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Investigating the Recycling of Andesite Waste from Quarry Mines in the Production of Artificial Stone: An Analysis of Environmental, physical-mechanical and Economic Issues

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Abstract

Environmental issues related to mine wastes have highlighted the importance of waste recycling. A study was conducted on sand mines in Kurdistan province, Iran, focusing on the construction of artificial stones from effluent to minimize environmental impact. The research included environmental, physical-mechanical, and economic analyses, using the Analytic Hierarchy Process (AHP) for environmental assessments. Tests on density, water absorption, and strength showed that stones containing effluents were superior to other products. Increasing effluent percentages did not significantly affect density but improved water absorption and strength. Artificial stones containing 40% effluent demonstrated the greatest resistance and the least water absorption. This formulation achieves compressive strengths of 36.07 MPa, flexural strengths of 15.09 MPa, and tensile strengths of 1.89 MPa. Furthermore, it possesses a dry density of 2.33 gr/cm³, and a water absorption rate of 3.82%. Additionally, stones with effluent demonstrated better resistance to corrosion acid. The research methodology employed in the environmental analysis involved the application of the Analytic Hierarchy Process (AHP). Findings from environmental studies indicated that the volume of waste emerged as the most significant criterion with 27.3% weight when evaluating the selection of construction products that are environmentally compatible. Furthermore, research in environmental studies indicates that artificial stone is at least 10% more preferred than natural stone, 48% more preferred than tile, and 63% more preferred than brick. The analysis within the economic section demonstrated that the production of artificial stone incorporating waste, which achieved an internal rate of return of 138%, was more cost-effective than comparable products.

1. Introduction

Nowadays the issues Environment have a special place among various indicators of sustainable development, and the development of economic and social indicators depends on sustainability. In this regard, the mining industry has also received special attention due to the amount of waste it leaves in the environment. In recent years, several methods for recycling and reducing the effect of Mineral tailings have been suggested. One of the mentioned methods is the use of waste in the artificial stone production industry (engineered stone). Using wastes and turning them into artificial stone particles for direct objects can be one of the economic methods appropriate to manage mineral waste, it was considered. Synthetic stone is composed of mineral by-products, fillers, colorants, and a binding agent, which may be either resin polymer or cement. The production of artificial stone from tailings and waste materials employs two primary methodologies: cement-based and resin-based processes. Overall, both the natural and synthetic stone sectors generate significant quantities of waste, which can be categorized into various forms such as powder,

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aggregate, and larger fragments. This waste is produced during the stone cutting process in manufacturing facilities or during extraction activities in mining operations. The environmental implications of these waste materials present numerous challenges for the future.

Iran generates approximately five million tons of waste each year, primarily consisting of stone fragments and sludge resulting from stone cutting processes.

Employing mining waste as a raw material for the production of artificial stone diminishes the reliance on natural stone and other traditional construction materials. This approach not only conserves natural resources but also aids in the protection of ecosystems and mitigates the environmental consequences linked to mining and quarrying operation [1]. Given the extensive operations of the stone industry in the country, coupled with prevailing environmental issues and the growing demand for stone products, it is imperative to undertake research focused on the development of artificial stones [2]. The production of artificial stone from mining waste represents a significant advancement in sustainable construction materials. This approach not only addresses environmental concerns by reducing waste disposal issues but also offers economically viable and mechanically robust alternatives to traditional materials. This research delves into the physical-mechanical properties, environmental benefits, and economic feasibility of artificial stone produced from mining waste.

Technology produced rock artificial, or so-called engineered stone, for the first time in Italy in 1960. In the same decade, the first factory in this country began producing this stone, an activity driven by the idea of creating artificial rock which improved building industry and the need for this product was developed. In 1991, Slim and colleagues successfully manufactured clay bricks exhibiting significant resistance using sludge derived from construction materials [3]. Subsequently, in 2003, Galtakis and Raka investigated the creation of artificial stone utilizing limestone dust. Galtakis and his team incorporated limestone in their artificial stone production process, resulting in a product with a strength exceeding 7 Mpa [4]. In 2005, the researchers used artificial stone in the reconstruction of 19th and 20th-century buildings, including the Florentine palace [5]. Also, Lee et al. made artificial stone slabs, 55% waste granite, and 37% glass powder mixed with polyester resin, and the result was a stone with a density of 2.5 gr/cm3, high strength of 148 MPa and water absorption coefficient of 20% [6]. In 2009, Alzboon and Mahasneh conducted a study in Jordan that examined the impact of incorporating stone quarrying sludge into concrete, focusing on its effects on concrete resistance [7]. In 2011, the researchers used stone powder in concrete and mortar as a substitute for natural sand in Bangladesh, and the results showed that concrete containing stone powder has a compressive strength of 15% higher than the sample made with natural materials [8]. In 2015, Maria Stefano used artificial stone as an alternative in the reconstruction of historical monuments. In this research, artificial stone produced by mortar technique and based on inorganic adhesives was investigated; based on this method a unique method for designing artificial stone similar to the natural stone of that area is needed in each study site [9]. In 2016, Barani and Esmaili in another research used marble waste and glass waste along with quartz powder to make artificial stone under the conditions of pressure and vibration in a vacuum environment [10]. In addition, a study conducted in 2017 focused on the physical and mechanical assessment of artificial marble. Through the application of tests measuring density, water absorption, porosity, bending strength, and compressive strength, the findings revealed that the artificial stone exhibited significant strength characteristics alongside minimal water absorption [11]. In 2018, Peng and Qin made artificial slates using sio2 waste and quartz sand. They used tests of uniaxial compressive strength, triaxial bending strength, bulk density, and water absorption test to determine the structural characteristics of the samples to conclude that the compressive strength of artificial stone is higher than natural stone [12]. In 2018, Carvalho et al. used granite waste in constructing two samples of artificial stone. In this work, granite particle waste was used in amounts of 85 and 90% together with epoxy resin to fabricate novel artificial stones [13]. In a study conducted by Amaral et al. in 2019, an artificial stone sample was created comprising 90% mineral dust by weight and 10% epoxy resin by weight. The resulting stone underwent physical and mechanical analyses, which revealed a shear strength of 32 MPa and a reduced porosity percentage [14]. In 2019, Gomez and colleagues developed a novel artificial stone composed of 85% granite waste and 15% epoxy resin. They conducted a comparative analysis of the physical and mechanical properties of this artificial stone against those of natural granite. The results indicated that the density, water absorption, and porosity of the artificial stone were measured at 2.24 grams per cubic centimeter, 0.19%, and 0.42%, respectively. Furthermore, the three-point bending strength of the artificial stone met the standards set for natural stone, demonstrating its considerable resistance [15].

Additionally, some wastes occur due to the inability to transport and move stones in the extraction and cutting process, as well as the slurry obtained from stone-cutting industries. The production capacity of travertine in Iran is also very high due to the presence of rich mines in the country. According to published statistics, Iran is one of the largest producers of travertine and, consequently, one of the largest producers of waste from this mineral in the world. Despite efforts to develop and improve the travertine extraction and processing industry, waste management of travertine remains a major challenge. In many areas, travertine waste is irregularly dumped, which can lead to soil, water, and air pollution [16]. In Iran, the silica tailings of the Alborz factory have been used to produce stone. The results showed that artificial stone has a water absorption ability close to zero and tensile and compressive strength is higher than natural stone.

Utilizing mining waste as a raw material for the production of artificial stone presents considerable cost advantages. Mining waste is typically abundant and low-cost, which helps to lower overall production expenses in comparison to conventional materials. Furthermore, incorporating waste materials into manufacturing processes reduces the necessity for costly extraction and processing of raw materials [17]. The demand for sustainable and eco-friendly construction materials is on the rise, fueled by heightened awareness of environmental concerns and regulatory requirements. Artificial stone derived from mining waste is ideally suited to fulfill this demand, providing a competitive alternative to traditional materials while supporting a circular economy [18].

Recent advancements in production technologies, including geo-polymerization and epoxy resin matrix systems, have enhanced both the quality and scalability of artificial stone manufacturing. These innovations facilitate the mass production of high-performance materials, rendering them suitable for a diverse array of construction applications [19]. Artificial stone developed from iron ore residue and epoxy resin has demonstrated compressive strengths comparable to natural stone, with values around 26.78 MPa [20]. Table 1 provides a summary of the mineral waste materials utilized in the manufacturing of artificial stone.

Table 1. A Comparative study of artificial stone fabricated from mining by-products

Mining waste material composition	Properties of artificial stone	Reference
Quartzite waste and vegetable polyurethane	Flexural strength: 17.31 MPa; Water absorption: 0.13%	[18]
Granite waste and glass waste in epoxy	Flexural strength: 32.77 MPa; Water absorption: 0.13%	[19]
Steel slag and bio-based phenalkamine	Compressive strength: 19.87 MPa; Bending strength: 26.78 MPa	[20]
Mining tailings and geopolymers	Compressive strength: 8–37.5 MPa; Water absorption: 0.14%–0.69%	[21 & 22]
Iron ore residue and epoxy resin	Compressive strength: 26.78 MPa; Water absorption: 0.21%	[23]

In this research aims to reduce the environmental effects and increase productivity and efficiency in the production process of artificial stones. The study focuses on using andesitic wastes of quarry sand mines in Kilak, a village in the central part of Sanandaj in Kurdistan province of Iran. Three different perspectives including environmental, rock mechanics and economic aspects have been developed in this research. Numerous sand mines in Kurdistan province of Iran have significant production of a large amount of sand annually. Among different shapes of waste, fifteen percent is in the form of effluent-containing and useless mud which is not applied in the construction industry. The present study aimed to implement environmental, physical-mechanical, and economic analyses on the construction of artificial stones from andesitic effluents of quarry sand mines to reduce the environmental impacts of waste. For this purpose, the present study performed the andesitic effluent sampling of a sand production complex in Kilak village in the Naran area.

2. Methodology

In this section, the methodology used for different parts of environmental, rock mechanics, and economic studies will be presented. The method of research in the environmental section was the development of the Analytic Hierarchy Process (AHP). The tests of density determination, water absorption, rock strength, and chemical resistance were examined in the physical and mechanical analysis. In economic studies, the absorption costing method was applied to estimate the cost of artificial stone production containing effluent wastes. In the environmental studies section, the focus was on a statistical population comprising engineers and mining specialists from the Kurdistan province. Data collection was executed through meticulously crafted questionnaires, and the subsequent analysis employed multi-criteria decision-making techniques based on the analytical hierarchy process. To assess the physical characteristics of the rock containing andesite residue, five physical and rock mechanics tests were conducted, including density determination, water absorption, bending strength, and acid resistance tests. A total of 120 samples, both laboratory and industrial, were evaluated according to eight distinct mixing plans. Furthermore, an economic analysis of the production costs associated with artificial stone made from waste was performed, comparing the expenses of producing artificial stone with those of natural stone and stone devoid of waste. This economic evaluation was grounded in the production costs from stone quarries and artificial stone manufacturing facilities located in Sanandaj city. Each section is elaborated upon with detailed findings presented.

The case study mine field and stone cutting facility is situated 3 kilometers from Kilak village in Sanandaj city, encircled by prominent mountains, including Kertobi and Sangar mountains. Kilak is a village in Naran Rural District, in the Central District of Sanandaj County, Kurdistan Province, Iran. The region's geomorphology features a variety of chemical and biochemical clastic sediments, which are silicified in the upper strata, alternating with radiolarian sediments. The local rock Facies comprises the irregular formation and the Zagros thrust Zone, both of which are dated to the Cretaceous and Eocene geological epochs. The rock sediments and their exposures consist of gray limestones and red marbles, commonly referred to as the red stone of Sanandaj, alongside andesitic intrusions and volcanics, also dating to the Eocene. Volcanic rocks primarily consist of basalt, tuff, and shear tuff, characterized by greenish-gray intrusive formations that exhibit a medium to coarse-grained texture. Additionally, these rocks include granite and diorite, along with sedimentary layers featuring calcareous shales interspersed with lime and radiolarite, which are part of the ophiolitic sequence. Overlying the volcanic rocks and tuff are sedimentary units composed of gray and black shales, accompanied by fine-grained siliceous sandstone that ranges in color from white to gray. The mine has an annual extraction capacity of 70,000 tons. According to the detailed plan of the current operator, the Sanandaj Bardineh Mining Company is set to establish and operate a sand and gravel producing plant within the designated area, adhering to permitted distances, and will extract minerals in a quarry format, thereby significantly contributing to the supply of aggregate materials for the Sannandaj province.

In this research, artificial stone samples were created using quarry sand mining waste as a cement base combined with resin. The components of these artificial stone samples included mining waste (serving as a substitute for rock powder), sand, Portland Type 4 cement, liquid resin (Polycarboxylate Ether), and pigment. Instead of using rock powder, mining effluent was utilized as a filler material in this study. Eight different mixing designs with varying percentages of waste were selected, as detailed in Table 2. Among these designs, five incorporated andesite effluent (quarry mining waste), while three were made with commercially sourced rock powder, devoid of any mining waste, for testing purposes.

Table 2. Mixing designs for the creation of Samples (Percentages indicated %)

Samples	Sand	Cement	Resin	Water	Pigment	Andesite Waste from Quarry Mines
S1	65	20.5	5	8	1.5	0
S2	55	20.5	5	8	1.5	10
S3	45	20.5	5	8	1.5	20
S4	35	20.5	5	8	1.5	30
S5	25	20.5	5	8	1.5	40
S6	15	20.5	5	8	1.5	50
S7	66	22	1	8	3	0
S8	64	21	3	10	2	0

Each mixing design was replicated three times in the experiments, and the average results were analyzed to assess the effectiveness of each design. To address the issue of quarry crusher wastewater, samples of andesite effluent were collected from the sand and gravel grading plant of Kani Bardineh Company in Sanandaj. Over a span of 10 days, the required volume of effluent was gathered at the tailings dam site using a 1 mm sieve and was transferred daily to the laboratory of Kani Bardineh Company. At the conclusion of the 10-day period, all collected samples were combined and utilized as stone powder for the laboratory samples. For the production of artificial stone samples, the materials were mixed and molded in a mixer according to the various mixing plans outlined in Table 2. Additionally, vibration operations were conducted using a vibrating table to ensure proper formation of the samples. During the sample molding process, the materials were subjected to 50 Hz vibration for 3 minutes to ensure complete uniformity. This vibration helps eliminate air bubbles from the samples prior to the drying phase. Once the vibration was finished, the materials were compressed under 3 tons of pressure for 10 minutes, allowing them to adopt the desired shape and achieve adequate compaction. After molding, the samples were placed in the mold and dried for 120 minutes at a temperature of 40 degrees Celsius. The samples and molds, crafted from PVC, were produced at Kani Bardineh Sanandaj Company in Sanandaj, as well as at the Specialized Artificial Stone Laboratory at the University of Zanjan. To create the artificial stone, six molds were designed in accordance with rock physics experiment standards. These molds are fully separable and consist of multiple pieces.

2.1. Environmental studies

The rapid expansion of sand production workshops, on the one hand, and the widespread use of sand as the main component of concrete in concrete structures, on the other hand, have led to the production of more wastewater in these units [24]. Therefore, targeted production management based on environmental protection has become a necessity. The ever-increasing growth of human knowledge has made it possible to make maximum use of disposable and low-value materials and to minimize the negative environmental effects as much as possible. The main goal of this part of the research is to study the environmental aspects of artificial stone production from mountain sand wastes, considering the case study of the Kilak sand mine in Kurdistan province, Sanandaj city. The production of artificial stones is done by different methods, the most common of which include the resin-based method and the cement-based method. The research implementation method in this section is (AHP) hierarchical analysis method. This method was proposed by Thomas Al Saati in 1980 and has been used in various sciences until now [25]. In fact (AHP) is a method in which a complex situation is broken down into smaller parts, then these parts are placed in a hierarchical structure, and finally the most important variables are revealed. In other words, the priority order of the variables is determined in this method based on the three principles of the model structure, judgments about options and criteria and determining priorities [26]. In modeling the problem and the goal of decision making it is taken as a hierarchy of decision elements that are related to each other. The process of hierarchical analysis requires breaking down a problem with several indicators into a hierarchy of levels. The high level represents the main goal of the decision-making process. The second level shows major and basic indicators that may be broken into sub-levels. The last level presents decision options. Figure 1 shows the hierarchy of the decision-making problem developed in this research.

To implement the hierarchical analysis method, first pairwise comparisons are made. The main basis of this part of the research is to use experts' opinions in the field of considered criteria and sub-criteria. According to the hourly scale, experts determine the priority of each criterion over other criteria [25]. To select relevant criteria, the study of previous sources was put on the agenda, and based on this, the criteria in Table 3 were chosen as decision criteria. The process began with the establishment of a tree-dynasty hierarchy and the computation of an average geometric framework for integrating evaluations. So, from making tree dynasty level and calculating the average a geometry for combining judgments, the purpose became to prioritize agents effectively, following math operations using applications like Expert Choice. At first standards were calculated based on the goal of choosing the most environmental friendly building product, then the items were compared with a couple of appointments they got, and weights were assigned to each standard considering their importance in achieving the goal, next the options were evaluated against these standards through pairwise comparisons and weight were assigned to each option.

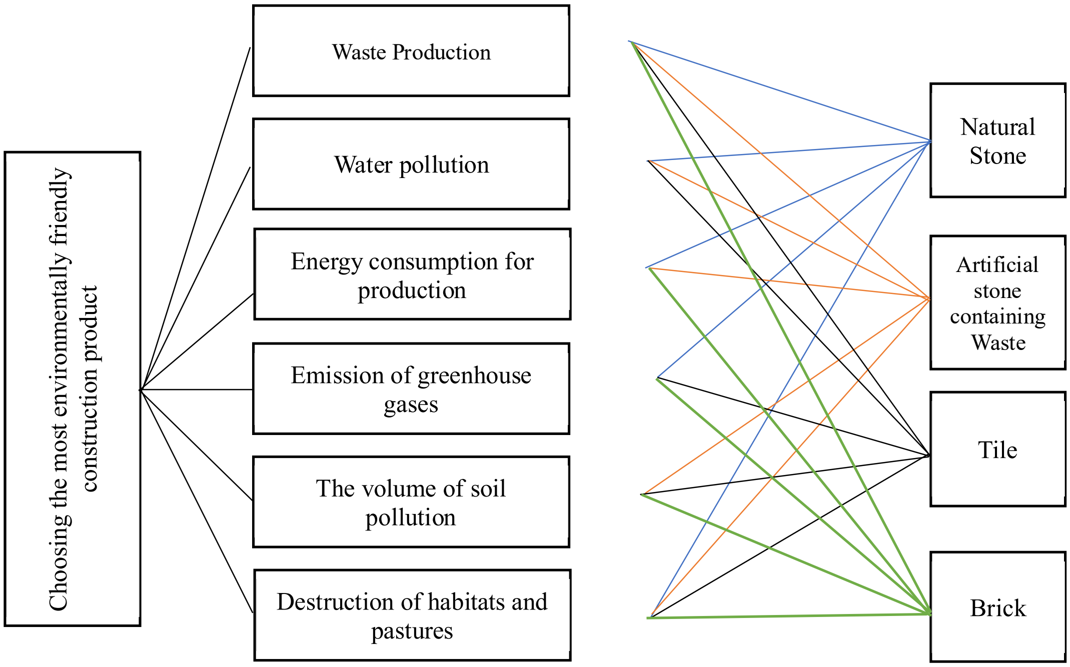


Figure 1. The flowchart of the hierarchical design in environmental analysis

Table 3. Environmental criteria affecting the selection of the most suitable construction product

No	Criterion	Definition
1	Product waste	Residue or waste is defined as solid, liquid, and gaseous materials (other than waste) that are directly and indirectly the result of human activity and are considered waste from the producer's point of view.
2	Water pollution	Water pollution means pollution of water bodies by human processes. Water areas for example include lakes, rivers, oceans, and aquifers.
3	Energy consumption	It is the total amount of energy that is consumed. It includes all the energy consumed from every energy source for the development of industry and technology in every country.
4	Emission of greenhouse gases	Greenhouse gases include carbon dioxide, nitrous oxide, methane, water vapor, and nitrogen. These gases are called greenhouse gases because they create a greenhouse atmosphere around the earth and cause the earth to heat up.
5	Soil pollution	Have any change at features components composted soil to so that use from it impossible pollution soil called will be.
6	Destruction of habitats and pastures	It is a process in which the natural habitat loses Its ability to support the living organisms inside It. In this process It reduces biodiversity.

2.2. Physical-mechanical property studies

By taking advantage of the experiment physical and mechanical, stone containing waste are compared with the non-residue ones in terms of quality and resistance. By comparing the results of laboratory samples containing mine waste and industrial samples without waste, the best mixing plan or the closest mixing plan to industrial samples can be identified. The best mixing plan found can be considered as a basis for the production of artificial stones containing waste.

In this study, the samples of artificial stone have been composed and made with a cement base and according to the standard of artificial stone, so that the wastewater from mountain sand washing crushers has been used as a substitute for filling materials in the construction of these stones. Among the eight mixing designs considered in this study, six designs contain different percentages of andesitic wastewater, and the remaining two mixing designs were prepared from industrial units without waste, and examples of each mixing design are evaluated according to the standards. Building stone is made to be tested. Also, in this research, the rock mechanics tests are used to determine the density, water absorption test, compressive strength test, bending strength test, tensile strength test, and acid test to check the laboratory samples and samples obtained from industrial units.

2.2.1. Density determination test

In the density test (Standard EN 13279-2:2014), relative density and dry density have been checked. The ratio of the density of the sample to the density of water at 4 degrees Celsius is called relative density (specific gravity). To test the relative density of samples according to the standard shape cylinder with a minimum diameter of 60 mm and a volume-to-area ratio of less than 1 mm, the samples were made by diamond saw cutting or coring, and then the volume of the cylindrical samples was calculated. In the next step, the density of water was obtained by the densitometer, and finally, the relative density was determined using the density of water and the volume of the sample. According to the definition, dry density is the weight of a unit volume of rock in a dry state. The ISRM (1979) standard was used to test the dry density.

2.2.2. Water absorption test

Maximum the amount of water absorbed by the material is called the amount of water absorption and is expressed as a percentage of the dry mass of the sample. To determine the water absorption coefficient, the national standard of Iran (no. 5699) was used. For this purpose, prism-shaped samples with a minimum dimension of 50 mm were prepared. The samples are placed inside the oven at the temperature (of 2±60) degrees Celsius for 48 hours and after the end of the test time, the dry weight of the stone is determined by a digital scale with an accuracy of 0.01, and then the samples are completely immersed in distilled water with a temperature of (2±22) degrees Celsius, immersed for 48 hours and at the end of the test time, we take out the samples and immediately weigh its surface with a dry damp cloth with approximately 0.01 grams to obtain the weight of the saturated sample with a dry surface. This test has been performed on all produced samples of artificial stone containing andesite waste and artificial stone without mining waste.

2.2.3. Compressive strength test

In this research, the standard of EN 13279-2:2014 has been used to test samples of artificial stones containing waste. For this purpose, first, the prefabricated samples were separated using the template, and then the samples were kept at a temperature of (2±60) degrees Celsius for 48 hours to dry. Then we place the samples on the central part of the compressive strength testing machine vertically so that the initial loading is applied through a spherical support cushion throughout the sample. The standard loading rate is 0.5 MPa per second and the loading is done uniformly and without impact. The load should be applied in such a way that the stress or strain rate remains constant throughout the test so that the stress or strain rate never changes by more than 10% from the selected fixed value. The process of increasing the stress or strain should be adjusted in such a way that the sample breaks between 3 and 15 minutes. Applying the load will continue until the sample is crushed, and finally, the compressive strength is calculated using the number displayed at the time of rock failure.

2.2.4. Bending resistance test

Since it is difficult to measure the tensile strength of stone directly, therefore, to determine the tensile strength indirectly, the Brazilian method with the international standard of rock mechanics standard ASTM C293/C293M-16 was used. For this purpose, samples in the form of rectangular cubes with a thickness of 50 mm were prepared, then cores with a length of 25 mm and a thickness of 50 mm were prepared by the corner and according to the standard method. Then this sample is inside the oven under temperature (2±60) degrees Celsius for 48 hours until the moisture of the sample is completely removed and dried. Next, the sample is loaded diagonally between two jaws. The load must be continuously applied to the sample at a constant rate of 200 N/s so that failure occurs in the weakest part of the rock within 15 to 30 seconds. The sample breaks by creating a tensile crack. Finally, the breaking load was recorded for each sample, and using the relations 2 and 3 of resistance, tension was calculated.

$$\sigma_t = 0.636\frac{P}{D \times t} \tag{1}$$

$$\sigma_t = \frac{2P}{\pi \times D \times t} \tag{2}$$

In this regard, the indirect tensile strength of the sample is in MPa. Where are:

P - The breaking load of the sample in Newton,

D - The diameter of the sample in millimetres,

T - The length of the sample in millimeters.

2.2.5. Chemical resistance test

Chemical resistance is a feature that determines the behavior of floor and wall covering materials in contact with corrosive chemical agents, as a result of which it is destroyed and its penetration is permanent, and in some situations, it is accompanied by a visible change in the surface. To perform this test, cube-shaped samples with dimensions of 50 mm were prepared and then the samples were heated at a temperature of (2±60) degrees Celsius for 24 hours after drying, then they were weighed by a digital scale with an accuracy of 0.01, and their dry weight was determined. Then, the dried sample is placed in an acid-containing solution for 24 hours to create the necessary opportunity for the stone to corrode. After 24 hours, the artificial stone is dried in the oven for 24 hours so that the water between the possible pores evaporate completely and the stone remains without any additional weight caused by water. After the drying stage, the artificial stone sample is weighed. The difference between the initial weight (before exposure to acid) and the final weight (after removal from acid and drying) indicates the degree of corrosion of the stone against acid. This test is performed on all samples produced with marble and granite wastes.

2.3. Economic studies

One of the main goals of this research is the economic evaluation of stone production synthetic products containing waste. For this purpose, artificial stone containing waste is economically evaluated and compared with two similar construction products including natural stone and artificial stone without waste. Costing methods and the examination of economic factors affecting costs have been used in the financial and economic analysis of building stones.

2.3.1. Absorption costing method

To find the cost price of each product, the cost price of the manufactured product is divided by the quantity produced of the same product. Based on the type and nature of production operations, factories, and mines prepare and adjust their cost and profit and loss statements based on (full) absorption costing. Using the absorption costing method, which is called absorption, complete or agreement costing, causes direct material costs, direct wages and an appropriate share of fixed and variable overhead to be allocated to the produced units. In Absorption costing method, all overhead costs are absorbed and produced is included in the finished price [27].

The finished price of the products is obtained from the total costs of direct materials, direct wages, fixed overheads, and variable overheads. Direct materials in the production of a product are materials that have the following three properties [27]:

- In terms of economic value, compared to other materials, they have a higher economic value.
- They are the main and integral part of the product.
- They are usually visible in the final product.

The direct wage means the wage price of each group, or in other words, the total cost of wages of workers and employees of that group. General or overhead costs mean all costs except direct material costs and direct wages. Overhead costs are divided into two groups: fixed and variable overhead costs. Meaning of cost fixed overheads are costs that are not dependent on production and do not change with changes in production volume. In contrast, variable overhead costs are indirect costs that change with production volume.

2.3.2. Economic factors affecting costs

To evaluate and estimate the costs more accurately, as well as to match the phased costing with the financial flow (production and market elasticity), two important and effective economic factors, including the depreciation factor and the inflation factor, were considered in the costing process.

3. Analysis of results

In this section, the results obtained in different sections of environmental, rock mechanics, and economic studies are analyzed.

3.1. Analysis of the results of environmental studies

In this section, the analysis of the data obtained from the paired comparisons conducted in the questionnaires, which are designed to find the most compatible construction product, is discussed. To analyze the data and extract the results from the pairwise comparisons of criteria and options is done using the Expert Choice software. Before dealing with the results of the hierarchical analysis, the hierarchical plan consisting of indicators, sub-indices, and options is stated. By setting up the matrix of paired comparisons, each of the main and sub-indexes as well as each of the options are judged pairwise (two by two). 25 experts have been included in this topic. The target statistical population consists of 80% men and 20% women with the following education level: 55%Bachelor, 5/37%Master's degree, and 5/7% Ph.D. With the geometric mean, the different judgments of the respondents to the questionnaire forms are analyzed. The hierarchical structure includes four levels: the first level is the goal, the second level is the main criteria, the third level is the secondary criteria, and the fourth level is the options. The hierarchical structure analysis method is used to determine the weights of criteria and options. In the AHP a pairwise comparison is made between each of the levels of the criteria. With the help of Expert Choice software, pairwise comparison questionnaires are analyzed and the inconsistency rate between them is determined. If the inconsistency rate is less than 0.1, the paired comparisons are acceptable and reliable.

In the first stage, to obtain the final weight of the options, it is necessary to combine the options. The results of combining the views of mining and construction experts indicate that among the effective factors in choosing the most compatible construction product, the amount of waste with the ratio of 0.273 is more important than other factors, and in contrast to the destruction of pastures, it is less important than other criteria with a ratio of 0.119. According to the scoring of the comparison between the six main indicators, for which a number from 1 to 9 is assigned, and according to the output of the Expert Choice software, the matrix of pairwise comparisons of the main criteria (relative to the residual volume criterion) is achieved according to Table 4. The inconsistency rate for pairwise comparison is equal to 0.05 (less than 0.1); therefore, the compatibility of the comparison of indicators affecting the environment is acceptable.

The ranking chart and the weighted value of determining the indicators affecting the environment about the waste volume criterion are shown in Figure 2. The priority order of the compared criteria is shown in Table 5.

In the following, by considering all the main indicators and sub-indices, the final result of environmental consideration in this research is obtained based on Figure 3.

Table 4. Pairwise comparison matrix of indicators affecting the environment

Waste production	Water pollution	Greenhouse gas	Soil pollution	Energy consumption	Destruction of pastures
	2.64	2	1.65	1.74	0.66
		2.05	1.85	1.68	1
			1.73	1.21	2.05
				1.03	1.43
					1.43
Inconsistency rate: 0.05					

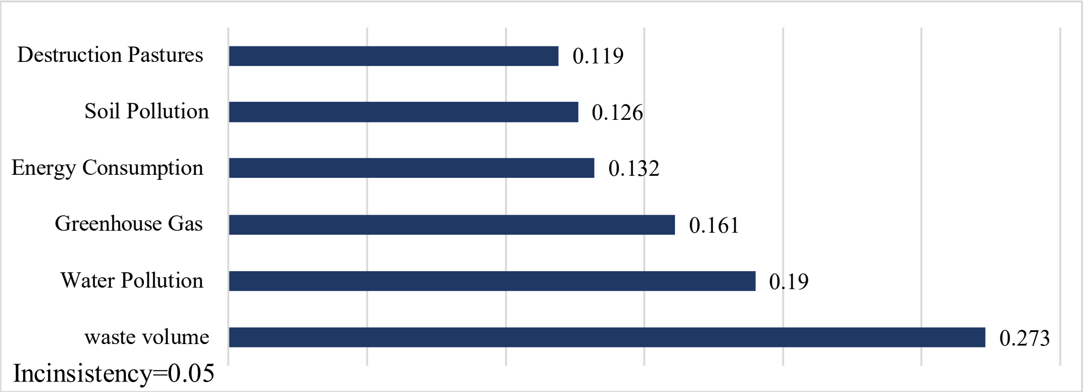


Figure 2. Ranking alternatives and weighted of indicators affecting the environmental criteria

Table 5. The priority of the criteria affecting the environmental index

Index name	Rank	Weighted value
Waste volume production	1	0.273
Water pollution	2	0.190
Greenhouse gases	3	0.161
Energy consumption	4	0.132
Soil pollution	5	0.126
Destruction of pastures	6	0.119

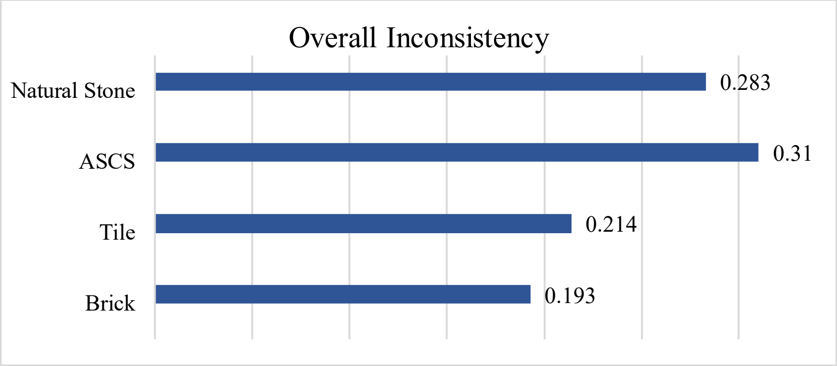


Figure 1. The conclusions drawn from the environmental comparison of building materials and artificial stone utilize mining waste (ASCS)

The results of paired comparison questionnaires, considering all the criteria, indicate that among the environmentally friendly construction products, artificial stone with a ratio of 0.31 is more important than other construction materials, and on the other hand, brick is also important with a ratio of 0.193. It is less than the rest of the criteria. Natural stone and tile construction products are the third and fourth priorities, respectively. Meanwhile as shown in the above Figure 3, the overall inconsistency rate is 0.04, which is less than 0.1 and therefore the results are reliable.

3.1.1. Sensitivity analysis

In the following, the sensitivity of different options in environmental studies to different criteria is examined. Figure 4 shows the ranking of different options of construction materials about the criteria.

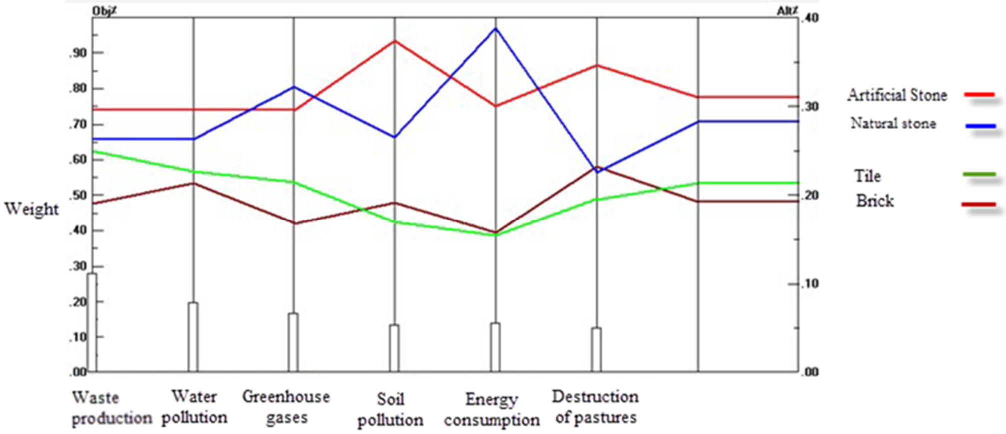
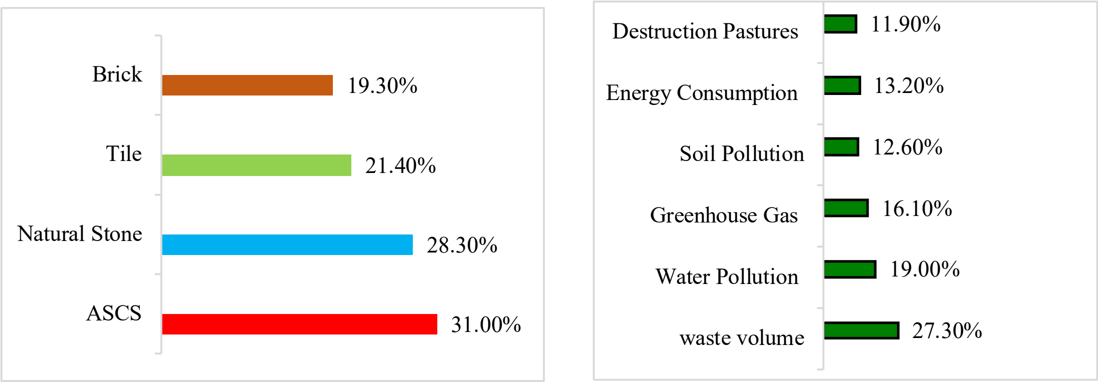


Figure 2. Sensitivity analysis based on efficiency to Goal

As can be seen in Figure 4, the stone-containing mining waste is the most sensitive to environmental criteria. In Figure 5, the sensitivity analysis has been implemented based on the dynamics of the overall goal, based on which, the most sensitive were the criteria of waste volume, water pollution, gas pollution, soil pollution, energy consumption, and destruction of pastures, respectively. That is, in prioritizing and choosing the most environmentally friendly construction product, the volume of waste has had the greatest impact. In addition to the prioritization of the criteria, the prioritization of construction products concerning the overall goal (choosing the most compatible construction product with the environment) is also shown. As can be seen, the stone containing the waste got the first rank and the natural stone, tile, and brick are placed in the next ranks respectively.

3.2. Analysis of rock mechanics results

For physical stone tests, in the first step, artificial stone raw materials were prepared along with andesite effluent from mountain sand factories. To prepare the samples, the raw materials are first homogenized using a 50-mesh sieve. After sieving, the raw materials were mixed according to the presented mixing plans. Then the mixed and homogenized materials were poured into the test molds and the samples containing the mixture of materials were completely uniformed under 50 Hz vibration for 3 minutes and the air inside the molds was removed to a large extent. After finishing the vibration stage, the materials were subjected to 3 tons of pressure for 10 minutes and the materials took the shape of the desired mold. After molding, the samples were transferred to the oven along with the mold and dried for 120 minutes at 40 degrees Celsius. The dried samples were separated from the molds to be used in tests (determination of density, water absorption, compressive strength, bending strength, and tensile strength).



Objective *Attribute*

Figure 3. Sensitivity analysis based on dynamics concerning the overall attribute and objective

As illustrated in Figure 5, artificial stone made from wastewater demonstrates a minimum of 10% greater desirability compared to natural stone, 48% compared to tile, and 63% compared to brick. Research on environmental impacts revealed that the product was superior to competing building materials.

3.2.1. Results of water absorption and density tests

The results of the experiments to determine the apparent density and the water absorption rate of the 8 mixing designs show that with the increase in the percentage of andesitic wastewater, the water absorption rate has decreased. Also, according to Table 6, which shows the results of these tests for the mixing designs, there is no significant relationship between the density and the increase in effluent. The results show that the sample contains waste 5SDue to the filling of the joints and empty spaces of the stone, the amount of water absorption is lower than other samples containing waste.

3.2.2. Compressive, bending, and tensile strength test results

In this part, selected samples were tested and their average results were used as evaluation criteria. The results of the average compressive, bending, and tensile strength of artificial laboratory stones containing waste and industrial samples without waste are shown in Table 6.

The compressive strength test was performed on cylindrical samples by a hydraulic jack with a capacity of 3000 KN and a loading speed of 0.5 MPa per second. The results of this experiment show that the increase of effluent in the samples increases the compressive strength, but in the 50% mixing scheme, this trend has decreased. This problem indicates that the amount of wastewater can affect the strength of the stone to some extent, but if it increases by more than 40%, the compressive strength of the stone will decrease.

To perform the bending resistance test, the three-point test is used. The results of this test show that samples containing waste are brittle, cracked, and have little ductility, but in industrial samples, the width of the cracks is greater and it shows more ductility. Also, all the cracks in the samples were done in the middle third. The results of the average bending strength of the mixing designs show that the mixing design 5SIt contains 40% wastewater and has the highest bending strength. Also, the results of the tensile strength test (Brazilian) show that the increase in the percentage of wastewater in the mixing designs has increased the tensile strength.

3.2.3. Chemical resistance test results

To determine the resistance of artificial stones in different chemical environments, a chemical resistance test was used using two types of acid including hydrochloric acid and sulfuric acid. The results of this experiment in Table 6 show that mixing scheme 1SDue to the high porosity and empty spaces of the rock has more corrosion against sulfuric acid. Also mixing plan 2SIt shows more corrosion than other mixing designs. In general, the results show that with the increase in the percentage of wastewater, the amount of stone corrosion against acids decreases.

3.3. Analysis of economic evaluation results

To value the manufactured product, the economic aspects of artificial stone production were investigated. For this purpose, first, the cost structure is defined and then the costs are determined separately. Using the absorption costing method, the finished price of the product is calculated. After calculating the total price, separate costs and sales, profit and loss estimation is done in the fiscal year 2019.

3.3.1. Separation of costs

For costing, first, the types of production costs are determined and the amounts of each cost are calculated separately. Separated costs include the cost of building production and office buildings, production tools and machines, production raw materials, packaging, electricity and gas consumption, administrative costs, sales, and fixed and variable general costs.

Table 6. The results of rock mechanics tests for artificial stone product by mining waste

Dry density (gr/cm3)	2.21	2.39	2.21	2.31	2.33	2.41	2.43	2.38
Relative density (gr/cm3)	2.17	2.34	2.20	2.26	2.26	2.12	2.39	2.33
Water absorption (%)	5.06	5.51	4.50	4.69	3.82	6.58	3.20	3.26
Compressive strength (MPa)	16.95	19.21	19.50	21.85	36.07	27.84	42.33	35.70
Bending strength (MPa)	7.6	10.68	10.62	30.12	15.09	12.99	14.30	14.75
Tensile strength (MPa)	1.19	1.38	1.33	1.36	1.89	1.56	1.81	2.06
Corrosion rate H2SO4 95% (%)	3.41	3.37	2.59	1.42	1.26	1.33	1.33	1.76
Corrosion rate HCl 37% (%)	0.90	0.61	0.65	0.78	0.54	0.84	0.78	0.69
Sample	S1	S2	S3	S4	S5	S6	S7	S8

3.3.2. Calculate the total price

Considering that the ultimate goal of determining the costs is to estimate the profit and loss of the production of each type of stone, therefore, by dividing the costs into four groups: direct material cost, direct wage cost, variable overhead cost, and fixed overhead cost, the total price of each unit of different types of stones has been calculated and shown in Table 7.

Profit and loss estimation in the absorption costing method is the sum of the amount of goods sold, the cost of goods, general and administrative expenses, and taxes. In Table 8, the profits and losses for the three types of stones studied are calculated by the absorption costing method.

Table 7. Cost of one unit of all kinds of stones ($)

The artificial stone contains waste	Artificial stone without waste	Natural stone	Cost
24750	29428	23751	Direct materials cost
9172	9172	687	Fixed overhead cost
2758	2758	2714	Variable overhead cost
40820	45498	32552	The cost of a product

Table 8. Calculation of profit and loss of all types of stones ($)

The artificial stone contains waste	Artificial stone without waste	Natural stone	commodity
4140	4140	5400	Direct salary
40820	45498	32552)	The cost price of the product
250	250	250	General and administrative cost
1035	1035	1350	Tax 25%
-37965	-42643	-28750	Benefit/Cost in first year

3.3.3. Financial analysis of artificial stone production

To better understand the profit and loss of producing each of the stones (natural stone, artificial stone without waste, artificial stone containing waste), the capital expenditure evaluation method has been used. In the financial analysis of the produced stones, the costs were re-considered and a 5-year period was determined to determine the domestic rate. The results of this analysis show that natural stone had little sales in the first year, but it was able to achieve stable production and supply in the following years. In the case of artificial stone containing waste and artificial stone without residue, results show that in the first year, due to investment in the infrastructure sector, such as construction of production and office-service buildings, production units, and construction of production lines, at the end of 2025, you will have a negative financial balance. In the years 2026 to 2030, due to the hypothetical control of inflation, the balance was positive, and therefore the production unit was profitable. Also, with sensitivity analysis, the rate of return on investment was done to produce each type of stone. The results of this sensitivity analysis show that the rate of return on investment for natural stone, artificial stone containing waste, and artificial stone without waste is equal to 33, 138 and 86%, respectively. According to the rate of return on investment, the production of artificial stone containing waste has a high economic value.

In brief, the following results are obtained from environmental and economic studies and characteristic tests:

- Environmental studies demonstrated that waste volume is the most influential criterion among the six criteria considered in selecting the most environmentally compatible construction product. Also, artificial stone containing effluent compatibility was better than other construction products regarding environmental aspects.
- In the economic section, the results of comparing the internal rate of return and the absorption cost of stones (natural stone, waste-free artificial stone, and waste-containing artificial stone) revealed that the production of artificial stone containing waste with an internal rate of return of 138%, compared to two other similar products was more economical. The economic evaluation affirmed the cost efficiency of manufacturing the previously mentioned artificial stone.
- The results of experiments to determine the relative density, dry density, and water absorption showed no significant relationship between increasing the percentage of andesitic

> effluent and changing the density. Despite the increasing effluent percentages, water absorption has decreased. The resistance tests also indicated increasing the percentages of effluent in the samples and the amount of compressive, tensile, and bending strength growths. According to the results, the stone containing 40% of andesitic effluent had the highest resistance and the lowest water absorption among other constructed samples. The chemical resistance tests also illustrated that raising the percentage of effluent in the samples increases corrosion resistance. The stones containing andesite effluent had less residual corrosion and significant resistance to acid rain.

Utilizing andesite waste in the creation of artificial stone as novelty of this research presents a variety of advantages, such as improved material characteristics, diminished environmental effects, financial benefits, and the introduction of advanced technological methods. By capitalizing on these benefits, the construction sector can progress towards more sustainable and environmentally responsible practices, thereby fostering a circular economy and lessening the ecological impact associated with conventional materials.

4. Conclusions

As environmental concerns regarding mining waste gain prominence, the recycling of such waste has emerged as a critical process. It is essential to explore effective methods for implementing recycling and optimizing waste utilization within the mining sector. In the context of environmental studies, the application of the Analytic Hierarchy Process (AHP) reveals that the volume of waste is the most significant criterion when selecting the most environmentally sustainable building materials. Subsequently, a prioritization of construction materials was established in relation to the overarching objective of identifying the most eco-friendly options. This analysis ranked stone containing waste as the top choice, followed by natural stone, tile, and brick in subsequent positions. The findings suggest that artificial stone incorporating waste is compatible with other construction materials. Additionally, artificial stone, produced from effluents, has been identified as a more environmentally friendly option compared to other construction materials. In the physical evaluation of stone, rock mechanics tests were conducted on samples adhering to standard geometrical specifications under controlled loading conditions. Experimental results measuring relative density, dry density, and water absorption rates indicated no significant correlation between the increase in the percentage of andesitic material post-water exposure and density changes. However, a decrease in water absorption tendency was observed with higher percentages of andesitic material. Notably, a sample containing 40% waste demonstrated reduced water absorption due to the filling of joints and voids within the stone compared to other waste-containing samples. Furthermore, resistance tests indicated that the compressive, tensile, and bending strengths of the samples improved with an increased percentage of wastewater.

The findings indicate that the stone composed of 40% andesite waste exhibits the highest resistance when compared to other samples. Furthermore, its resistance is comparable to that of other synthetic stones. Chemical resistance tests reveal that an increase in the percentage of wastewater in the samples correlates with enhanced corrosion resistance. Stones that incorporate corrosion residue demonstrate minimal corrosion and maintain acceptable resistance to acid rain. In the realm of economic analysis, a comparison of the return on investment and absorption costs for various types of stones namely natural stone, artificial stone without waste, and artificial stone containing waste suggests that the production of artificial stone with waste, which boasts an internal efficiency rate of 138%, is more economically viable than the other two construction products.

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دانشگاه صنعتی شاهرود

بررسی بازیافت باطله‌های آندزیتی معادن کواری در تولید سنگ مصنوعی: تحلیلی بر مسائل زیست محیطی، فیزیکی- مکانیکی و اقتصادی

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کلمات کلیدی

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چکیده

امروزه مشکلات زیست محیطی پسماندهای معدنی، اهمیت بازیابی باطله ها را برجسته کرده است. در این تحقیق مطالعه‌ای بر روی معادن سنگ ساختمانی استان کردستان ایران با تمرکز بر ساخت سنگ های مصنوعی از پساب برای به حداقل رساندن اثرات زیست محیطی انجام شده است. این تحقیق شامل تجزیه و تحلیل های زیست محیطی، فیزیکی- مکانیکی و اقتصادی می باشد. آزمایش‌ها بر روی چگالی، جذب آب و مقاومت نشان داد که سنگ های حاوی پساب نسبت به سایر محصولات، برتری دارد. افزایش درصد پساب تاثیر معنی داری بر چگالی نداشته اما جذب و استحکام آب را بهبود بخشیده است. سنگ های مصنوعی حاوی ۴۰ درصد پساب، بیشترین مقاومت و کمترین جذب آب را از خود نشان دادند. این ترکیب به مقاومت فشاری ۳۶/۰۷ مگاپاسکال، مقاومت خمشی ۱۵/۰۹ مگاپاسکال و مقاومت کششی ۱/۸۹ مگاپاسکال دست یافت. علاوه بر این چگالی خشک آن ۲/۳۳ gr/cm^3 و نرخ جذب آب ۳/۸۲ درصد بدست آمد. بعلاوه سنگ های دارای پساب مقاومت بهتری در برابر خوردگی اسید از خود نشان دادند. برای تحلیل زیست محیطی از فرآیند تحلیل سلسله مراتبی استفاده شد. یافته‌های حاصل از مطالعات زیست‌محیطی نشان داد که معیار حجم باطله با ۲۷/۳ درصد وزن به‌عنوان مهم‌ترین معیار هنگام ارزیابی انتخاب محصولات ساختمانی سازگار با محیط‌زیست در نظر گرفته شد. همچنین بررسی زیست محیطی نشان می‌دهد که سنگ مصنوعی حداقل ۱۰٪ بیشتر از سنگ طبیعی ۴۸٪ بیشتر از کاشی و ۶۳٪ بیشتر از آجر ترجیح داده می‌شود. تجزیه و تحلیل در بخش اقتصادی نشان داد که سرمایه گذاری تولید سنگ مصنوعی حاوی باطله، نرخ بازده داخلی ۱۳۸٪ را به دست آورده و مقرون به صرفه تر از محصولات قابل مقایسه است.

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