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Sustainable textile based thermal insulation material development by lamination method: Adhesive influence

Laminasyon yöntemi ile sürdürülebilir tekstil tabanlı ısı yalıtım malzemesi geliştirilmesi: Yapıştırıcının etkisi

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Abstract

This study aims to address the environmental and health issues posed by conventional thermal insulation materials. It focuses on developing sustainable interior thermal insulation materials through the lamination of nonwoven fabrics made from waste fibers with chenille upholstery fabric using various adhesives (Polyether Sulfone (PES), polyamide (PA), Ethylene Vinyl Acetate (EVA), Thermoplastic Polyurethane (PU), and copolyester (CoPES)) in three forms (web, film, and powder). The research evaluates the impact of the form, raw material, and quantity of adhesive on the thermal conductivity, thickness, air permeability, stiffness, and bending rigidity of the resulting laminates. Moreover, the use of chenille upholstery as the surface layer not only enhances the visual appeal of these insulation materials but also brings an aesthetic perspective to technical textiles. Adhesives in web form exhibited notable thermal insulation due to their porous structure, while powder adhesives affected the fabric density and thermal conductivity. Notably, an increase in the amount of adhesive reduced air permeability and increased thermal conductivity. These findings emphasize the significant influence of adhesive selection (raw material, form, and quantity) on the thermal and mechanical properties of textile-based insulation materials. In conclusion, the study suggests the potential for developing sustainable and efficient thermal insulation solutions using waste fibers and tailored adhesive selection for building applications, while also enhancing the aesthetic value of such materials.

Highlights

- *Sustainable textile-based heat insulation from waste fibers,*
- *Different adhesive forms and amounts significantly impact the thermal and mechanical properties,*
- *Enhanced aesthetics with chenille upholstery fabric on the upper layer, adding value to interiors,*
- *Web adhesives enhanced thermal insulation; powder adhesives increased density and conductivity,*
- *Suitable for decorative and functional interior applications, especially wall coverings.*

Keywords: Sustainable insulation materials, Recycling, nonwovens, Adhesive effect, Technical textiles, Thermal conductivity.

Öz

Bu çalışma, geleneksel ısı yalıtım malzemelerinin yol açtığı çevre ve sağlık sorunlarını ele almayı amaçlamaktadır. Atık elyaflardan üretilen nonwoven kumaşların şönil döşemelik kumaş ile üç farklı formda (web, film ve toz) çeşitli yapıştırıcılar (Polieter Sülfon (PES), poliamid (PA), Etilen Vinil Asetat (EVA), Termoplastik Poliüretan (PU) ve kopolyester (CoPES)) kullanılarak laminasyonu yoluyla sürdürülebilir iç mekân ısı yalıtım malzemeleri geliştirmeye odaklanmaktadır. Araştırma, yapıştırıcı formunun, ham maddesinin ve miktarının, ortaya çıkan laminatların termal iletkenliği, kalınlığı, hava geçirgenliği, sertliği ve bükülme rijitliği üzerindeki etkisini değerlendirmektedir. Üstelik şönil kumaşın yüzey katmanı olarak kullanılması, bu yalıtım malzemelerinin görsel çekiciliğini artırmanın yanı sıra teknik tekstillere estetik bir bakış açısı da kazandırıyor. Ağ formundaki yapıştırıcılar gözenekli yapılarından dolayı kayda değer bir ısı yalıtımı sergilerken, toz yapıştırıcılar kumaş yoğunluğunu ve ısıl iletkenliğini etkilemiştir. Özellikle yapıştırıcı miktarındaki artış hava geçirgenliğini azaltmış ve termal iletkenliği arttırmıştır. Bu bulgular, yapıştırıcı seçiminin (hammaddesi, formu ve miktarı) tekstil bazlı yalıtım malzemelerinin termal ve mekanik özellikleri üzerindeki önemli etkisini vurgulamaktadır. Sonuç olarak çalışma, atık elyaflar ve bina uygulamaları için özel yapıştırıcı seçimi kullanılarak sürdürülebilir ve verimli ısı yalıtım çözümleri geliştirmenin yanı sıra bu tür malzemelerin estetik değerini de artırma potansiyelini ortaya koymaktadır.

Öne Çıkanlar

- *Atık liflerden sürdürülebilir tekstil tabanlı ısı yalıtımı,*
- *Farklı yapıştırıcı form ve miktarları yalıtım malzemelerinin özellikleri üzerinde önemli etkilere sahip,*
- *Üst katmandaki şönil döşemelik kumaş ile artırılmış estetik, iç mekânlarda artan değer,*
- *Ağ formundaki yapıştırıcılar termal yalıtımı artırdı; toz yapıştırıcılar yoğunluğu ve iletkenliği artırdı,*
- *Dekoratif ve fonksiyonel iç mekân uygulamaları için uygun, özellikle duvar kaplamaları.*

Anahtar kelimeler: Sürdürülebilir yalıtım malzemeleri, Geridönüşüm, dokusuz yüzeyler, Yapıştırıcı etkisi, Teknik tekstil, Isıl iletkenlik.

1 Introduction

The focus on achieving energy efficiency, responsible resource utilization, and waste material reuse is becoming increasingly prominent in various fields and sectors. Heating and cooling systems in buildings, transportation, and industrial suppliances are major contributors to global energy consumption, resulting in increased CO_2 emissions [1],[2]. Buildings are estimated to account for approximately 40% of the world's total energy consumption [3]. The implementation of thermal insulation

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systems in buildings has proven to be an effective strategy for reducing energy consumption. Studies have indicated that efficient thermal insulation has the potential to reduce energy consumption by more than 60% in residential buildings [4].

There are various types of thermal insulation materials, classified as inorganic and organic. Commonly used building insulation materials, such as glass fiber, mineral wool, and plastics, may pose risks to human health and the environment in both the pre-and post-consumption phases [4],[5]. Thermal insulation materials are expected to satisfy specific requirements such as ease of application, high durability, maintenance of insulation properties, satisfactory mechanical strength, flame retardancy, and compliance with health standards [5]. Unlike traditionally knitted or woven fabrics, nonwoven fabrics constitute a category of textile surfaces produced by combining layers of fibers in a disconnected or irregular manner. They may offer advantages over conventional thermal insulation materials owing to their unique characteristics, such as porous structure, breathability, low density, and flexibility [6]. Parameters such as fiber linear density, cross-section, fiber diameter distribution, fiber orientation distribution, areal density, bulk density, thickness, porosity, void size, pore size distribution, and air permeability also play crucial roles in determining the thermal insulating capacity of a fabric [6]-[10]. The insulation characteristics of nonwoven fabrics can be tailored by manipulating these parameters. One significant advantage of these fabrics is their ability to be produced from waste fibers, facilitating the adoption of a sustainable approach in the textile industry.

In recent years, the textile and apparel sector has witnessed a substantial increase in its manufacturing capacity. This growth can be attributed to various factors such as population growth, the rise of low-cost mass production of apparel, the expansion of the fashion segment, and shifts in consumer trends [11], [12]. Consequently, this surge in production has led to a significant amount of pre- and post-consumer waste, which contradicts sustainability and circular economy principles. This situation becomes even more concerning when considering the relatively low recycling rate (15%) in the textile and apparel industry. Therefore, recycling and upcycling processes are crucial for minimizing waste and exploring new avenues for utilizing the waste generated during the manufacturing and disposal phases [4],[13],[14]. In light of these considerations, nonwoven fabrics have emerged as a promising solution to address sustainability concerns [15].

Several researchers have studied the thermal insulation characteristics of nonwoven materials produced from recycled fibers. Karimi et al. (2022) found that an increment in fiber orientation in the through-plane (TP) direction negatively impacted the thermal insulation characteristic, and thicker fibers caused higher thermal conductivity for nonwoven fabrics [6]. At a specific porosity, increasing the diameter of fibers leads to a decrease in the quantity of fiber-to-fiber connections, which causes a reduction in the occurrence of bottlenecks along the heat flow pathways, thereby raising heat transmission by conduction. An increase in the TP fiber orientation results in an increase in thermal conductivity, and this increment is more prominent at lower porosities. This phenomenon is explained as follows: an increment in TP fiber orientation enhances the possibility of heat flowing along the fiber length as opposed to flowing in the direction perpendicular to the fiber length, where the fiber-to-fiber connections are significantly narrower, restricting the transfer of heat [6]. Mahmoud (2015) investigated the effect of fiber type, fabric weight, number of beats, and puncture depths on the thermal insulation characteristic of needle-punched nonwoven polypropylene/waste polyester fibers and polypropylene/polyester/polyester hollow waste fibers with mixture ratios of 50/50 and 15/50/35, respectively. They concluded that a higher thickness results in good thermal insulation. In addition, it was observed that the thermal insulation of the nonwoven fabrics increased with increasing fabric weight, number of beats/min, and puncture depth [15]. Muthu Kumar et al. (2020) examined thermal insulation characteristics of needle-punched nonwovens from alkali-treated 100% recycled polyethylene terephthalate (r-PET) fibers and comber noil blending. It was concluded that nonwovens from alkali-treated r-PET fibers have higher insulation values than nonwovens manufactured from untreated r-PET fibers. The incorporation of a comber noil with alkali-treated r-PET fibers had an unfavorable effect on the insulating properties of the nonwovens [16]. Cai et al. (2021) investigated the thermal resistance characteristics of needle-punched nonwoven fabrics manufactured from waste and virgin wool fibers with a mixture ratio of 1:1. The thermal resistance increased with an increase in the areal density of the wool nonwovens, which was ascribed to the crimp structure of the wool fiber. The nonwoven fabrics with an areal density of 790 g/m^2 exhibited greater thermal resistance with a value of 0.63 °C m^2/W compared to other wool-nonwoven and conventional insulating materials, including polyester and cotton/polyester [17]. El Wazna et al. (2017) analyzed thermal conductivity, thermal resistance, and air permeability characteristics of four different needle-punched nonwovens from the acrylic and wool textile waste of the fabrics. The thermal conductivity of the fabrics was found to be in the range of 0.0339-0.0355 W/mK [18]. Patnaik et al. (2015) measured thermal conduction coefficients of needle-punched nonwoven fabrics from 100% waste wool, 100% r-PET fibers, and waste wool/r-PET fibers in 50/50 proportions. The average thermal conduction coefficients of the fabrics were in the range of 0.032-0.035 W/mK [19] . Rubino et al. (2021) designed 100% recycled wool nonwoven fabrics that were thermally bonded with PET/PET bi-component fibers. The thermal conduction coefficients of the fabrics were in the range of 0.044-0.057 W/mK [20]. Ghermezgoli et al. (2021) examined the thermal insulation behavior of wool fabrics having waste wool fibers in the weft direction. The thermal conduction coefficients were in the range of 0.0322-0.0386 W/mK [21]. Muthu Kumar et al. (2022) fabricated nonwovens using comber noil, silk cocoon waste, polyester/cotton flat strip waste, and comber noil with silk cocoon waste in 50/50 proportions through the needle punching method. It was concluded that the fabric from 50/50 comber noil/silk cocoon waste displayed good thermal insulation behavior with a thermal resistance of 0.212 m^{2}K/W [22]. Sakthivel et al. (2020) investigated the thermal conductivity characteristics of chemically bonded two-layer mats from cotton, PET, and recycled cotton/PET fiber in 50/50 proportions with colored and white groups for each sample. The lowest thermal conduction coefficient was found for the white cotton and colored cotton fabrics, with values of 0.123 and 0.126 W/mK, respectively [23]. Bogale et al. (2023) examined the thermal conductivity characteristic of chemically bonded nonwoven fabrics from r-cotton/r-PET with different proportions. Nonwovens showed the values in the range of 0.127-0.166 W/mK [24].

Most studies have focused on the thermal insulation behavior of nonwoven textiles made from waste fibers, as reported in the literature. Nonwovens were used in these investigations without any additional decorative components. In the case of potential use in interior design, such as wall coverings, nonwoven fabrics require an accompanying fabric layer for both an aesthetic appearance [21] and specific requirements such as durability, structural rigidity, optimal flexibility, and mechanical stability. Therefore, in this study, we laminated nonwovens with upholstery fabrics and produced composite fabrics that can potentially be used in interior design, as they are both aesthetic and strong and this study may contribute to the literature from these aspects.

This study aims not only to improve thermal insulation efficiency, but also to contribute to sustainable material development by using 100% recycled fibers and an eco-friendly lamination process. In this study, nonwoven fabrics from waste PET fibers were laminated to chenille acrylic/polyester upholstery fabric using seven different types of hot-melt adhesives, available in the form of webs, films, and powders. Hot-melt lamination is intrinsically eco-friendly: it uses no solvents or water and generates virtually zero volatile organic compounds during bonding. Utilizing waste fibers to manufacture nonwoven fabrics for thermal insulation not only reduces the environmental impact of textile waste but also promotes a circular economy approach within the industry. By repurposing waste materials, this study contributes to minimizing the carbon footprint and resource depletion associated with the production of conventional insulation materials. The thermal conduction coefficients of the designed fabrics were investigated to evaluate their thermal insulation behavior of the laminated fabrics. The study also questions the relationship between the adhesive type and the thermal conductivity characteristics of fabrics. Accordingly, the research question of this study is how different forms of adhesives, including webs, films and powders, affect the thermal conductivity coefficient of laminated fabrics. Additionally, the structural properties of the fabrics, including the thickness, air permeability, stiffness, and bending rigidity, were examined. Researching thermal conductivity in textile-based materials is a limited field in the literature. The novelty of this work is that it offers a unique fabric combination by laminating woven chenille fabrics and nonwoven fabrics with adhesives in different forms. It is anticipated that experimental and statistical examination of the effects of different forms of adhesives on thermal and mechanical properties will fill an important knowledge gap in the literature.

2 Material method

2.1 Material

In this study, two types of fabrics (chenille upholstery and needle punched nonwovens from recycled fibers) and seven hot melt adhesives were used. Chenille upholstery fabrics were supplied from Tosunoglu Tekstil, Denizli where nonwovens from Karateke, Uşak. In this study, seven hot-melt adhesives were selected from Schaetti's readily available stock, in five different polymers-polyester (PES), polyamide (PA), ethylene-vinyl acetate (EVA), thermoplastic polyurethane (TPU) and co-polyester-ether (Co-PES)-and three physical forms (web, film and powder). Detailed formulations could not be disclosed owing to commercial confidentiality. This diversity was chosen to investigate the influence of polymer chemistry and adhesive form on the thermal insulation performance of the laminates. Hot-melt adhesives in the forms of web, powder, and film were gifted by Schaetti Group, Switzerland. The technical properties of the fabrics used in this study are presented in Table 1.

Table 1. The technical properties of the laminated fabrics.

	Fabrics		
	Face fabric (upholstery)		Back fabric (nonwoven)
Air permeability (l/m^2.s)	276		427
Thickness (mm)	1.07		3.55
Areal density (g/m^2)	445		1000
Weft density (wefts/cm)	15		
Warp density (warps/cm)	66		
Yarn count	Weft yarn (Nm)	5	
	Warp yarn (Denier)	150	
Fiber/yarn type	Weft	Acrylic chenille	Recycled PET
	Warp	Polyester	

Chenille upholstery fabric was selected as the face fabric (the upper layer), whereas nonwoven fabric, which was manufactured from recycled polyester, was selected as the back fabric. The use of recycled polyester fibers in the nonwoven back fabric aligns with the principles of sustainability and environmental responsibility. By incorporating waste materials into the laminated fabrics, this study demonstrates the potential for developing eco-friendly thermal insulation solutions that minimize resource consumption and waste generation.

The face and back fabrics were laminated using adhesives in different forms: web, film, or powder. Seven different adhesives were used in this study. In industry, webs, films, and powders are usually defined in terms of areal weight, thickness, and particle size, respectively. The web adhesives used in this study were selected in two different areal weights, while films in two thicknesses, and powder adhesives in three different particle sizes and raw materials. The technical properties of the adhesives, including the raw material type, areal weight, thickness, and particle size, are given in Table 2, and the adhesive types are shown in Figure 1.

2.2 Lamination method

The face and back fabrics were cut into 15*15 cm squares before lamination process. Then the cut fabrics were laminated using a hot press under constant heat and pressure for all the samples. First, optimization studies were performed for different holt melt adhesives to determine the amount of adhesive needed and the process parameters. The pressing times differed, and the pressure and heat were kept the same for all laminations. After the optimization studies, the chenille and nonwoven fabrics were laminated according to the optimized durations, as listed in Table 3. For the powder adhesives, three different amounts (1, 2, and 3 g) per one 15*15 cm^2 lamination process. During the lamination process, the powders were poured homogeneously on the back surface of the chenille fabric. Subsequently, the hot plate of the press was in contact with the nonwoven fabric surface. Laminated fabrics are shown in Figure 2.

Table 2. The properties of the adhesives.

Adhesive Code	Adhesive labels (Company; Schaetti)	Form	Raw Material Type	Explanation
1	PES 300W 16/150	Web	Polyether sulfone (PES)	16 g/m^2
2	PA 200W.20 155	Web	Polyamide (PA)	20 g/m^2
3	EVA 100F-14 150	Film	Ethylene Vinyl Acetate (EVA)	Thickness: 14 microns
4	EVA 100F 20/150	Film	Ethylene Vinyl Acetate (EVA)	Thickness: 20 microns
5	EVA SF 2050 100-500	Powder	Ethylene Vinyl Acetate (EVA)	Particle Size: 100-500 microns
6	PU SF 6220 100-500	Powder	Thermoplastic Polyurethane (PU (TPU))	Particle Size: 100-500 microns
7	CoPES SF376 200-300	Powder	Copolyester (CoPES)	Particle Size: 200-300 microns

(a) (b) (c)

Figure 1. Adhesive forms. (a): Web. (b): Film. (c): Powder.

Table 3. The process parameters.

	Laminated Fabric Code	Adhesive Label	Process Duration (s)	Explanation
1	1	PES 300W 16/150	60	1 ply web
2	2	PA 200W.20 155	150	1 ply web
3	3	EVA 100F-14 150	60	1 ply film
4	4	EVA 100F.20/150	60	1 ply film
5	5A	EVA SF 2050 100-500	90	1 g powder
6	5B	EVA SF 2050 100-500	90	2 g powder
7	5C	EVA SF 2050 100-500	90	3 g powder
8	6A	PU SF 6220 100-500	120	1 g powder
9	6B	PU SF 6220 100-500	120	2 g powder
10	6C	PU SF 6220 100-500	120	3 g powder
11	7A	CoPES SF376 200-300	90	1 g powder
12	7B	CoPES SF376 200-300	90	2 g powder
13	7C	CoPES SF376 200-300	90	3 g powder

(a) (b)

Figure 2. The laminated fabrics. (a): Nonwoven surface of the fabric. (b): Upholstery surface of the fabric.

2.3 Test method

2.3.1 Thickness

To evaluate the effect of adhesive type on the thickness of the laminated fabrics, thickness measurements were performed using a digital thickness gauge. The measurements were repeated five times for each of the thirteen laminated fabrics. In addition, the effect of thickness on thermal conduction was investigated.

2.3.2 Thermal Conductivity

To evaluate thermal insulation, the thermal conduction coefficients of the fabrics were obtained using a quick thermal conductivity meter (Kyoto Electronics QTM-500, Figure 3). This device uses the hot wire method to measure the thermal conductivity by analyzing the temperature vs. log(time) curve, which is based on the temperature rise of a heater wire in contact with the sample. The measurements were repeated five times for each of the thirteen laminated fabrics.

Figure 3. Position of laminated fabrics under the test equipment, Kyoto Electronics QTM-500.

2.4 Thermal resistance

To evaluate the thermal resistance of the laminated fabrics, equation 1 was used [8].

$$R_{th} = \frac{t}{\lambda} \qquad (1)$$

Where R_{th} (m^2K/W) is the thermal resistance, t (m) is the fabric thickness, and $\lambda\,(W/mK)$ is the thermal conduction coefficient.

2.5 Air permeability

The air permeability refers to the airflow rate through a porous material. The mathematical representation is as follows:

$$k = \frac{Q}{S.t} \qquad (2)$$

Where k is the flow rate (l/m^2s) , Q is the volume of air passing through the sample [l], t is time [s], and S is the cross-sectional area [m²].

To reveal the effect of the adhesive type on the air permeability of the laminated fabrics, air permeability test was performed using a Karl Schroder KG Air Permeability Tester according to the EN ISO 9237 standard with a head area of 50 cm² and a pressure of 200 Pa. The measurement was repeated ten times for each of the thirteen laminated fabrics.

2.6 Stiffness and bending rigidity

To evaluate the effect of the adhesive type on the stiffness and bending rigidity of the laminated fabrics, Prowhite stiffness tester and Shirley stiffness tester were utilized in accordance with the ASTM D4032 and TS 1409 standards, respectively.

2.7 Statistical analysis

All experiments were repeated five times to ensure reliability and reproducibility. The results are presented as the means. The effects of the adhesive amount and raw material on thermal conductivity were evaluated using one-way analysis of variance (ANOVA). Post-hoc comparisons were conducted with Tukey's Honestly Significant Difference (HSD) test using SPSS 22. Statistical significance was set at $p < 0.05$. The relationship between the air permeability and thermal conductivity of the samples was assessed using correlation analysis performed in Microsoft Excel.

3 Results and discussıon

3.1 Thicknesses of the laminated fabrics

The thickness values of the laminated fabrics are shown in Figure 4. When the effect of the adhesive form on the thickness of the fabrics was evaluated, the 7C-coded fabric, which utilized 3 grams of CoPES powder form adhesive, had the highest thickness with a value of 4.9042 mm. When the adhesive groups are compared within themselves, the thickness of the 2 coded fabric, which is PA web adhesive incorporated, is higher than that of the PES web adhesive incorporated one. Among the powder adhesives, the fabrics that were either 3-gram PU or 3-gram CoPES adhesive utilized had a greater thickness than the fabrics that were 1- and 2-gram powder adhesive utilized alternatives. In both film-form adhesive and EVA powder-utilized fabrics, as the thickness of the film adhesive or the amount of powder adhesive increased, an inconsistency case was observed. This contradiction in the thickness of the fabrics can be attributed to the nonhomogeneous orientation of the nonwoven fabrics.

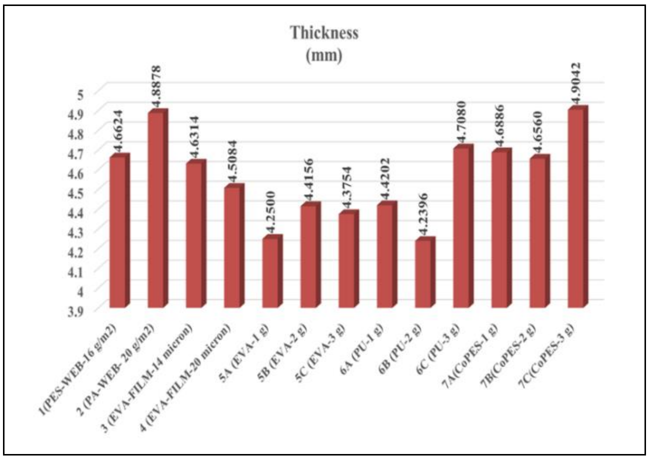

Figure 4. The thickness values of the laminated fabrics.

3.2 Thermal conductivity and thermal resistance values of the laminated fabrics

The thermal conduction coefficient, also known as the thermal conductivity, represents the capacity of a material to conduct heat. As the thermal conduction coefficient of a material decreases, the material has a higher insulating capacity. Conversely, as the thermal conduction coefficient of the material increases, the material becomes a better conductor. To be classified as an insulating material within a building element, the thermal conduction coefficient of the material must be below 0.065 W/mK [25]. On the other hand, thermal resistance refers to the resistance of a fabric to heat conduction. A fabric with a high heat insulation capacity has a high thermal resistance value. The thermal conduction coefficients and thermal resistance values of the laminated fabrics used in this study are shown in Figure 5.

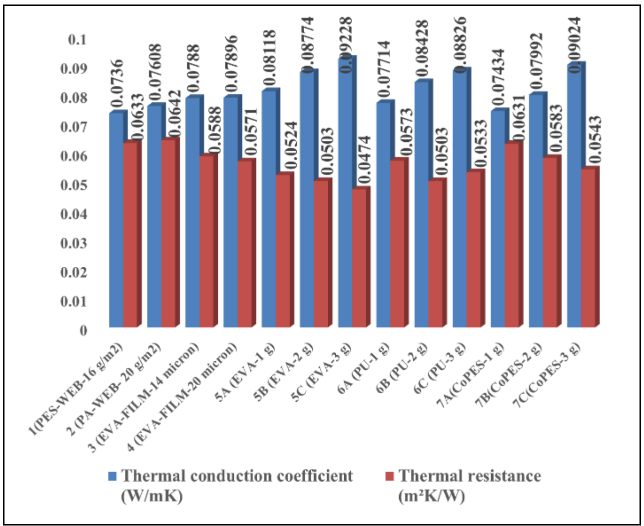

Figure 5. The thermal conduction coefficients and thermal resistance of the laminated fabrics.

As can be seen in the Figure 5, the thermal conduction coefficients of the laminated fabrics exceeded the threshold of 0.065 W/m·K. This can be attributed lamination may cause compaction of fabric layers and hence reduced air entrapment. Additionally, increased fabric density without micro-air gaps may exaggerate thermal transfer capability of the fabrics.

As expected, the inverse proportional relationship between the thermal conductivity coefficient and thermal resistance is observed among the sample groups. The lowest thermal conductivity value, found in sample coded 1, also corresponds to a significantly high thermal resistance (0.0633 m^2K/W). Notably, as we move from sample 5A to sample 5C, there is a substantial decrease in thermal resistance alongside an increase in conductivity. This indicates that the increase in adhesive quantity, which enhances thermal conductivity, reduces the heat retention capacity of the fabric. Similarly, among samples coded B, a decrease in thermal resistance is noted with the increase in thermal conductivity value. However, sample coded 6C deviated from this trend and exhibited higher thermal resistance (0.0533 m^2K/W) than anticipated, which can be attributed to the inhomogeneous fiber distribution in the fabric structure. A similar trend was observed in the samples coded 7. Thermal resistance decreased as thermal conductivity increased from sample 7A to sample 7c. Sample 7A has one of the highest thermal resistance values (0.0631 m^2K/W). When evaluating all samples in terms of thermal conductivity and thermal resistance values, samples coded 1 and 7A demonstrated lower thermal conductivity coefficients and relatively higher thermal resistances, making them suitable for consideration as potential thermal insulation fabrics.

3.3 Effect of adhesive form on thermal conductivities

In this study, three different forms of adhesives were used: web (1 and 2), film (3 and 4), and powder (5, 6, and 7). As can be seen in the figure, the lowest conductivity was displayed as 0.0736 W/mK by 1 coded fabric in which web form adhesive was used. When the effect of adhesive forms on the thermal conduction coefficient value was examined, in general, it was seen that the fabrics containing web-form adhesives showed a better performance than the others except for 7A coded fabric. This may be attributed to the fact that web-form adhesives have the potential to form a network of fibers and a more porous structure when incorporated. Such an entangled structure may contain fewer contact points with the fabric than fabrics containing powder adhesives with a solid nature or film adhesives with a continuous structure. This characteristic of web-form adhesives may have the ability to trap air pockets, which leads to trapped air acting as a barrier that restricts the heat transfer.

3.4 Effect of adhesive raw material on thermal conductivities

The adhesive materials consisted of PES, PA, EVA, CoPES, and PU. However, the exact proportions of these components are unknown. Among these, the EVA, PU, and CoPES adhesives are in powder form with particle sizes of 100-500, 100-500, and 200-300 microns, respectively. Because the comparison focuses on raw materials, it is appropriate to compare only those in the powder form. EVA and PU had the same particle size range (100-500 microns). When comparing samples with equal adhesive amounts (5A with 6A, 5B with 6B, and 5C with 6C), the thermal conductivity coefficients of all 6-coded samples are significantly lower than the 5-coded ones ($p=0.01$, $p=0.01$, and $p=0.022$). This suggests that PU has a lower thermal conductivity coefficient than EVA. Additionally, the code 7 samples had lower thermal conductivity coefficients than those coded 5 and 6. Specifically, when comparing 5A, 6A, and 7A; 7A exhibits the lowest thermal conductivity coefficient significantly ($p<0.01$); likewise, 7B is the lowest when comparing 5B, 6B, and 7B ($p<0.01$). However, although the average thermal conductivity coefficient of 7C was the lowest when comparing 5C, 6C, and 7C, the difference was not statistically significant ($p=0.065$). Ignoring the particle size effect, the thermal conductivity coefficient of the CoPES adhesive was lower than those of the other two adhesives. Therefore, for better thermal insulation, CoPES, PU, and finally EVA should be preferred in order.

The thermal conductivity coefficients change depending on the raw material of the adhesive and the components that enter it. PU, EVA, CoPES, PA, and PES had varying thermal conductivity coefficients. Therefore, to maximize the thermal insulation, the composition should be taken into consideration.

3.4.1 Effect of adhesive amounts on thermal conductivities

When the samples coded 1 and 2 were compared, the thermal conductivity coefficients were 0.07360 W/mK and 0.07608 W/mK, respectively. The difference between these two samples is the raw material and the thickness of the web adhesive. Therefore, it is not possible to say that if this difference is due to the amount of adhesive or the raw material type, both parameters may influence the thermal conductivity coefficient. However, for the other samples, it can be said that as the amount of adhesive increased, the thermal conductivity coefficient also increased.

To further analyze the effect of only the amount of adhesive, a t-test was performed between 3 and 4; a one-way ANOVA was conducted between 5A, 5B, and 5C, a one-way ANOVA was performed between 6A, 6B, and 6C, and a one-way ANOVA was conducted between 7A, 7B, and 7C, with all other parameters remaining constant.

When 3 and 4 were compared, there was no significant difference ($p = 0.59$). This is due to the fact that the thicknesses of the film adhesives are very similar. If the effect of the amount of powder adhesive for samples 5A, 5B, and 5C, that is the adhesive is EVA powder is evaluated, it is found that the fabric's thermal conductivity increases in proportion to the amount of adhesive, negatively affecting the fabric's insulating properties. However, in our sample, this effect was not statistically significant ($p= 0.341$).

In the case of 6A, 6B and 6C, where powder PU adhesives were used, it was seen that the thermal conductivity coefficient increased as the amount of adhesive used increased. This increase was statistically significant ($p<0.01$). The same was true for samples 7A, 7B and 7C where CoPES adhesives were used ($p<0.01$).

This could be the outcome of the fabric's density increasing as the amount of glue increased. Denser fabrics are known to exhibit a trend toward higher thermal conductivity and worse heat insulation, which facilitate heat transfer. To summarize, the amount of powder adhesive affects the fabric thermal conductivity, affecting the insulation. Increased powder adhesive amount leads to higher fabric density, affecting heat transfer. Even though laminated fabrics have higher thermal conduction coefficients than nonwovens made from waste fibers and conventional insulating materials [26], these laminated textile-based materials are still promising because they can be used in interior design.

According to Abdel-Rehim et al. (2006) higher fabric thickness provides good insulation. This situation may result from the occurrence of smaller pores within the fabrics as the thickness increases [27] . However, to compare this result with our study, it is necessary to know the density of the fabrics because the density of the fabric is a critical factor in determining the thermal insulation characteristics [28].

Among other fabrics, there is no clear relationship between the thickness and heat conduction coefficient. This can be attributed nonhomogeneous orientation of the nonwoven fabrics.

3.5 Air permeability values of the laminated fabrics

Air permeability values of the laminated fabrics are given in Figure 6. The highest air permeability value was found for 7A coded fabric with value of 223.5 $l/m^2.s$, while the lowest value was found for 7C coded fabric with value of 133.5 $l/m^2.s$. This means that 7C fabric has the ability of air trapping in its structure. Indeed, the fabric having the highest permability value which contains 1 g CoPES powder adhesive has quite low thermal conduction coefficient.

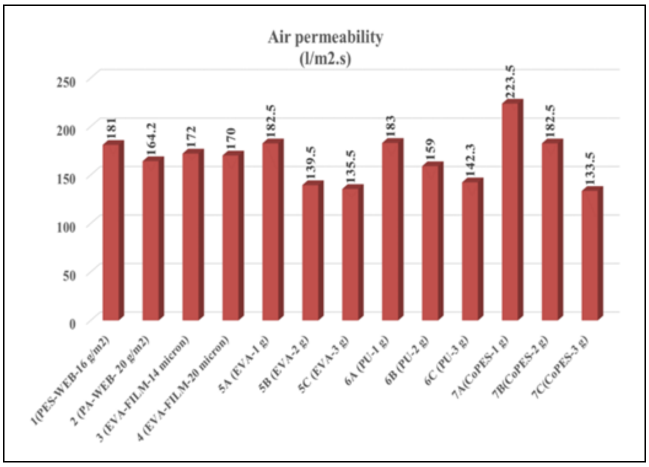

Figure 6. Air permeability of the laminated fabrics.

On the other hand, the fabric having the lowest permeability value which contains 3 g CoPES powder adhesive has quite high thermal conduction coefficient. When web form adhesives evaluated, 2 coded fabric had lower permeability value than 1 coded fabric whereas thermal conduction coefficients of 2 coded fabric is higher than that of 1 coded fabric. In case of film form adhesives, 3 and 4 coded fabrics displayed almost similar permeability values similar to their thermal conduction coefficients. Interestingly enough, for all types of powder adhesives, as amount of powder increases, the air permeability decreases while the thermal conduction coefficient increases. It can be concluded and seen from Figure 6 that an increase in adhesive quantity is accompanied by a reduction in air permeability. There is a negative correlation between adhesive amount and air permeability.

From Figures 5 and 6, as the amount of adhesive increases, the thermal conductivity coefficient increases and the air permeability decreases. There is a moderate negative correlation between thermal conductivity coefficient and air permeability ($r=-0.85$). In this case the coefficient of determination (r^2) is 0.7225 which means that only 72% of the values in thermal conductivity coefficient values can be explained by the air permeability values. This result is not surprising as the relationship between air permeability and thermal conductivity of fabrics is complex and influenced by multiple factors such as fabric structure, material composition, thickness, porosity, weight, and treatment processes [29].

Research has shown that air permeability significantly influence the effective thermal conductivity of materials like nonwoven samples [30]. Also in the literature, the correlation between air permeability and heat conduction coefficient has been extensively studied in various materials and compatible with our study, Banks-lee et al. (2004) stated that higher air permeability generally leads to lower thermal conductivity, indicating better thermal insulation properties [30].

However, unlike our findings, El Wazna et al. (2017) reported that thermal conductivity decreases with decreasing air permeability, meaning a positive correlation [18]. On the other hand, similar to our result, Muthu Kumar et al. (2022) reported that as thermal resistance increases, air permeability also increases [22]. It should also be mentioned that flow rate through the fabric is strongly influenced by width, shape, and tortuosity of the conducting channel besides fabric porosity [18].

3.6 Stiffness and bending rigidities of the laminated fabrics

The stiffness and bending rigidity test results of the laminated fabrics are displayed in Figure 7 and Figure 8, respectively. As seen in Figures 7 and 8, the fabric containing film form adhesives displayed the lowest value for both stiffness and bending rigidity, while the fabric containing powder-form adhesives displayed the highest value for both stiffness and bending rigidity. The stiffness attitude of a fabric denotes the attribution of resistance to deformation under an applied load like bending or compressing. As depicted in Figure 7, the 4 coded sample (film adhesive was used) has 13287 cN, while the 7C sample (powder adhesive) has 36667 cN stiffness values. Namely, among all fabrics, 7C fabric needs more force to expose a significant shape change. However, it is a fact that the flexibility of fabrics decreases as they get stiffer. Such a characteristic can bring about advantageous outcomes in certain applications.

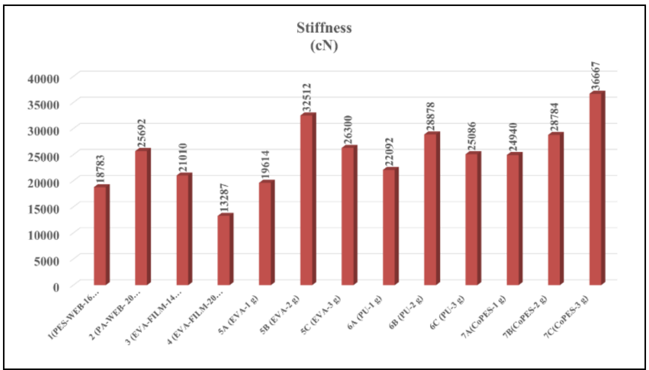

Figure 7. Stiffness values of the laminated fabrics.

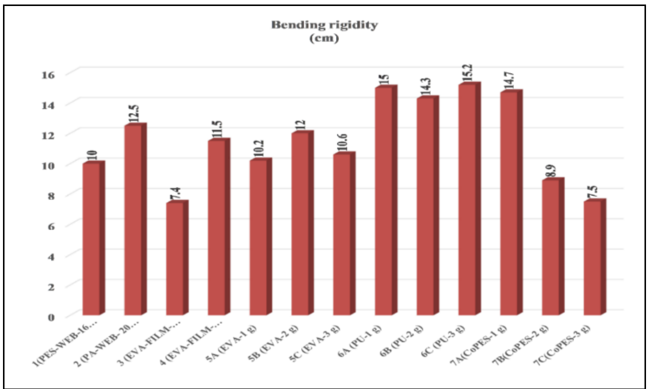

Figure 8. Bending rigidity values of the laminated fabrics.

Bending rigidity specifically quantifies resistance to bending when applied to the bending moment. As shown in Figure 8, the 3 coded sample (film adhesive was used) has 7.4 cm, while the 6C coded sample (powder adhesive was used) has 15.2 cm bending rigidity values. This means that 6C fabric has a higher tendency to maintain an upright position in the absence of external support. On the other hand, 3 coded fabric can be interpreted as having a greater tendency for drapability. Like stiffness, bending rigidity or drapability are desired attitudes in specific applications. Increased stiffness and bending rigidity may be desired in applications where support is needed like furniture, automotive, and outdoor upholstery, floor installations, architectural textiles, and the construction of tents, upholstery, and banners.

When the effect of adhesive raw material is examined in web forms, the fabric in which PA adhesive was incorporated has a higher value in both stiffness and bending rigidity. In terms of film thickness and stiffness value, in cases of increased thickness, stiffness is decreased. Conversely, in cases of increased thickness, bending rigidity increased. If the effect of adhesive form on stiffness is examined, powder adhesive-utilized fabrics showed the highest stiffness. Also, the highest bending rigidity values were seen in the fabrics that incorporated 1- and 3-gram PU adhesives in powder form, with values of 15 and 15.2 cm, respectively. The lowest stiffness and bending rigidity values were displayed in the samples in which film adhesives were incorporated, with values of 13287 cN and 7.4 cm. This may be attributed to the fact that adhesives in web or film form often have a thinner and more flexible structure similar to textile fabric construction. Film and web adhesives spread more homogeneously on the surface, they preserve the flexibility of the fabric and cause the stiffness to remain at lower levels. In contrast, powder form has an inherently stiff and rigid structure. The fact that the stiffness and rigidity of powder adhesive-embedded fabrics are higher than those of web or film adhesive-embedded fabrics can be explained as follows: After the lamination process, the powder adhesive settles more densely between the fibers and creates a tighter bond structure, reducing the flexibility of the fabric and giving it a stiffer structure.

4 Conclusion

In this study, we investigated the potential for innovative, environmentally friendly, and aesthetically pleasing fabrics to replace the commonly used synthetic thermal insulating materials in interior design, particularly for wall coverings. In order to achieve this, three distinct types of adhesives were used to laminate two distinct fabrics, one of which was made from waste fibers. We looked into how the amount, form, and raw materials of the adhesive affected the thermal conductivities and specific physical characteristics of the textile-based insulation materials. In addition to their technical performance, the developed laminated fabrics support sustainability goals through the use of waste-based nonwoven substrates and solvent-free hot-melt adhesives, enabling low-impact production and resource efficiency. The findings suggest that the choice of adhesive material, form, and amount significantly affects the performance of these materials. Web-form adhesives, particularly PU and CoPES, exhibited better thermal insulation properties due to their porous structure and ability to trap air, which acts as an effective barrier to heat transfer. Powder adhesives, on the other hand, influenced fabric density and thermal conductivity, with an increase in adhesive quantity leading to reduced air permeability and increased thermal conductivity. We also examined the relationship between air permeability and thermal conductivity, revealing a moderate negative correlation (r=-0.85). However, this relationship is complex and influenced by multiple factors, such as fabric structure, material composition, thickness, porosity, weight, and treatment processes. In terms of physical properties, fabrics with powder adhesives exhibited the highest stiffness and bending rigidity values, while those with film adhesives had the lowest. This suggests that the choice of adhesive can be tailored to specific applications, where enhanced stiffness and rigidity may be desirable, such as in furniture, automotive, and outdoor upholstery, or where flexibility and drapability are preferred, such as in clothing and interior textiles. The scope of this study was limited to specific types of fabrics and adhesives. Future studies could explore a wider range of waste nonwovens, adhesives, and lamination techniques to further optimize the performance of textile-based insulation materials. Investigating the delamination strength for further studies would also be crucial for the durability of the laminated fabrics during the end use. Additionally, conducting life cycle assessments to evaluate the environmental impact and sustainability of these materials would provide a more comprehensive understanding of their viability as alternatives to conventional insulation solutions. As a result, it is highlighted that there is a potential of textile-based insulation materials as sustainable alternatives to conventional insulation solutions. By carefully selecting adhesives and optimizing their form and quantity, it is possible to design textile-based insulation materials with enhanced thermal and physical properties. Although the laminated fabrics produced in the study, cannot outperform the conventional counterparts, it is worth to improve thermal insulation characteristic of these materials in future. The findings of this study have significant implications for the development of sustainable thermal insulation materials. The incorporation of recycled materials reduces the environmental burden associated with the production of conventional insulation materials, contributing to the advancement of sustainable building practices. In future studies, these fabrics may become much more functional by the application of some coatings like flame retardancy, water repellence etc.

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6 Author contribution statements

In the scope of this study, the Cansu Var contributed to the literature review, investigation, visualization, data curation, and writing original draft; Ayşe Özkal contributed to the conceptualization, methodology, supervision, writing-review & editing.

7 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared".

"There is no conflict of interest with any person / institution in the article prepared".

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