the cement industry, this will not cause any problem. When the average amounts of waste are examined, it can be highlighted that approximately 28 tons of solid waste and 27 tons of sludge (solid + liquid) waste are generated daily for each plant. These figures are extremely important in determining the total amount of waste. It should be emphasized that, as production capacity increases, the amount of waste also increases. Determining the causes of waste formation is as important as determining the amount of waste generated in natural stone processing plants. Parameters that play a role in waste formation are explained below.

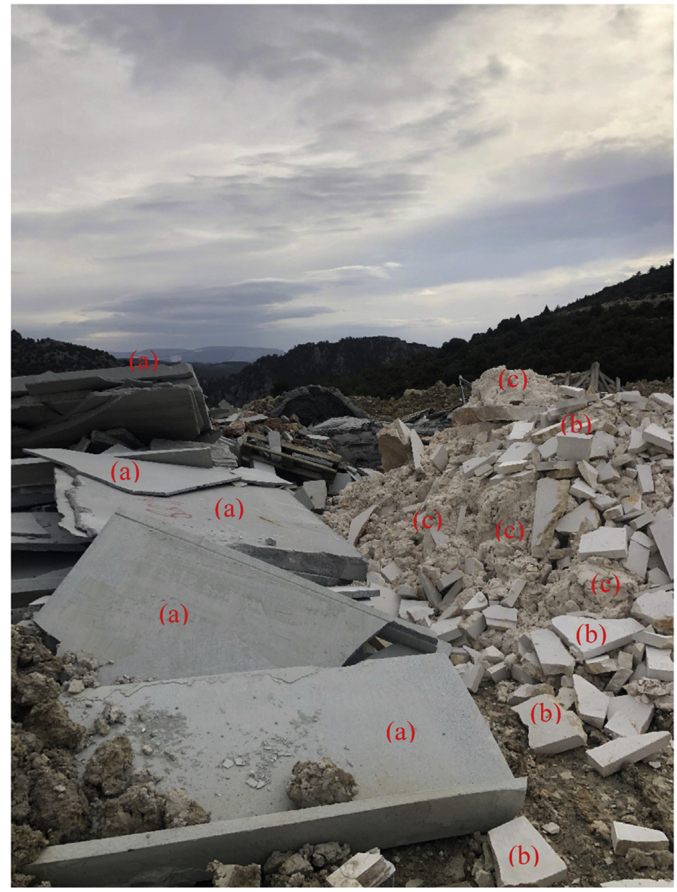

Fig. 7. Overview of different marble types in the natural stone waste collection sites in Bilecik (a) block cutter waste of more than 1 m in size (b) waste of mainly less than 30 cm in size (c) sludge waste.

3.2. Measurements made in natural stone processing plants and waste formation

3.2.1. Cutting tool thickness

One of the most important factors affecting the amount of waste generated in natural stone processing plants is the thickness of the cutting tools (segment, saw blade, wire and suchlike) used related to the operating mechanism of the cutting process. Fig. 7 shows a theoretical cutting model of a block of 1 m in width, length and height (1 m^3). The calculations given in Fig. 7 are based on thickness values of two and 3 cm the most-commonly used values in flooring and coating processes in the natural stone industry. In natural stone processing processes, the most-commonly used block cutter to cut a block into plates is a gangsaw machine. Segment thicknesses of the gangsaw machine used in the natural stone industry vary between 5 and 8 mm. However, the segment thickness is shown as 5 mm in the created theoretical model (Fig. 9).

According to data obtained from Fig. 9, the on-site measurements and the observations from the natural stone processing plants, the amount of waste generated due to blade thickness was calculated. 41 cuts were made to obtain a plate with a thickness of 2 cm from a block of 1 m in width and height. 40 slabs, each with a thickness of 2 cm were obtained as the result of these cuts. This means that a groove with a volume of 0.2 m^3 converts into waste at each cut (a total of 41 cutting grooves).

According to Fig. 9, approximately 0.2 m^3 material in a block of 1 m^3 was converted into waste, except for the block edge trimming

Fig. 8. Overview of the marble waste site in Bilecik (heap height is approximately 65 m).

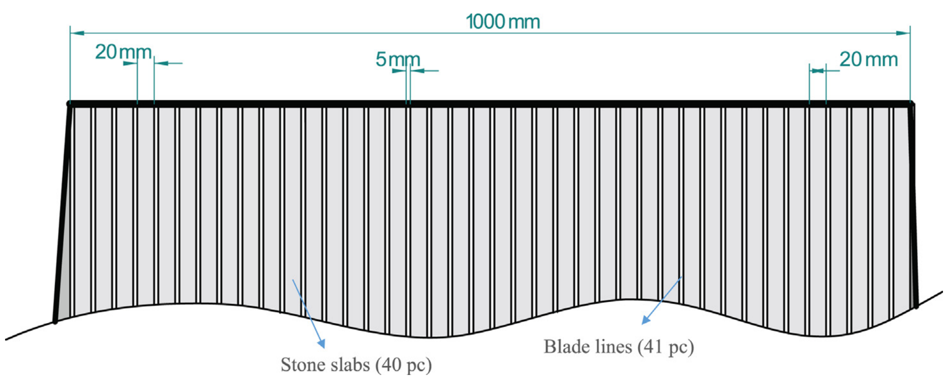

Fig. 9. Cutting lines in a block with a volume of 1 m^3 (Block dimensions 1 × 1× 1 m) and slab production with gangsaw machine (slab thickness 2 cm, segment thickness 5 mm).

process. In other words, a 20% cutting loss was experienced in a block of 1 m^3. Approximately 20% of block volume was converted into cutting waste in the first cutting of any raw block, except for structural defects of natural stone without performing any dimensioning process. If the density of marble, the most commonly-used source in the natural stone market is taken as 2.7 tones/m^3, approximately 540 kg waste is generated from a block of approximately 1 m^3, converted into slurry.

Every edge of each block is also cut by a minimum 3 cm for edge trimming. It should also be noted that the amount of solid waste increases due to the trimming process. It was observed that almost of the blocks were trimmed by approximately 3–8 cm in the measurements made at the plants.

Table 4 shows the amount of waste generated from the cutting process using gangsaw machine and the percentage of loss by different block sizes. In general, blocks with a volume of 2–6 m^3 are cut using gangsaw machine. Each block from the quarry is cut into one or more pieces. Table 4 shows the amount of loss for blocks of different sizes (1 m^3, 2 m^3, 6 m^3). The column next to the block size column in the table shows the amount of waste resulting from the trimming process using a gangsaw machine (Fig. 10).

In a cutting process using a gangsaw machine, the cutting thickness usually ranges between 2 and 5 cm. However, the calculations given in the table are made based on a thickness of 2 cm. The amount of trimming waste was 0.06, 0.12 and 0.19 m^3 for blocks of 1, 2 and 6 m^3, respectively. In cutting processes using gangsaw machine, slabs with a thickness of 2 or 3 cm are cut depending on the requirement of the final product. In a block of 1 m^3, 41 cuts are made for shaping purposes to obtain slabs with a thickness of 2 cm (Fig. 9). If the thickness of each blade is 5 mm, 0.265 m^3 of a natural stone block of 1 m^3, 0.41 m^3 of 2 m^3 and 1.23 m^3 of 6 m^3 is converted into waste as a result of the shaping cutting. This waste is discarded as slurry. When expressed as a percentage, 27% of a block of 1 m^3 is discarded as cutting waste. In other words, a block of 1 m^3 generates approximately 716 kg of waste in total. When a block of 6 m^3, the largest and most commonly-used block size that can be cut by a gangsaw machine, is cut to obtain slabs with a thickness of 2 cm, approximately 3834 kg

Table 4
The amounts of waste generated with a gangsaw machine with various block sizes and percentages of loss.

LxHxW	Trimming waste m^3 (solid + slurry)	Number of Cuts for Dimensioning		Dimensioning Waste (m^3)		Total Waste (m^3)		Total Dimensioning Loss (%)		Total Sludge Waste (kg)	
Block Size (m)	Slab Thickness (cm)										
	2cm-3 cm	2 cm	3 cm	2 cm	3 cm	2 cm	3 cm	2 cm	3 cm	2 cm	3 cm
1 × 1 × 1	0.06	41	29	0.205	0.145	0.265	0.205	26.50	20.50	716	554
2 × 1 × 1	0.12	41	29	0.41	0.290	0.530	0.41	26.50	20.50	1431	1107
3 × 2 × 1	0.19	41	29	1.23	0.870	1.420	1.06	23.67	23.67	3834	2862

Fig. 10. Gangsaw machine cutting and waste from gangsaw machine (unshaped slabs on the right and left side).

of natural stone waste is generated.

When a block with a volume of 1 m^3 is cut using block cutters, machines commonly-used in natural stone plants, thirty-five plates are obtained due to the thickness of the circular saw blade (8 mm). The amount of waste in the block is approximately 28% with 36 cuts. If the density of marble, the most commonly-used stone in the natural stone market, is taken as 2.7 tones/m^3, then approximately 756 kg waste is generated from a block of approximately 1 m^3, which is converted into slurry.

It should be noted that the amounts are a minimum one because the bottom section of the block of about 20 cm cannot be cut in the cutting processes using 8 mm block cutters, causing an increase in the amount of waste. Since block trimming is performed under normal cutting conditions, the stone with a thickness of approximately 3 cm directly converts to waste in any edge trimming processes. In addition, when using block cutters, since a second side cut is made in order to obtain a plate from the block by separating the plate from the main block, the number of cuts and the amount of waste increase depending on the size of the desired product.

Approximately 30 m^2 of intermediate stone product is obtained per 1 m^3 in gangsaw machine cutting while an intermediate stone product of 17–22 m^2 is obtained per 1 m^3 when the same process is performed with block cutter. The loss is directly associated with the saw thickness and the physical-mechanical properties of the stone. This ratio is about 80% for gangsawing.

3.2.2. Irregularity of the block surfaces in natural stone processing plants

Shaping errors occur in the block when cutting the blocks from natural stone quarries using a diamond wire cutting method dependent on an operator's skill, overall cutting performance of the diamond wire, natural stone discontinuities and color selection. In addition, the blocks arriving at the factory are not in regular shapes in general due to the such things as the irregularities of the fractures separated from the main rock and rock discontinuities characterization (Fig. 11). For this reason, trimming at a thickness of 1–3 cm is performed on block edges regardless of the cutter used (Fig. 11b). As can be seen in Fig. 10b, the thickness of the upper section in the first calibration cutting is about 2 cm and it can reach 6 cm depending on the irregularity of the block at the bottom. In this cutting, a cutting loss of about 0.06 m^3 is formed in the first cutting performed to obtain a 1 m^3 of block and this section is directly discarded as solid waste. This is caused by the difference between the top and bottom thickness of the cut piece. An operator starts cutting the top section at a minimum thickness to enable a lesser amount of waste to be generated from the stone (Fig. 11b).

(a)

(b)

Fig. 11. Irregularities and shaving in blocks.

Approximately 0.02 m^3 of this 0.06 m^3 of waste is converted to slurry due to the saw thickness, while the remaining part forms solid waste. Following the block trimming, regular plate cutting in the desired dimensions are initiated. The waste generated contains only saw waste since the block trimming is performed on raw rock. It consists completely of rock waste.

3.2.3. Formation mechanism of plate dimensioning waste in natural stone processing plants

In natural stone processing processes, plates/slabs exiting block cutters (gangsaw machine and block cutter) are shaped and converted into a product. Although the plate dimensions vary depending on the block from the quarry, slabs are obtained from gangsaw machine while plates are obtained from block cutter.

Slab/plate shaping waste is generated depending on the dimensions of the product to be cut unless a crush or a crack exists in the stone. As can be seen in Fig. 9, an example of the mechanism of waste formation from the slab produced in the gangsaw machine is presented. As can be seen in Fig. 12 the shaping of a standard slab of 1.2 × 1.2 m dimension is presented. The size of the product is 30 × 30 cm, and the blade thickness is 5 mm. As shown in Fig. 12, a total of twelve products can be obtained from a plate of such dimensions, while the remaining 28.5 cm plate is converted into waste if a smaller product is not produced. In practice, this waste is converted into another product for reuse.

For a slab with dimensions of 1.2 m × 1.2 m x 2 cm (width x

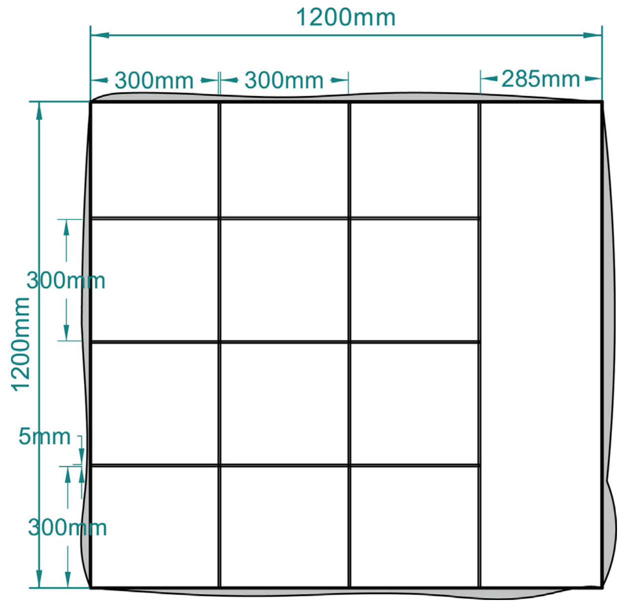

Fig. 12. Mechanism of formation of slab shaping waste (product dimensions of 30 × 30 cm; slab dimensions of 1.2 × 1.2 m).

length x thickness), the cutting loss occurs when cutting products of 30 × 30 cm of different dimensions are shown in Table 5.

As shown in Table 5, waste of 8–9 kg is generated from processing a slab of approximately 1.44 m^2 in dimension, commonly used in floor and wall covering operations. Table 5 shows only cutting waste regardless of the physical and mechanical properties of the natural stone cut. As can be seen in Table 5, a product of around 0.72–1.08 m^2 in size, is obtained from a slab of 1.44 m^2 and the remaining part is converted into waste.

3.3. Waste sorting

In this study, the waste was sorted into two different categories, based on the results obtained.

3.3.1. Solid waste

3.3.1.1. Reusable waste. Usually, these are regular and irregular shaped pieces which can be used in floor covering smaller than 30 × 30 varying thickness depending on the processing machine. Among this waste, the pieces with four sides have a regular shape can be reused according to the market demands. In addition, those with regular or irregular shape can be recut and used as input, especially in the mosaic industry. The most decisive factor is whether the sale price of the product to be created by reuse will meet the cost of cutting and marketing the product. The colored stone and white stone, currently preferred in the natural stone market, meet this requirement (Fig. 3).

3.3.1.2. Waste that is relatively costly to convert to another product. These are normally irregular shaped pieces of varying thickness and containing natural crushes. The natural stone waste containing colors and patterns, which are not demand in another market, are included in this group. All the regional stone discussed in the study belongs to this group except for Golden Tobacco stone. Golden Tobacco is a rare type of stone preferred in the natural stone market since it is a type of stone that can be used in combination with black and white colored stone due to its contrast effect (Fig. 13, top left).

Of the solid waste, that which can be converted to waste after being subjected to a surface treatment process and that can be converted to an input for another natural stone industry, is considered as quality waste in terms of both productivity and national economy. Quality waste is formed after time consuming and costly treatments such as honing, polishing and flame finishing. Considering the results and observations in this study, 40% of the solid waste was of a quality waste level and this finding is significant. Further studies are required to bring such waste into production, without being consigned to waste, in order to be used in sectors other than the natural stone industry (cement, aggregate and others).

In addition, the limestone with beige characteristics in the Bilecik province cause the formation of structures with cracks and crushes due to its nature. The formation of waste should be prevented in all plants using methods such as epoxy, bundle epoxy and netting. According to the results obtained from this study, quality waste has a thickness of 2 cm (2nd grade), up to sizes of 2–50 cm. Non-quality waste is generated from block cutters and gangsaw machines during the conversion of the main block into slabs/plates. Such waste typically has sizes of 15–80 cm, thicknesses of 2–3 cm, depending on the production process, and is not polished or subjected to any surface finishing process. Such waste constitutes the largest part of the total waste, proportionally. In addition, reusing this waste, in collaboration with public and private sectors, should certainly be considered.

3.3.2. Sludge waste

Another result is that the amount of sludge waste almost equals the amount of solid waste. In figures, twenty-five tons of slurry is generated daily in a normal natural stone processing plant. Sludge waste is normally placed at the bottom of waste trucks and then solid waste is dumped on top of it. As a result, solid waste and slurry (or sludge waste) are stored in the waste storage site without being sorted (Fig. 7). Slurry, referred to as sludge waste, has the same physical-mechanical properties as solid waste. In light of information in the literature, it is possible to use almost all waste directly in the cement and construction industry. However, the use of such waste is extremely limited due to its high moisture content and since it is not produced in a single region in sufficient amounts. As a result of on-site inspections in the waste storage site in the Bilecik province, it was found that the waste from the plants is not sorted and granite waste, limestone waste and other natural stone waste are kept as mixed. In this case, its reuse becomes impossible.

Table 5
The amount of waste generated when cutting a 1.2 × 1.2 m slab.

Product dimension (cm)	Number of trimming cuts	Trimming waste (m^3)	Number of cuts for dimensioning	Dimensioning waste (m^3)	Total waste (m^3)	Total waste (kg)	Total dimensioning waste (%)	Remaining part (m^3)	Final product (m^2)
30 × 30	4	0.00288	6	0.00072	0.00400	9.720	0.125	0.00684	1.08
40 × 40	4	0.00288	4	0.00048	0.00336	9.072	0.117	0.00936	0.96
60 × 60	4	0.00288	2	0.00024	0.00312	8.424	0.108	0.01428	0.72
40 × 60	4	0.00288	3	0.00036	0.00324	8.748	0.113	0.01428	0.72

Fig. 13. Solid waste of different sizes and characteristics in the waste storage containers at the plant.

4. Conclusion

The studies conducted so far are studies investigating generally how natural stone waste can be used in which industries. The generation of waste as a result of natural stone processing is inevitable. Except for waste generation due to the structural defects of natural stone as well as end user demands, waste is generated at each phase of the cutting process where cutting tools (diamond tools, wire, saw blades and so on) come in contact with the stone. It is concluded in this study that waste of average 540–756 kg is generated for 1 m^3 block cuts and that, generally an average of approximately fifty tons of waste (solid and sludge) is generated daily in a plant with a processing capacity of 2000–3000 m^2/day. Given the average number of natural stone processing plants in Turkey, which is around 3000, it should be noted that the amount of waste generated is sizeable. In the literature, there are few studies where the amount of waste is calculated and discussed regionally. According to the amount of waste produced, it is really important to create waste dumps that comply with legal norms and, more importantly, are suitable for the reuse of waste.

Waste generated in natural stone processing plants in the Bilecik region is collected in storage areas and stored randomly without sorting. The pollution impact of this waste is not great, but storing such large-volume waste is challenging. Therefore, the amount of waste generated can be reduced through changes in cutting technology, especially in the cutting phase where approximately 40% of the waste is generated. For example, the waste generated may be expected to reduce by 50% if the segment thickness in large diameter (1000–2300 mm) saw blades used worldwide can be decreased from 8 mm to 4 mm.

The amount of waste can be directly associated with monthly production capacity. Furthermore, there are also other important factors that can affect the amount of waste. These include the cutters used in natural stone processing, the physical and mechanical properties of the natural stone to be processed, whether epoxy is used or not, skills of the operators involved in natural stone cutting process, and the dimensions requested by the customer. Moreover, it is extremely important to store sludge and solid waste, especially at local waste dumps, operating some form of sorting system. The waste generated at natural stone processing plants is currently transferred to waste dumps without sorting. As a result, the waste from all plants is randomly discharged in waste dumps. Therefore, it is extremely difficult to remove and recycle the different types of waste from these waste dumps. Careful sorting would enable the million tons of waste collected at waste dumps to be transferred to new usage areas that could be determined in the medium and long term.

The Bilecik region is a highly developed ceramic industry area. More detailed studies on the use of marble waste in the ceramic industry, which is quite high in quantity, and the utilization of waste locally, are important fields of future studies.

It is vital to reorganize existing waste dumps, especially considering European Union laws, and to ensure that future waste dumps comply with such European Union laws. In addition, it is necessary, for a sustainable environment, to reorganize the solid waste area of the Bilecik region through future studies and to seriously reconsider this area, where hundreds of thousands of tons of waste are deposited every year.

CRediT authorship contribution statement

Murat Yurdakul: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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