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EVALUATION OF ACOUSTIC PERFORMANCE OF HEMP AND COTTON FIBER REINFORCED THERMOPLASTIC COMPOSITES

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Abstract: In a developing and increasing world, the increment in the consumption of natural resources brings environmental problems together. The use of plant raw materials has great importance in the construction industry, which has a high consumption rate. Increasing demand to develop sustainable and environmentally friendly materials has increased the use of natural fibers in sustainable building materials (sound absorption, heat and sound insulation). The fact that hemp fiber does not have high water consumption in the production, can be grown without the need for fertilizers and pesticides, as well as leaving a rich soil structure for the next crop by destroying weeds ensures the protection of the soil and the environment. From this point of view, in this study sound insulation properties of hemp fiber reinforced composites were investigated. Polypropylene fiber was used as a matrix material. To compare the performance of hemp fiber, cotton fiber was also utilized and different constructions were produced from these materials. The composites were produced by the hot-press method. It was found that the composites made of hemp fiber showed significantly higher sound insulation than the cotton fiber reinforced composites and can be used as a sound isolation material at specific high frequencies.

Keywords: Hemp, Composite, Sound absorption, Sound transmission loss

Kenevir / Pamuk Elyaf Takviyeli Termoplastik Kompozitlerin Akustik Performansının Değerlendirilmesi

Öz: Gelişen ve her geçen gün çoğalan dünyamızda, doğal kaynakların tüketiminin hızla artması çevresel problemleri de beraberinde getirmektedir. Tüketim oranı yüksek olan inşaat endüstrisinde bitkisel hammaddelerin kullanımı büyük önem arz etmektedir. Sürdürülebilir ve çevre dostu malzemeler geliştirmek için artan talep, doğal liflerin sürdürülebilir yapı malzemelerinde (ses yutum, ısı/ses yalıtımı) kullanımını artırmıştır. Kenevir lifi üretiminde su tüketiminin düşük olması, gübre ve tarım ilacına ihtiyaç duymadan yetiştirilebilmesinin yanı sıra yabani otları yok ederek sonraki ürün için zengin bir toprak yapısı bırakması gibi nedenlerle toprak ve çevrenin korunmasını sağlamaktadır. Bu noktalardan yola çıkarak bu çalışmada, kenevir elyaf katkılı kompozit yapıların ses yalıtım özellikleri incelenmiştir. Matris malzemesi olarak polipropilen elyafı kullanılan çalışmada, kenevir elyafının performansını karşılaştırabilmek için pamuk elyafı da kullanılmış ve bu malzemelerden farklı ağırlık oranlarına sahip farklı konstrüksiyonlarda üretimler yapılmıştır. Kompozit malzeme, sıcak pres yöntemiyle elde edilmiştir. Elde edilen sonuçlara göre; kenevir elyafı takviyeli kompozitlerin, pamuk takviyeli kompozitlerden önemli ölçüde daha yüksek bir ses yalıtım özelliğine sahip olduğu ve yüksek frekanslarda ses yalıtım malzemesi olarak kullanılabileceği görülmüştür.

Anahtar Kelimeler: Kenevir, Kompozit, Ses yutum, Ses iletim kaybı

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1. INTRODUCTION

Since people began to live with each other from the start of old ages, more crowded cities are formed, and it created pollution which brings diseases with itself. They can be the basis for psychological and physical health problems and can be the trigger of different situations, because of that engineers and designers made huge investments and choices for sound isolation. Sound isolation is the most crucial topic for crowded areas (Masterton et al., 1969).

There are two methods to reduce sound level. These are sound absorption and sound insulation. Sound absorption is based on the conversion of sound energy into heat energy through friction. The sound transmission loss is calculated by measuring the difference of decibels between the incident sound and the permeated sound. The greater the amount, the stronger the sound-isolating property is (Yang and Li, 2012).

There are many commercial materials used to provide sound insulation. The most important of them are glass wool, foam and mineral fibers (Süvari, 2020; Xiang et al., 2013; Ersoy and Küçük, 2009). In addition to these commercial materials, there are many studies on the use of different textile structures in sound insulation (Özdil et al., 2020; Lim et al., 2018; Makki and Oktariani, 2019; Kaya and Dalgar, 2017; Küçük and Korkmaz, 2012). While the sound absorption properties of cotton and kenaf fibers are similar to rock wool (Lim et al., 2018; Oldham et al., 2011) coconut fiber is known to have high sound absorption at low and medium frequencies (Berardi and Iannace, 2015). Besides, hemp fibers in building construction have proven essential for noise reduction applications. While the sound absorption coefficient of hemp fiber is high at medium and high frequencies, it is negligible at low frequencies (Berardi and Iannace, 2017).

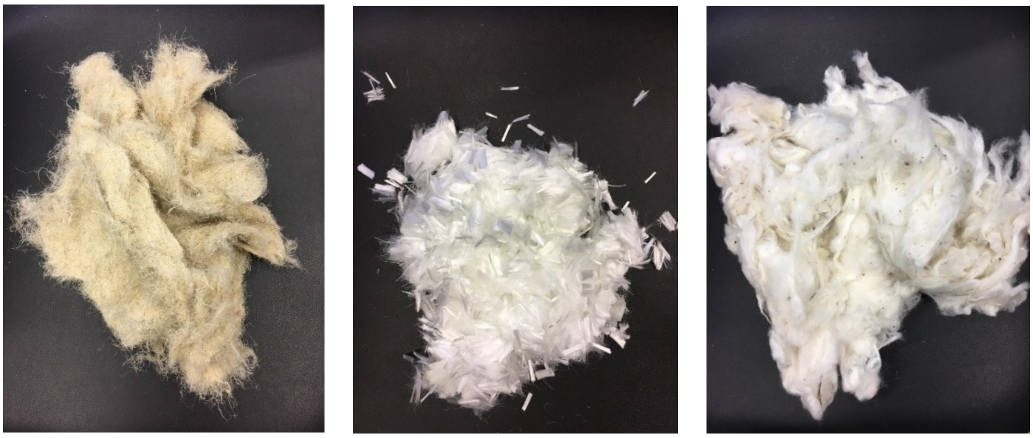
In addition to textile materials, studies on the use of textile reinforced composites have also attracted attention in recent years. In one of these studies, Olcay and Kocak (2020) used alkali-treated and untreated artichoke stem fibers and polyurethane matrix at different reinforcement ratios (5, 10, 15 and 20%) to produce bio-fiber based composites. The results showed that alkali treatment of the fibers optimized the composites' sound absorption coefficients and the best sound absorption properties were obtained for treated 5% artichoke stem waste fibers reinforced polyurethane composites. In another study, Selver (2019) manufactured glass/epoxy, flax/epoxy, jute/epoxy and their hybrid composite structures with different stacking sequences by vacuum infusion method and measured their sound absorption coefficient and sound transmission loss values. It was observed that the order of lining plays a critical role and composites whose outer surface was made of natural fibers had higher sound absorption. Moreover, it was indicated that with the increment in fiber thickness, sound absorption also increases and hybrid composites provide greater sound absorption relative to individual fibers. In a study by Le et al. (2014) experimental research was performed to examine the mechanical and acoustical performance of composite materials made from starch and hemp. Specimens of starch-hemp composite materials with five hemp/starch ratios (H/S 1⁄4 6, 8, 10, 12 and 14) were produced by using the ideal binder and two shives of hemp (0-15 mm and 0-20 mm). The results showed that starch-hemp composite materials were a good sound absorber material for medium and high frequencies with a value about 0.7 due to the porous nature of the material. The study conducted by Aly et al. (2021) implied that increased impact sound reduction values at low frequencies were obtained by all composite samples. However, at high frequency levels jute and jute-polyester composites performed a decrease in impact sound reduction. Dragonetti et al. (2020) investigated the sound transmission loss of a new hemp fiber reinforced bio-epoxy resin-based sandwich structure and found that the sound transmission loss of woven hemp sandwich structures gave adequate results compared to honeycomb structures and demonstrated its usability for practical applications.

In this research, hemp fiber reinforced thermoplastic composite structures, which require a small amount of water and chemicals during their production, have been designed and produced with the hot press method to develop a sustainable sound insulator. Cotton and cotton/hemp fiber reinforced samples were also produced for performance comparison. The effect of thickness/density and fiber configuration change of the composite material on the sound absorption and sound transmission loss values were investigated.

2. EXPERIMENTAL STUDY

2.1. Materials

In this study, to produce a sustainable sound isolation material raw cotton and hemp fibers were utilized as reinforcement material and polypropylene (PP) fiber was used as matrix material (see Figure 1). The properties of fibers are given in Table 1.



(a) (b) (c)

Figure 1:
***a**. Hemp fiber, **b.** Polypropylene fiber, **c.** Cotton fiber*

Table 1. Properties of fibers

Fiber type	**Fiber diameter (micrometer)**	**Fiber length (mm)**	**Melting Temperature (°C)**	**Density (g/cm^3)**
Cotton	15	32	-	1.54
Hemp	22	36	-	1.40
Polypropylene	30	12	160	0.91

2.2. Method

2.2.1. Production Method

There were three stages in the production process of this study which were preparation of reinforcement and matrix materials, a homogeneous blending of reinforcement and matrix materials and production of composite materials by hot press technique.

- **Preparation of Reinforcement and Matrix Materials:** Fibers were separately placed on carding machine to obtain homogeneous and coherent structure. Carding process was made at least two times per material to get a smoother and thinner surface.
- **Homogeneous Blending of Reinforcement and Matrix Materials:** Carded fibers were then blended in certain volume fractions with each other and placed on carding machine again to prepare webs for hot press machinery to produce composite structures (Figure 2a).

- **Production of Composite Materials by Hot Press Technique:** The fibers were opened and blended by a Merdan Laboratory Type Carding Machine. The twelve web structures produced with six different contents were pressed in two different thicknesses using metal rings in the hot press machine to evaluate the effect of thickness and density on the acoustic performance of composite samples (Figure 2b). Each of the samples was transferred to the hot press machine between Teflon paper to prevent the sticking of matrix material to the machine. During the hot press process, the production temperature was adjusted to 180°C according to the melting temperature of polypropylene fiber (≈ 160°C). A pressure of eight tons was applied to the structures. The samples were kept for one hour under this temperature and pressure. Produced composite samples can be seen from Figure 2c. Sample codes and properties of composite samples are given in Table 2.

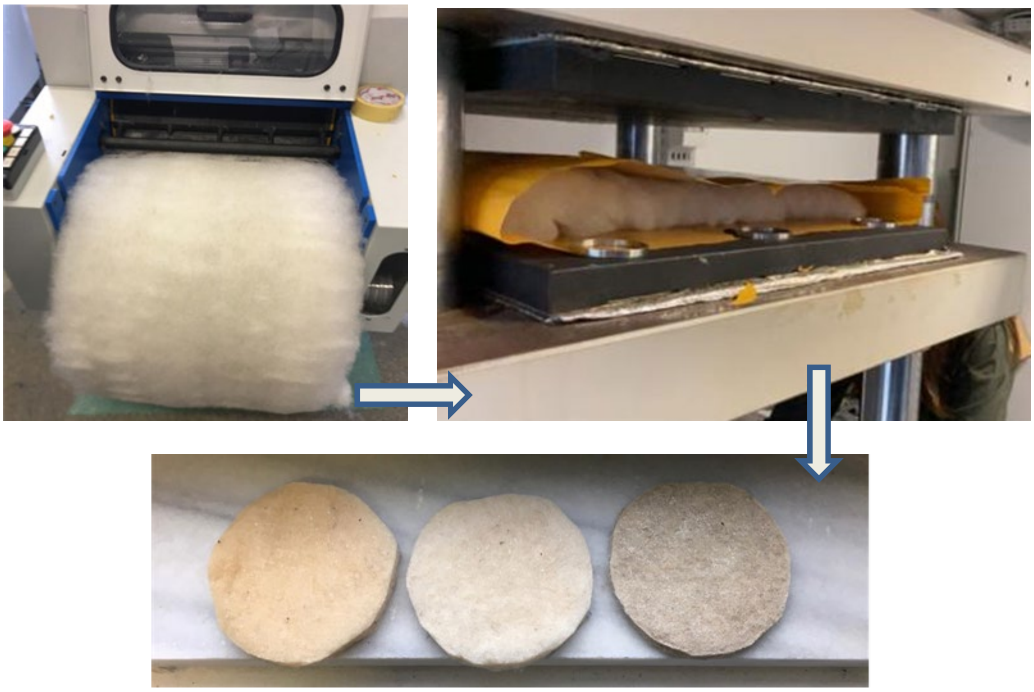


Figure 2:

a. *Carded web on carding machine,* ***b.*** *Composite production by hot press technique,* ***c.*** *Produced samples*

Table 2. Sample codes and properties

Sample code	Reinforcement type and ratio (%)	Matrix type and ratio (%)	Thickness (mm)	Density (g/cm³)	Areal density (g/m²)
Co/PP-50-6	Cotton (50)	PP (50)	6	0.0350	210
Co/PP-50-12	Cotton (50)	PP (50)	12	0.0205	246
Co/He/PP-50-6	Cotton (25) / Hemp (25)	PP (50)	6	0.0450	270
Co/He/PP-50-12	Cotton (25) / Hemp (25)	PP (50)	12	0.0193	232
He/PP-50-6	Hemp (50)	PP (50)	6	0.1250	750
He/PP-50-12	Hemp (50)	PP (50)	12	0.0590	708

Co/PP-67-6	Cotton (33.5)	PP (67.5)	6	0.0740	444
Co/PP-67-12	Cotton (33.5)	PP (67.5)	12	0.0445	534
He/PP-67-6	Hemp (33.5)	PP (67.5)	6	0.2050	1230
He/PP-67-12	Hemp (33.5)	PP (67.5)	12	0.0965	1158
Co/He/PP-67-6	Cotton (16.75) / Hemp (16.75)	PP (67.5)	6	0.1100	660
Co/He/PP-67-12	Cotton (16.75) / Hemp (16.75)	PP (67.5)	12	0.0845	1014

The fiber volume ratios of the composite samples produced are given in Table 3. While the PP fiber volume ratio in samples containing 50% by weight of PP varied between 60-63%, this ratio increased to 76-77% in samples containing 67% by weight of PP.

Table 3. Fiber volume fractions

Sample code	Cotton fiber volume fraction (%)	Hemp fiber volume fraction (%)	Polypropylene fiber volume fraction (%)
Co/PP-50-6	37	-	63
Co/PP-50-12	37	-	63
Co/He/PP-50-6	18	20	62
Co/He/PP-50-12	18	20	62
He/PP-50-6	-	40	60
He/PP-50-12	-	40	60
Co/PP-67-6	23	-	77
Co/PP-67-12	23	-	77
He/PP-67-6	-	24	76
He/PP-67-12	-	24	76
Co/He/PP-67-6	11	12	77
Co/He/PP-67-12	11	12	77

2.2.2. Acoustical Analysis

To figure out sound absorption coefficient and sound transmission loss at high and low-frequency levels, acoustic tests were performed. To measure sound absorption coefficient in the frequency ranges from 50 Hz to 6400 Hz, two microphone impedance measurement tube (TestSens Sound Tube) was used in accordance with the ISO 10534-2 standard.

A four-microphone impedance test tube was used for measuring sound transmission loss values of composites. The test was conducted according to the ASTM E2611-09 standard. Transfer function factor measured with four-microphone test tube was used to find the value of transmission loss coefficient. Then, transfer functions were calculated in every position and these values were collected in graphs.

2.2.3 Statistical Analysis

The statistical significance of the obtained results was examined by using Student's t test in Minitab 16 software program.

3. RESULTS

3.1. Sound Absorption Behaviour of Composites

3.1.1. Effect of Thickness

The graphical comparison of measured sound absorption coefficients of composite samples by thickness is given in Figure 3. By changing the thickness with metal links on a hot press machine, samples were produced in two different thicknesses (6 and 12 mm). The produced composites behaved as porous materials and showed sound-absorbent performances. The results of this adjustment revealed that the difference of thickness created only a slight change between the same group of samples. As can be seen in Table 2, while the thicknesses of the samples increased, their densities decreased. For this reason, these two elements eliminated and neutralized each other and made their sound absorption properties remain as the same.

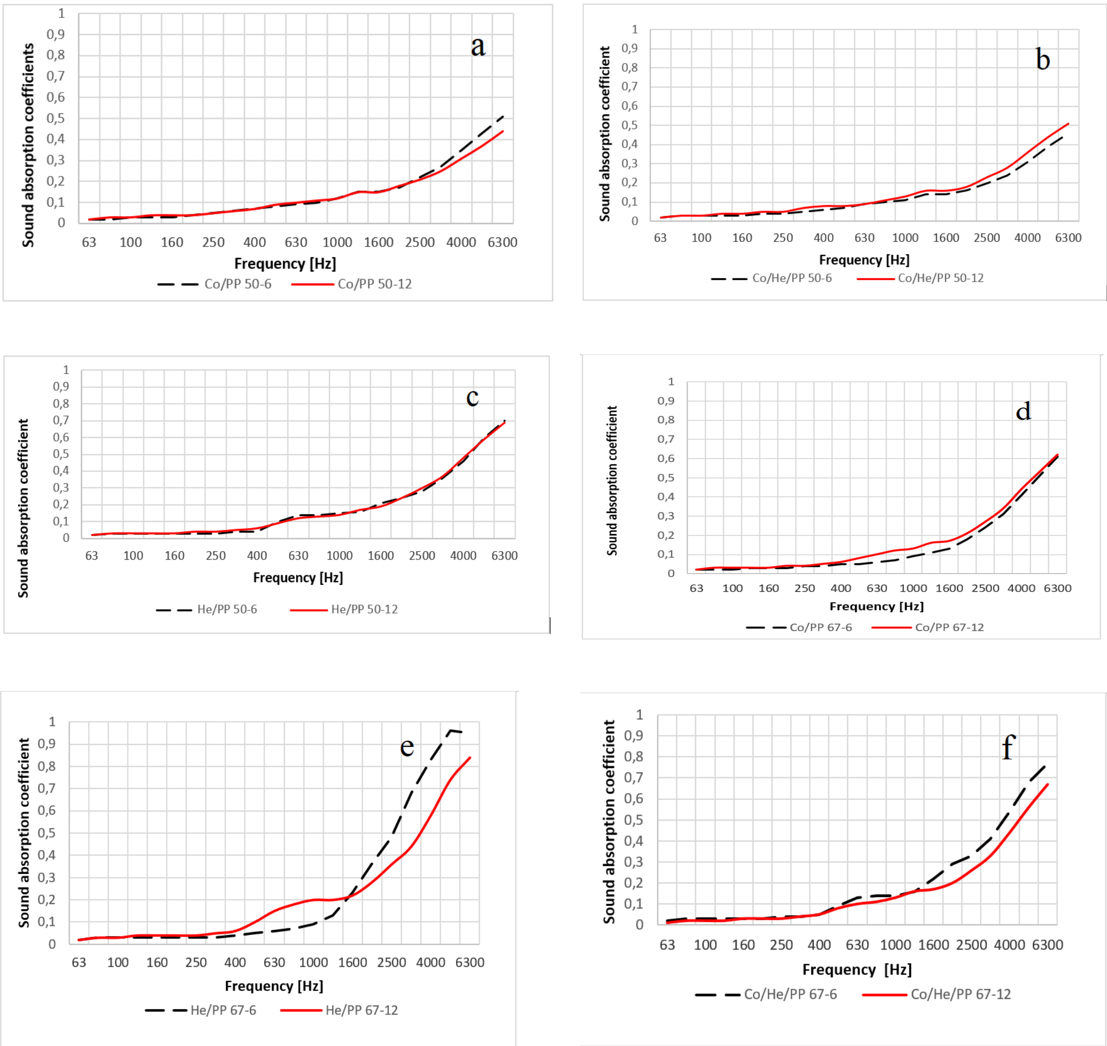


Figure 3:
Graphical comparison of measured sound absorption coefficients by thickness; ***a.*** *Co/PP 50-6 and Co/PP 50-12* ***b.*** *Co/He/PP 50-6 and Co/He/PP 50-12* ***c.*** *He/PP 50-6 and He/PP 50-12* ***d.*** *Co/PP 67-6 and Co/PP 67-12* ***e.*** *He/PP 67-6 and He/PP 67-12* ***f.*** *Co/He/PP 67-6 and Co/He/PP 67-12*

3.1.2 Effect of Fiber Type

The graphical comparison of measured sound absorption coefficients by weight fractions of fibers is given in Figure 4. The test results indicated that the increase in polypropylene and hemp fiber ratio in composite structures results in an increment in sound absorption coefficient. In a study in the literature, it was stated that composite materials produced with starch and hemp have good sound-absorbing properties (α: 0.7) at medium and high frequencies (Le et al., 2014). This situation supports these results.

It was seen that at the low-frequency level sound absorption coefficient values of hemp and cotton fiber reinforced composite samples were very close to each other, while hemp reinforced composites reached higher sound absorption coefficient values compared to the others when the high-frequency values were reached. It was stated in the literature that the sound absorption coefficient of hemp fiber is high at medium and high frequencies, but it is negligible at low frequencies (Liao et al., 2020). This situation supports the result obtained.

In addition, since the produced samples are suitable for high frequency use, Student's t test was applied to the sound absorption values obtained at 4000 Hz, and the significance of the results was examined. The sound absorption value of the hemp-reinforced sample in each group was compared with the other samples, and the *p* value was found 0.016 and below in these comparisons. In this study, which was conducted with a 95% confidence interval, the *p* value being below 0.05 showed that the results obtained were statistically significant.

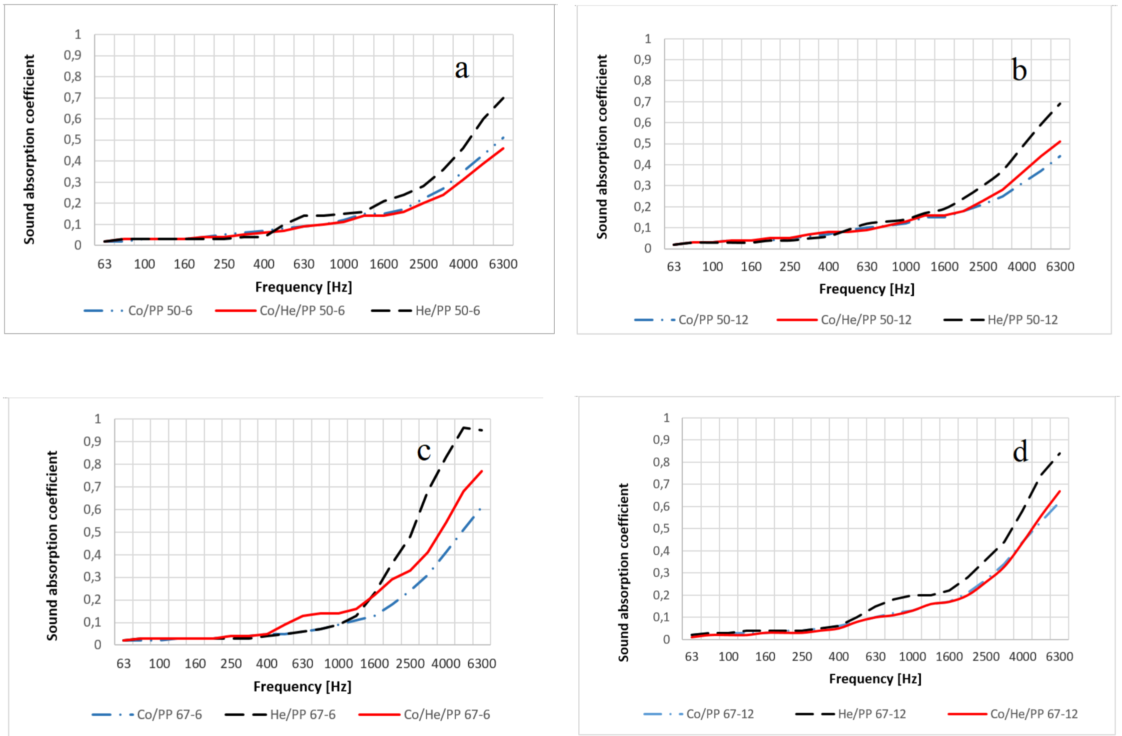


Figure 4:

Graphical comparison of measured sound absorption coefficients by fiber type;
a. *Co/PP 50-6, Co/He/PP 50-6 and He/PP 50-6* ***b.*** *Co/PP 50-12, Co/He/PP 50-12 and He/PP 50-12* ***c.*** *Co/PP 67-6, He/PP 67-6 and He/PP 67-6* ***d.*** *Co/PP 67-12, He/PP 67-12 and Co/He/PP 67-12*

3.2. Sound Transmission Loss Behaviour of Composites

Sound transmission loss (STL) helps to determine the amount of noise reduction that is achieved by an object, material or construction assembly as sound travels through it. Thus, it is very important to characterize the sound isolation property of homogeneous materials and composite structures (Dragonetti et al., 2020).

3.2.1 Effect of Thickness

Figure 5 shows the sound transmission loss values of the fiber reinforced composite samples. As the frequency increases from 63Hz to 6300 Hz, the transmission loss value was also increased for all samples. In addition, it was found that the maximum sound transmission loss occurred at 6300 Hz frequency for all samples.

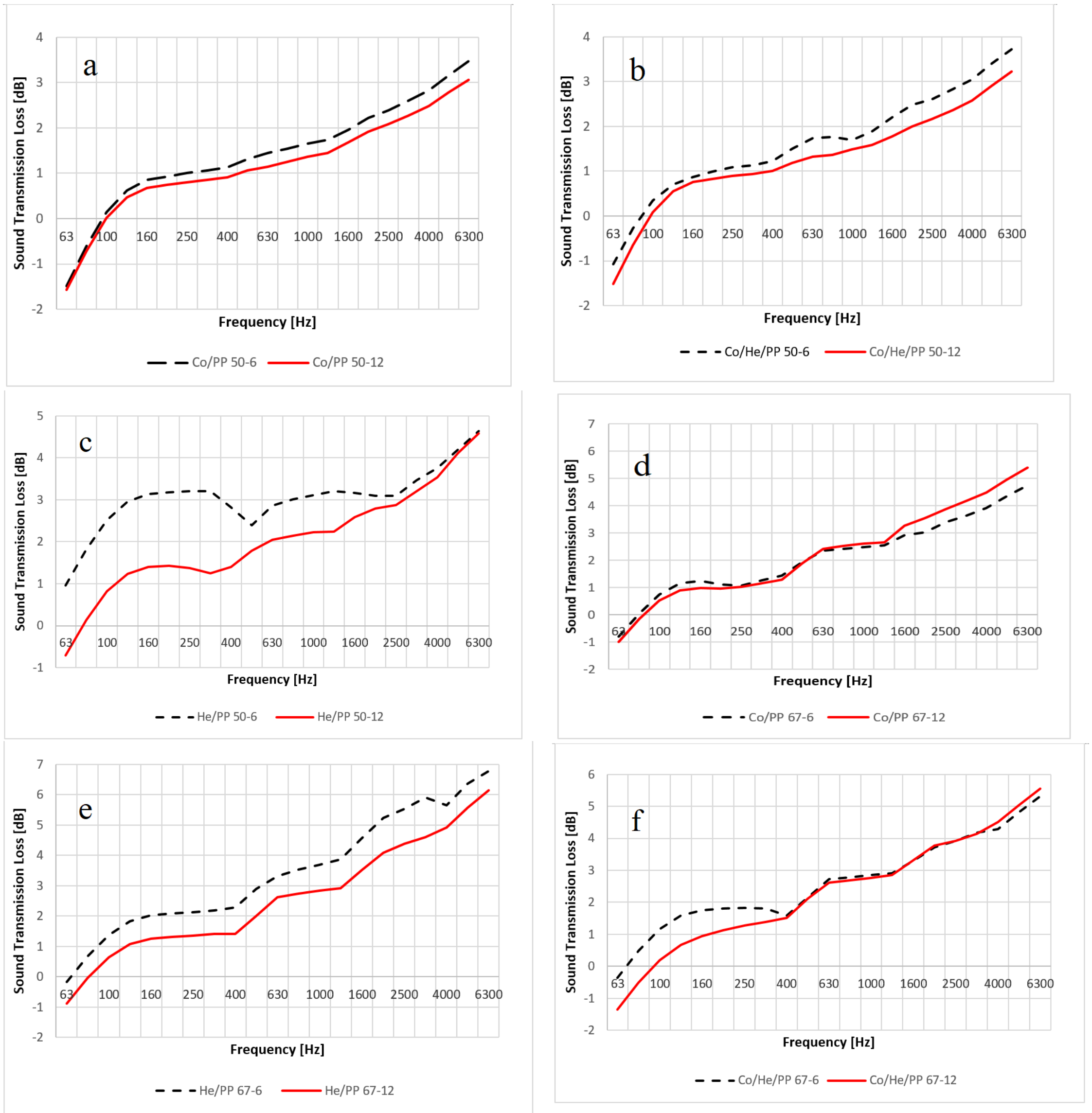


Figure 5:

Graphical comparison of sound transmission loss values by thickness;
a. *Co/PP 50-6 and Co/PP 50-12* ***b.*** *Co/He/PP 50-6 and Co/He/PP 50-12* ***c.*** *He/PP 50-6 and He/PP 50-12* ***d.*** *Co/PP 67-6 and Co/PP 67-12* ***e.*** *He/PP 67-6 and He/PP 67-12* ***f.*** *Co/He/PP 67-6 and Co/He/PP 67-12*

Based on the experimental data obtained throughout the tests, the sound transmission loss of the fiber reinforced composites tended to increase with the decrement of thickness. According to the literature, density is the most considerable factor that strongly influences the acoustical behavior of the material (Gokulkumar et al., 2020). High-density materials show greater resistance to the propagating sound wave as they have more fiber content per unit area, which results in an improvement in the transmission loss value of the material. This indicates that the sound waves traveled for a longer time in the sample thickness (Munde et al., 2019). In this study, the mass per unit area of all sample groups were the same (Co/He/PP-50-6 Co/He/PP-50-12 and Co/He/PP-67-6 Co/He/PP-67-12). Thus, density values of the samples were increased and became more compact with the decrease of the thickness (Table 2). However, at low frequencies increasing density insignificantly enhanced the sound insulation.

3.2.2. Effect of Fiber Type

When Figure 6 is examined, independent from both fabric thickness and weight fraction of matrix material, it was observed that the transmission loss values of fiber reinforced composite structures made of hemp fibers were higher compared to cotton one for all frequencies (63–6300 Hz). When the sound contacts with the textile structure, due to the resistance the amplitude of sound is decreased and the sound wave transforms to heat energy and gets dumped (Islam and Alam, 2018). As it is known, hemp fiber has a very rough and uneven surface than cotton (Bismarck et al., 2002) and due to giant fibril longitudinal splitting, it shows many cracks and cavities (Zhang et al., 2016) which might have increased the friction between the fiber surface and the sound, resulting in a decrease in the sound transmission of samples and insulate the noise better than the cotton one. Especially, the difference was more distinct at high-frequency bands. It is thought that the small difference in the low frequency range is due to the decrease in porosity after the hot pressing process. Moreover, the results showed that the transmission loss level depends upon the weight fraction of matrix material (polypropylene) such that the transmission loss level seemed to be slightly higher with an increasing weight fraction of matrix in the composite structure.

When the significance of the effect of the addition of hemp fiber on the sound transmission loss behavior compared to the others was examined with the Student's t test, it was seen that the *p* value was 0.004 and lower in all comparisons. This has statistically proven that the acoustic properties of hemp reinforced samples are better than the other samples.

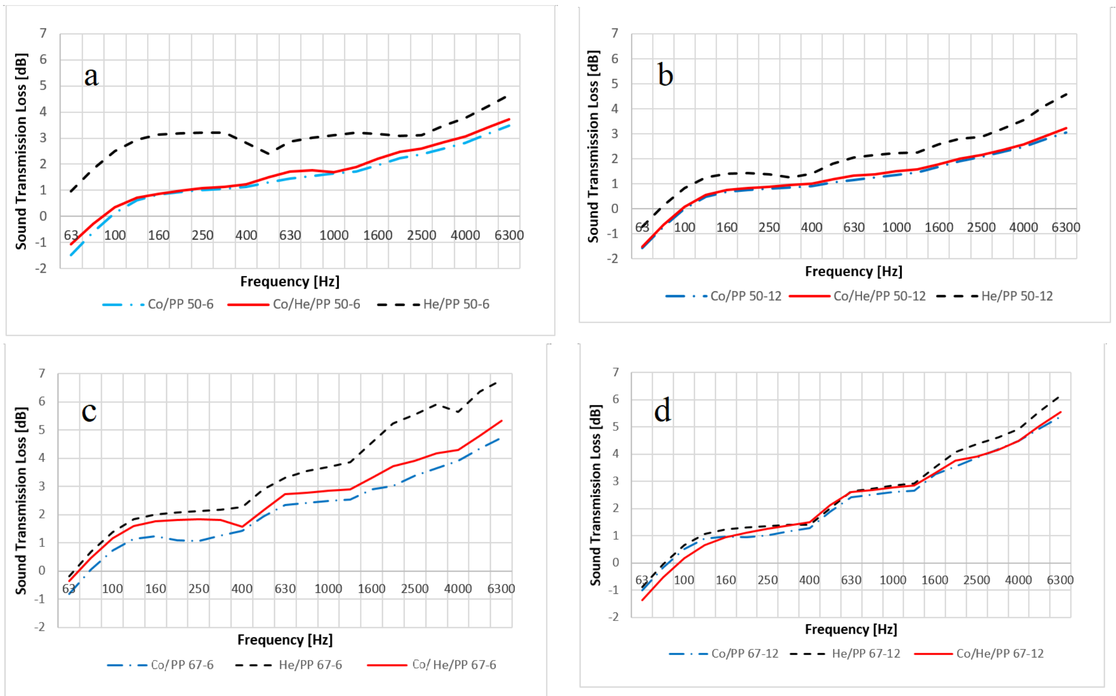


Figure 6:
Graphical comparison of sound transmission loss values by fiber type;

a. *Co/PP 50-6, Co/He/PP 50-6 and He/PP 50-6* ***b.*** *Co/PP 50-12, Co/He/PP 50-12 and He/PP 50-12* ***c.*** *Co/PP 67-6, He/PP 67-6 and He/PP 67-6* ***d.*** *Co/PP 67-12, He/PP 67-12 and Co/He/PP 67-12*

4. CONCLUSION

A total of twelve different composite materials were prepared and produced with the help of a hot press machine by using cotton and hemp fiber as reinforcement material and polypropylene fiber as matrix material. The results showed that reducing the thickness of the composite material does not have a significant effect on the sound absorption properties of the material as the density increases at the same time. Moreover, the composite structure made of hemp fiber presented a significantly higher degree of sound insulation than the cotton fiber reinforced and cotton/hemp fiber reinforced composites and can be utilized in noise isolation applications at high frequencies. The proposed natural fiber combination is easy to manufacture and recycle. Sustainable hemp fiber provided a great deal of potentiality to be used as sound insulation and absorber material, especially for noise control. In future studies, it is aimed to further improve the acoustic properties by applying surface modifications to natural fibers with different chemical treatments.

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CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper

AUTHOR CONTRIBUTION

Hande Sezgin: Determining the concept and design process of the research, data collection and analysis, interpretation of results, Sena Cimilli Duru: Determining the concept and design process of the research, data collection and analysis, interpretation of results, Cevza Candan: Research management, data analysis and interpretation of results.

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