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Life Cycle Assessment of Marble Plate Production

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Abstract: Sustainable use of natural resources in the production of construction materials has become a necessity both in Europe and Turkey. Marble plate is a construction material that is frequently preferred because of its neutrality and durability for a long time. Beside these technical specifications, its environmental performance should also be considered. From this point of view, it was aimed to investigate environmental impacts generated from marble plate production by using Life Cycle Assessment methodology. The functional unit was determined as to be 1 m^2 of marble plate. Foreground data were obtained from a marble production plant which has a quarry in Bilecik city and background data was gathered from Ecoinvent database. The CML-IA method included in the SimaPro 8.2.0 software was used to calculate environmental impact categories. Results showed that marble quarry (the unprocessed product before the marble plate) and electricity are the main contributors to the environmental effects of the marble plate. For marble quarry, the effects of diesel and electricity are significant. Abiotic depletion potential, global warming potential, and human toxicity potential were the main environmental loads of the marble plate production. The sensitivity of the results was determined by using the data obtained from ELCD database in addition to Ecoinvent and it was seen that there is no so much difference between the results obtained by using two different databases. Additionally, environmental performance of the marble plate was compared to the ceramic tile since they are both floor covering materials and alternatives of each other. This comparison showed that fossil fuel-based abiotic depletion potential of marble plate (24.7 MJ) was higher than fossil fuel-based abiotic depletion potential of ceramic tile (0.935 MJ). On the other hand, GWP and HTP values of the ceramic tile (7.97 kg CO_2 eq. and 1.17 kg 1,4-DB eq., respectively) is greater than GWP and HTP values of the marble plate (3.96 kg CO_2 eq. and 0.554 kg 1,4-DB eq., respectively).

Mermer Plaka Üretiminin Yaşam Döngüsü Değerlendirmesi

Anahtar Kelimeler
Yaşam döngüsü değerlendirmesi,
Mermer üretimi,
Yapı malzemeleri

Özet: Yapı malzemelerinin üretiminde doğal kaynakların sürdürülebilir kullanımı, hem Avrupa'da hem de Türkiye'de gerekli hale gelmiştir. Mermer plaka, doğallığı ve dayanıklılığı nedeniyle uzun süredir sıklıkla tercih edilen bir yapı malzemesidir. Bu teknik özelliklerin yanı sıra, mermer plakanın çevresel performansı da dikkate alınmalıdır. Bu noktadan hareketle, Yaşam Döngüsü Değerlendirmesi yöntemiyle mermer plaka üretiminden kaynaklanan çevresel etkilerin araştırılması amaçlanmıştır. Fonksiyonel birim olarak 1 m^2 mermer plaka seçilmiştir. Çevresel etki kategorilerini hesaplamak için, SimaPro 8.2.0 yazılımında yer alan CML-IA yöntemi kullanılmıştır. Elde edilen sonuçlar, mermer bloğu ve elektriğin, mermer plakanın çevresel etkisine neden olan ana sebepler olduğunu göstermiştir. Mermer blok (mermer plakadan önceki işlenmemiş ürün) için dizel ve elektriğin etkileri önemlidir. Abiyotik tükenme, küresel ısınma potansiyeli, insanlar üzerine toksisite potansiyeli, mermer plaka üretiminin başlıca çevresel yükleridir. Mermer plakanın çevresel performansı ayrıca, ikisi de yer kaplama malzemesi ve birbirinin alternatifi olması açısından seramik karo ile de karşılaştırılmıştır. Karşılaştırma, mermer plakanın fosil yakıt bazlı abiyotik tükenme potansiyeli (24,7 MJ) değerinin seramik karonun fosil yakıt bazlı abiyotik tükenme potansiyeli (0,935 MJ) değerinden daha yüksek olduğunu göstermiştir. Diğer yandan, seramik karonun diğer etki değerlerinin (GWP, HTP), mermer plakanın değerlerinden yüksek olduğu görülmüştür.

1. Introduction

Marble is newly built rocks that are formed by the crystallization of dolomitic limestone and/or limestone at specific ratios, different pressures, and temperatures. In other words, they are carbonated rocks that can be extracted as appropriate blocks, can be cut in the desired form, can be optionally polished, and composed of dolomite and/or calcite minerals. It is possible to list marble use areas as follows;

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interior, facade and floor covering in buildings, stairs, roads, park and garden decoration, artistic structures like sculpture, monumental tomb, heat and sound insulation in buildings [1].

When examining into the marble world market, China has 8,000 marble quarries and 1,000 kinds of forms, and it is in the first line of marble production. This order is followed by Italy, Spain, India, Brazil, Korea, and Turkey. Italy, China, India, Spain, Brazil have a great importance in export. In import, China, Italy, Japan, France, Saudi Arabia, Taiwan, Germany, Belgium, Spain are the leading countries [2].

Turkey has reserves of 4 billion m^3 of cuttable marble, 1 billion m^3 of granite and 2.8 billion m^3 of travertine. These values are equivalent to 40% of all natural stone reserves in the world. Marble reserves in Turkey have approximately 650 different textures and colors. The intensive regions of marble production and reserves are Bilecik, Konya, Eskişehir, Afyon, Rize, Çanakkale, Denizli, Balıkesir, Ordu, Kırklareli, Tokat, Aydın, İzmir, Diyarbakır, Gümüşhane and the surrounding areas [3]. Turkey's most known marble types in the international arena are Gemlik Diabase, Tiger Skin, Elazığ Cherry, Manyas White, Bilecik Beige, Supren, Akşehir Black, Afyon Sugar, Denizli Travertine, Aegean Rose, and Milas Lilac. Turkey’s export profile shows a continuous increase, especially in processed marble. The most important markets for Turkey are China, Germany, Saudi Arabia, Italy, the USA, and Israel. In addition, block marble and raw platters are exported to Israel, Taiwan, Italy, and Hong Kong and hard stone and granite are exported to Austria, Germany, and the Netherlands.

Marble is a valuable construction material and from an ecological point of view, construction materials should be considered in terms of their potential effects and influence on the surrounding environment [4].

Construction materials and therefore buildings have long lifetimes, so estimating the process from cradle-to-grave is difficult. During the lifetime, buildings change in function and unit. These changes are more remarkable than materials’ initial state because most of the environmental effects are seen at usage stage. Assessing the environmental loads is crucial to minimize their environmental effects [5].

Building industry uses a vast amount of raw materials and it requires high energy consumption. The extraction of minerals reduces the exergy of the planet’s natural reserve. It is possible to reduce the environmental impacts of materials with giving them a second life cycle. For instance, concrete cause important CO_2 emission and reusing concrete as a filler material in infrastructure can reduce its emissions in quarry and process stages. Using the best available techniques, eco-innovative plants, if it is possible, recycling and reusing can reduce impacts of construction materials significantly [6].

Life cycle Assessment (LCA) is one of the tools that helps to achieve sustainable building practices. LCA is a method that is used to evaluate environmental loads throughout the life of processes and products. The assessment contains the whole life cycle of a product, a process or a system including the extraction and processing of a raw material, manufacturing, transport and distribution, use, reuse, maintenance, recycling and final disposal. LCA is a widely used methodology because it applies the system, impact assessment, and data quality in an integrated way [7]. The life cycle approach must help decision-making when selecting the best technology available and minimizing the environmental impact of the buildings through their design or refurbishing [8].

Building materials have become a hot topic in LCA studies in recent decades. Several building materials such as glass, aluminum alloy, stone, and ceramic materials have been analyzed by using the LCA method [9-13]. Furthermore, some LCA studies have been conducted for a number of ceramic products [14-19]. Additionally, LCA has also been largely applied to determine the environmental impacts of the cement production [20-26]. However, there are limited LCA study of marble production due to the difficulties of obtaining data. Nicoletti *et al.* (2002) [18] conducted a comparative LCA between marble and ceramic tiles to determine the best environmental profile and hot spots of the two systems. According to the analysis, the marble tile has a better environmental profile. In the study of Liguori *et al.* (2008) [27], the energy and environmental controls of the marble plate and marble block produced in Custonaci, Italy, were simply compared with those produced in the city of Carrara. However, environmental impacts were investigated in terms of energy consumption, wastewater, soil air emissions, and resource consumption. Traverso *et al.* (2010) [28] used LCA to analysis the energy and environmental performance of Sicilian marble.

There are many studies about comparative analysis for different building materials. Borjesson *et al.* compared CO_2 emissions of building with a timber and a concrete frame. According to the results, fossil fuel-based energy consumption is 60-80% higher in concrete material production [29]. Similarly, Gustavsson *et al.* [30] studied about energy and CO_2 emission changes in a wood and a concrete based building for manufacture and usage stages. For all stages, wood has a lower effect.

Xing *et al.* [32] compared a steel-framed and a concrete-frame building in China. While energy consumption per area is higher in concrete-frame, in usage stage, steel-framed building has a larger effect for whole life cycle state according to the energy consumption and emissions [31]. Asif *et al.* calculated the CO_2 emissions of eight construction materials (ceramics tiles, timber, concrete, plasterboard, aluminum, glass, slate, damp course, and mortar). Accordingly, concrete has the highest embodied energy (61%), and ceramic tiles (15%) and timber (14%) tag after. Concrete is also responsible for 99% of CO_2 emissions of construction processes, especially in production stage.

Additionally, studies about flooring materials' environmental effects and to compare their results are present. Potting and Blok investigated four types of flooring material (linoleum, tufted carpet with a woolen pile, tufted carpet with a polyamide pile and cushion vinyl) according to their environmental effects. Results show that main effects are due to the energy consumption and the best profile is seen at linoleum's [33]. Jönsson *et al.* [34] compared the environmental effects of three flooring materials linoleum, vinyl flooring, and solid flooring during their life cycle. According to the results, solid wood flooring proved to be clearly the most environmentally sound flooring. Linoleum was found more environmentally than vinyl flooring.

The aim of this paper is to realize an LCA for marble plate to investigate its environmental performance. Marble mining industry, is one of the emergent industries in Turkey, which needs new approaches, techniques, and researches. Though there are plenty of LCA works about mining industries, there are fewer LCA works and literature data about marble mining which has an important place in Turkey among other mining sectors. Additionally, environmental performance of marble plate was compared with ceramic tile like many other comparative LCA studies although it is not a part of the aim of the study.

2. Material and Method

ISO 14040 and ISO 14044 guidelines are used for LCA that consists of four steps; goal and scope definition, inventory analysis, impact assessment, and interpretation [35-38].

2.1. Goal and scope definition

The goal of this study was to determine the environmental burdens of marble production and to compare with ceramic tile by using LCA methodology. The functional unit is 1 m^2 floor covering. A cradle to gate LCA was performed and use and end of life stages were not considered. System boundaries are given Figure 1.

2.2. Life cycle inventory

Data regarding the marble plate production process (foreground data) were obtained from a marble production plant which has a quarry in Bilecik city and background data was gathered from Ecoinvent database.

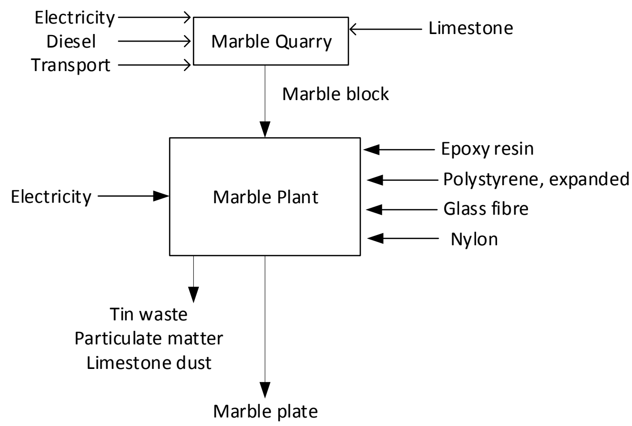

Figure 1. System boundaries of marble plate production

For the production method, diamond wire cutting method is used. Block marbles that are cut by a diamond wire are transported to production plant. Diamond wire cutting method consists of steel wire, diamond dots, roller machine, and auxiliary equipment. Cutting process includes several stages which are perforation of vertical and horizontal holes onto rock, cutting with diamond dotted wire, splitting of cutted block from parent rock and resizing of blocks. In order to cool the wire used during cutting process and remove tiny particles sourced from process, water is spilled onto the wire. Hence, a small amount of dust and waste are generated. The particulate matter (PM) measurement was taken from the air emission measurement report of the plant. The marble block production data are given in Table 1. After cutting process, marble plates are reinforced by using epoxy resin. Epoxy resin is used to fill crackles onto stone and bring durability to marble. It is formed with a mixing of resin and hardener agent. Reinforced marble plates are dimensioned by bridge-cutting machine and placed into wooden cases. Marble plate production data is given in Table 2 assuming that thickness was 1.8 cm and the average weight 48.6 kg/m^2 [18].

Table 1. 1 kg of marble block production data

Data component	Amount
Inputs	
Limestone (kg)	1
Diesel consumption (L/kg marble block)	8.16
Electricity consumption (kWh/kg marble block)	0.024
Transport (km. kg marble block)	50
Outputs	
Marble block (kg)	1
Mining waste kg marble block (kg/kg marble block)	14.5

Marble quarries are often located in high and rough terrain, and there is a very high need for water in the mills, so water is a costly input. For that reason, marble production plants use recycled water (100%) Therefore, in the study, it is assumed that there is no wastewater generation from the production.

Table 2. 1 m² of marble plate production data

Data component	Amount
Inputs	
Marble block (kg/m²)	85.54
Epoxy resin (g/m²)	25.27
Glass fiber (g/m²)	111.29
Polystyrene, expanded (g/m²)	55.89
Nylon (g/m²)	3.89
Electricity consumption (kWh/m²)	2.04
Outputs	
Product marble (m²)	48.6
Limestone dust (g/m²)	36.94
Tin waste (from epoxy resins packaging) (g/ m²)	0.425
Particulate matter (PM) (g/m²)	0.160

2.3. Life cycle impact assessment

LCA calculations were carried out using SimaPro 8.2.0 LCA software. At the impact assessment stage, the CML-IA baseline (v.3) method was applied for impact categories of abiotic depletion (elements and fossil fuel, ADP_e and ADP_{ff}), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity (FAETP), terrestrial ecotoxicity (TEP), photochemical oxidation potential (POP), acidification potential (AP) and eutrophication (EP). Only one impact category was not used in this study, Marine Aquatic Ecotoxicity (MAETP), since there is no direct impact on the marine environment. CML as a midpoint method was chosen for its common units for impact categories.

Electricity profile data was adapted from Günkaya *et al.* (2016) [39] by using the electricity generation mix percentages of Turkey for the year of 2017. Considered electricity generation mix is composed of 35% natural gas, 24.6% hydraulic, 31% coal (mainly hard coal, imported coal and lignite), 10.9% wind and 2% geothermal.

3. Results

A cradle-to-gate LCA results are presented in Table 3. According to the Table 3, ADP_{ff}, GWP and HTP are the main environmental loads of the marble production.

Distribution of main environmental loads to the processes is shown in Figure 2. At first sight, it can be concluded that marble block production and electricity use for plate production have almost the same percentages in the distribution. When Figure 2 was investigated in detail the followings were observed:

Fossil fuels basis ADP mainly resulted from marble block production and production of consumed electricity. Diesel and electricity consumptions have an important role for the ADP_{ff} impact of the marble block. ADP_{ff} impact of electricity production mostly results from the resource extraction stages of coal mining.

Table 3. Characterization results of marble plate production

Impact category	Unit	Total
ADP_e	kg Sb eq./m²	3.36E-06
ADP_{ff}	MJ/m²	48.3
GWP	kg CO_2 eq./m²	3.96
ODP	kg CFC-11 eq./m²	1.46E-07
HTP	kg 1,4-DB eq./m²	0.554
FAETP	kg 1,4-DB eq./m²	2.76E-02
TEP	kg 1,4-DB eq./m²	3.22E-03
POP	kg C_2H_4 eq./m²	6.55E-03
AP	kg SO_2 eq./m²	2.78E-02
EP	kg PO_4^{---}eq./m²	2.47E-03

GWP was affected mainly by the extraction of limestone from quarry and use of electricity for cutting of the blocks to the plates. Diesel use and electricity consumption required for the industrial equipment were almost about the same GWP effects in the extraction process.

HTP impacts of marble quarry and electricity were 49% and 48%, respectively. Sulfur dioxide and nitrogen oxides generated from the burning of diesel for extraction, lignite, coal, and natural gas for electricity generation are the cause of HTP.

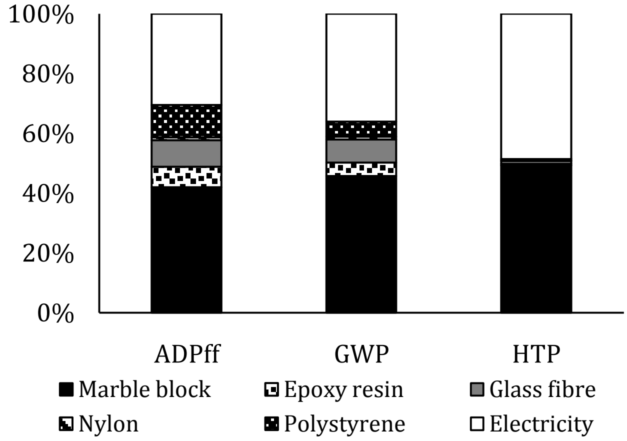

Figure 2. Distribution of main environmental impacts of marble production to the processes

4. Sensitivity Analysis

The sensitivity analysis due to the uncertainty of input data has been conducted. Therefore, in addition to Ecoinvent, ELCD and USLCI databases were investigated. ELCD database was matched the input data but for USLCI there was so much lack of data. The data gathered from ELCD was analyzed and compared to the results of Ecoinvent (Table 4). Table 4 shows that, there is no so much difference between the results obtained by using Ecoinvent and ELCD databases.

5. Comparison with Ceramic Tile

In this part of the study, marble plate was compared with ceramic tile. Marble and ceramic plates are both floor covering materials and they are alternatives of each other. Turkey has an important role with its marble and ceramic sectors.

Table 4. Characterization results of marble plate production

Impact Category	Unit	Ecoinvent	ELCD
ADPe	kg Sb eq./m^2	3.36E-06	3.49E-07
ADPff	MJ/m^2	48.3	43.2
GWP	kg CO_2 eq./m^2	3.96	3.68
ODP	kg CFC-11 eq./m^2	1.46E-07	1.05E-07
HTP	kg 1,4-DB eq./ m^2	0.554	0.244
FAETP	kg 1,4-DB eq./m^2	2.76E-02	2.61E-02
TEP	kg 1,4-DB eq./m^2	3.22E-03	1.99-03
POP	kg C_2H_4 eq./m^2	6.55E-03	6.48E-03
AP	kg SO_2 eq./m^2	2.78E-02	2.53E-02
EP	kg PO_4^{---}eq./m^2	2.47E-03	2.23E-03

Marble is produced by using natural resource (limestone) whereas ceramic plate production contains natural resources and also additives. The marble production is simpler than the ceramic plate production. Marble plate is heavier than ceramic tile for the same surface area. Ceramic tile production is under environmental control. For that reasons, they were compared to determine their strengths and weaknesses to each other in terms of environmental impacts. It was assumed that the marble and ceramic were used for the same function. The functional unit of comparison is 1 m^2 floor covering. The data for 1 m^2 ceramic plate with a weight of 18 kg is given in Table 5 [32]. Wastewater generation for 1 m^2 ceramic tile production is 12 L [15]. Wastewater emissions were calculated by using wastewater volume and the discharge limits given by Turkish Regulation on Water Pollution Control.

LCA comparison results of marble plate and ceramic tile productions are presented in Table 6. According to the Table 6, potential of marble plate (24.7 MJ was higher than that of ceramic tile (0.935 MJ. On the other hand, GWP and HTP values of ceramic tile (7.97 kg CO_2 eq. and 1.17 kg 1,4-DB eq., respectively) is greater than those of marble plate (3.96 kg CO_2 eq. and 0.554 kg 1,4-DB eq., respectively). When the results tables of software were investigated it was seen that GWP values of ceramic tile was resulted from high amounts of CO_2 emissions whereas HTP was mainly resulted from hydrogen fluoride (HF) and wastewater emissions, respectively.

6. Discussion and Conclusion

Sustainable use of natural resources and to protect the environment in the production of construction materials has become a necessity both in Europe and Turkey. Construction products in Europe should have European Conformity (CE) and Environmental Product Declaration (EPD) certificate, an independently verified and registered document in line with the European standard EN 15804. An EPD certificate can be created by performing an LCA study. But there is no an available EPD certificate for marble plate in Turkey.

Table 5. Ceramic production data [15]

Data component	Amount
Inputs	
Masses raw materials (kg / m^2 ceramic tile)	
Clay	10.47
Feldspar	10.29
Quartz	2.21
Frit raw materials (g / m^2 ceramic tile)	
ZnO_2	100
Zirconium	40
Colemanite	160
Dolomite	210
Borax	140
Sand, quartz	320
Feldspar	280
AlO_2	10
Energy (kJ / m^2 ceramic tile)	
Heat (by natural gas)	7950 (average value, a.v.)
Electricity	210 (a.v.)
Outputs	
Atmospheric emissions (g/m^2 ceramic tile)	
PM	6 (a.v.)
HF	0.4
Pb	0.02
CO_2	7893
SO_2	6
NO_x	4.86
VOC	525.87
Waste materials (g/m^2 ceramic tile)	
Glazing wastes	100
Sludge	120 (a.v.)
Scrap tiles	1000 (a.v.)
Wastewater emissions (mg/m^2 ceramic tile)	
Chemical Oxygen Demand (COD)	960
Suspended solids	1200
Pb	12
Cd	1.2
Zn	36

Table 6. Comparison of marble plate and ceramic tile production

Impact Category	Unit	Marble plate	Ceramic tile [32]
ADPe	kg Sb eq. /m^2	3.36E-06	5.4E-05
ADPff	MJ/m^2	48.3	0.955
GWP	kg CO_2 eq. /m^2	3.96	7.97
ODP	kg CFC-11 eq. /m^2	1.46E-07	5.62E-09
HTP	kg 1,4-DB eq. /m^2	0.554	1.17
FAETP	kg 1,4-DB eq. /m^2	2.76E-02	7.48E-03
TEP	kg 1,4-DB eq. /m^2	3.22E-03	3.6 E-04
POP	kg C_2H_4 eq. /m^2	6.55E-03	5.18E-04
AP	kg SO_2 eq. /m^2	2.78E-02	9.99E-03
EP	kg PO_4^{---}eq. /m^2	2.47E-03	6.82E-04

In this study, marble plate production, as a construction material, was investigated in terms of environmental performance by using LCA. Results showed that the effects of marble block and electricity were significant in the marble plate production. For marble block, the effects of diesel and electricity were significant.

In addition to environmental observations, marble plate was compared to the ceramic tile. Since they are both floor covering materials and alternatives of each other. Results show that fossil fuel based abiotic depletion value of marble plate is higher than the ceramic tile. On the other hand, global warming and human toxicity values of ceramic tile are greater than those of marble plate. Fossil fuel consumption and global warming potential impacts are primarily focused among the environmental concerns. For that reason, to make a certain conclusion to suggest to prefer marble plate or ceramic tile is inappropriate.
Marble plate producer should take an action to reduce its energy consumption. One of the ways to reduce environmental impact values is to use renewable energy sources because of the electricity affecting environmental impact categories. Use of renewable sources will enhance the environmental performance of the marble production. Solar energy panels are proposed for electricity generation in marble production. Moreover, usage of the new industrial equipment can be beneficial to lower diesel consumption can also affect the environmental performance. On the other hand, ceramic tile producers should revise global warming potential of their production by developing new projects. In addition to this, it's known that HF emissions of ceramic sector cause environmental problems as observed in this study. For that reason, some additional cautions should be taken to reduce these emissions.

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