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Effect of Recycled Polypropylene and Metallic Fiber Waste on the Sound Absorption Performance of Artificial Stone

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Abstract:

Noise pollution is a major problem in industrial and urban environments. Artificial stone has suitable mechanical properties but its acoustic performance can be limited. This study evaluated the effects of recycled polypropylene fibers and metallic fiber waste on the sound absorption performance of artificial stone. Response Surface Methodology was used to investigate polypropylene fiber content metallic fiber content and sample thickness. Fiber contents ranged from 0 to 28 percent and sample thickness ranged from 1 to 5 cm. Twenty experimental runs and five control samples without fibers were prepared. Sound absorption was measured using a two microphone impedance tube according to ISO 10534-2. Polypropylene fiber content had an important effect on sound absorption especially in the middle and high frequency ranges. Increasing polypropylene fiber content from 0 to 28 percent increased the mean sound absorption coefficient from 0.185 to 0.55 in the middle frequency range under fixed metallic fiber content and thickness. Metallic fibers showed a nonuniform effect that depended on the combination of variables. Two samples with different thicknesses showed very similar high frequency sound absorption coefficients of 0.528 and 0.5257. Surface porosity alone did not explain the acoustic response. The results indicate that recycled polypropylene and metallic fiber waste can be used to modify the acoustic performance of artificial stone when fiber content and sample thickness are appropriately selected.

Keywords: Artificial stone. Sound absorption coefficient. Polypropylene fibers. Metallic fiber waste. Response Surface Methodology. Building acoustics.

Introduction

Noise pollution is one of the main challenges in industrial and urban environments. It can affect physical health and mental health. It can also reduce work productivity and quality of life (2 ,1). Occupational exposure to high sound levels is a common cause of sensorineural hearing loss. It can also cause stress. It can disturb sleep. It can reduce cognitive performance (8-3). Therefore good acoustic conditions are important in workplaces (7 ,4). There are different methods for noise control. Sound absorption is one of the most useful methods. It can be applied during different stages of design and construction. It can also be effective over a wide range of frequencies (9). The main principle is simple. Sound absorbing materials reduce reflected sound energy. This happens by increasing the sound absorption coefficient of the surface. The use of building materials with good acoustic properties is a practical approach. Artificial stone is widely used in building facades

and indoor spaces. It has several advantages. It has a relatively low weight. It can be produced in different sizes and textures. It also has good mechanical strength and environmental durability -10) (12. However its natural acoustic performance may not be enough for some applications. Further improvement may be needed in sensitive environments such as food and cosmetic industries where both acoustic and hygienic conditions are important (14 ,13). One useful approach is to modify the microstructure of artificial stone by adding fibers. Different types of fibers can be used. These include natural fibers. They also include polymeric fibers and metallic fibers. These fibers can increase sound energy dissipation inside the material. They can also improve sound absorption over different frequency ranges (16 ,15). Polypropylene fibers are one of the most common synthetic fibers. They have a low production cost. They have a low density. They also have good chemical stability. They resist moisture and corrosion. In addition they can absorb and dissipate vibration energy. Previous studies have shown that polypropylene fibers can provide useful sound absorption especially at middle and high frequencies (19-17). Metallic fibers have different properties. They are mainly used to improve the mechanical performance of composites. They can increase tensile strength. They can improve crack resistance. They can also control crack development. Their high elastic modulus and high density can change the dynamic behavior of the base material. Therefore they may also affect its acoustic response (20). Large amounts of polymeric and metallic waste are produced by industrial activities. These wastes can create environmental problems. Recycling these materials in new building products can reduce waste. It can also reduce environmental pollution. This approach is also consistent with the principles of circular economy and sustainable development.

Many studies have evaluated polymeric fibers and metallic fibers separately. Most studies have focused on mechanical and physical properties. However the combined effect of these two fiber types on the acoustic behavior of artificial stone is still not clear. Their effects may also change across different frequency ranges. This issue has not been studied in detail.

The main aim of this study was to design and evaluate artificial stone containing different amounts of recycled polypropylene fibers and metallic fiber waste. The study examined the combined effects of these materials on the sound absorption coefficient. It also aimed to identify suitable combinations for high acoustic performance in different frequency ranges. Response Surface Methodology was used for the experimental design. It was also used for mathematical modeling and multivariable optimization. The results may provide a useful basis for the development of recycled artificial stone with improved acoustic performance. Such materials may also support healthier and quieter indoor and occupational environments.

Materials and Methods

Study design and samples

This experimental study evaluated the combined effects of recycled polypropylene fibers and metallic fibers on the acoustic performance of artificial stone. Response Surface Methodology was used to reduce the number of experiments and to evaluate the interaction between the factors. The experimental design was developed using Design Expert software from Stat Ease Inc. Minneapolis USA.

Polypropylene fiber content ranged from 0 to 28 percent. Metallic fiber content also ranged from 0 to 28 percent. Sample thickness ranged from 1 to 5 cm. These parameters were considered as the input variables. The sound absorption coefficient was considered as the response. It was evaluated in three frequency ranges. The low frequency range was 50 to 500 Hz. The middle frequency range was 500 to 1600 Hz. The high frequency range was 1600 to 6300 Hz. The experimental design included 20 runs. Six runs were independent center point replicates. These replicates had the same factor levels but were prepared and tested independently. Five additional control samples without fibers were also prepared. The weight percentages of the components are presented in *Table 1.*

Raw materials and mixture design

The artificial stone matrix consisted of Portland cement type II. Washed standard sand was used according to ASTM C33. The maximum sand particle size was 0.6 mm. Fine aggregate with a size range of 5 to 15 mm was also used. Water and polymeric carboxylate resin were added to the mixture. The mixture contained 14 kg of cement and 46 kg of aggregate. The mixture also contained 166 g of polymeric carboxylate resin. Recycled polypropylene fibers were obtained from waste produced by Aria Sanat Masoumi Company. The waste mainly contained irregular fibers and broken filaments. The material was manually separated. It was then washed and oven dried. Mechanical size reduction was then performed. The final fiber diameter ranged from 3 to 6 μm. Metallic fibers were obtained from machining waste. The waste included metallic chips and filaments. The material was sieved using different mesh sizes according to ASTM E11. It was then cleaned in an ultrasonic bath using water and detergent. The cleaning process lasted 15 to 30 min at 40 to 50 °C. The metallic waste was finally dried under ambient conditions.

Sample fabrication and curing

All samples were produced in an artificial stone workshop. The materials were first weighed. Cement sand and aggregate were dry mixed for 2 min. Water was then added. Mixing continued until a uniform mortar was obtained. The resin was added next. The required amounts of polypropylene and metallic fibers were gradually added. Mixing continued until the fibers were uniformly distributed. The fresh mixture was placed in cylindrical polyethylene molds. Samples with a diameter of 100 mm were used for low and middle frequency measurements. Samples with a diameter of 30 mm were used for high frequency measurements. Sample thickness ranged from 1 to 5 cm. The molds were placed on a vibration table for 40 to 60 s. This step was used to reduce trapped air and increase sample density. The samples were then cured at 70 °C for 20 h. After demolding they were stored in a standard water bath for 28 days. Before the acoustic tests the diameter and thickness of each sample were measured using a digital caliper. Samples with dimensional deviations were corrected by surface sanding.

Sound absorption measurement

The sound absorption coefficient was measured according to ISO 10534-2. The transfer function method was used. The measurements were performed at Shahid Beheshti University of Medical Sciences. A two microphone impedance tube system was used. The system was a BSWA SW477 manufactured in China. A 100 mm impedance tube was used for low and middle frequency

measurements. Measurements from 50 to 1600 Hz were included in the analysis. A 30 mm impedance tube was used for high frequency measurements from 1600 to 6300 Hz. The microphones were calibrated before testing. Calibration was performed at 1000 Hz and 114 dB. The laboratory temperature was maintained at 23 ± 1 °C. Relative humidity was maintained at 50 ± 5 percent. Normal atmospheric pressure was maintained. Each sample was tested under three backing conditions. These conditions were 0 mm 10 mm and 20 mm air gaps. Three independent measurements were performed for each condition. The mean value was used for further analysis. An overall absorption index was calculated to facilitate comparison between samples. It was obtained from the mean sound absorption coefficients at the selected one third octave band frequencies used in this study.

Morphological characterization

The morphology of the samples was evaluated using Field Emission Scanning Electron Microscopy. A MIRA3 TESCAN microscope was used. The images were used to examine fiber distribution in the stone matrix. They were also used to evaluate the fiber matrix interface. Images were obtained at different magnifications. These images provided direct information about surface morphology fiber distribution and porosity.

Surface porosity

Surface porosity was evaluated using SEM images. ImageJ software was used for image analysis. The images were converted into binary black and white images. The pore phase was separated from the solid matrix. Surface porosity was calculated from the ratio of black pixel area to the total image area. The surface porosity percentage was reported as Ps.

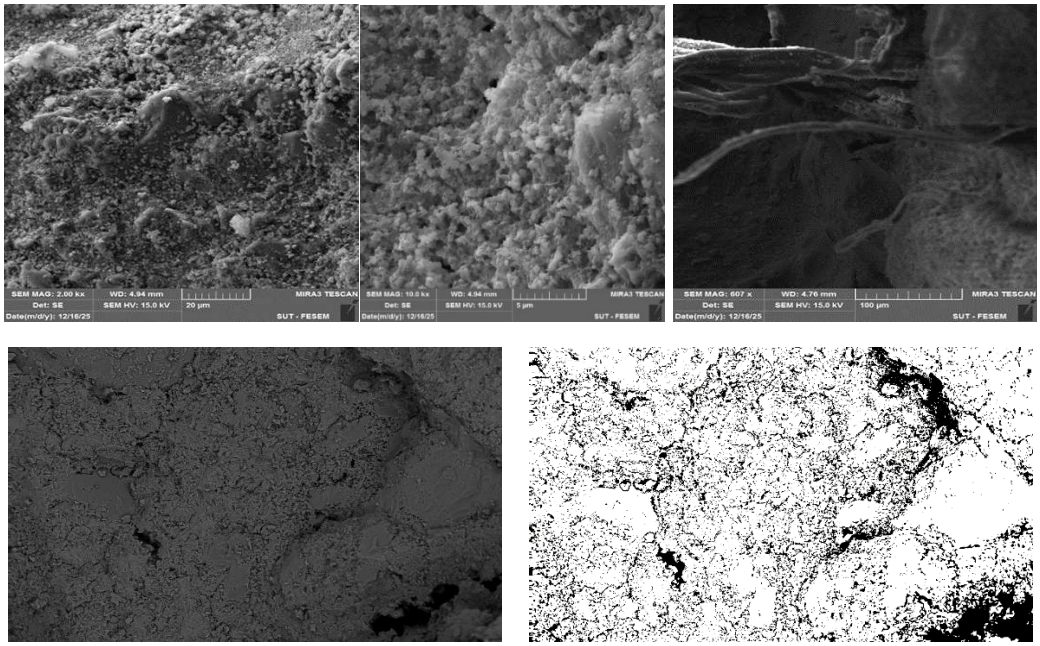


Figure 1. *Electron microscopy images of a sample with a thickness of 3 cm and 14 percent polypropylene fibers and 14 percent metallic fibers. a FESEM images. b Original SEM image on the left and binary black and white image on the right.*

Statistical analysis

Statistical analysis was performed using Design Expert software. The software was used to predict the response variables. It was also used to determine suitable experimental conditions. The direct effects and interaction effects of the parameters were evaluated using analysis of variance. SPSS version 27 was used for data management and descriptive analysis of the air gap measurements.

Results

In the response surface models A represented polypropylene fiber content. B represented metallic fiber content. C represented sample thickness. The mean sound absorption coefficient was used as the response for each frequency range. The models for all three frequency ranges were statistically significant at the 0.05 level. A summary of the analysis of variance and the coefficients of determination is presented in Table 2.

Acoustic performance of samples without fibers

Among the control samples without fibers the highest mean sound absorption coefficient in the low frequency range was 0.31. This value was obtained for the sample with a thickness of 4 cm and an air gap of 20 mm. Under the no air gap condition the 3 cm control sample showed the highest mean absorption in the middle and high frequency ranges. The values were 0.3166 and 0.36 respectively. The overall absorption index of this sample was 0.263. The 5 cm control sample without an air gap had an overall absorption index of 0.175. Therefore increasing the thickness from 3 to 5 cm did not increase the overall mean sound absorption in this comparison.

Low frequency range

According to Table 2 polypropylene fiber content and sample thickness had significant effects on the mean sound absorption coefficient in the low frequency range. Their p values were 0.0016 and 0.0030 respectively. The main effect of metallic fiber content was not significant. Its p value was 0.8270. However the interaction between polypropylene and metallic fibers was significant. The p value for this interaction was 0.0018. Under the no air gap condition run 13 showed the highest mean sound absorption coefficient in this range. This run contained 28 percent polypropylene fibers and 14 percent metallic fibers. Its thickness was 3 cm. The mean sound absorption coefficient was 0.13. The lowest value was 0.0411. It was observed in run 6. This run contained 14 percent polypropylene fibers and 28 percent metallic fibers. Its thickness was 3 cm. At a constant polypropylene content of 14 percent and a constant thickness of 3 cm the effect of metallic fiber content was not monotonic. The mean sound absorption coefficients at 0 percent 14 percent and 28 percent metallic fiber were 0.0433 0.0766 and 0.0411 respectively. Therefore the absorption first increased and then decreased. At a constant composition of 14 percent polypropylene fibers

and 14 percent metallic fibers the mean sound absorption coefficients at thicknesses of 1 cm 3 cm and 5 cm were 0.0611 0.0766 and 0.11 respectively. Under the no air gap condition increasing thickness was associated with higher mean sound absorption in the low frequency range.

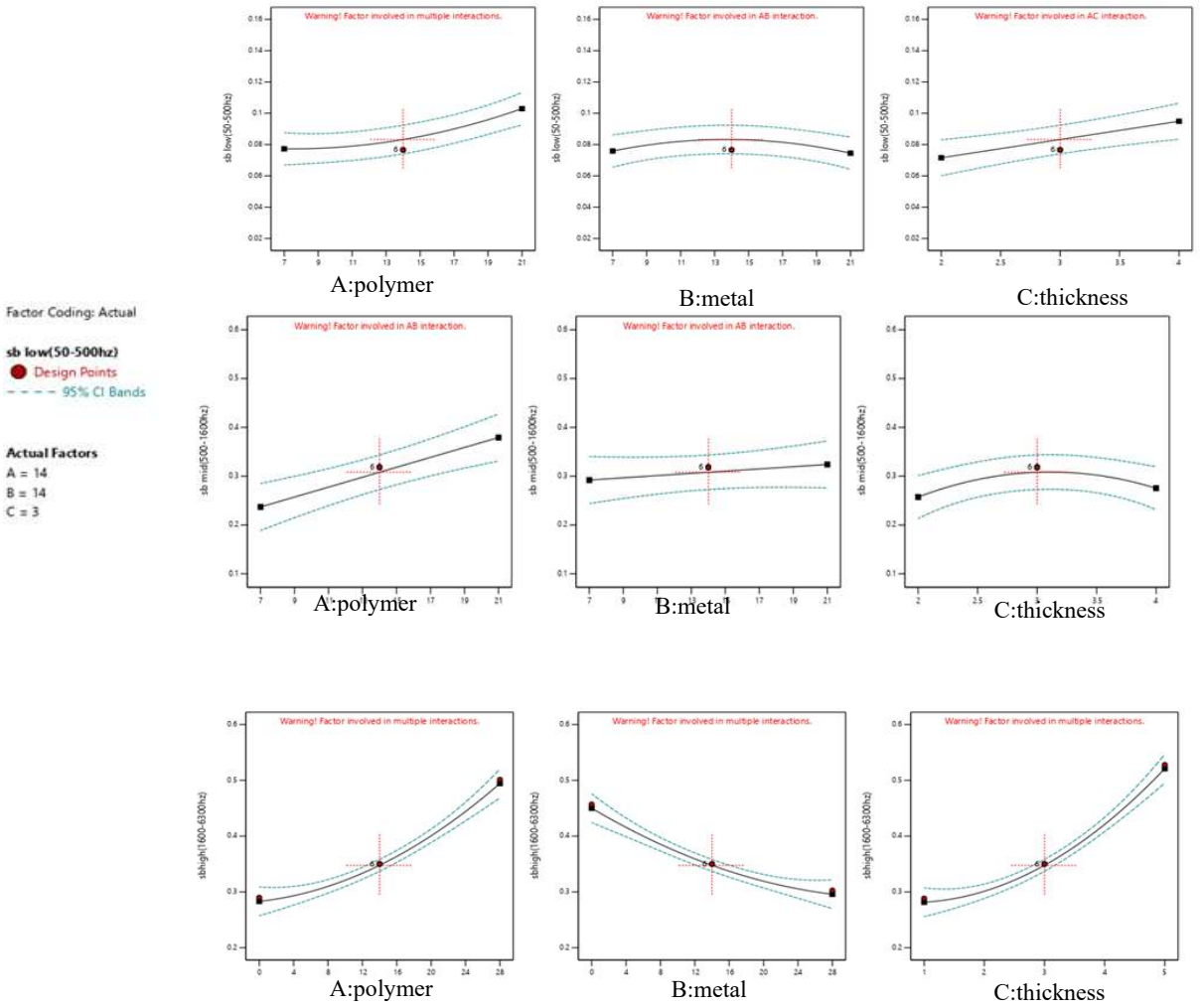


Figure 2. *Predicted mean sound absorption coefficient as a function of polypropylene fiber content metallic fiber content and sample thickness. a Low frequency range. b Middle frequency range. c High frequency range. In each plot one variable changes while the other two variables remain constant.*

Middle frequency range

In the middle frequency range from 500 to 1600 Hz the mean sound absorption coefficient of all runs under the no air gap condition was higher than the corresponding value in the low frequency range. According to Table 2 the effect of polypropylene fiber content was statistically significant. In contrast the main effect of metallic fiber content was not significant. The direct interaction between polypropylene and metallic fibers was also not significant. At a constant metallic fiber content of 14 percent and a constant thickness of 3 cm increasing polypropylene fiber content from

0 to 28 percent increased the mean sound absorption coefficient from 0.185 to 0.55. This was an increase of about 197 percent. Run 13 showed the highest mean sound absorption coefficient in this frequency range. It contained 28 percent polypropylene fibers and 14 percent metallic fibers. Its thickness was 3 cm. The mean sound absorption coefficient was 0.55. Run 17 showed the next highest value. It contained 21 percent of each fiber type and had a thickness of 2 cm. Its mean sound absorption coefficient was 0.4416. The lowest mean value was 0.125. It was observed in run 10. This run contained 14 percent of each fiber type and had a thickness of 1 cm. At a constant composition of 14 percent polypropylene fibers and 14 percent metallic fibers the effect of thickness was not monotonic. The mean sound absorption coefficients at thicknesses of 1 cm 3 cm and 5 cm were 0.125 0.3183 and 0.225 respectively. Therefore the 3 cm sample showed the highest mean sound absorption in the middle frequency range among these thicknesses.

High frequency range

In the high frequency range from 1600 to 6300 Hz the effects of polypropylene fiber content metallic fiber content sample thickness and the direct interaction between the two fiber types were statistically significant according to Table 2. Under the no air gap condition the metallic fiber content was fixed at 14 percent and the sample thickness was fixed at 3 cm. Increasing polypropylene fiber content from 14 to 28 percent increased the mean sound absorption coefficient from 0.35 to 0.5014. In contrast polypropylene fiber content was fixed at 14 percent and thickness was fixed at 3 cm. Increasing metallic fiber content from 0 to 28 percent decreased the mean sound absorption coefficient from 0.4571 to 0.3028. Run 5 showed the highest mean sound absorption coefficient in this frequency range. It contained 14 percent of each fiber type and had a thickness of 5 cm. Its mean sound absorption coefficient was 0.528. Run 17 contained 21 percent of each fiber type and had a thickness of 2 cm. Its mean sound absorption coefficient was 0.5257. Therefore the two runs showed very similar mean absorption values despite their different thicknesses and fiber compositions.

Sound absorption peaks

Some samples showed high sound absorption coefficients at specific frequencies. Run 17 showed the highest peak value. Its sound absorption coefficient was 0.90 at 1600 Hz. Runs 14 10 and 5 showed absorption coefficients of 0.83 0.71 and 0.75 at 2500 Hz 3150 Hz and 4000 Hz respectively. These results show that the position of the absorption peak also changed among the different compositions.

Table 1. Mean sound absorption coefficient of the experimental runs in three frequency ranges and the overall absorption index under the no air gap condition

Experimental run	Polypropylene fibers (%)	Metallic fibers (%)	Thickness (cm)	Mean sound absorption coefficient 50 to 500 Hz	Mean sound absorption coefficient 500 to 1600 Hz	Mean sound absorption coefficient 1600 to 6300 Hz	Overall absorption index

1	14	14	3	0.0766	0.3183	0.35	0.22
2	14	14	3	0.0766	0.3183	0.35	0.22
3	0	14	3	0.074	0.185	0.29	0.1715
4	14	14	3	0.0766	0.3183	0.35	0.22
5	14	14	5	0.11	0.225	0.528	0.2715
6	14	28	3	0.0411	0.265	0.3028	0.1765
7	14	0	3	0.0433	0.30	0.4571	0.2967
8	14	14	3	0.0766	0.3183	0.35	0.22
9	21	7	4	0.1222	0.1983	0.3528	0.2145
10	14	14	1	0.0611	0.125	0.2885	0.149
11	7	21	2	0.06	0.1633	0.3528	0.175
12	14	14	3	0.0766	0.3183	0.35	0.22
13	28	14	3	0.13	0.55	0.5014	0.3435
14	7	7	2	0.10	0.1833	0.37	0.207
15	14	14	3	0.0766	0.3183	0.35	0.22
16	7	7	4	0.09555	0.1816	0.3728	0.21
17	21	21	2	0.11	0.4416	0.5257	0.318
18	7	21	4	0.0611	0.2366	0.3428	0.2035
19	21	21	4	0.1288	0.305	0.4157	0.263
20	21	7	2	0.0488	0.2283	0.2328	0.1605

Surface porosity and sound absorption

The results under the no air gap condition showed that higher surface porosity was not always associated with a higher overall absorption index. As shown in Figure 4b runs 13 and 17 had lower surface porosity than the center point runs. However their overall absorption indices were higher. According to Table 1 the overall absorption indices of runs 13 and 17 were 0.3435 and 0.318 respectively. The corresponding value for the center point runs including runs 1 2 4 8 12 and 15 was 0.22. Therefore the ranking of the samples based on surface porosity was not the same as the ranking based on the overall mean sound absorption coefficient.

A

Factor Coding: Actual

sb low(50-500hz)

Design Points

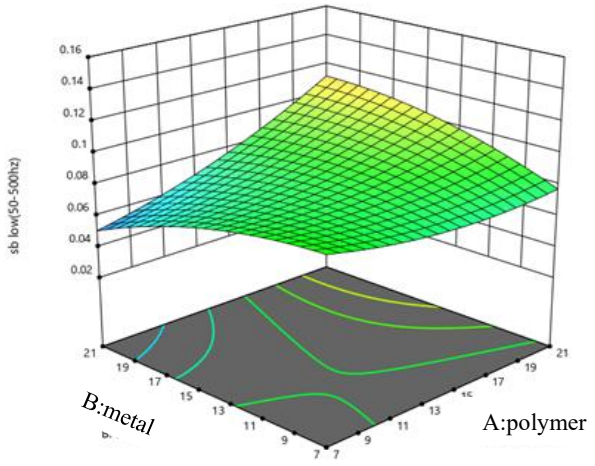
0.0411 0.13

X1 = A

X2 = B

Actual Factor

C = 3



B

Factor Coding: Actual

sb mid(500-1600hz)

Design Points

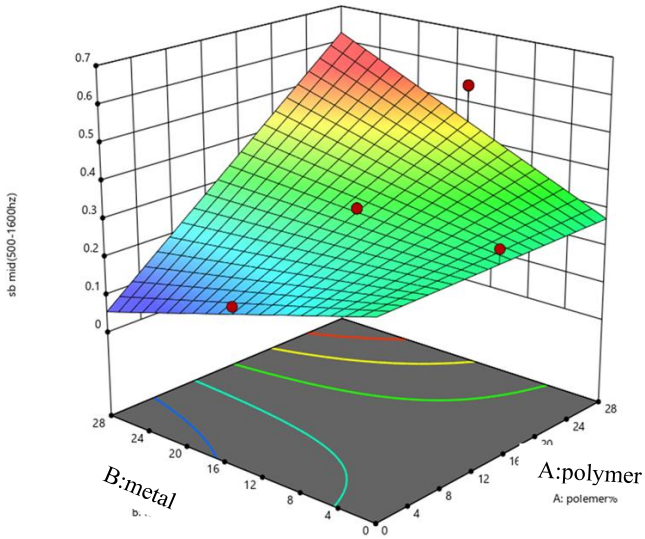
0.105 0.55

X1 = A

X2 = B

Actual Factor

C = 3



C

Factor Coding: Actual

sbhigh(1600-6300hz)

Design Points

0.2328 0.528

X1 = A

X2 = B

Actual Factor

C = 3

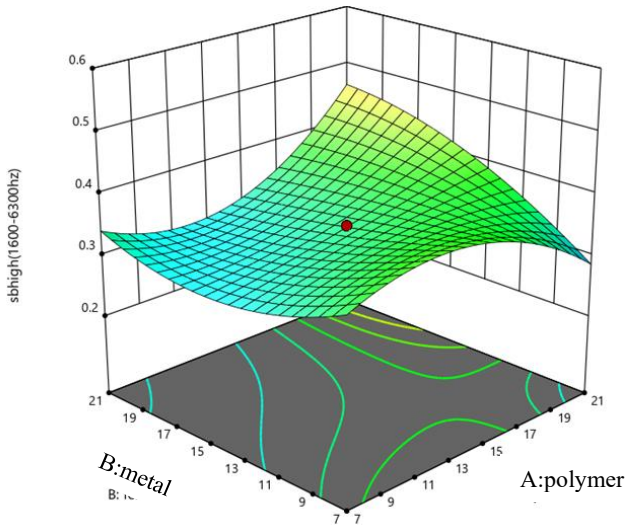


Figure 3. *Three dimensional response surfaces for the combined effects of polypropylene fiber content and metallic fiber content on the mean sound absorption coefficient at a fixed thickness of 3 cm. a Low frequency range. b Middle frequency range. c High frequency range.*

Table 2. Summary of analysis of variance results and coefficients of determination for the response surface models in three frequency ranges

Frequency range	Model	R^2	A Polypropylene	B Metal	C Thickness	AB
Low 50 to 500 Hz	Significant	0.8808	0.0016	0.8270	0.0030	0.0018
Middle 500 to 1600 Hz	Significant	0.9372	0.0002	0.3935	0.0624	0.09
High 1600 to 6300 Hz	Significant	0.9986	<0.0001	<0.0001	<0.0001	<0.0001

Note. A represents polypropylene fiber content. B represents metallic fiber content. C represents sample thickness. AB represents the interaction between polypropylene and metallic fibers. The values reported for A B C and AB are the p values of the corresponding model terms. R^2 represents the coefficient of determination.

Effect of air gap

Increasing the air gap behind the samples changed the sound absorption pattern. The overall mean absorption values were compared at air gaps of 0 mm 10 mm and 20 mm. In most runs a larger air gap was associated with higher absorption. The highest overall values were mainly observed at an air gap of 20 mm. The effect of the air gap was more evident in the low frequency range. In some samples increasing the air gap shifted the absorption peak toward lower frequencies. For example run 7 reached a sound absorption coefficient of about 0.97 at 400 Hz. Run 18 also showed an absorption coefficient of about 0.90 at 315 Hz. These changes were observed at an air gap of 20 mm. For overall performance run 17 showed the highest mean sound absorption coefficient among the experimental runs at an air gap of 20 mm. The value was about 0.40.

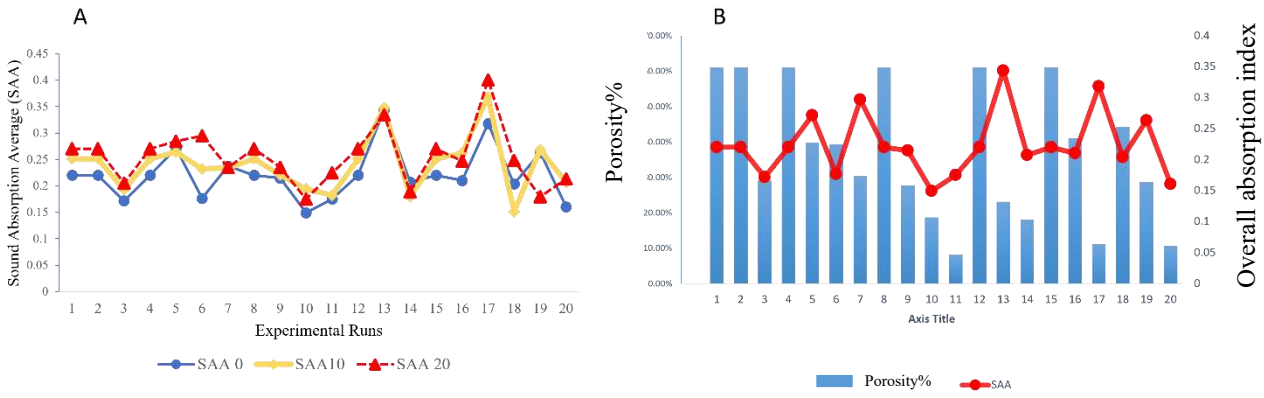


Figure 4. a Comparison of the overall absorption index of the experimental runs at air gaps of 0 mm 10 mm and 20 mm. b Comparison of surface porosity and the overall absorption index under the no air gap condition.

Separate response surface models were fitted for the three frequency ranges. A represented polypropylene fiber content. B represented metallic fiber content. C represented sample thickness. The response of each model was the mean sound absorption coefficient in the corresponding frequency range. The equations of the models are presented in Table 3.

Table 3. Mathematical equations of the models obtained for the low middle and high frequency ranges

Frequency range	Equation
Low	SB LOW 50 to 500 Hz = +0.0832 + 0.0128 A - 0.0007 B + 0.0117 C + 0.0178 AB + 0.0119 AC + 0.0069 A^2 - 0.0081 B^2
Middle	SB MID 500 to 1600 Hz = +0.3081 + 0.0712 A + 0.0159 B + 0.0091 C + 0.0356 AB - 0.0418 C^2
High	SB HIGH 1600 to 6300 Hz = +0.3477 + 0.0529 A - 0.0386 B + 0.0504 AB + 0.0021 AC - 0.0304 BC + 0.0271 ABC + 0.0772 A^2B - 0.0595 A^2C - 0.0418 AB^2

Numerical optimization

Numerical optimization was performed using the fitted response surface models. The predicted responses for the three frequency ranges were considered simultaneously. The optimization procedure generated several candidate solutions with different desirability values. Some predicted solutions extended slightly beyond the experimental polypropylene range. These solutions were considered model based extrapolations and were not treated as experimentally validated conditions. The solution within the experimental domain is also presented for comparison.

Table 4. Numerical optimization solutions predicted by the response surface models

Solution	Polymer (%)	Metal (%)	Thickness (cm)	Air gap	Predicted mean sound absorption 50 to 500 Hz	Predicted mean sound absorption 500 to 1600 Hz	Predicted mean sound absorption 1600 to 6300 Hz	Desirability
1	30.000	18.624	3.000	0	0.172	0.535	0.800	0.694
2	30.000	12.982	1.000	2	0.369	0.549	0.800	0.845
3	28.000	21.000	3.46	0	0.168	0.536	0.700	0.651

Solutions 1 and 2 should be interpreted as extrapolative model predictions because the polypropylene content was 30 percent while the experimental range was limited to 28 percent. Solution 3 remained within the experimental domain. Therefore only solution 3 can be directly interpreted within the validated factor space of this study.

Discussion

Role of polypropylene fibers in acoustic behavior

The results showed that increasing the polypropylene fiber content was associated with higher sound absorption. This effect was more evident in the middle and high frequency ranges. In the middle frequency range the metallic fiber content was fixed at 14 percent. The sample thickness was also fixed at 3 cm. Increasing the polypropylene fiber content from 0 to 28 percent increased the mean sound absorption coefficient from 0.185 to 0.55. A similar trend was observed in the high frequency range. Increasing the polypropylene fiber content from 14 to 28 percent increased the mean sound absorption coefficient from 0.35 to 0.5014. These findings suggest that polypropylene fibers can modify the acoustic behavior of the artificial stone matrix. One possible reason is a change in the internal microstructure and the air flow paths inside the material.

However surface porosity alone could not explain the changes in sound absorption. In porous materials other parameters may also affect sound propagation and energy dissipation. These parameters include pore structure and airflow resistance (21-23). Kim et al. also reported that porosity is one of the important factors that affects the sound absorption characteristics of sound absorbable concrete (23).

The present findings are also consistent with previous studies on recycled polypropylene materials for acoustic applications. Galindo et al. evaluated waste polypropylene textiles as an absorbing layer in acoustic ceilings. They showed that this waste material can be used as a sound absorbing material (22). This finding also supports the use of recycled polypropylene for both acoustic improvement and waste recovery (23).

Role of metallic fibers in acoustic behavior

Unlike polypropylene fibers the effect of metallic fibers was not linear or uniform across all frequency ranges. In the low frequency range the main effect of metallic fiber content was not statistically significant. In contrast metallic fiber content and its interaction with polypropylene fibers were significant in the high frequency range. This difference suggests that the effect of metallic fibers depends on frequency. It also depends on the composition of the sample. At a constant polypropylene fiber content of 14 percent and a constant thickness of 3 cm increasing the metallic fiber content from 0 to 14 percent decreased the mean sound absorption coefficient in the high frequency range from 0.4571 to 0.35. A further increase in metallic fiber content to 28 percent reduced this value to 0.3028. Therefore increasing the metallic fiber content reduced sound absorption under these specific conditions. However this trend should not be considered as a general independent effect of metallic fibers. The acoustic response depended on the combined levels of polypropylene fibers metallic fibers and sample thickness. Previous studies on porous materials containing metallic fibers have also shown that acoustic performance depends on fiber content pore structure pore size and fiber arrangement (24). Zhu et al. showed that changes in gradient structure and pore distribution can considerably affect the sound absorption coefficient of porous metallic fiber materials (24).

Wang et al. also reported that different arrangements and layer structures of metallic fibers can produce different sound absorption responses even at the same material thickness (25). These findings are consistent with the present study. They show that metallic fiber content alone is not sufficient to predict acoustic performance. More recent studies have also shown that steel fibers

can affect the acoustic behavior of mineral based composites through changes in pore structure and pore connectivity. Hong et al. studied steelmaking slag concrete. They reported that the effect of steel fibers depended on the porous structure of the composite. They also showed that the combined use of fibers and lightweight aggregate could change acoustic performance (26). This result also supports the importance of the overall microstructure in controlling the acoustic effect of metallic fibers.

Effect of thickness in the low frequency range

Sample thickness had a significant effect on the mean sound absorption coefficient in the low frequency range. At a constant composition of 14 percent polypropylene fibers and 14 percent metallic fibers increasing the thickness from 1 to 3 and then to 5 cm increased the mean sound absorption coefficient from 0.0611 to 0.0766 and 0.11. This trend shows that increasing thickness can improve low frequency sound absorption for this specific composition. This behavior is consistent with the known principles of sound absorption in porous materials. A thicker material provides a longer propagation path for the sound wave. This can increase sound absorption at lower frequencies. Increasing thickness can also shift the first absorption peak toward lower frequencies (27). Lashgari et al. studied sound absorbers made from wood chips. They showed that increasing sample thickness improved low frequency absorption. They also reported a shift of the first absorption peak toward lower frequencies (27). However the effect of thickness was not the same for all compositions in the present study. Therefore thickness should not be interpreted as an independent factor. Its effect should be considered together with polypropylene and metallic fiber contents.

Sound absorption behavior in the middle frequency range

The mean sound absorption coefficient of most samples was higher in the middle frequency range than in the low frequency range. In this range polypropylene fiber content had a statistically significant effect. In contrast the main effect of metallic fiber content was not significant. The direct interaction between polypropylene and metallic fibers was also not significant. At a constant metallic fiber content of 14 percent and a constant thickness of 3 cm increasing the polypropylene fiber content from 0 to 28 percent increased the mean sound absorption coefficient from 0.185 to 0.55. This result shows that polypropylene fiber content played an important role in the acoustic response in this frequency range. The higher absorption in the middle frequency range may be related to greater viscous and thermal losses caused by air movement through the porous pathways of the material. In porous and fibrous materials several structural parameters can affect sound absorption. These include pore geometry specific surface area path complexity and airflow resistance (29 ,28). Recent studies on sound absorbing cement based materials have also shown that good acoustic performance depends on a balance between porosity density and surface structure (29).

The effect of thickness was also not uniform in this frequency range.

At a constant composition of 14 percent polypropylene fibers and 14 percent metallic fibers the mean sound absorption coefficients at thicknesses of 1 cm 3 cm and 5 cm were 0.125 0.3183 and 0.225 respectively. Therefore increasing thickness from 1 to 3 cm increased sound absorption. A further increase to 5 cm reduced the response. This result shows that the effect of thickness in the middle frequency range depends on the material structure and composition. It cannot be explained only by an increase in thickness.

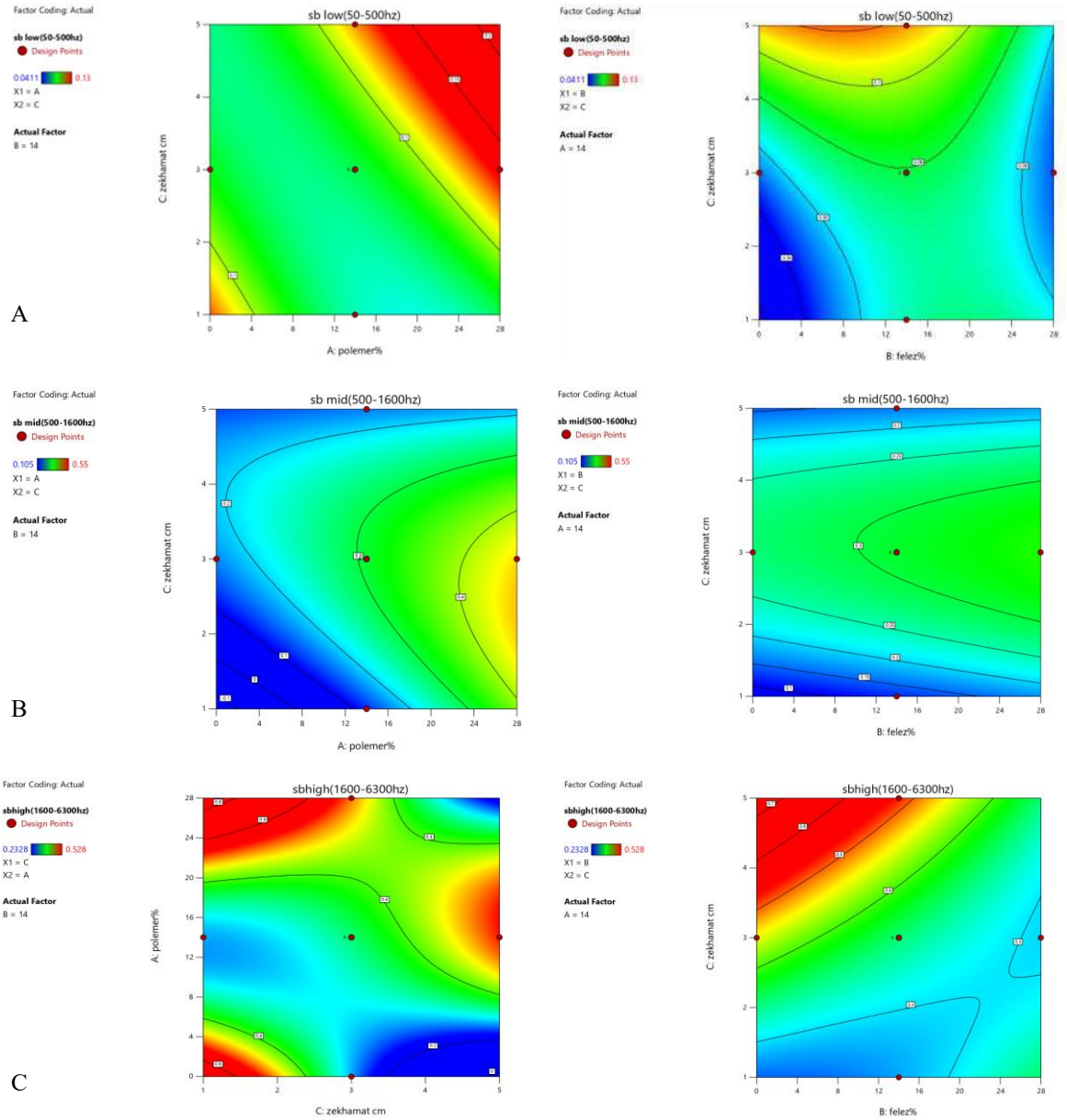


Figure 5. *Contour plots showing the interaction between fiber content and sample thickness on the mean sound absorption coefficient. a Low frequency range. b Middle frequency range. c High frequency range. In each row the left plot shows the interaction between polypropylene fiber content and thickness. The right plot shows the interaction between metallic fiber content and thickness.*

Sound absorption behavior in the high frequency range

In the high frequency range the effects of polypropylene fiber content metallic fiber content sample thickness and the direct interaction between the two fiber types were statistically significant. This result shows that the acoustic response in this range was sensitive to the combined levels of the variables. At a constant composition of 14 percent polypropylene fibers and 14 percent metallic fibers increasing the thickness from 1 to 3 and then to 5 cm increased the mean sound absorption coefficient from 0.2885 to 0.35 and then to 0.528. One important finding was the very similar performance of runs 5 and 17. Run 5 had a thickness of 5 cm. It contained 14 percent polypropylene fibers and 14 percent metallic fibers. Its mean sound absorption coefficient was 0.528. Run 17 had a thickness of only 2 cm. It contained 21 percent of each fiber type. Its mean sound absorption coefficient was 0.5257. Therefore an appropriate increase in fiber content produced a similar acoustic performance in a thinner sample. This finding may be useful for the design of thinner sound absorbing materials. The behavior of porous and fibrous materials at high frequencies depends on several parameters. These include pore geometry airflow resistance path complexity and surface characteristics (29 ,28). Recent review studies have also shown that porosity alone is not enough to predict sound absorption in cement based and fibrous materials. Pore structure and airflow resistance should also be considered (29 ,28).

Relationship between surface porosity and acoustic performance

The present results showed that higher surface porosity was not necessarily associated with higher sound absorption. The center point runs had relatively high surface porosity. However their overall mean absorption was about 0.22. Runs 13 and 17 had lower surface porosity. However they showed higher overall mean sound absorption. The Spearman correlation analysis also showed no significant relationship between surface porosity and the overall absorption index under the no air gap condition. This result suggests that a two dimensional measure of surface porosity is not sufficient to fully describe the acoustic performance of these composites. In established porous material models several parameters are used to describe sound propagation and energy dissipation. These include airflow resistance tortuosity viscous characteristic length and thermal characteristic length (27). Lashgari et al. also showed that sound absorption cannot be predicted accurately by porosity alone. A combination of porosity airflow resistance and other structural parameters can provide a better prediction of absorber behavior (27).

Conclusion

The results showed that recycled polypropylene and metallic fibers can significantly change the sound absorption behavior of artificial stone. The effect of the fibers depended on frequency range fiber content and sample thickness. Polypropylene fibers played an important role in improving sound absorption especially in the middle and high frequency ranges. In the middle frequency range increasing the polypropylene fiber content from 0 to 28 percent increased the mean sound absorption coefficient from 0.185 to 0.55. In this comparison the metallic fiber content was fixed at 14 percent and the thickness was fixed at 3 cm. The effect of metallic fibers was not uniform. It

depended on the combination of the other variables. In the high frequency range polypropylene fiber content metallic fiber content sample thickness and the direct interaction between the two fiber types had statistically significant effects. The results also showed that increasing thickness did not always increase sound absorption. The effect of thickness depended on the frequency range and fiber composition. One important finding was the similar high frequency performance of two samples with different thicknesses. Run 17 had a thickness of 2 cm and contained 21 percent of each fiber type. Its mean sound absorption coefficient was 0.5257. Run 5 had a thickness of 5 cm and contained 14 percent of each fiber type. Its mean sound absorption coefficient was 0.528. This result shows that an appropriate fiber composition may provide good acoustic performance even at a lower sample thickness. The surface porosity results also showed that higher porosity alone did not guarantee higher sound absorption. Future studies should therefore evaluate other structural parameters. These include pore structure pore connectivity and airflow resistance. Overall recycled polypropylene and metallic fibers have potential for the development of sound absorbing artificial stone. Their performance depends on the proper selection of fiber content and sample thickness. Further acoustic microstructural and mechanical tests are recommended before practical application.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

Z.F. performed the experiments and data collection. A.M. contributed to data analysis and manuscript preparation. M.E. contributed to data interpretation and manuscript revision. R.H. supervised the study and contributed to study design and manuscript revision. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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