Cement & Concrete Composites 30 (2008) 583–587

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Artificial stone slab production using waste glass, stone fragments and vacuum vibratory compaction

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ARTICLE INFO

Article history:
Received 27 June 2006
Received in revised form 27 March 2008
Accepted 27 March 2008
Available online 6 April 2008

Keywords:
Artificial stone slabs
Waste glass
Stone fragments
Recycling
Compressive strength

ABSTRACT

In this research, waste glass and stone fragments from stone slab processing are recycled as raw materials for making artificial stone slabs using vibratory compaction in a vacuum environment. Waste glass powder (40%) and fine granite aggregates (60%) are mixed with unsaturated polymer resins (8%) as binder. Under compaction pressure of 14.7 MPa, vibration frequency of 33.3 Hz and vacuum condition at 50 mm Hg, artificial stone slabs with high compressive strength of 148.8 MPa, water absorption below 0.02%, density of 2.445, and flexural strength of 51.1 MPa are obtained after 2 min compaction. The artificial stone slabs fabricated in this study prove to be superior to natural construction slabs in terms of strength and water absorption.

1. Introduction

During stone processing, a great amount of stone fragments are left as waste [1], while waste glass accounts for a major proportion of recycled materials collected [2,3]. Previous studies have reported the use of these waste materials for fabricating asphalt concrete pavement and sidewalk slabs [4], aggregates for mixing with cement concrete [5–9] and its durability [10], low strength materials [11], lightweight aggregates [12], and construction materials such as red bricks with resins added. However, the wide difference in types and colors of these waste materials undermines the profits of commercialized recycling [2,3]. Currently, most glass-making companies use merely 30–40% of waste glass in their production. Moreover, Waste glass can also be used to replace 10–15% of the sandstone used in asphalt pavement [4]. To date, there is no study on the fabrication of high-value construction slabs using recycled waste materials. Like real marble, high-value construction slabs have complex twists and veins that go deep into the stone. High-value construction slabs, therefore, provide a durable surface which is far more permanent and realistic in appearance than faux surfaces, usually wood, which are painted to resemble marble.

Natural stone slabs are quarried and processed in large amounts as construction materials because they are hard, durable, fire-resistant, and have a glossy surface. The amount of slabs used worldwide in 2006 is estimated at 878.3 million square meter, demanding a total of 80.47 million tons of mined stone [13].

The amount of stone waste produced yearly in Taiwan reaches 500 thousand tons. Stone fragments, after being crushed, serves mainly as mixing aggregates, which are worth less than US$20 per ton [14]. Stone sludge has been employed to fabricate products such as calcium silicate boards, ceramic handicrafts, chemical materials and fertilizers using cementation, sintering and extraction processes [1,14]; however, the high production cost and low market demand pose constraints in its recycling as raw material.

In spite of the large quantity used and high unit price, artificial stone slabs are more cost-efficient compared with high-class ceramic slab because of their excellent flexural strength and surface gloss. For scagliola (scales or chips of marble) slabs to be suitable for paving floors, they must be durable with Mohs hardness above 6 and non-porous with water absorption below 0.02%.

This research aims to study the effect of the three processing conditions, namely compaction pressure, vacuum condition, and vibration frequency, on the physical properties of artificial stone slabs fabricated at different glass/fine aggregate ratios. Artificial stone slabs obtained through vacuum vibratory compaction undergo

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doi:10.1016/j.cemconcomp.2008.03.004

traditional processing steps of grinding, cutting and polishing. Being non-porous and of low water absorption, artificial stone slabs are superior to natural ones, whose drawbacks include low flexural strength, high water absorption, and high porosity, thus making them ideal construction materials for covering walls or paving floors. In view of the depleting supply of natural resources, the recycling of stone leftover fragments and waste glass into construction materials not only creates brand-new products for use, but also offer an ecological and economic alternative to waste treatment.

2. Materials and methods

2.1. Waste glass powder

Of the recycled glass in Taiwan, container glass and window glass account for the greatest proportions. Table 1 shows the chemical composition of different types of waste glass. As can be seen, the recycled container glass used in this study is comprised of mainly SiO_2, Na_2O, CaO, and a small proportion of Al_2O_3 and MgO. Recycled glass collected was crushed, washed and dried. With impurities removed, the dried glass aggregates were ground into powder and sieved through Mesh No. 200.

2.2. Stone leftover fragments

Marble and granite are the main construction slabs used in Taiwan. Marble leftover is not used for recycling because of its low Mohs hardness degree of 4, high porosity, and high water absorption of 0.5%. In contrast, granite leftover is comprised of mainly SiO_2, as shown in Table 1, and has Mohs hardness degree above 6 and water absorption below 0.06%. Granite leftover used in this research is taken from a slab processing factory in Hualien, Taiwan. The stone leftover fragments are crushed and graded into three categories: (1) 4 mm in diameter through Mesh No. 5, (2) 2 mm in diameter through Mesh No. 10, and (3) 0.6 mm in diameter through Mesh No. 30. After being washed and heated at 105 °C till constant weight is reached, the granite fragments can serve as aggregates for recycling.

2.3. Binder

The binder used in this research is unsaturated polymer resins (ETERSET 2238P, Chang Chun Company, Taiwan), with characteristics of intermediate viscosity and low exothermic temperature. It contains 32–37% styrene and its viscosity ranges between 450 and 550 cps when spindled at 60 rpm at 25 °C. Added with 0.5% of the hardener, which is comprised of 6% cobalt (Co), the binder becomes gelated within 19–33 min at 25 °C. The shortest hardening time ranges between 9 and 13 min while the highest sintering temperature is 130–155 °C. The compressive strength of the binder tested using ASTM D 790 is found to be 102.0 MPa.

2.4. Sample preparation

Fig. 1 summarizes the manufacturing process of artificial stone slabs in this study. First, crushed and washed granite fragments are categorized into three sizes. According to the densified mixture, the waste glass powder and fine aggregates are mixed at different mix proportions with unsaturated polymer resins added as the binder using the planetary gear mixer and put in a 120 mm × 120 mm molding machine. The thickness of the original paste is 20 mm. With the vibration frequency and vacuum condition set, the sample is compacted under compression using the vacuum vibratory compactor depicted in Fig. 2. The molded samples are cured for 90 min in a drying oven at constant temperature of 95 °C and further cured at room temperature for 7 days. Finally, the samples are cut, grinded and polished into artificial stone slabs of 12 mm thickness with sharp edges removed.

The density and water absorption of the artificial stone slabs were analyzed according to ASTM C97. ASTM C880 and ASTM C170 were adopted to determine the flexural strength and compressive strength, respectively. Artificial stone slabs fabricated in this research are intensively compacted without air or pores; thus it was difficult to examine the pores between aggregates using the BET surface area analyzer. Instead, POM (Polarized optical microscope) observations were made to analyze the existence of pores and the structure of aggregates in the artificial stone slabs.

3. Results and discussion

3.1. Effects of compaction pressure

Fig. 3 shows the compressive strength of artificial stone slabs mixed at different glass/fine aggregate ratios and compacted under different compaction pressures. As can be seen, higher compressive strength can be obtained at glass/fine aggregate ratios between 45:55 and 50:50 and under compaction pressure exceeding 14.7 MPa. From the perspective of particle packing, the 45:55 and 50:50 mixing ratios appear to be most effective. That is, waste glass powder takes a role in filling the gaps between stone leftover fragments. When the waste glass powder is insufficient, the gaps cannot be entirely filled, which lowers the compressive strength. On the other hand, if the amount of waste glass powder is excessive, the compacted packing bursts as the waste glass powder, rather then the stone leftover fragments, directly receives the pressure with compacted packing, which lowers the level of compressive strength.

Table 2 also shows the compressive strength of artificial stone slabs prepared under different compaction pressures. As can be seen, under the highest vibration frequency of 50.0 Hz and vacuum condition at 50 mm Hg, compressive strength increases with increasing compaction pressure. For example, the sample reaches the highest compressive strength at 151.3 MPa under compaction pressure of 14.7 MPa. However, compaction pressure exceeding 19.6 MPa reduces compressive strength. This is because too high pressure crushes the edges of the stone fragment into pieces, as observed in the POM image shown in Fig. 4(a). On the other hand, too low pressure cannot compact the aggregates, making the structure less densified as seen in Fig. 4(b). For example, under compaction pressure of 4.9 MPa, the compressive strength reaches only 83.7 MPa, indicating that the lower the compaction pressure, the lower the compressive strength achieved.

Table 1
Chemical composition of waste glass and granite fragments

Element (%)		SiO_2	Al_2O_3	MgO	CaO	Na_2O	Fe_2O_3	Others
Waste glass	Container	72.2	1.9	1.5	9.6	14.6	–	0.2
	Window	72.0	1.3	3.5	8.2	14.3	–	0.7
	Lamp	71.5	2.0	2.8	6.6	15.5	–	1.6
Granite fragments		57.2	5.4	4.6	11.8	–	3.3	17.7

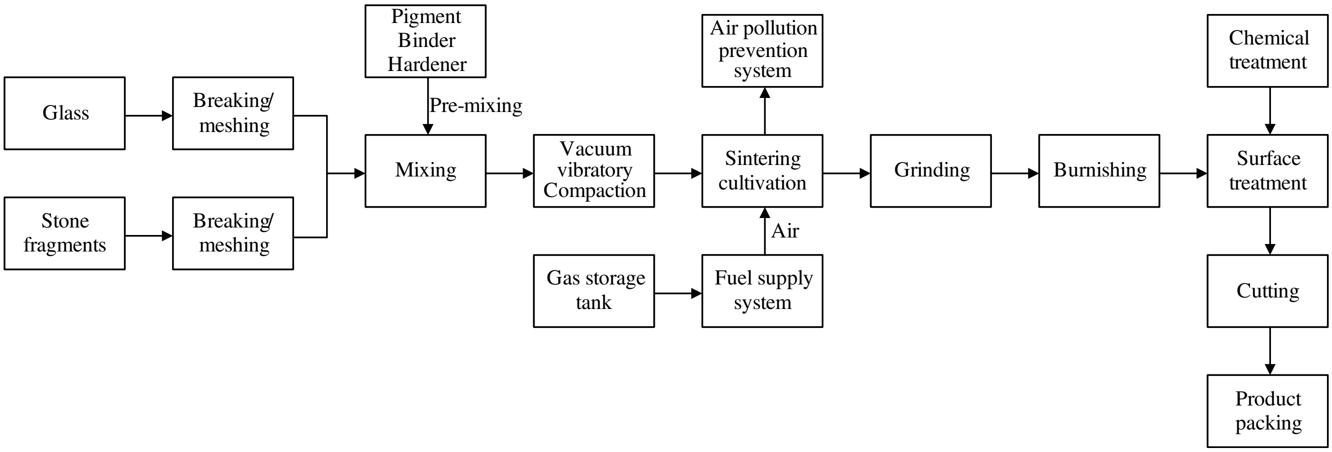

Fig. 1. Manufacturing procedure of artificial stone slabs.

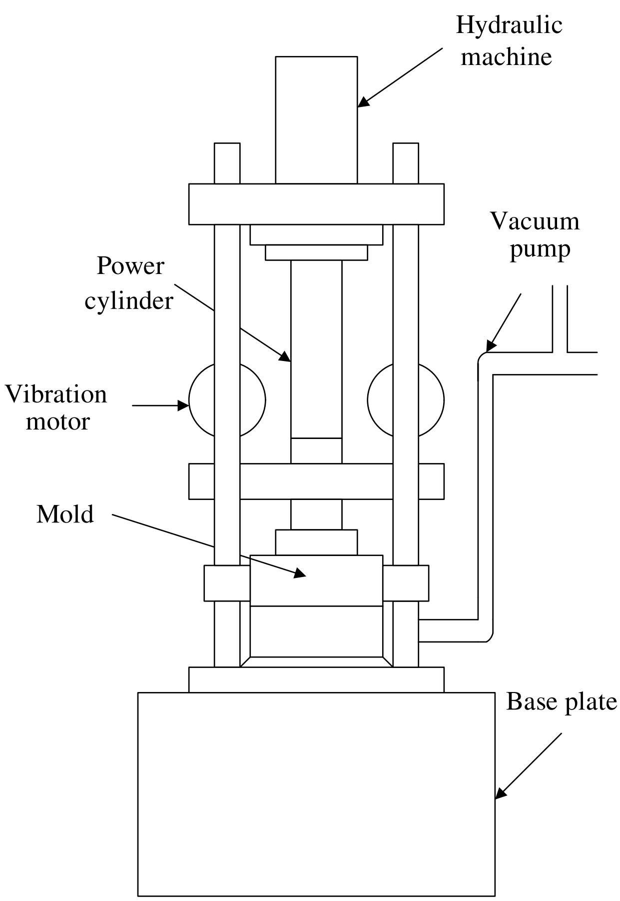

Fig. 2. Vacuum vibrating compactor.

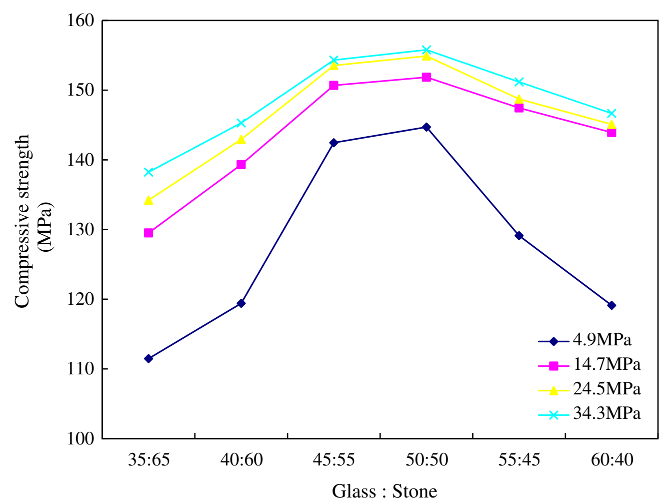

Fig. 3. Effect of compaction pressure and glass/fine aggregate ratio on compressive strength.

Table 2
Physical properties obtained under different compaction pressures

Compaction pressure (MPa)	4.9	9.8	14.7	19.6
Density	2.030	2.114	2.446	2.410
Water absorption (%)	0.221	0.203	0.011	0.015
Flexural strength (MPa)	27.9	46.3	52.7	44.6
Compressive strength (MPa)	83.7	119.2	151.3	128.4

Conditions: vibration frequency (50.0 Hz), vacuum (50 mm Hg).

3.2. Effects of vacuum

Fig. 5 shows the changes in compressive strength of artificial stone slabs mixed at different glass/fine aggregate ratios and compacted under different vacuum levels. As can be seen, higher compressive strength can be obtained at glass/fine aggregate ratios between 45:55 and 50:50 and under vacuum below 50 mm Hg. Moreover, as shown in Table 3, at vibration frequency of 50.0 Hz and compaction pressure of 14.7 MPa, compressive strength decreases with vacuum conditions above 50 mm Hg.

As mentioned above, the binder used in this study is unsaturated polymer resins, which is viscous in nature. Once the structure is compacted, the air trapped between aggregates during mixing cannot be easily removed. Air can only be eliminated when compaction is conducted in a vacuum. Removing the air serves to prevent formation of pores between aggregates, which will increase water absorption and undermine the compacted structure, thus lowering compressive strength. Hence, it is important to reduce the air content in the molding machine during compaction. As seen in Fig. 6(a), no pores are discernable in the densified structure formed under vacuum at 50 mm Hg with compressive strength reaching 151.3 MPa. Under vacuum condition above 50 mm Hg, the air content increases relatively, forming pores and undermining the compressive strength. As seen in Fig. 6(b), a great number of pores are found in the sample prepared under vacuum at 200 mm Hg.

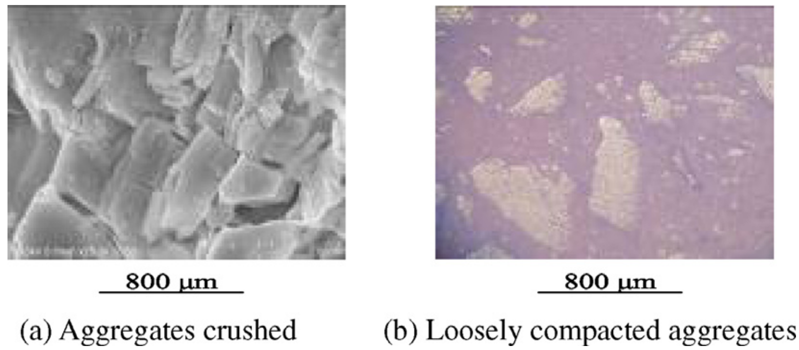

Fig. 4. POM image of sample prepared under (a) high pressure (14.7 MPa) and (b) low pressure (4.9 MPa).

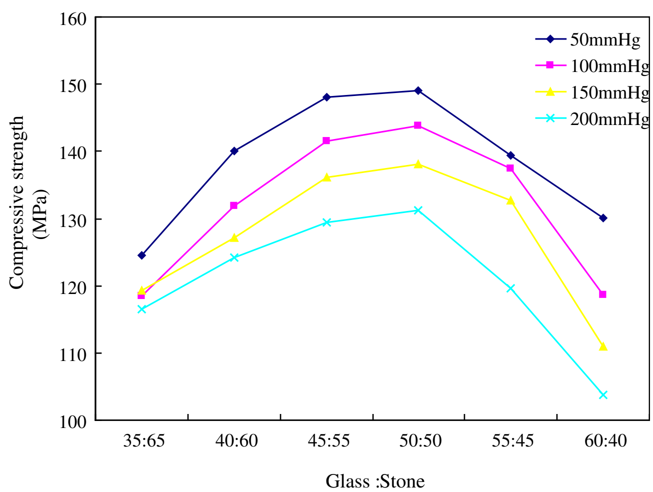

Fig. 5. Effect of vacuum and glass/fine aggregate ratio on compressive strength.

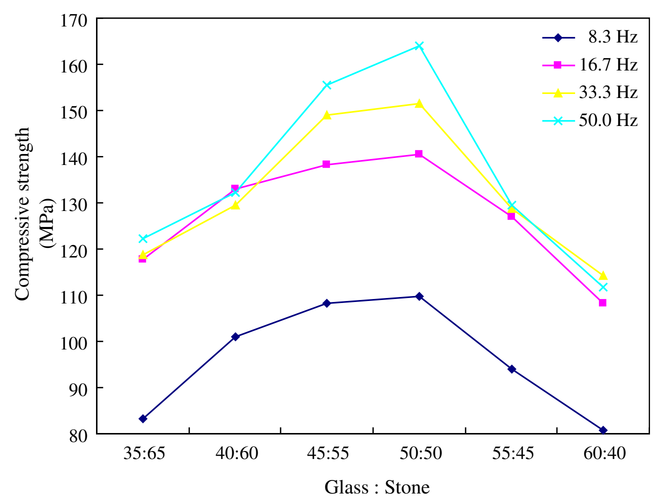

Fig. 7. Effect of vibration frequency and glass/fine aggregate ratio on compressive strength.

Table 3
Physical properties obtained under different vacuum levels

Vacuum (mm Hg)	50	100	150	200
Density	2.444	2.303	2.248	2.048
Water absorption (%)	0.011	0.125	0.202	0.211
Flexural strength (MPa)	52.1	47.9	40.7	32.0
Compressive strength (MPa)	151.3	106.0	94.6	78.7

Conditions: vibration frequency (50.0 Hz), compaction pressure (14.7 MPa).

3.3. Effects of vibration frequency

Fig. 7 shows the changes in compressive strength of artificial stone slabs mixed at different glass/fine aggregate ratios and compacted under different vibration frequencies. As can be seen, higher compressive strength can be obtained at glass/fine aggregate ratio of 50:50 and vibration frequency of 50.0 Hz. Vibration serves to adjust the orientation of the aggregates in order to pack them into a more compact structure. As seen in Fig. 8(a), the microstructure of the artificial slab prepared under high vibration frequency is densified and closely compacted (the surface of fine stone fragments is covered by waste glass powder and unsaturated polymer resins), while a loosely compacted structure is seen in Fig. 8(b) for artificial stone slabs prepared under low vibration frequency.

Table 4 shows the physical properties of artificial stone slabs prepared under different vibration frequencies. As can be seen, under

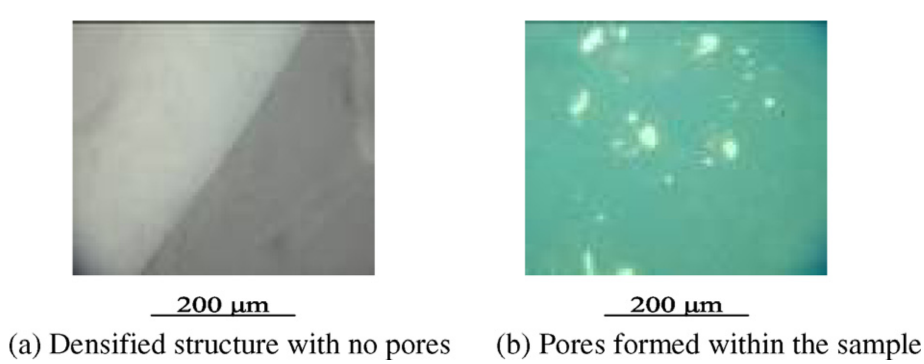

Fig. 6. POM image of sample prepared under vacuum condition (a) 50 mm Hg and (b) 100 mm Hg.

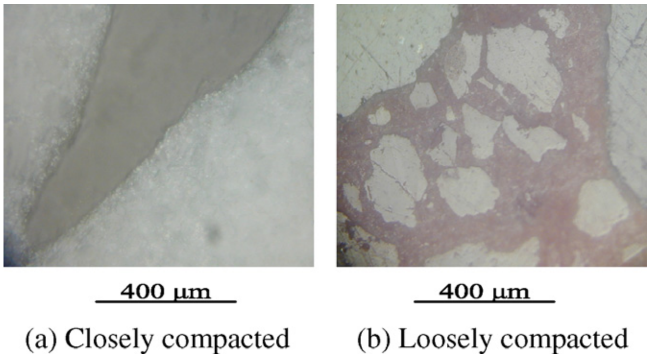

Fig. 8. POM image of sample prepared under (a) high vibration frequency (50.0 Hz); (b) low vibration frequency (16.7 Hz).

Table 4
Physical properties obtained under different vibration frequencies

Vibration frequency (Hz)	8.3	16.7	33.3	50.0
Density	2.134	2.216	2.445	2.448
Water absorption (%)	0.210	0.205	0.012	0.011
Flexural strength (MPa)	29.6	38.2	51.1	51.9
Compressive strength (MPa)	109.5	123.3	148.8	151.3

Conditions: compaction pressure (14.7 MPa), vacuum (50 mm Hg).

compaction pressure of 14.7 MPa and vacuum at 50 mm Hg, better physical properties can be obtained at higher vibration frequencies. For example, at 50.0 Hz, the density is 2.448, the water absorption drops to 0.011%, flexural strength reach 51.9 MPa, and compression strength rises to 151.3 MPa. It can be inferred from the results that within the short 2 min duration, vibration at too low frequency fails to compact the aggregates into a densified structure.

4. Conclusions

(1) This study has successfully manufactured artificial construction slabs from stone leftover fragments crushed into fine aggregates and waste glass ground into powder. Under compaction pressure of 14.7 MPa, vibration frequency of 33.3 Hz and vacuum condition at 50 mm Hg, we obtained artificial stone slabs of densified structure with compressive strength exceeding 148.8 MPa and water absorption below 0.02%. Moreover, both density and flexural strength of these materials increase with increasing compressive strength. Hence, waste glass and stone fragments can be recycled into quality products of high unit price.

(2) Experimental results reveal that using high compaction pressure alone will not yield densified structure. Vibration is also needed to adjust the orientation of aggregates to become more closely compacted. In addition, excessive pressure crushes aggregates, producing cracks and thus decreasing the compressive strength. In this research, the optimal compaction pressure obtained is 14.7 MPa.

(3) Among the three processing conditions, compaction pressure is the chief determinant of compressive strength, while vibration frequency and vacuum condition influence compact density, which in turn affects compressive strength. To produce high-quality artificial stone slabs with no pores, the air trapped between aggregates during the mixing process must be eliminated using a vacuum pump. Only at vacuum condition below 50 mm Hg can the formation of pores be prevented.

(4) The success of recycling techniques is dependent on the commercial profits they can bring. Hence, the development of recycling techniques has to take into consideration market demand and unit price of the recycled products. This research has successfully led to three patents in Taiwan [15–17]; and the market price of artificial stone slabs has increased to US$4160 per cubic meter. In sum, the manufacturing of artificial stone slabs from recycled waste products not only offers an ecological alternative to natural construction stones, its production and applications also generate great economic benefits.

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