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SOUND AND THERMAL INSULATION PROPERTIES OF SANDWICH COMPOSITES MADE OF WASTE KEVLAR® MATERIALS

ATIK KEVLAR® MALZEMELERDEN YAPILAN SANDVİÇ KOMPOZİTLERİN SES VE ISI YALITIMI ÖZELLİKLERİ

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SOUND AND THERMAL INSULATION PROPERTIES OF SANDWICH COMPOSITES MADE OF WASTE KEVLAR® MATERIALS

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ABSTRACT: This paper examines the thermal and acoustic insulation characteristics of sandwich composites with waste Kevlar® fiber-reinforced face materials and polyurethane/paper cardboard cores. Waste Kevlar® short fibers (carding waste) were reinforced into the sandwich composites' core part in varying ratios (2%, 5%, and 10%). Kevlar® fabric edge waste (waste of weaving process) was used to produce the face materials of sandwich composites. Sandwich composites were also stitched using Kevlar® yarns to observe the effect of the through-thickness reinforcement on sound and thermal insulation properties. The sound insulation test results showed that reinforcement of short Kevlar® fibers into the core parts of sandwich composites somewhat raised their sound absorption coefficients. Because the stitching holes created air spaces for sound vibrations, the sound absorption coefficient values improved. The sound transmission losses of sandwich composites were also increased up to 30 dB after short Kevlar® fiber addition. The thermal conductivity coefficient of sandwich composites decreased, indicating that the addition of Kevlar® fibers increased their insulation properties.

Keywords: Sandwich composites, Kevlar®, thermal insulation, sound absorption, polyurethane rigid foam.

ATIK KEVLAR® MALZEMELERDEN YAPILAN SANDVİÇ KOMPOZİTLERİN SES VE ISI YALITIMI ÖZELLİKLERİ

ÖZ Bu makalede, atık Kevlar® lifi ile güçlendirilmiş yüzey malzemeleri ve poliüretan/karton çekirdeğinden meydana gelen sandviç kompozitlerin ses ve ısı izolasyon özellikleri incelenmektedir. Kevlar® kısa lifleri (tarak altı telefi) sandviç kompozitlerinin çekirdek bölümlerine farklı oranlarda (2%, 5% ve 10%) takviye edilmiştir. Kevlar® kumaş kenar atığı (dokuma proses atığı) sandviç kompozitlerin yüzey malzemelerinin üretilmesinde kullanılmıştır. Kalınlık-boyunca dikişin, sandviç kompozitlerin ses ve ısı yalıtımı özellikleri üzerindeki etkisini gözlemlemek için Kevlar® iplikleri kullanılarak dikim işlemi yapılmıştır. Ses yalıtımı test sonuçları, sandviç kompozitlerin çekirdek kısmına kısa Kevlar® lifi takviyesinin ses yutum katsayısını bir miktar arttırdığını göstermiştir. Dikiş delikleri, ses titreşimleri için hava alanları oluşturduğundan, ses yutum katsayısı değerleri iyileştirilmiştir. Sandviç kompozitlerinin ses iletim kaybı kısa Kevlar® lifi takviyesi ile birlikte 30 dB'e kadar artmıştır. Sandviç kompozitlerinin ısı iletkenlik katsayısı azalmış, bu da Kevlar® liflerinin yalıtım özelliklerini arttırdığını göstermiştir.

Anahtar Kelimeler: Sandviç kompozitler, Kevlar®, ısı yalıtımı, ses yutum, poliüretan sert köpük.

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1. INTRODUCTION

A sandwich composite is a unique combination of laminated component materials composed of a relatively lightweight, thick, and compatible core and stiff, strong, and thin face layers [1]. The face parts form a stress couple to counteract the structure's bending stress, with one face compressed and the other in tension. The core portion resists shear stresses and increases structural stiffness, ensuring appropriate support for the face sheets [2]. Depending on the final use of the sandwich composites, several face and core materials can be employed. Some of the common face materials are carbon, Kevlar®, glass, and natural fibers [3-6] while foams and honeycombs are the most common core materials [7-9].

The sound absorption coefficient (SAC) and transmission losses (STL) properties of sandwich composites have been investigated in the literature [10, 11]. Dong et al. [12] used carbonized cotton with a hierarchical pore structure and a micro-perforated honeycomb for the core of the sandwich panel. They noticed improved sound-absorbing capacity in the construction without considerably increasing its weight. Xie et al. [13] attempted to improve the acoustic properties of sandwich composites manufactured from Nomex honeycomb filled with polyester fiber. The testing results showed that increasing the porosity of the filler enhanced the sound absorption coefficient of the sandwich composite. Sharma and Kumar [14] intended to combine waste coconut husk and calcium silicate board to create a sandwich panel using polyurethane (PU) foam as the core component. They observed that using coconut husk reduced the cell size and enhanced the acoustic behavior of sandwich composites up to a frequency of 1600 Hz. Liu et al. [15] created a noise-reducing composite based on the honeycomb sandwich structure by filling it with various plant (cotton and kapok) and synthetic (polyester) fibers. Cotton and polyester filling have the highest average sound absorption coefficients of 0.532 and 0.483 among the materials investigated, whereas the unfilled sample has an absorption coefficient of approximately 0.15. Yang et al. [16] investigated at how the sound absorption coefficient and sound transmission loss were affected by glass fiber assembly with various filler shapes, fiber diameter, fiber content, and air layer. They found that adding more fiber can increase STL and that the best STL comes from random glass fiber assembly with fine fibers. Harikrishnan et al. [17] reinforced rigid PU foam with varying amounts of carbon nanofibers. It has been indicated that the reinforcement of carbon nanofibers increases the thermal insulation and flame retardancy of PU rigid foams. Widya and Macosko [18] produced PU rigid foams reinforced with nanoclay at different ratios. It is stated that clay reinforcement reduces the cell size of PU foams. The reduction in cell size leads to a decrease in permeability properties of PU rigid foam due to the dispersed nanoclay acting as a diffusion barrier.

It has been reported that the thermal conductivity decreases in foam structures where high amounts of additives are used, and it is expressed that the reason for this is the smaller cell size resulting from heterogeneous nucleation [19].

Previous studies have shown that employing micro and nanofillers in core parts improves the acoustic and thermal characteristics of sandwich composites. However, a little attention has been dedicated to incorporating waste elements in the core and face components of sandwich composites to improve their acoustic and thermal qualities. Therefore, this paper investigates the acoustic characteristics (sound absorption coefficient and sound transmission loss) and thermal insulation properties of sandwich composites composed of polyurethane/ paper cardboard cores with varying proportions of waste Kevlar® short fibers and waste Kevlar® fiber-reinforced face materials.

2. EXPERIMENTAL

2.1. Materials

Honeycomb paper cardboard with a 12 mm cell size and 10 mm height and polyurethane (PU) rigid foams were used as the core materials of sandwich composites. PU foam has two components: polyol and isocyanate. PLUSOL PD-327 was employed as the polyol, whereas PLUSNATE 200 was used as the isocyanate (100/120). Waste Kevlar® short fibers (carding waste) were reinforced into the sandwich composites' core part. Kevlar® fabric edge waste (waste of weaving process) was used to produce the face materials of sandwich composites.

2.2. Manufacturing

2.2.1. Core part manufacturing

Honeycomb cardboards were filled with PU foam reinforced with varying amounts (0%, 2%, 5%, and 10% by weight) of carding waste Kevlar® fibers. A fiber-cutting machine (060 KCE/PLS, Kaym Makine, Türkiye) was utilized to cut the waste fibers into 9.2 mm lengths (Figure 1a). The chopped Kevlar® fiber was mixed with the polyol in two stages, using a mechanical mixer (Isolab, Germany) at 500-2000 rpm for 20 minutes (Figure 1b) and an ultrasonic bath (35 kHz, Isolab, Germany) at 23±2°C for 5 minutes (Figure 1c). Next, isocyanate was added to the mixture, and stirring was done manually until the foam formed. The PU foam reinforced with Kevlar® fiber was manually transferred to the honeycomb cardboard construction at room temperature (Figure 1d). To create the core of the sandwich composite, the cardboard containing PU was put in a press (Wermac® H501, Türkiye) and allowed to stand at room temperature with a pressure of 6 bar for 45 minutes (Figure 1e).

2.2.2 Face and sandwich composite manufacturing

Sandwich composites were produced by combining Kevlar® fabric edge waste as face materials and core structures that were produced in previous steps. The Kevlar® fabric edge waste is 3000 deniers with eight weft yarns per centimeter and width is 65 mm. The Kevlar® fabric edge waste also includes polyester warp yarns with a density of 12 strands per cm, as depicted in the Figure 2.

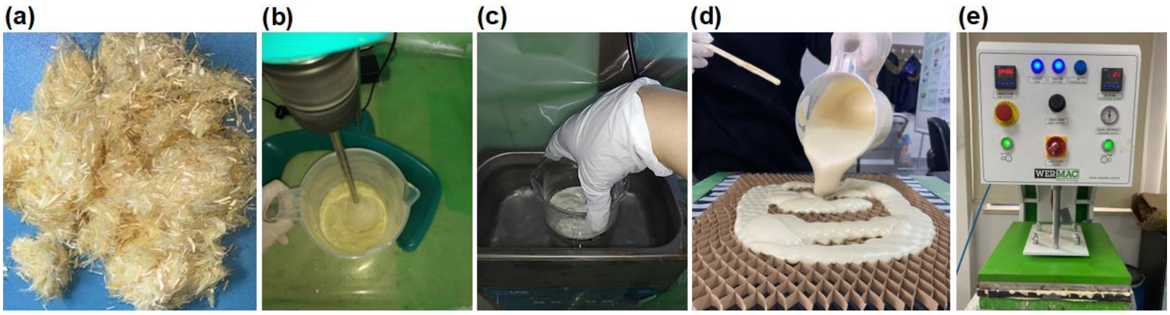

Figure 1. Core parts manufacturing stages; chopped Kevlar® fibers (a), mechanical stirring (b), ultrasonic stirring (c), molding (d), (e).

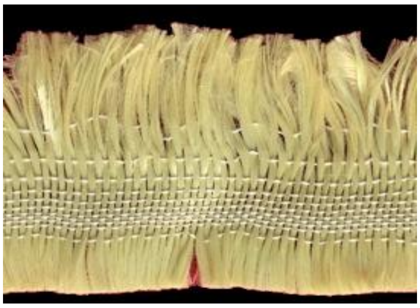

Figure 2. The waste selvage of the Kevlar® fabric.

The Kevlar® fabric edge waste was inserted in a frame mold (50 cm × 50 cm) with 2 cm spacing using a fiber placement machine to achieve a $[0°/90°]_5$ stacking sequence for the sandwich composites' face. After completing the $[0°/90°]_5$ lay-up, the core parts were positioned in the center of the face materials, as illustrated in the Figure 3a. Sandwich composites with Kevlar® waste structures in the upper and lower parts and a cardboard/PU core in the middle were created using the vacuum infusion process at 50 °C with epoxy resin (L160 resin/H160 hardener, 100/25) for 2 hours (Figure 3b).

Sandwich composites were also stitched with a robotic stitching machine. The cured sandwich composites were drilled to a diameter of 4 mm using a CNC machine, leaving 1 cm of raw and column gaps. Figure 4 shows that the sandwich composites were placed on the frame in the center of the robotic stitching mechanism and secured vertically. The robotic arms, designed to stitch at a specific width (1 × 1 cm), utilized Kevlar® yarns (3000 denier). Table 1 shows all of the unstitched and stitched sandwich composites with various fiber reinforcements in the core components.

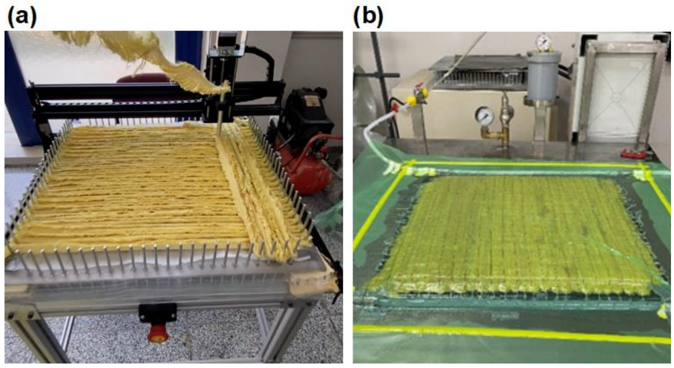

Figure 3. Fiber placement (a) and vacuum infusion (b) of sandwich composites.

Figure 4. Robotic stitching of sandwich composites.

Table 1. Definitions of sandwich composites.

Label	Core material		Face material	
	Kevlar® fiber ratios (%)	Polyurethane rigid foam	Fiber type	Stitching
NPU	-	-	Kevlar®	-
PU0	0	+	Kevlar®	-
PU2	2	+	Kevlar®	-
PU5	5	+	Kevlar®	-
PU10	10	+	Kevlar®	-
S-NPU	-	-	Kevlar®	+
S-PU0	0	+	Kevlar®	+
S-PU2	2	+	Kevlar®	+
S-PU5	5	+	Kevlar®	+
S-PU10	10	+	Kevlar®	+

2.3. Test methods

The densities of the sandwich composites were determined using a density meter (Precisa) in accordance with the ASTM D792-13 (2013) test standard.

The sound absorption coefficient and sound transmission loss were determined using the impedance tube method in accordance with the ASTM E1050-12 and ASTM E2611-17 standards, respectively. Sound testing was done by using BIAS TestSens analysis devices and a four-microphone medium-type impedance tube at frequencies from 100 to 1600 Hz. The sound absorption coefficient (α) is calculated using according to the equation (1).

$$Sound\ absorption\ coefficient\ (\alpha) = \frac{absorbed\ acoustic\ energy}{incident\ acoustic\ energy} \qquad (1)$$

Thermal conductivity measurements were performed with the Thermtest (HFM-100, Canada) test unit. Thermal conductivity was measured in accordance with the ASTM C518 standard. The device estimated the thermal conductivity value (λ, W/m K) using the equation (2).

$$\lambda = q.h / \Delta T \qquad (2)$$

Where; q represents heat flow (W/m^2), ΔT is temperature differential (K), and h is thickness (m).

3. RESULTS AND DISCUSSIONS

Table 2 shows the densities of sandwich composites with varying amounts of Kevlar® fiber in the core parts. The density of sandwich composites increased slightly after adding 5% and 10% Kevlar® fiber. The densities of the stitched sandwich composites were reduced as a result of creating holes through-the-thickness directions to guide the stitching yarns.

Table 2. Densities of sandwich composites.

Label	Density (g/cm^3)
NPU	0.520 (±0.010)
PU0	0.503 (±0.103)
PU2	0.500 (±0.010)
PU5	0.540 (±0.020)
PU10	0.633 (±0.025)
S-NPU	0.517 (±0.023)
S-PU0	0.417 (±0.096)
S-PU2	0.483 (±0.071)
S-PU5	0.503 (±0.015)
S-PU10	0.547 (±0.049)

3.1. Sound absorption coefficient test results

Figure 5 and 6 present the sound absorption properties of sandwich composites containing different ratios of Kevlar® short fiber between 100-1600 Hz. It is evident that sandwich composites with polyurethane (PU0, PU2, PU5, and PU10) and those without polyurethane (NPU) differ slightly in their sound absorption coefficients (Figure 5a). When compared to samples containing polyurethane at 400 Hz, the NPU sample exhibits the greatest coefficient values. At the same frequency (400 Hz), other samples, however, show extremely similar coefficient values. This might be because some samples were filled with polyurethane, but the NPU samples had air holes between the cardboard. The short Kevlar® fiber inclusion has a more noticeable effect at higher frequencies (600–1000 Hz). For example, the coefficient values for NPU are approximately 0.2, whereas for the samples of PU0, PU2, PU5, and PU10, they are approximately 0.25, 0.95, 0.1, and 0.1, respectively. This means around 95% of the incident sound energy was absorbed by the PU2 sample. It is expected that as short fiber ratios rise, the coefficient values would as well. However, sandwich composites with 5% and 10% Kevlar® fibers showed coefficient values that were lower than those with 2%. This could be the result of Kevlar® fibers sticking together in polyurethane foam when core parts are being made. The PU2 sample has the lowest density values when compared to other sandwich composites, and porosity increases with decreasing material density, allowing the material to absorb more sound waves [20]. All foam core sandwich composites exhibit comparable reductions in coefficient after 1000 Hz, however NPU composites exhibit undulations.

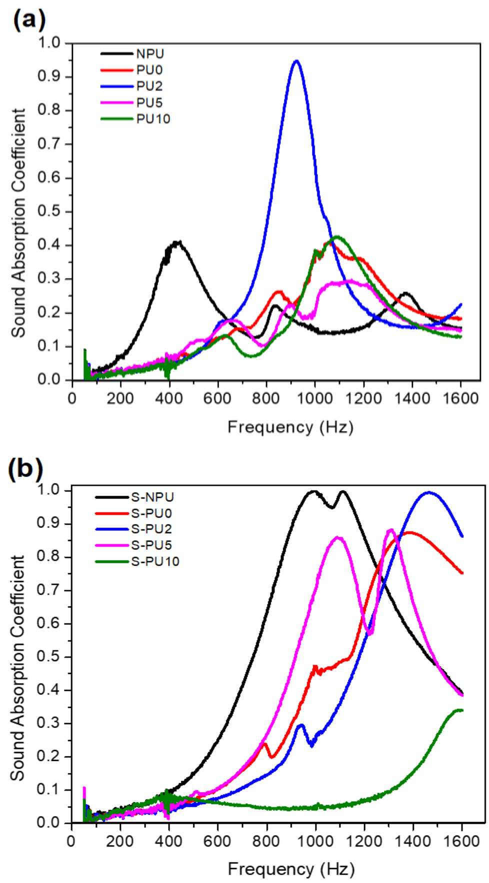

Figure 5. Sound absorption properties of unstitched (a) and stitched composites (b).

Figure 5b shows the sound coefficient values for the stitched sandwich composites. The coefficient values differ significantly from those of unstitched sandwich composites. This is due to holes formed during the stitching process, which causes air and sound vibrations. This allows for more sound absorption. All composites have coefficient values that are relatively comparable until 400 Hz. However, the coefficient values rise quickly until 1000-1500 Hz, depending on the sample types. For instance, the coefficient values are about 1.0, 0.8, 0.7, 0.55, and 0.1 for NPU, PU0, PU2, PU5 and PU10 samples, respectively at 1200 Hz. As with the unstitched sandwich composites, the sandwich composites with the highest Kevlar® ratio also exhibit the lowest coefficient values.

3.2. Sound transmission loss test results

The ability to absorb acoustic energy is measured by the coefficient of absorbency (α), whereas the ability to reflect or block sound is measured by sound transmission loss (STL) [21]. The STL of the unstitched composites at various frequencies (100-1600 Hz) is shown in Figure 6a. With an approximate STL of 17 dB, the PU10 has the highest of all the samples at around 100 Hz. Figure 6a implies that the PU10 sandwich composite can block approximately 17 dB of sound at this frequency.

Figure 6a also demonstrates that STL increases with frequency up to 800 Hz. The PU10 sample still has the highest STL value (about 30 dB) of any foam core sandwich composite. This demonstrates that increasing the fiber content in the foam core enhances the composites' STL values. However, the NPU sample, which does not contain any PU foam core, had higher STL values (around 40 dB) than other samples at 800 Hz. This could be attributed to air spaces in the NPU sample, which provides higher sound blocking than PU foams at 800 Hz. Between 800 and 1600 Hz, the STL values of NPU and PU10 are nearly identical and somewhat higher than those of other sandwich composites.

Figure 6b shows the STL of the stitched composites at 100- 1600 Hz frequencies. It is apparent that all unstitched sandwich composites have lower STL values than unstitched composites. This is due to the holes generated during sandwich composite stitching, which reduces sound transfer blocking. Sandwich composites with 0%, 5%, and 10% fiber reinforcement produce STL values that are comparable, as Figure 6b illustrates. In contrast to foam core sandwich composites, S-NPU sandwich composites had significantly lower STL values, particularly at high frequencies (1600 Hz). Stitching holes appear to have a greater effect on STL characteristics in sandwich composites than fiber contents. It is also important to understand the dB levels of sounds to evaluate the materials. For instance, over time, sounds louder than 70 dB will deteriorate hearing [22]. The harmful noises can be reduced to normal sound levels using the PU10 sandwich composite, which can reduce noise levels by up to 30 dB.

3.3. Heat insulation test results

The heat insulation characteristics of both unstitched and stitched sandwich composites are shown in the Table 3. Given that the thermal conductivity decreases from 0.0964 to 0.0725 W/mK, it is evident that the heat insulation rises with an increase in the Kevlar® fiber ratio for unstitched sandwich composites. There is a roughly 30% increase in thermal insulation after reinforcing 10% of Kevlar® short fibers. The thermal conductivity of NPU sandwich composite is lower than that of the foam core sandwich composites, indicating that using PU foams enhance the thermal insulation of sandwich composites. Additionally, Table 3 shows that sandwich composites with PU foam core that are stitched offer superior insulation compared to sandwich composites with a cardboard core alone (S-NPU). Similar thermal conductivity trends were observed as in unstitched composites, with S-PU10 having the lowest thermal conductivity value. The data also shows that, following the stitching process, the thermal conductivity coefficient values increased (except from PU2 and S-PU2) because holes were created, which facilitated heat transfer.

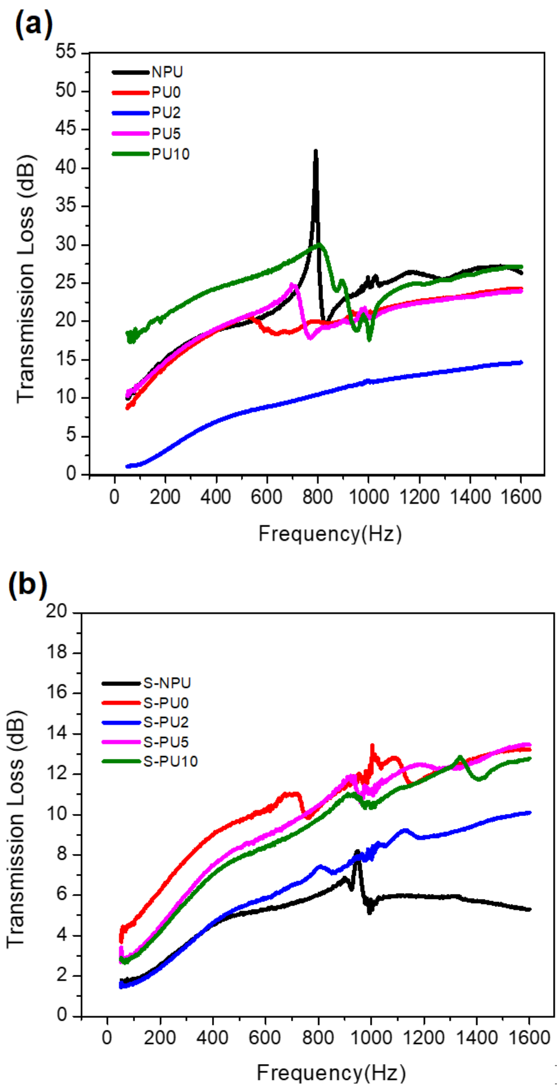

Figure 6. Sound transmission properties of unstitched (a) and stitched composites (b).

Table 3. Heat insulation properties of sandwich composites.

Label	Thermal conductivity coefficient (W/mK)
NPU	0.1091
PU0	0.0964
PU2	0.0936
PU5	0.0930
PU10	0.0725
S-NPU	0.1008
S-PU0	0.0976
S-PU2	0.0856
S-PU5	0.0952
S-PU10	0.0828

4. CONCLUSIONS

This paper investigated the sound and thermal insulation properties of sandwich composites made of short Kevlar® fiber-reinforced polyurethane/cardboard cores and Kevlar® fabric edge waste reinforced face layers. The following conclusion can be taken from this work:

- The addition of short fibers to the core parts of sandwich composites slightly increased the densities of the composites.
- The insertion of short Kevlar® fibers to sandwich composites resulted in a small increase in the sound absorption coefficient, particularly at low fiber ratios (2%) and lower sandwich densities.
- The stitching of sandwich composites increased the sound absorption coefficient of the materials due to creating air zones to vibrate during the sound penetration.
- The short Kevlar® fibers added to unstitched sandwich composite samples resulted in an increase in sound transmission losses of up to 30 dB. Since the stitching process decreased the transmission losses, a lower volume of sound-roughly 14 dB-was stopped.
- Increasing the Kevlar® fiber ratio increased sandwich composites' thermal conductivity coefficient (W/mK). As a result, improved insulating properties were achieved. The stitching reduced insulating characteristics by allowing heat to pass through the perforations more easily.

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