Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering
15 (3) (2023) 0015~0025
DOI 10.71939/jsme.2023.1091984

*Research article*

# The effect of physical and mechanical properties on the abrasion resistance of artificial stones produced with granite waste

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(Manuscript Received --- 21 Nov. 2022; Revised --- 03 Jan. 2023; Accepted --- 24 Jan. 2023)

**Abstract**

The recycling of mine stone waste has been interesting for the creation of employment opportunities and added value and the prevention of environmental pollution. The present study examined the effects of the physicomechanical properties on the abrasion resistance of artificial stones produced with granite cut waste. A total of four artificial specimens were produced under different compositions and methods. Their physicomechanical properties, such as density, porosity, water absorption, hardness, compressive strength, and abrasion resistance, were evaluated. Finally, the artificial stones were compared to natural granite and marble in abrasion resistance. It was found that an increase in the porosity and water absorption reduced hardness, compressive strength, and abrasion resistance. Furthermore, hardness, compressive strength, and abrasion resistance declined as the porosity and water absorption increased. The increased rotational speed and load in the Taber abrasion test diminished abrasion resistance. The epoxy resin-based artificial stone exhibited the highest performance among the artificial specimens. It had almost the same porosity and water absorption as natural granite and marble. However, the epoxy resin-based stone with lower Mohs hardness and compressive strength showed less abrasion resistance compared to the natural granite and marble. As a result, all four artificial stones showed satisfactory performance for the flooring of congested areas.

*Keywords:* Artificial stone, Granite waste, Hardness, Compressive strength, Abrasion resistance.

## 1- Introduction

The processing of natural stones produces huge amounts of stone waste every year. Demolished buildings and other stone industries also leave large quantities of stone waste in the environment. This waste has poor biodegradability and poses negative impacts on environmental landscapes [1,2]. It may even endanger the ecosystem. In particular, granite processing has 30-40% waste directly discharged into the environment as it has no use. The collection and disposal of such waste in manufacturing units would be expensive and non-profitable for manufacturers. However, the reuse of such waste in industries could not only provide profits to the manufacturers and help create employment opportunities but also allow for preventing the associated environmental impacts [3]. The production of artificial stones is a very effective approach to recycle such waste. Artificial stones are various in color, size, and shape. They are also more affordable than natural stones in some countries, including Iran. In light of lower densities, artificial stones help significantly lower the total weight of a structure, particularly in large buildings. The other advantages of artificial stones include controllable physicomechanical properties, e.g., abrasion resistance, thermal resistance, and water absorption [4]. The recycling of stone waste, specifically for the production of artificial stones, has drawn significant attention across the world. Numerous studies investigated the production and properties of artificial stones. Peixoto et al. [5] produced an artificial stone of acceptable strength using building waste, particularly a combination of glass and epoxy resin. It had low water absorption and could be easily cleaned. Gomes et al. [6] conducted a physicomechanical analysis of an artificial stone produced using granite waste and epoxy resin. The stone was fabricated through vacuum vibration pressing. It had high thermal, vibration, impact, and abrasion resistance. Hence, it was argued to be efficient for road flooring. Silva et al. [7] studied the physicomechanical properties of an artificial stone based on marble calcite waste and epoxy resin. They fabricated the stone using the vacuum vibration press and reported satisfactory flexural and compressive strength. They demonstrated that the stone was economical and not only reduced the disposal of stone waste in the environment but also created employment opportunities and added value. Gomes et al. [8] fabricated and characterized a novel artificial stone using brick waste and mine dust in an epoxy matrix. They found that the dust-based atone was economical and had satisfactory mechanical, thermal, physical, and chemical properties. The stone was resistant to HCl and underwent low abrasion. Kim et al. [9] evaluated the thermal properties of an integrated phase change of artificial stone materials based on the biochar load content. They showed that biochar not only was biodegradable but also could, in combination with construction materials, help control the temperature. Shishehgaran et al. [10] analyzed the mechanical strength of artificial stones containing travertine, gravel, and sand waste. They fabricated a stone by combining travertine and epoxy resin and cured it for 4 h at 60 °C. The best specimens had a compressive strength of 67.3 MPa and a flexural strength of 60.7 MPa, suggesting excellent strength for an artificial stone. Lee et al. [11] used incinerator ash fused slag as an artificial stone. The fused slag was treated and cooled into fine crystals. The crystals were utilized in place of rock flour to produce artificial stone. The stone showed similar compressive and tensile strengths to artificial stones produced with common methods. This procedure also recycles slag and prevents its discharge into the environment. According to the literature reviews, a few researches were carried out on the physicomechanical properties and wear behavior of artificial stones produced with granite waste. Therefore, the present study sought to evaluate the effects of physicomechanical properties on the abrasion of four artificial stones. The artificial stones were compared to common natural construction stones, e.g., marble and granite. The fabricated artificial stones were subjected to abrasion testing, exploring the effects of the rotational speed and load on abrasion. Then, the stones were tested for water absorption, porosity, density, hardness, and uniaxial compressive strength. Finally, the effects of the measured physicomechanical properties on abrasion resistance were explored.

## 2- Materials and methods

The present work used white granite with black specks ($S_A$) extracted from mines in Najafabad, Iran, in 400*400*20 mm cuts. Marble cuts of the same size ($S_B$) were obtained from mines in Abadeh, Iran. To fabricate artificial stones, granite waste from Rose Stone Company in Najafabad was employed. The additives included grey cement ISIRI-389, white cement ISIRI-393, lime powder ISIR-5719, and epoxy resin ML-506. Specimen 1 ($S_C$) was fabricated using 50% granite waste, 40% grey cement, and 10% epoxy resin. The specimen was molded and vibrated without pressing to remove bubbles. Once it had been dried, the specimen was demolded in a 400*400*20 mm size. Specimen 2 ($S_D$) was produced by combining 40% granite aggregates, 20% granite powder, and 40% grey cement. It was molded and pressed at 800 tons. Then, it was demolded in a size of 400*400*20 mm to be dried. Specimens 3 ($S_E$) and 4 ($S_F$) were fabricated under the same conditions as $S_D$, except that $S_E$ consisted of 40% granite aggregates, 20% lime power, and 40% grey cement, and $S_F$ contained 40% granite aggregates, 20% lime powder, and 40% white cement. The natural and artificial specimens were surface-finished and cut into disks with an outer diameter of 98.3 mm, an inner diameter of 10 mm, and a thickness of 20 mm using a water jet, as shown in Fig. 1. Then, the Taber abrasion test was carried out using a test machine manufactured by Tajhiz Sanat Company according to ASTM C1353 to evaluate the abrasion properties of the stones. Fig. 2 shows the Taber abrasion test machine. A rotational speed of 1000 rpm was applied. The specimens were placed in an oven at 60°C for 24 h before and after the abrasion test to be completely dried. To measure the weight loss, the specimens were weighed using a scale with a precision of ±0.01 g. The effects of the rotational speed and load on the abrasion properties of the stones were evaluated in the abrasion test. Table 1 ranks the influential parameters. A total of 36 abrasion tests were performed on 36 specimens of 6 stones. The abrasion resistance index was calculated as the abrasion measure of the stones, as in (1):

$$I_w=\frac{36.75}{w_o\text{-}w_i}\times p\times\frac{n}{1000} \tag{1}$$

In this regard: $I_w$ abrasion resistance index, $w_o$ initial mass of the sample in terms of grams, $w_i$ sample mass after 1000 rotations in grams, $p$ actual sample density and $n$ number of rotation cycles during the test.


Fig. 1 (a) granite, (b) marble, (c) artificial stone made with resin, (d) artificial stone made with stone powder, (e) artificial stone made with lime and grey cement and (f) artificial stone made with lime and white cement.


Fig. 2 Taber abrasion test machine.

**Table 1:** Ranking of abrasion test parameters.

| Parameters | First level | Second level | Third level |
|---|---|---|---|
| Rotational speed (rpm) | 30 | 50 | - |
| Load (N) | 5 | 10 | 15 |

apparent density was calculated as the mass-to-volume ratio. The porosity was calculated based on ASTM C914, as in (3):

$$\emptyset = \left(1-\frac{\rho_R}{\rho_A}\right)\times 100 \qquad (3)$$

where in: $\emptyset$ percentage of porosity, $\rho_R$ actual density and $\rho_A$ apparent density.
Hardness was measured using the Mohs hardness scale based on ASTM C1895.

Hardness indenters (ITAT, China) were used. A uniaxial compressive test machine (Sigma Sanat Company) was utilized to evaluate the compressive strength of the stones based on ASTM C170.

## 3- Results and discussion

### 3-1- Abrasion resistance

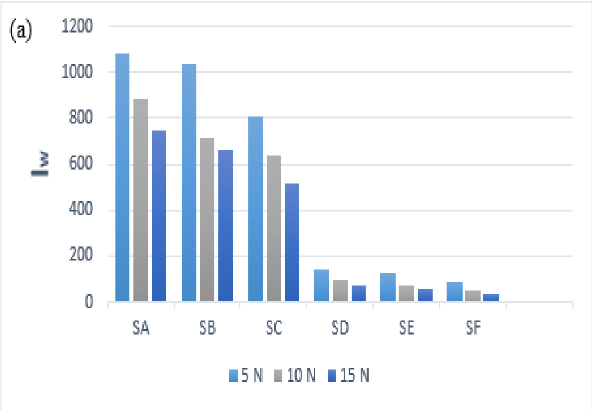
Table 2 represents the design of experiment for the Taber abrasion testing of the natural and artificial stones along with the weight loss and abrasion resistance index.

**Table 2:** Design of experiment for the Taber abrasion test, weight losses, and abrasion resistance indices.

| Test number | Stone name | Speed (rpm) | Load (N) | Weight loss (g) | Abrasion resistance index |
|---|---|---|---|---|---|
| 1 | $S_A$ | 30 | 5 | 0.09 | 1080.85 |
| 2 | $S_A$ | 30 | 10 | 0.11 | 884.33 |
| 3 | $S_A$ | 30 | 15 | 0.13 | 748.28 |
| 4 | $S_B$ | 30 | 5 | 0.09 | 1035.53 |
| 5 | $S_B$ | 30 | 10 | 0.13 | 716.90 |
| 6 | $S_B$ | 30 | 15 | 0.14 | 665.70 |
| 7 | $S_C$ | 30 | 5 | 0.11 | 809.50 |
| 8 | $S_C$ | 30 | 10 | 0.14 | 636.03 |
| 9 | $S_C$ | 30 | 15 | 0.17 | 517.76 |
| 10 | $S_D$ | 30 | 5 | 0.56 | 139.32 |
| 11 | $S_D$ | 30 | 10 | 0.83 | 94 |

| | | | | | |
|---|---|---|---|---|---|
| 12 | $S_D$ | 30 | 15 | 1.04 | 75.01 |
| 13 | $S_E$ | 30 | 5 | 0.58 | 127.73 |
| 14 | $S_E$ | 30 | 10 | 1.01 | 73.35 |
| 15 | $S_E$ | 30 | 15 | 1.34 | 55.28 |
| 16 | $S_F$ | 30 | 5 | 0.79 | 91.96 |
| 17 | $S_F$ | 30 | 10 | 1.43 | 50.80 |
| 18 | $S_F$ | 30 | 15 | 1.89 | 38.44 |
| 19 | $S_A$ | 50 | 5 | 0.10 | 968.76 |
| 20 | $S_A$ | 50 | 10 | 0.12 | 782.34 |
| 21 | $S_A$ | 50 | 15 | 0.14 | 654.50 |
| 22 | $S_B$ | 50 | 5 | 0.10 | 877.68 |
| 23 | $S_B$ | 50 | 10 | 0.15 | 597.86 |
| 24 | $S_B$ | 50 | 15 | 0.17 | 544.63 |
| 25 | $S_C$ | 50 | 5 | 0.13 | 668.23 |
| 26 | $S_C$ | 50 | 10 | 0.17 | 519.61 |
| 27 | $S_C$ | 50 | 15 | 0.21 | 416.18 |
| 28 | $S_D$ | 50 | 5 | 0.72 | 107.86 |
| 29 | $S_D$ | 50 | 10 | 1.07 | 72.28 |
| 30 | $S_D$ | 50 | 15 | 1.37 | 56.85 |
| 31 | $S_E$ | 50 | 5 | 0.76 | 96.26 |
| 32 | $S_E$ | 50 | 10 | 1.37 | 53.87 |
| 33 | $S_E$ | 50 | 15 | 1.84 | 40.09 |
| 34 | $S_F$ | 50 | 5 | 1.07 | 67.79 |
| 35 | $S_F$ | 50 | 10 | 1.99 | 36.40 |
| 36 | $S_F$ | 50 | 15 | 2.65 | 27.32 |

Fig. 3 plots the abrasion resistance index at rotational speeds of 30 and 50 rpm and loads of 5, 10, and 15 N. As can be seen, a rise in the load reduced the abrasion resistance index at both speeds. An increased load raises friction and, therefore, abrasion. Abrasion resistance declines as abrasion rises. Karaca et al. [12] reported the same result for granite; they found that abrasion increased as the load increased. An increase in the load by 1 N in the range of 5-15 N at 30 rpm led to a 3%, 3.5%, 3.6%, 4.6%, 5.6%, and 5.8% decrease in the abrasion resistance of $S_A$, $S_B$, $S_C$, $S_D$, $S_E$, and $S_F$, respectively. It can be inferred that abrasion resistance was more sensitive to an increased load in the epoxy-free stones than in the natural and epoxy-containing artificial stones. The highest load dependence was observed in $S_F$ as it experienced the largest abrasion resistance decline (5.8%) for a 1 N rise in the load. The epoxy resin-containing artificial stone had the lowest dependence on the load among the artificial stones (with the natural stones having the highest load independence). The same case holds for 50 rpm. Moreover, a rise in the rotational speed at a given load diminished abrasion resistance due to increased friction. In fact, a larger speed led to greater friction, increasing abrasion and diminishing abrasion resistance. At a load of 5 N, a rise in the speed from 30 to 50 rpm reduced the abrasion resistance indices of $S_A$, $S_B$, $S_C$, $S_D$, $S_E$, and $S_F$ by 10%, 15%, 17%, 22%, 24%, and 25%. The highest rotational speed dependence was observed in $S_E$. The same case holds for loads of 10 and 15 N. It can be inferred that natural stones (granite and marble) had higher abrasion resistance than the artificial stones. Granite showed higher abrasion resistance than marble. The epoxy-free artificial stones had lower abrasion resistance. The lowest abrasion resistance was observed in $S_F$. As an artificial stone, $S_C$ showed excellent abrasion (almost as resistant as the natural specimens).



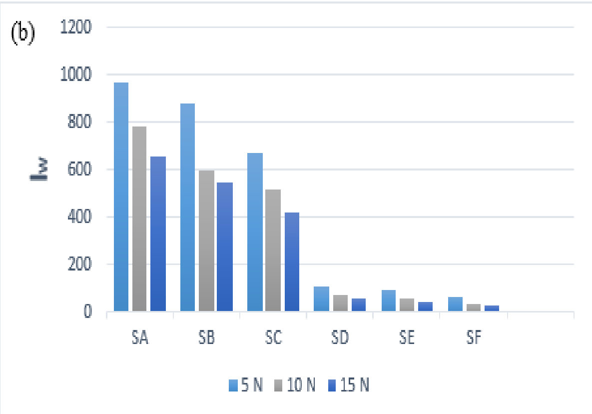




Fig. 3 Abrasion resistance index at (a) 30 and (b) 50 rpm under loads of 5, 10, and 15 N.

**3-2- Density, porosity, and water absorption**

Table 3 represents the densities, porosities, and water absorption of the stones. As can be seen, the apparent densities were in good agreement with the actual densities. The apparent densities were slightly higher than the actual ones. This difference arose from voids in the porous structure of the stones. In fact, the apparent density incorporates the voids, leading to an error in the density. The lowest porosity was found in the natural stones (nearly 1%). Hence, the natural stones had the lowest difference between the actual and apparent densities. Among the artificial stones, $S_C$ (the resin-containing stone) had the lowest porosity (i.e., 1.63%). It can be concluded that the epoxy resin-based artificial stone showed a very similar porosity to that of the natural stones. This demonstrates the contributions of epoxy resin to the artificial stone. The epoxy resin fills up the voids and reduces the porosity. Although it was not pressed, the resin-based artificial stone ($S_C$) showed a lower porosity than the resin-free pressed artificial stones (i.e., $S_D$, $S_E$, and $S_F$). This suggests that pressing may improve the properties of artificial stones but cannot be as effective as resin. The porosity of $S_D$ was smaller than those of $S_E$ and $S_F$, suggesting that stone powder would have higher contributions than lime powder to the enhancement of stone properties. Despite the same fabrication process, $S_E$ had a lower porosity than $S_F$. It can be said that grey cement is more efficient than white cement in the production of artificial stones. In addition, the natural stones and the resin-based artificial stone had much lower water absorption. The resin-containing artificial stone showed almost the same water absorption as the natural ones (<1%). Fig. 4 plots water absorption versus porosity. As can be seen, the porosity and water absorption are directly related; a rise in the porosity raised water absorption. The resin-free artificial stones significantly differed from the natural and resin-containing artificial specimens in the porosity and water absorption; the water absorption of $S_E$ and $S_F$ was twenty times as high as that of the natural stones. The direct relationship between the porosity and water absorption was also reported in earlier works. Kearsley and Wainwright [13] studied a concrete and reported that water absorption increased as the porosity increased.

**3-2-1- Density, porosity and abrasion**

Fig. 5 plots the abrasion resistance index versus density at 30 rpm and 5 N to evaluate their relationship. As can be seen, the abrasion resistance index and density are directly related; a rise in the density increased abrasion resistance [14].

**Table 3:** Density, porosity, and water absorption.

| Stone name | Sample mass (g) | Sample size ($cm^3$) | Apparent density ($g/cm^3$) | Actual density ($g/cm^3$) | Porosity (%) | Water absorption (%) |
|---|---|---|---|---|---|---|
| $S_A$ | 401.2 | 150 | 2.674 | 2.647 | 0.98 | 0.36 |
| $S_B$ | 385.6 | 150 | 2.570 | 2.536 | 1.31 | 0.75 |
| $S_C$ | 369.6 | 150 | 2.464 | 2.432 | 1.63 | 0.77 |
| $S_D$ | 368.8 | 150 | 2.458 | 2.123 | 13.60 | 5.84 |
| $S_E$ | 363.6 | 150 | 2.424 | 2.016 | 16.82 | 7.66 |
| $S_F$ | 362.1 | 150 | 2.414 | 1.977 | 18.07 | 8.31 |

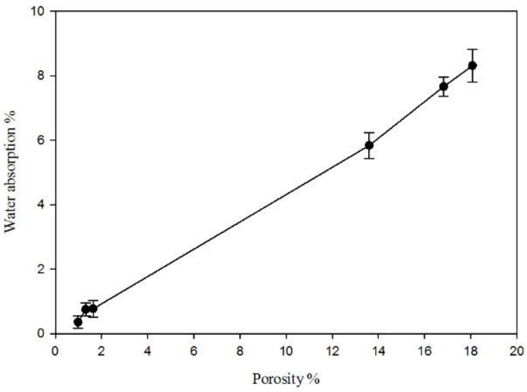


Fig. 4 Water absorption-porosity plot.

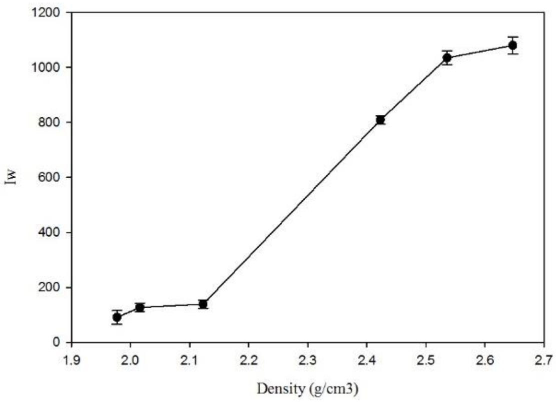


Fig. 5 Abrasion resistance-density plot at 30 rpm and 5 N.

Fig. 6 plots the abrasion resistance index versus porosity at 30 rpm and 5 N. In contrast to the density, the porosity had an inverse relationship with abrasion resistance; a rise in the porosity raised abrasion and reduced abrasion resistance. An increased number of voids reduces the contact area in the abrasion test, enhancing the contact pressure [15] and diminishing abrasion resistance. The relationship between the porosity and abrasion has been frequently studied. Yavuz et al. [14] explored the relationship between the porosity and abrasion. They concluded that a rise in the porosity increased abrasion in carbonate stones.

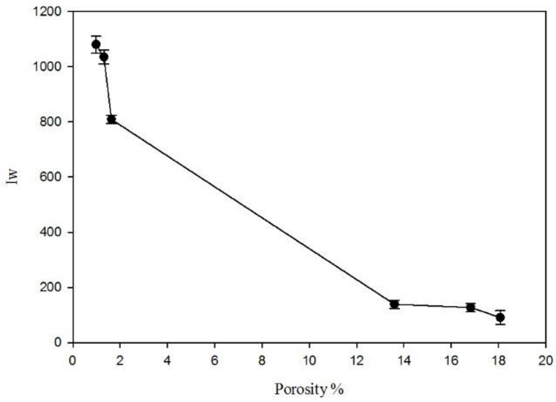


Fig. 6 Abrasion resistance-porosity plot at 30 rpm and 5 N.

### 3-2-2- Water absorption and abrasion

Fig. 7 depicts the abrasion resistance index versus water absorption at 30 rpm and 5 N. According to this figure, water absorption and abrasion resistance had an inverse relationship; higher water absorption led to lower abrasion resistance, leading to greater abrasion in the stone. This can be attributed to the voids in the stone. Yilmaz et al. [16] studied granite and reported a direct relationship between water absorption and abrasion; i.e., higher water absorption represented lower abrasion resistance and thus a larger abrasion rate.

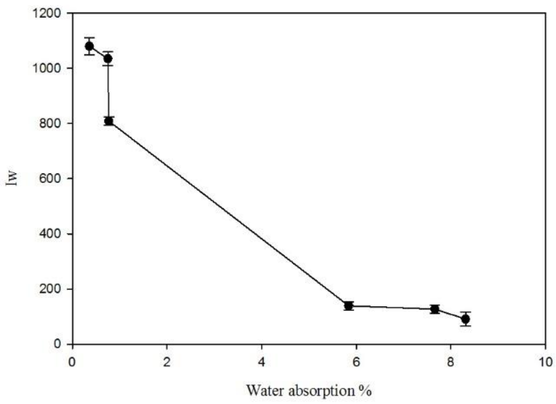



Fig. 7 Abrasion resistance index versus water absorption at 30 rpm and 5 N.

### 3-3- Hardness

Table 4 provides the Mohs hardness results. The resin-based artificial stone ($S_C$) had a relatively high Mohs hardness scale (7.5), suggesting more similar hardness than the other artificial specimens to the natural stones. The higher hardness of $S_C$ can be attributed to its resin content. According to Fig. 8, a rise in the porosity reduced hardness. An increased number of voids reduced resistance to indenter-induced deformation in the hardness test and increases the penetration depth [17].

**Table 4:** Mohs hardness of stones.

| Stone name | Mohs Hardness |
|---|---|
| $S_A$ | 8.5 |
| $S_B$ | 8 |
| $S_C$ | 7.5 |
| $S_D$ | 7 |
| $S_E$ | 6.5 |
| $S_F$ | 6 |

#### 3-3-1- Hardness and abrasion

Fig. 9 plots the abrasion resistance index versus Mohs hardness at 30 rpm and 5 N. As can be seen, hardness and abrasion resistance had a direct relationship; i.e., a rise in hardness reduced the abrasion rate and increased abrasion resistance, consistent with the Archard wear equation [18]. Earlier works analyzed the relationship between Mohs hardness and stone abrasion [19,20]. Yilmaz et al. [19] investigated granite flooring stones and found that increased Mohs hardness reduced abrasion in granite.

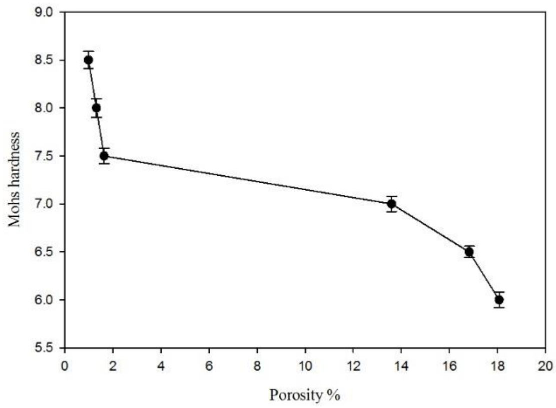



Fig. 8 Mohs hardness-porosity plot.

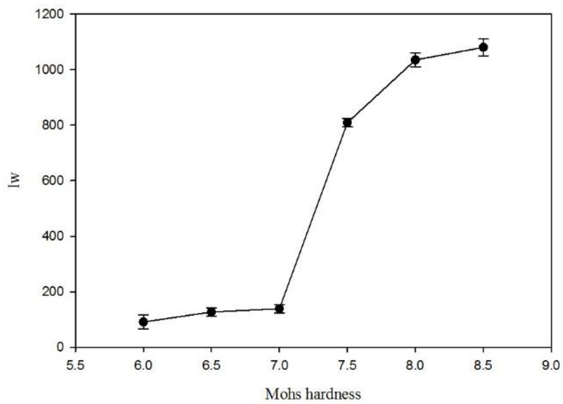



Fig. 9 Abrasion resistance versus Mohs hardness at 30 rpm and 5 N.

### 3-4- Compressive strength

Table 5 provides the uniaxial compressive test results. It can be observed that the natural stones had the highest compressive strength and represented better alternatives for flooring. The compressive strength of $S_C$ and $S_D$ was nearly half that of the natural stones. Furthermore, $S_E$ and $S_F$ had the lowest compressive strength; their compressive strength was below 20% of that of the natural stones. According to Fig.

10, an increase in the porosity reduced compressive strength [21]. An increased number of voids reduces the cross-sectional area and negatively affects mechanical properties, e.g., compressive strength [22]. Bashin's equation related porosity and compressive strength, as in (4) [23]:

$$\sigma_c=\sigma_0(1-\rho)^n \quad (4)$$

where $\sigma_c$ is the compressive strength at a porosity of $p$, $\sigma_0$ is the compressive strength at a porosity of 0, and $n$ is a power coefficient.

**Table 5:** Uniaxial compressive strength of stones.

| Stone name | Compressive strength (MPa) |
|---|---|
| $S_A$ | 129.48 |
| $S_B$ | 113.63 |
| $S_C$ | 60.13 |
| $S_D$ | 57.60 |
| $S_E$ | 23.30 |
| $S_F$ | 22.70 |

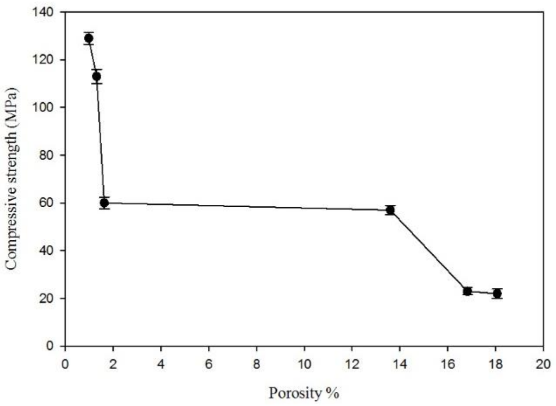


Fig. 10 Compressive strength versus porosity.

**3-4-1- Compressive strength and abrasion**

Fig. 11 plots the abrasion resistance index versus uniaxial compressive strength at 30 rpm and 5 N. As can be seen, a rise in the uniaxial compressive strength enhanced abrasion resistance. Earlier works analyzed marble and reported the same relationship between abrasion resistance and compressive strength [24]. Research has shown that increased compressive strength diminishes the abrasion rate of carbonate stones [14].

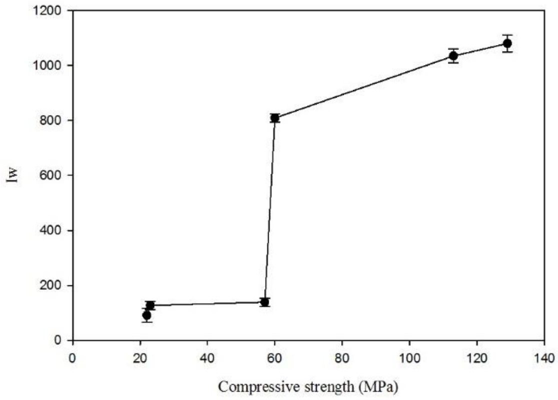


Fig. 11 Abrasion resistance index versus compressive strength at 30 rpm and 5 N.

**4- Conclusion**

The present study fabricated four artificial stones using granite waste. The effects of their physicomechanical properties on abrasion resistance were explored relative to natural granite and marble. It was found that:

- Epoxy resin improved the physical properties of artificial stones by reducing the porosity to (1.63%) and water absorption to 0.77%.
- The epoxy resin-based artificial stone ($S_C$) with Mohs hardness of 7.5 exhibited the highest hardness among the artificial stones. The compressive strength of $S_C$ (60.13 MPa) was nearly half that of natural granite and marble. These two parameters are determinants of stone applications. According to the Mohs hardness and compressive strength results, $S_C$ is an effective flooring alternative for congested areas.
- A rise in the rotational speed to 50 rpm and load to 15 N in the Taber abrasion

test increased abrasion and diminished abrasion resistance.

- The porosity and water absorption had inverse relationships with abrasion resistance.
- The density, Mohs hardness, and compressive strength had direct relationships with abrasion resistance. The plots were validated through comparison to earlier works.

**Declaration of Conflicting Interests**

The Authors declare that there is no conflict of interest.

**References**

[1] Bagherpor, Z., Nazari, S., Bagherzadeh, P., Fazlavi, A. (2019). Description and effective parameters determination of the production process of fine-grained artificial stone from waste silica. *SN Applied Sciences, 1*(11), 1-10**.**

[2] Poudel, J., Lee, YM., Kim, HJ., Oh, SC. (2021). Methyl methacrylate (MMA) and alumina recovery from waste artificial marble powder pyrolysis. *Journal of Material Cycles and Waste Management, 23*(1), 214-221.

[3] Sepahvand, Z., Barani, K. (2018). Production of Artificial Stone from Dimension Stone Waste. *Amirkabir Journal of Civil Engineering, 50*(3), 453-460

[4] Barani, K., Esmaili, H. (2016). Production of artificial stone slabs using waste granite and marble stone sludge samples. *Mining and Environment, 7*(1), 135-141.

[5] Peixoto, J., Carvalho, EAS., Gomes, MLPM., da Silva Guimarães, R., Monteiro, SN., de Azevedo, AR., Vieira, CMF. (2022), Incorporation of Industrial Glass Waste into Polymeric Resin to Develop Artificial Stones for Civil Construction. *Arabian Journal for Science and Engineering, 47* (4), 4313-4322

[6] Gomes, MLP., Carvalho, EA., Demartini, TJ., de Carvalho, EA., Colorado, HA., Vieira, CMF. (2021). Mechanical and physical investigation of an artificial stone produced with granite residue and epoxy resin. *Journal of Composite Materials, 55* (9), 1247-1254

[7] Silva, FS., Ribeiro, CEG., Rodriguez, RJS. (2017). Physical and mechanical characterization of artificial stone with marble calcite waste and epoxy resin. *Materials Research, 21* (1), 1-6.

[8] Gomes, MLP., Carvalho, EA., Sobrinho, LN., Monteiro, SN., Rodriguez, RJ., Vieira, CMF. (2018). Production and characterization of a novel artificial stone using brick residue and quarry dust in epoxy matrix. *Journal of materials research and technology, 7* (4), 492-498

[9] Kim, YU., Yun, BY., Nam, J., Choi, JY., Wi, S., Kim, S. (2021), Evaluation of thermal properties of phase change material-integrated artificial stone according to biochar loading content. *Construction and Building Materials, 305*, 124682

[10] Shishegaran, A., Saeedi, M., Mirvalad, S., Korayem, AH. (2021). The mechanical strength of the artificial stones, containing the travertine wastes and sand. *Journal of Materials Research and Technology, 11*, 1688-1709

[11] Lee, M-G., Lo, S-L., Kan, Y-C., Chiang, C-H., Chang, J-H., Yu-Min, S., Yatsenko, E., Hu, S-H. (2022), Water quenched slag from incinerator ash used as artificial stone. *Case Studies in Construction Materials, 16*, e00827.

[12] Karaca, Z., Yılmaz, NG., Goktan, R. (2012). Abrasion wear characterization of some selected stone flooring materials with respect to contact load. *Construction and Building Materials, 36*, 520-526.

[13] Kearsley, E., Wainwright, P. (2001). Porosity and permeability of foamed concrete. *Cement and concrete research, 31*(5), 805-812.

[14] Yavuz, H., Ugur, I., Demirdag, S. (2008). Abrasion resistance of carbonate rocks used in dimension stone industry and correlations between abrasion and rock properties. *International Journal of Rock Mechanics and Mining Sciences, 45*(2), 260-267.

[15] Hamid, AA., Ghosh, P., Jain, S., Ray, S. (2008). The influence of porosity and particles content on dry sliding wear of cast in situ Al (Ti)–$Al_2O_3$ ($TiO_2$) composite. *Wear, 265*(1-2), 14-26.

[16] Yılmaz, NG., Goktan, R., Kibici, Y. (2011). An investigation of the petrographic and physico-mechanical properties of true granites influencing diamond tool wear performance, and development of a new wear index. *Wear 271*(5-6), 960-969.

[17] Sinha, A., Farhat, Z. (2015). A study of porosity effect on tribological behavior of cast Al A380M and sintered Al 6061 alloys. Journal of Surface Engineered *Materials and Advanced Technology, 5*(01), 1.

[18] Abedinzadeh, R., Safavi, S., Karimzadeh, F. (2015). A comparative study on wear properties of nanostructured Al and Al/$Al_2O_3$ nanocomposite prepared by microwave-assisted hot press sintering and conventional hot pressing. *Journal of Mechanical Science and Technology, 29*(9), 3685-3690.

[19] Yılmaz, NG., Goktan, R., Onargan, T. (2017). Correlative relations between three-body abrasion wear resistance and petrographic properties of selected granites used as floor coverings. *Wear, 372*, 197-207.

[20] Jeong, D., Erb, U., Aust, K., Palumbo, G. (2003). The relationship between hardness and abrasive wear resistance of electrodeposited nanocrystalline Ni–P coatings. *Scripta Materialia, 48*(8), 1067-1072.

[21] Justo, J., Castro, J. (2021). Mechanical properties of 4 rocks at different temperatures and fracture assessment using the strain energy density criterion. *Geomechanics for Energy and the Environment, 25*, 100212.

[22] Ternero, F., Rosa, LG., Urban, P., Montes, JM., Cuevas, FG. (2021). Influence of the total porosity on the properties of sintered materials- A review. *Metals, 11*(5), 730.

[23] Li, Y-X., Chen, Y-M., Wei, J-X., He, X-Y., Zhang, H-T., Zhang, W-S. (2006). A study on the relationship between porosity of the cement paste with mineral additives and compressive strength of mortar based on this paste. *Cement and concrete research, 36*(9), 1740-1743.

[24] Pathri, B., Chaudhary, R., Mali, H., Nagar, R. (2017). Abrasion wear characterization of natural stones subjected to foot traffic and correlation between abrasion and mechanical properties. *Res Pap, 4*(4), 10-17.