# Investigation on Acoustic and Thermal Properties of Powdered Granular Mask (PGM) Reinforced Green Epoxy Composites

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**Abstract:** This study investigates the acoustic and thermal properties of powdered granular mask (PGM) reinforced green epoxy (GE) composites, with PGM contents of 30 vol.%, 40 vol.%, and 50 vol.%. The aim is to develop sustainable, high-performance materials with enhanced insulation properties. Among the samples, S4 (PGM/50 vol.% GE) exhibited the highest Noise Reduction Coefficient (NRC) of 0.30, demonstrating excellent acoustic shielding. Increasing the GE content improved the Transmission Loss (TL) by densifying the composite structure, significantly enhancing sound attenuation. In the high-frequency range, S2 (PGM/30 vol.% GE), S3 (PGM/40 vol.% GE), and S4 recorded TL peaks of 39.3 dB, 43.5 dB, and 44.9 dB at 1372 Hz, 1552 Hz, and 1544 Hz, respectively, confirming improved acoustic performance with higher PGM content. Thermal stability also increased with higher GE content, with S4 showing the highest decomposition inflection temperature of 472°C, indicating enhanced heat resistance. The novelty of this work lies in the dual functional benefits of PGM/GE composites, which offer both superior acoustic insulation and thermal stability. These properties make the composites ideal for aircraft flooring systems, particularly in areas such as cockpits and passenger cabins, where both sound insulation and thermal control are critical. The findings underscore the potential of PGM/GE composites for sustainable, high-performance applications requiring both acoustic and thermal management.

**Keywords:** Powdered Granular Mask, Green Epoxy, Noise Reduction Coefficient, Transmission Loss, Thermal stability.

## 1. INTRODUCTION

After the outbreak of the covid-19 pandemic, all the countries have been facing adverse financial and environmental crises [1]. Approximately 20 million people have lost their livelihood, whereas 10 million have lost their lives and their children and family were left abandoned. The effect of the pandemic and the continuous lockdown have entirely worsened the economy of the top wealthy countries like the USA and the USSR [2]. So, the impact of the pandemic on countries like India was terrific and pathetic as India ranks 2nd largely populated country in the world, where 60% of people belong to the middle class and are below the poverty line where their livelihood mainly depends on daily wages [3]. In countries like India, nearly 20% are homeless and non-readers, including women and children. This primarily affected the people's economic activity, which involved the Indian economy [4]. India is a country where the economy depends on various sectors like tourism, heritage culture, agriculture, Telecom, imports, exports, etc. By the sudden shutdown, almost all the domestic and international sectors have declined by this pandemic [5].

On the one hand, the country suffered from increased positive cases and death rates. Further, the nation has been running into a shortage of economy, food, and medical facilities [6]. Besides all these concerns, the major problem during the pandemic was the disposable management of used surgical masks

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and medical Personal Protective Equipment (PPE) suits [7]. Especially used masks take a vast and primary role in this aspect of disposable as they were thrown easily after a single usage by ordinary people and medical professionals [8]. So, it was essential to manage all these used masks as infected and uninfected people may use them. It was estimated that nearly 1 million masks were thrown into the garbage, approximately second place after plastic wastage [9]. It is the responsibility of every citizen to take the necessary steps to properly dispose of these used masks. It is required to dispose of these used masks as they may be a cause for spreading of disease faster [10].

In the past few decades, researchers carried out various research on the acoustic characteristics of Polyurethane foam, which consists of Isocyanate and polyol, as significant constituents considered toxic and harmful to humanity [11]. To overcome the emerging issue, exploring various ways to recycle and manage used surgical masks and other equipment is necessary [12]. The study of acoustic behavior mainly deals with the mechanical waves in solids, liquids, and gaseous materials [13]. The importance and applications of acoustic properties are increasing in almost all industries to reduce noise control [14], [15]. The word acoustics is also called sonics, which refers to frequencies below and above the audible range called ultrasonic and infrasonic. The primary feature of any material for investigating sound absorption is that the material should be porous, absorbent, thin, and light in weight with cost-efficient [16], [17].

Generally, two methods are adopted to evaluate acoustic properties: the reverberation room technique and the impedance tube method [18], [19]. There are many limitations to the reverberation technique, such as ample space requirements, skilled persons, and many samples [20], [21]. We adopt the impedance tube method as it is cost-effective, time-saving, and requires limited samples. In the impedance tube method, we adopt a circular hollow tube with varying dimensions concerning frequency [22], [23]. We assume an impedance tube with a size of 96mm for a low-frequency range up to 4KHz, whereas for high frequency, an impedance tube with a dimension of 34mm with a frequency range up to 6.3KHz [24].

Hasssan *et al*. [19] have investigated the acoustic properties of bio-epoxy composites reinforced with coconut, cotton, and sugarcane fibers. The results indicated that, SAC of coconut fiber-reinforced epoxy composites (C/E) was higher than that of the sugarcane and cotton fiber-reinforced epoxy composites. This variation in performance can be attributed to the porosity of the coconut fibers compared to the other fiber types. Further, Yang *et al*. [25] examined the acoustic characteristics of epoxy composites reinforced with ramie, flax and jute fibers. Their findings revealed that jute/epoxy composites exhibited superior sound absorption properties near 1000 Hz. Additionally, both jute/epoxy and flax/epoxy composites demonstrated enhanced noise reduction coefficient.

Thermogravimetric analysis (TGA) is a thermal analysis technique used to evaluate the thermal stability and composition of materials by measuring weight changes as a function of temperature or time [26]. This method provides critical insights into the degradation patterns and thermal behavior of composites, enabling a better understanding of their performance in high-temperature applications [27]. Mateusz *et al*. [28] reported on the thermogravimetric analysis of epoxy resin composites incorporating waste hemp fibers. Results demonstrated that the TGA and derivative thermogravimetry (DTG) curves exhibited a consistent trend across the analyzed composites. Up to a temperature of approximately 230°C, all the composites remained thermally stable, with the initial temperature of degradation (ITD) ranging from 213.1°C to 247.7°C. The composite containing 30 wt.% eco-filler displayed the largest thermal residue mass (RM) at the final temperature. The inclusion of ecological fibers as a filler significantly enhances the thermal resistance of the composites, indicating the potential for utilizing waste materials in the development of high-performance, sustainable composite material.

Techawinyutham *et al*. [29] studied the use of ground coffee waste (GCW) and tea leaf waste (TLW) as natural reinforcements and pigments in polypropylene (PP) composites. Maleic anhydride polypropylene (MAPP) was added to enhance the compatibility between the fillers and the polymer matrix. Composites with varying ratios of GCW and TLW (0–30 wt.%) were prepared, with the optimal hybrid composite consisting of 10 wt.% GCW, 20 wt.% TLW, and 1.5 wt.% MAPP. These hybrid composites exhibited improved mechanical, thermal, and rheological properties. Srisuk *et al*. [30] investigated the extraction and characterization of natural fibers from *Bambusa flexuosa*, a bamboo species, focusing on their thermal properties. The fibers were extracted from discarded bamboo stems, with the raw fibers showing thermal stability up to 251.32°C, while the treated fibers exhibited enhanced stability, reaching 264.57°C. Ayyappan *et al*. [31] explored the use of carbon-innegra hybrid (CI) fabrics and pineapple fabrics to fabricate hybrid multi-material composites, with varied stacking sequences. The results indicate the composite's potential for semi-structural applications, with flexibility in stacking sequence design. A motorcycle battery cover was fabricated using the composite, demonstrating its practical viability. In another study, Senthil Kumar *et al*. [32] conducted an investigation into hybrid composites reinforced with hemp (H) and sisal (S) fibers, employing various layering arrangements and utilizing the hot press molding technique for fabrication. Their study focused on analyzing the properties of these hybrid composites, revealing that the HHSS configuration demonstrated the highest thermal resistance. The enhanced thermal stability observed in specific hybrid configurations suggests their potential applicability in structural engineering.

This present research work is an attempt to reclaim used surgical masks to investigate acoustic and thermal properties. So, this investigation paves the way for recycling and repurposing used masks, offering a suitable and improved alternative for aircraft flooring systems.

## 2. MATERIALS AND METHODOLOGY

The overall methodology carried out for the investigation work has been illustrated in Figure **1**. Initially used and disposed of surgical masks were collected from the nearby primary health centers, markets, residential apartments, and offices, which local workers and volunteers did. Then, these collected surgical masks are thoroughly sanitized using clinical sanitizers and processed to make them free from impurities and infection-spreading viruses. Further, these cleaned masks are separated from nylon belts and crushed into small pieces using a cutting machine to make them granular. Then, these PGMs are fabricated into composite panels using a bio-based epoxy resin with 30 vol.%, 40 vol.%, and 50 vol.% of epoxy resin. Finally, these composite mask panels are carried out for various acoustical and structural characterizations.

### 2.1. Materials

Used and disposed surgical masks were collected from local primary health centers, markets, residential apartments, and offices. A bio-based resin SR green epoxy 56 and hardener SD surf cleaner were procured from Sicomin, France. The physical properties of resin and hardener are listed in Table **1**.

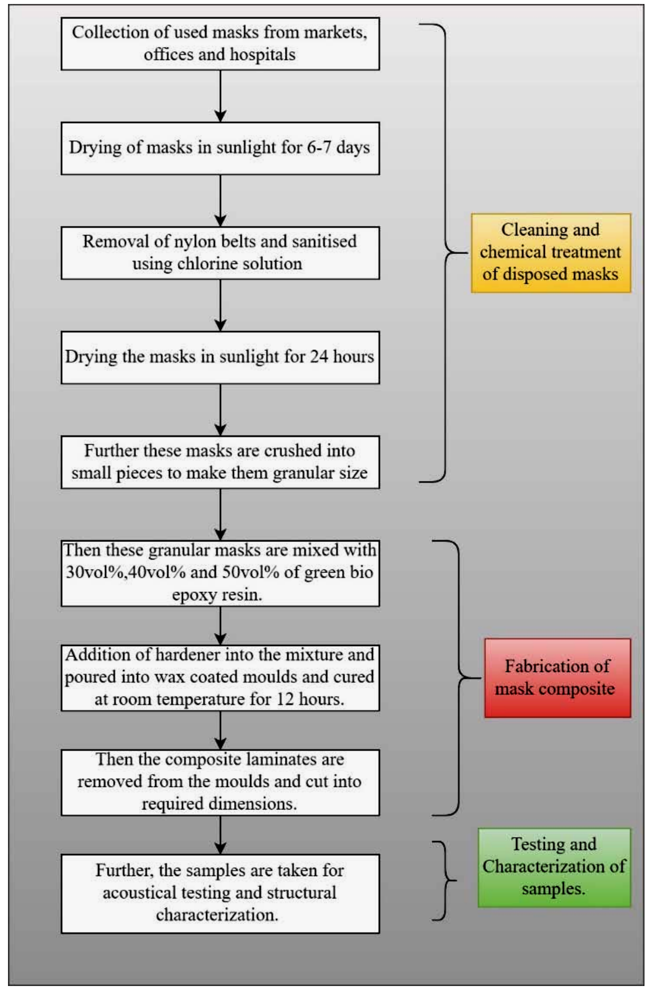


**Figure 1:** Overall methodology of research work.

**Table 1: Physical properties of SR Green Epoxy 56 and SD surf clear Hardener**

| S. No | Physical Properties | SR Green Epoxy 56 | SD Surf Clear Hardener |
|---|---|---|---|
| 1. | Color | Clear liquid | Clear liquid |
| 2. | Viscosity | 1400 mPa.s at 20°C | 60 mPa.s at 20°C |
| 3. | Density | 1.198 at 20°C | 0.958 at 20°C |

### 2.2. Chemical Treatment of Facial Masks

All this waste and disposed masks were collected with the help of workers and volunteers. After collecting, these masks are entirely dried in sunlight for 6-7 days as the life span of the novel virus on masks rests up to one week. Then these masks are collected, and the nylon belts are removed individually for further processing. Further, these masks are washed thoroughly using clinical sanitizers and bleached using chlorine solution and bleaching powders, followed by drying in sunlight for 24 hours. Finally, these masks are crushed into small pieces to make them granular size.

### 2.3. Fabrication of Mask Composites

Once the masks are completely crushed and made into granular size, a simplistic way is chosen to fabricate composite panels. These powdered granular masks are mixed with 30vol.%, 40vol.%, and 50vol.% of green bio epoxy resin. This mixing of granular masks and epoxy should be carefully spread throughout the epoxy as reinforcing fillers. Finally, the hardener is added to the pre-prepared mixture and stirred manually until the hardener is mixed throughout the composite mix. Here the weight ratio of resin and hardener is taken as 100:37. Further, this entire blended mixture is poured onto wax-coated molds and thin mylar sheets. The entire setup is cured at room temperature for 12 hours. Then the composite laminates are removed from the molds and cut into the required dimensions. The entire fabrication method of laminated composites is shown in Figure **2**. Finally, these laminated samples are taken for acoustic testing and structural characterization. Table **2** lists the sample codes and their compositions.

**Table 2: Sample Code and their Compositions**

| S. No | Sample Code | Compositions |
|---|---|---|
| 1. | S1 | Green Epoxy (GE) |
| 2. | S2 | PGM/ 30vol.% GE |
| 3. | S3 | PGM/ 40vol.% GE |
| 4. | S4 | PGM/ 50vol.% GE |

### 2.4. Acoustic Setup for Sound Absorption Coefficient

The acoustic setup consists of an impedance tube with a length of 900mm, a speaker with a frequency range of 20-2000Hz, two microphones, and a computer installed with MATLAB, which automatically controls the readings. The fabricated mask composite samples are placed inside the impedance tube. Using the collected data, the sound absorption coefficient of the samples is calculated one by one using MATLAB software. The primary function of microphones was to estimate the absorption coefficient and the reflection coefficient (R) and the impedance ratio of the test samples. Figure **3** represents the experimental acoustic setup of the sound absorption coefficient. The noise reduction coefficient (NRC) was obtained from the sound absorption coefficient by the following formula:

$$NRC = (\alpha 250+\alpha 500+\alpha 1000+\alpha 2000)/4 \quad (1)$$

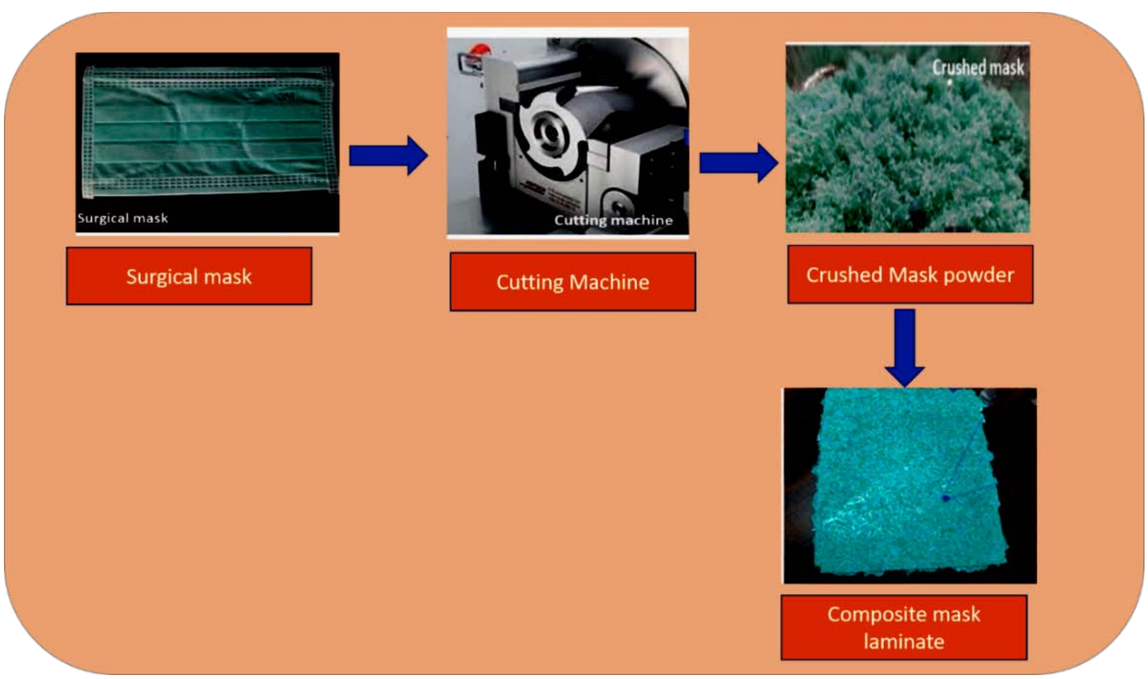


**Figure 2:** Fabrication of laminated mask composite.

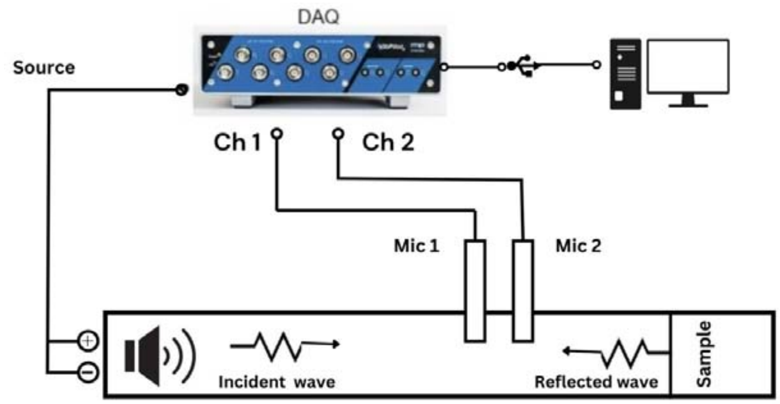


**Figure 3:** Sound absorption coefficient test using impedance tube method.

where,

α250 = Sound absorption coefficient at 250 Hz frequency, α500 = Sound absorption coefficient at 500 Hz frequency, α1000 = Sound absorption coefficient at 1000 Hz frequency and α2000 = Sound absorption coefficient at 2000 Hz frequency.

### 2.5. Acoustic Setup for Sound Transmission Loss

Similarly, for transmission loss the acoustic setup consists of an impedance tube with a length and diameter of 900mm and 1000mm, a speaker with a frequency range of 20-2000Hz, four microphones, and a computer installed with MATLAB is taken. The samples have been tested at the impedance tube's absorbent opening and closing end, as shown in Figure **4**. The theoretical STL values are calculated by equation (2) using a transfer function method.

$$STL = -20\lg|t| \quad (2)$$

Where t is the ratio of the transmitting sound energy to the incident sound energy, the sample is in the middle of the tube, the speaker produces the sound wave, and four microphones are used to measure the sound power. Sound transmission loss (TL) measures are essential to characterize the sound isolation property of homogeneous materials and composite structures. Standard test methods are often used to measure the TL under a diffuse (or random) sound field. They can be performed in a reverberation room or directly in situ and generally require large specimens. However, large quantities of materials are not always available when setting up new materials. Typically, measuring properties using the previous standards is not very simple and fast. It would be more convenient to measure the acoustic properties on small samples to have the possibility to perform more tests and waste less material. For this purpose, it is possible to use the standing wave tube method. In this case, however, the boundary conditions influence the results more than a large specimen due to the small size of the specimen. Furthermore, the cross-section of the impedance tube is circular. This increases the difficulty of the transmitted sound energy, and the reflected sound energy.

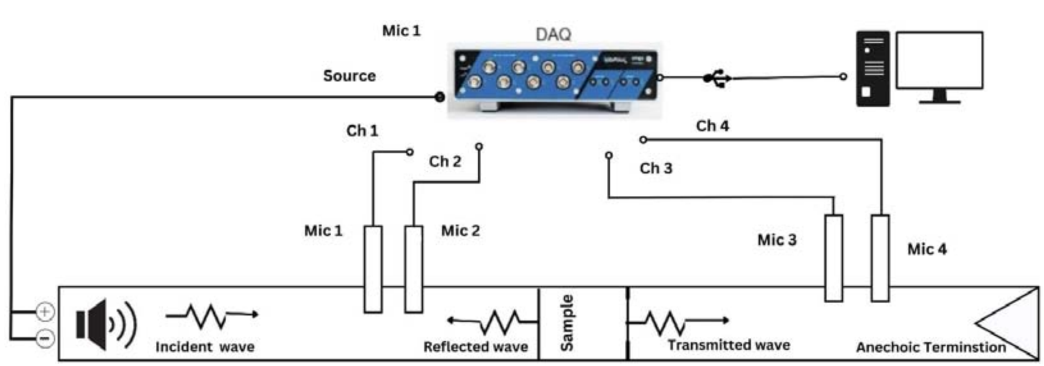


**Figure 4:** Sound transmission loss test using impedance tube setup.

### 2.6. Thermogravimetric Analysis

Thermal stability was evaluated according to ASTM E1131 standards using a TGA/DSC3+ Mettler Toledo instrument. The analysis was carried out under a nitrogen atmosphere over a temperature range of 30–700°C, with a heating rate of 10°C/min. Composite samples, each weighing approximately 10 mg, were used for testing.

## 3. RESULTS AND DISCUSSIONS

### 3.1. Morphological Characterization

Scanning Electron Microscopy (SEM) was used to evaluate the morphological structure of laminated mask composites. Morphological characterization provides a clear image of granulated or powdered masks and their dispersion within the epoxy resin. The composites were analyzed at magnifications of 200X, 400X, and 800X, with an accelerated voltage of 15 kV. Figure **5** illustrates the microstructure of a PGM embedded in an epoxy matrix at these different magnifications (200X, 400X, and 800X).

At each magnification level, distinct features of the PGM-epoxy composite can be observed. At 200X magnification (Figure **5a** & **b**), a broad view of the particle distribution and general dispersion of the PGM within the epoxy is provided. Larger clusters and the overall spatial arrangement of the particles can be identified. At 400X magnification (Figure **5c** & **d**), there is a closer examination in quality of the dispersion. Additional details, such as the interfaces between the PGM and the epoxy matrix, begin to appear. At 800X magnification (Figure **5e** & **f**), fine details of the particle

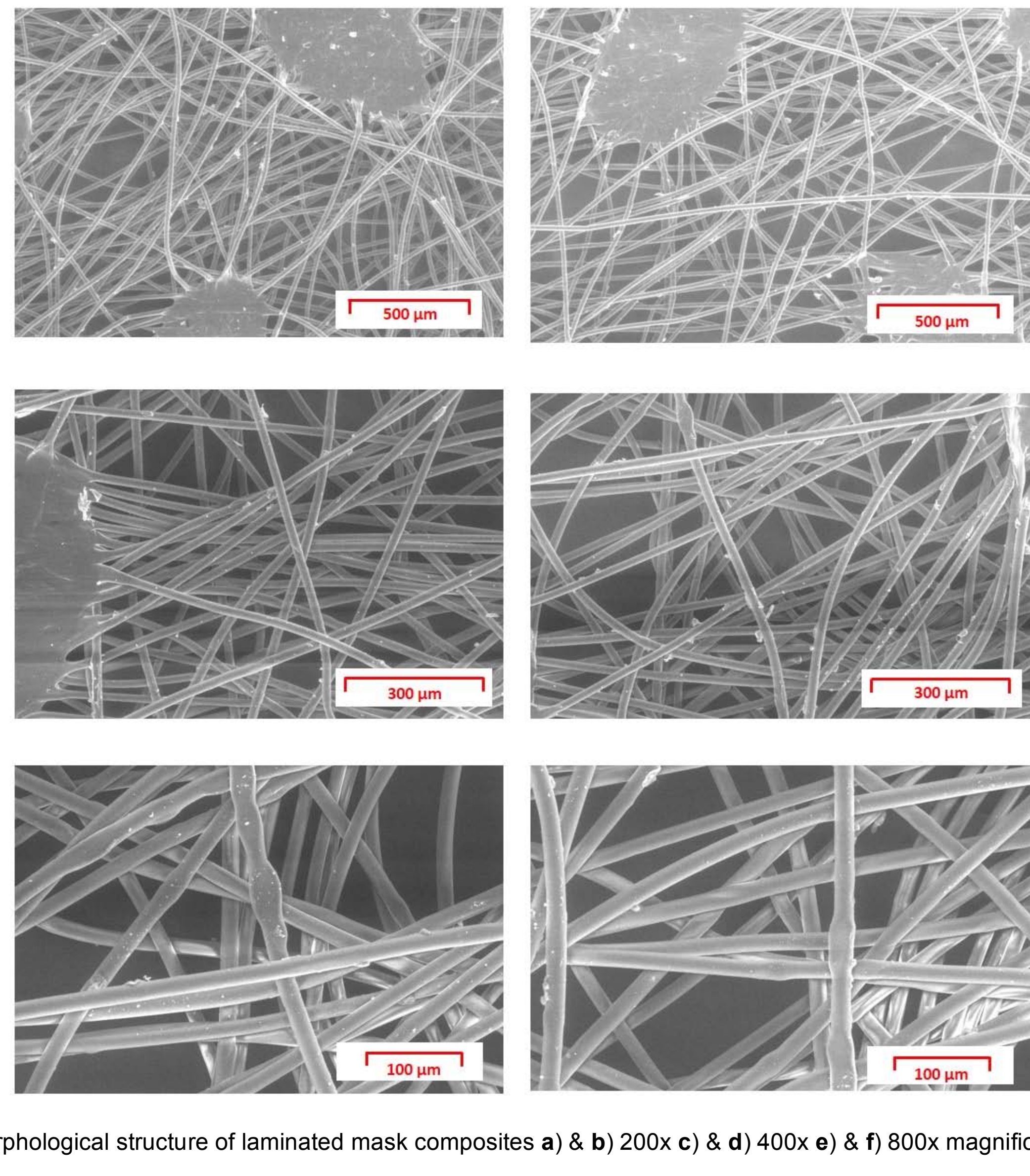


**Figure 5:** Morphological structure of laminated mask composites **a**) & **b**) 200x **c**) & **d**) 400x **e**) & **f**) 800x magnification.

surfaces and their interactions with the epoxy matrix become visible.

### 3.2 Sound Absorption Coefficient (SAC)

The results of Figure **6** led to the conclusion that specimen S2 has the best high-frequency acoustic shielding characteristics among all the samples, with a peak SAC of roughly 0.80 at about 1350 Hz. Additionally, samples S2 and S3's analysis of the trials show that a minimum SAC value of greater than 0.6 was attained in the high-frequency range of 1100-1750 Hz. According to Fig. **6**, specimen S4 had the best mid-frequency acoustic shielding characteristics of all the samples, with a peak SAC of 0.98 at about 1000 Hz. This finding implies that the sample has the best acoustic shielding properties. As indicated in Table **3**, all three samples with reinforcement exhibited better acoustic shielding qualities than sample S1, a pure green epoxy without reinforcement. This trend suggests that increasing the GE content results in a more compact and denser composite, improving sound attenuation and making the PGM/GE composites more effective in high and mid-frequency sound shielding. Table **3** shows that sample S4 has the highest NRC value of 0.30, which shows it has the best acoustic shielding properties among all the samples.

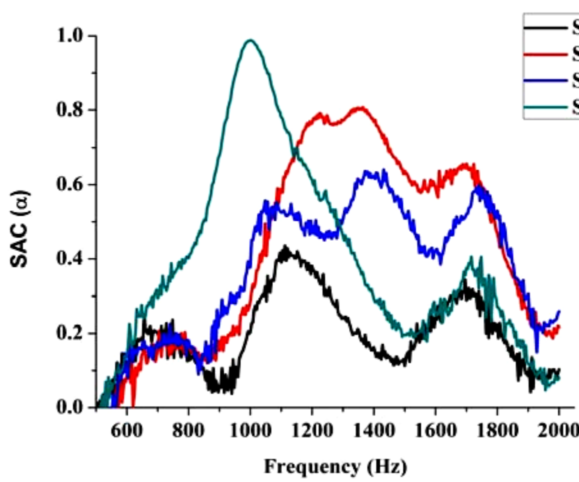


**Figure 6:** Experimental analysis of Sound Absorption Coefficient (SAC).

In comparison, flax-reinforced epoxy composites exhibit a peak Sound Absorption Coefficient (SAC) of 0.45 at around 1000 Hz, while sisal fiber-reinforced polypropylene composites show a maximum SAC of 0.23 [17, 33]. These values are significantly lower than the peak SAC of 0.98 at approximately 1000 Hz observed for PGM/epoxy composites, highlighting the superior acoustic performance of PGM-based composites. It can be attributed to the dense and compact structure created by the powdered granular mask (PGM) reinforcement, which enhances sound absorption capabilities. In contrast, natural fibers like flax and sisal have lower density and porosity, which limits their ability to absorb sound, leading to lower SAC values. Additionally, PGM's micro-structure allows for more effective sound wave dissipation across a wider frequency range, improving overall acoustic insulation compared to natural fiber composites.

**Table 3: Experimental Results of Sound Absorption Coefficient (α) and Noise Reduction Coefficient (NRC)**

| Sample | SAC (α) with Respect to Frequency (Hz) | | | | NRC |
|---|---|---|---|---|---|
| | 250 | 500 | 1000 | 2000 | |
| S1 | 0.05 | 0.01 | 0.20 | 0.10 | 0.10 |
| S2 | 0.11 | 0.03 | 0.28 | 0.22 | 0.16 |
| S3 | 0.12 | 0.02 | 0.38 | 0.26 | 0.20 |
| S4 | 0.10 | 0.04 | 0.98 | 0.08 | 0.30 |

### 3.3. Sound Transmission Loss (STL)

Higher transmission loss is associated with less sound transmission through the composite panel. Figure **7** displays the transmission variance for frequency traces from manufactured samples with a 99 mm diameter and 5 mm thickness. The first peak values for samples 2, 3, and 4 are 29.7, 37.3, and 32.6 dB in the 352, 384, and 372 Hz low-frequency zone. The second peak values for samples 2, 3, and 4 are 40.2, 41.6, and 33.7 dB in the 844, 532, and 544 Hz Mid-frequency range. Because of the uniform

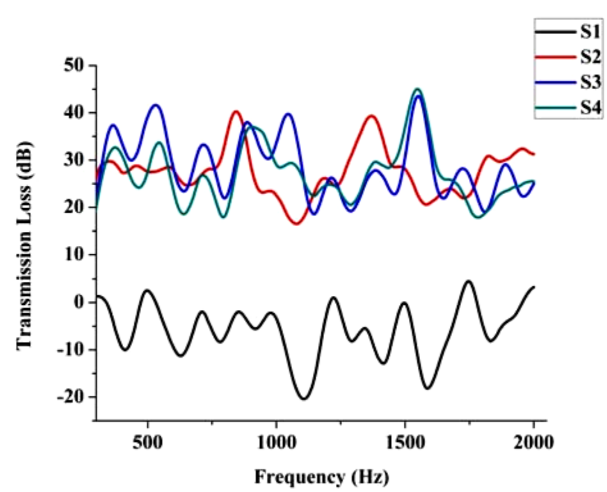


**Figure 7:** Experimental analysis of Sound Transmission Loss (STL).

distribution of powdered granular masks incorporated in the green epoxy, there is an improvement in TL of samples 2, 3, and 4, indicates a positive effect and also makes the composite structure more compact while increasing the density of the composites, resulting in an improvement in TL. This means that the sound waves travelled further in the sample thickness. In the high-frequency region, the third peak of samples 2, 3, and 4 reached 39.3, 43.5, and 44.9 dB in 1372, 1552, and 1544 Hz. The damping levels of samples 2, 3, and 4 configurations were higher than those of the pure epoxy composites (S1). The use of hybrid structures improved the TL due to the effects of size, density, and uniform distribution of powdered granular masks.

### 3.4. Thermogravimetric Analysis of PGM/Green Epoxy Composites

The thermogravimetric analysis was performed to evaluate the thermal stability and decomposition behavior of the PGM/GE composites [34]. The analysis was conducted on samples with varying proportions of PGM mixed with GE at 30 vol.%, 40 vol.%, and 50 vol.%.

The TGA results, as illustrated in Figures **8**, reveal distinct degradation patterns for the pure green epoxy (S1) and the PGM/GE composites (S2, S3, and S4). Pure green epoxy exhibited single-step degradation with a decomposition temperature range between 446–473°C. This indicates a straightforward degradation pathway for the matrix in the absence of reinforcement. Conversely, all PGM/GE composites demonstrated two-step degradation behavior. The initial degradation stage, occurring between 346–382°C, corresponds to the breakdown of certain components within the composite, likely due to the interaction of PGM with the green epoxy matrix. The subsequent degradation stage occurs between 448–483°C. This two-step degradation indicates that the PGM reinforcement influences the thermal decomposition profile of the composites.

The thermal stability of the composites is enhanced with increasing GE content, as evidenced by the higher decomposition temperatures recorded. Notably, the absence of any peaks in the 30–100°C range confirms that no significant moisture was present in the samples, suggesting proper drying and good compatibility of PGM within the green epoxy matrix. Table **4** presents the inflection temperatures associated with the thermal degradation of various composite samples. Among the composites, Sample S4 (PGM/50 vol.% GE) exhibited the highest thermal stability due to the increased green epoxy content, which enhances the crosslinking density and molecular integrity, providing better resistance to thermal degradation. Additionally, the incorporation of PGM contributes to a denser composite structure, which slows down heat diffusion and improves overall thermal resistance. In comparison, S2 showed the lowest thermal stability with an inflection temperature of 467°C, while S3 and S4 samples demonstrated similar thermal stability at 470°C and 472°C, respectively. Owing to the increased volume of green epoxy, this enhanced cross-linking and improved the material's ability to withstand higher temperatures.

The residual weight percentages after thermal degradation of the PGM/Green Epoxy composites are summarized in Table **4**. Among the samples, S3 composites exhibited the highest residual weight percentage, indicating superior thermal stability and char formation capability. Additionally, S4 and S2 composites demonstrated higher residual weight percentages compared to the pure green epoxy sample (S1), further underscoring the positive effect of GE reinforcement on thermal residue retention. These

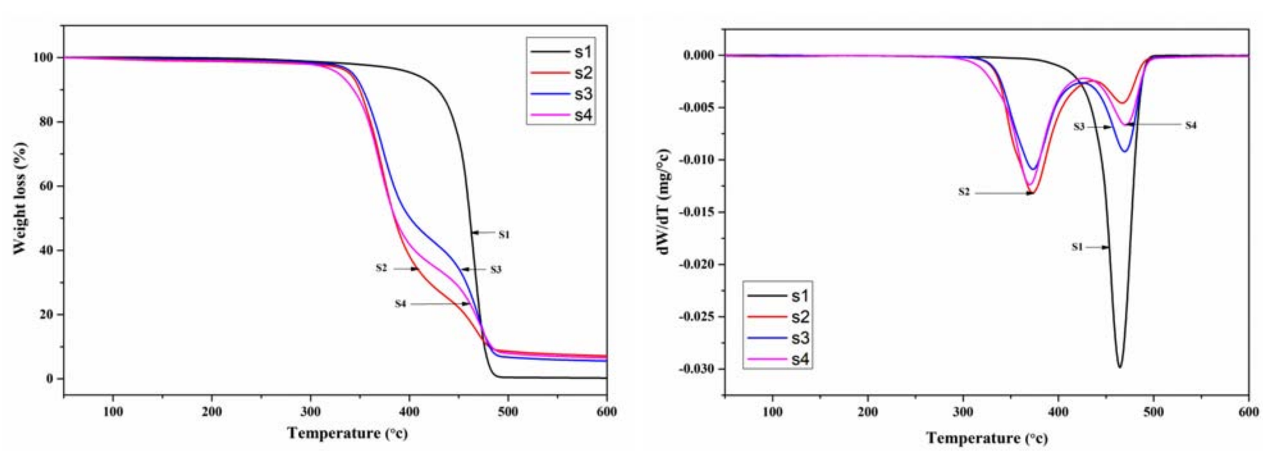


**Figure 8:** Primary and derivative thermograms of PGM/Green Epoxy composites.

results suggest that the incorporation of PGM with different volume of GE contributes to increased thermal stability and residue yield, potentially enhancing the material's performance in high-temperature applications.

**Table 4: Degradation Temperature Ranges of PGM/Green Epoxy Composites**

| Degradation Temperature (°C) | | S1 | S2 | S3 | S4 |
|---|---|---|---|---|---|
| **Step 1** | Onset | 446.74 | 348.95 | 350.81 | 346.99 |
| | Inflection | 462.50 | 373 | 372.50 | 369.17 |
| | End set | 473.07 | 382.06 | 377.92 | 373.70 |
| **Step 2** | Onset | - | 448.47 | 453.90 | 452.86 |
| | Inflection | - | 466.82 | 470.50 | 472.14 |
| | End set | - | 479. 51 | 479. 63 | 482.26 |
| **Residue (%)** | | **7.3123** | **47.4964** | **61.5752** | **58.7812** |

## 4. CONCLUSIONS

The acoustic and thermal properties of Powdered Granular Mask (PGM) reinforced green epoxy composites were evaluated, revealing enhanced performance across all PGM/GE samples compared to the unreinforced green epoxy (S1). Notably, Sample S4 demonstrated superior acoustic shielding in the mid-frequency range, achieving a peak Sound Absorption Coefficient (SAC) of 0.98 at approximately 1000 Hz, alongside the highest Noise Reduction Coefficient (NRC) of 0.30. Additionally, Sample S3 exhibited a peak Sound Transmission Loss (STL) of 37.3 dB in the low-frequency range, while Sample S4 excelled at high frequencies with a peak STL of 44.9 dB. Thermogravimetric analysis (TGA) indicated that Sample S4 provided the highest thermal stability, with an inflection temperature of 472°C. These results suggest that PGM-reinforced bio-based epoxy composites offer significant potential for applications requiring advanced acoustic and thermal performance. Their combination of sound attenuation and heat resistance makes them a promising, sustainable material solution for aircraft flooring systems, particularly in critical areas such as cockpits and passenger cabins, where noise reduction and thermal insulation are essential for enhancing comfort and efficiency.

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