

# **The Multifunctional Sandwich-structured Textile Materials**

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## **Doctoral studies**

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1. SGS-2021-6025 Effect of geometry and concentration of fly ash and laponite on impact and dynamic mechanical properties of filled epoxy matrix, researcher, 2021.
2. SGS-2022-6012 Non-woven fabrics with copper coating processed with parylene encapsulation technology, researcher, 2022.
3. Hybrid Materials for Hierarchical Structures (HyHi) project (Reg. No. CZ.02.1.01/0.0/0.0/16\_019/0000843), researcher, 2021-2022.
4. SGS-2023-6375 Influence of different matrix types on selected properties of carbon fiber reinforced composites, team leader, 2023.
5. SGS-2024-6422 Mechanical decomposition of polyester textiles, researcher, 2024.
6. SGS-2025-6544, Epoxy composites filled with mechanically decomposed waste textiles, researcher, 2025.
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EMI shielding effectiveness test for company Bochemie a.s., researcher, 2020-2023.

## Abstract

Sandwich-structured textiles have gained increasing attention in recent years due to their low weight, high strength, and multifunctional capabilities. These materials usually have a multilayer architecture, where the outer layers provide high mechanical resistance or comfort and the inner core fulfills a functional or damping role. As a result, they find applications in a wide range of areas—from personal protective equipment to aerospace and building insulation systems. However, current research focuses mainly on optimizing individual properties, such as thermal insulation or shielding against electromagnetic interference, while studies integrating multiple functions into a single sandwich system are still limited. In addition, the challenges associated with finding trade-offs between structural integrity, functionality, manufacturability, and adaptability to different environmental conditions persist.

In this dissertation, two types of multifunctional sandwich-structured textile materials were developed and systematically investigated in order to address the aforementioned limitations and respond to the growing demand for integrated solutions for the personal protection, construction, automotive, and aerospace industries. These materials have been designed, prepared, and comprehensively characterized with different combinations of functional layers to meet the specific requirements of each application, while ensuring an optimal compromise between mechanical strength, thermal comfort, electromagnetic shielding, sound absorption, and structural flexibility.

The first type (designation (A)) is soft and flexible textile sandwich materials, intended for protective clothing, interior building panels, or wearable devices. These structures consist of a functional middle layer made of polyester nonwovens covered by submicron copper particles, which provide both electromagnetic shielding and resistive heating capabilities. The outer layers are made of acrylic-bonded polyester nonwovens, selected for their low thermal conductivity and porous structure, which contributes to effective thermal insulation and sound absorption. This multi-layer construction not only increases user comfort in various environments, but also allows for use in protective structures.

The second type (designation (B)) is a rigid composite with a sandwich structure, aimed at applications requiring high mechanical and structural stability, such as vehicle components, aircraft panels, or electronic system housings. This configuration includes surface composite layers reinforced with carbon fibers, which provide high tensile strength and stiffness, thereby improving the mechanical integrity of the system. The middle layer is melamine-formaldehyde foam, which is a lightweight and self-extinguishing material known for its excellent thermal insulation properties. Similar to the soft composite, a layer of polyester fabric covered by sub-micron copper particles is used here to provide electromagnetic shielding and resistive heating. Selected variants of these sandwich composites use an epoxy matrix filled with graphite to improve thermal and electrical conductivity further.

Both types of sandwich composites exhibit a favorable combination of properties in the areas of electromagnetic shielding, thermal insulation, and resistive heating, while maintaining structural flexibility and low weight. This dissertation therefore represents a significant contribution to the development strategy of next-generation sandwich-structured textiles with integrated and adaptable multifunctionality, opening up new possibilities for sustainable and intelligent material solutions.

**Key words:** sandwich-structured textile materials, electromagnetic shielding effectiveness, thermal insulation, ohmic heating performance, mechanical properties, sound absorption

## Abstrakt

Textilie se sendvičovou strukturou si v posledních letech získaly rostoucí pozornost díky své nízké hmotnosti, vysoké pevnosti a multifunkčním schopnostem. Tyto materiály obvykle mají vícevrstvou strukturu, kde vnější vrstvy zajišťují vysokou mechanickou odolnost nebo komfort a vnitřní jádro plní funkční nebo tlumicí roli. Díky tomu nacházejí uplatnění v širokém spektru oblastí – od osobních ochranných prostředků až po letectví a izolační systémy budov. Současný výzkum se však zaměřuje převážně na optimalizaci jednotlivých vlastností, jako je tepelná izolace nebo stínění proti elektromagnetickému záření, zatímco studii integrujících více funkcí do jednoho sendvičového systému je stále málo. Kromě toho přetrvávají problémy spojené s nalezením kompromisů mezi strukturální integritou, funkčností, výrobitelností a přizpůsobivostí k různým podmínkám prostředí.

V této disertační práci byly vyvinuty a systematicky zkoumány systematicky dva typy multifunkčních textilních materiálů se sendvičovou strukturou s cílem řešit výše zmíněná omezení a reagovat na rostoucí poptávku po integrovaném řešení pro oblasti osobní ochrany, stavebnictví, automobilového průmyslu a letectví. Tyto materiály byly navrženy, připraveny a komplexně charakterizovány s různými kombinacemi funkčních vrstev tak, aby vyhověly specifickým požadavkům jednotlivých aplikací, při zajištění optimálního kompromisu mezi mechanickou pevností, tepelným komfortem, elektromagnetickým stíněním, zvukovou absorpcí a strukturální flexibilitou.

Prvním typem (označení (A)) je měkký a ohebný textilní sendvičový materiál, určený pro ochranné oděvy, interiérové panely budov nebo nositelná zařízení. Tato struktura se skládá z funkční střední vrstvy vyrobené z polyesterových netkaných textilií pokrytými submikronovými částicemi mědi, které poskytují jak elektromagnetické stínění, tak schopnost odporového ohřevu. Vnější vrstvy tvoří akrylátem pojené polyesterové netkané textilie, zvolené pro jejich nízkou tepelnou vodivost a porézní strukturu, která přispívá k účinné tepelné izolaci a zvukové absorpci. Tato vícevrstvá konstrukce nejen zvyšuje komfort uživatele v různých prostředích, ale zároveň umožňuje použití pro ochranné struktury.

Druhým typem (označení (B)) je tuhý kompozit se sendvičovou strukturou, zaměřený na aplikace vyžadující vysokou mechanickou a strukturální stabilitu, jako jsou součásti vozidel, letecké panely nebo kryty elektronických systémů. Tato konfigurace obsahuje povrchové kompozitní vrstvy vyztužené uhlíkovými vlákny, které poskytují vysokou pevnost v tahu a tuhost, čímž zlepšují mechanickou integritu systému. Střední vrstvu tvoří melamin-formaldehydová pěna, což je lehký a samozhášivý materiál známý svou vynikající tepelně izolační schopností. Podobně jako u měkkého kompozitu je zde použita vrstva polyesterové textilie pokryté submikronovými částicemi mědi pro zajištění elektromagnetického stínění a odporového ohřevu. Vybrané varianty těchto sendvičových kompozit využívají epoxidovou matici plněnou grafitem pro další zlepšení tepelné a elektrické vodivosti.

Oba typy sendvičových kompozit vykazují příznivou kombinaci vlastností v oblasti elektromagnetického stínění, tepelné izolace a odporového ohřevu, přičemž si zároveň zachovávají konstrukční flexibilitu a nízkou hmotnost. Tato disertační práce tedy představuje významný příspěvek ke strategii vývoje textilií se sendvičovou strukturou nové generace s integrovanou a přizpůsobitelnou multifunkčností, čímž otevírá nové možnosti pro udržitelná a inteligentní materiálová řešení.

**Klíčová slova:** textilie se sendvičovou strukturou, účinnost elektromagnetického stínění, tepelná izolace, odporový ohřev, mechanické vlastnosti, absorpce zvuku

## List of Figures

<b>Figure 1.</b> Main application and properties of Sandwich-structured textile materials.....	<b>1</b>
<b>Figure 2.</b> Schematic diagram of the active layer material (a), insulation layer material (b), and the sandwich-structured materials with three layers (c).....	<b>8</b>
<b>Figure 3.</b> Scanning electron microscope (SEM) picture of active layer (AL) materials.....	<b>9</b>
<b>Figure 4.</b> EM SE for all AL and IL samples (a), relative SE according to areal mass performance compared with other metalized textiles (b).....	<b>10</b>
<b>Figure 5.</b> EM SE for samples AL10, AL20, AL30 and sandwich-structured samples from 1 to 9.....	<b>11</b>
<b>Figure 6.</b> Relationship between the thermal conductivity of the sandwich-structured materials and their copper plated and acrylic binder content (a), and relationship between the thermal resistance of sandwich-structured materials and their thermal conductivity and thickness (b).....	<b>13</b>
<b>Figure 7.</b> Ohmic-heating test results for sample AL10 and sandwich-structured materials with sample AL10 (a), sample AL20 and sandwich-structured materials with sample AL20 (b), sample AL30 and sandwich-structured materials with sample AL30 (c).....	<b>15</b>
<b>Figure 8.</b> The relationship between the thermal resistance of the insulation layer, the copper-plated content of the active layer, and the temperature of ohmic heating for sandwich-structured materials.....	<b>16</b>
<b>Figure 9.</b> The mean value of sound absorption coefficient from 100 to 6000 Hz of the AL and IL samples...	<b>17</b>
<b>Figure 10.</b> The mean value of sound absorption coefficient from 100 to 6000 Hz of sandwich-structured materials (a) and the relationship between the areal mass, thickness, and mean value of sound absorption coefficient from 100 to 6000 Hz for sandwich-structured materials (b).....	<b>18</b>
<b>Figure 11.</b> Schematic diagram of Carbon fabric (a), Meftex 30 (b), Basotect (c), and sandwich-structured composites with four layers (d).....	<b>19</b>
<b>Figure 12.</b> Schematic diagram of surface morphology: CFRC surface (a), CFRC+Gr surface (b), Basotect surface structure (c), Basotect cross-section structure (d), SEM picture of Basotect with fiber distribution (e), Meftex 30 surface structure (f), SEM picture of Meftex 30 with fiber distribution (g), Cu particle distribution on PET fibers of Meftex 30 (h).....	<b>21</b>
<b>Figure 13.</b> EMI shielding effectiveness of sandwich-structured composites from 30 MHz to 3 GHz.....	<b>22</b>
<b>Figure 14.</b> The relationship between EMI shielding effectiveness and volume electrical conductivity (a) and the EMI shielding effectiveness at 1.5 GHz of sandwich-structured composites compared to that of other leading research materials (b).....	<b>23</b>
<b>Figure 15.</b> The thermal conductivity (a) and thermal resistance (b) of the sandwich-structured composites..	<b>24</b>
<b>Figure 16.</b> Ohmic-heating test results under different voltages for CFRC samples (a) and CFRC+Gr samples (b), CFRC series' (c and d) and CFRC+Gr series' (e and f) temperature changes after 300 s under a 5 V direct current.....	<b>25</b>

## List of Tables

<b>Table 1.</b> Basic information of AL and IL materials.....	7
<b>Table 2.</b> Basic physical properties of AL and IL materials.....	8
<b>Table 3.</b> Reflectance, transmittance, and absorbance of AL and IL materials at a wavelength of 10 $\mu\text{m}$ .....	9
<b>Table 4.</b> Basic information and physical properties of the sandwich-structured materials.....	9
<b>Table 5.</b> Thermal conductivity and resistance of AL and IL materials.....	12
<b>Table 6.</b> Thermal conductivity and resistance of the sandwich-structured materials.....	12
<b>Table 7.</b> Thermal resistance of insulation layer, copper plated content of active layer, and temperature of ohmic heating for sandwich-structured materials.....	16
<b>Table 8.</b> The maximum sound absorption coefficient and features of sample 9 compared to those of other leading research materials.....	18
<b>Table 9.</b> Basic information of carbon fabric, Meftex 30, Basotect, graphite particle, and CHS Epoxy 200....	19
<b>Table 10.</b> Basic information of the sandwich-structured composites with different combinations.....	20
<b>Table 11.</b> Tensile test results of sandwich-structured composites compared with those of metal materials....	26

## **List of abbreviation**

**EM SE:** Electromagnetic interference shielding effectiveness

**EMI:** Electromagnetic Interference

**CFRC:** Carbon fiber reinforced composites

**EV:** Electric vehicle

**CF:** Carbon Fiber

**MGO:** Magnetic graphene oxide

**AL:** Active layer

**IL:** Insulation layer

**SEG:** Specific electromagnetic shielding effectiveness

## List of symbols

***SE***: Electromagnetic interference shielding effectiveness

***P<sub>1</sub>***: Received power without the shielding material

***P<sub>2</sub>***: Received power with the shielding material

***α<sub>mean</sub>***: Mean value of sound absorption coefficients

***f<sub>l</sub>***: Lower frequency

***f<sub>h</sub>***: Upper frequency

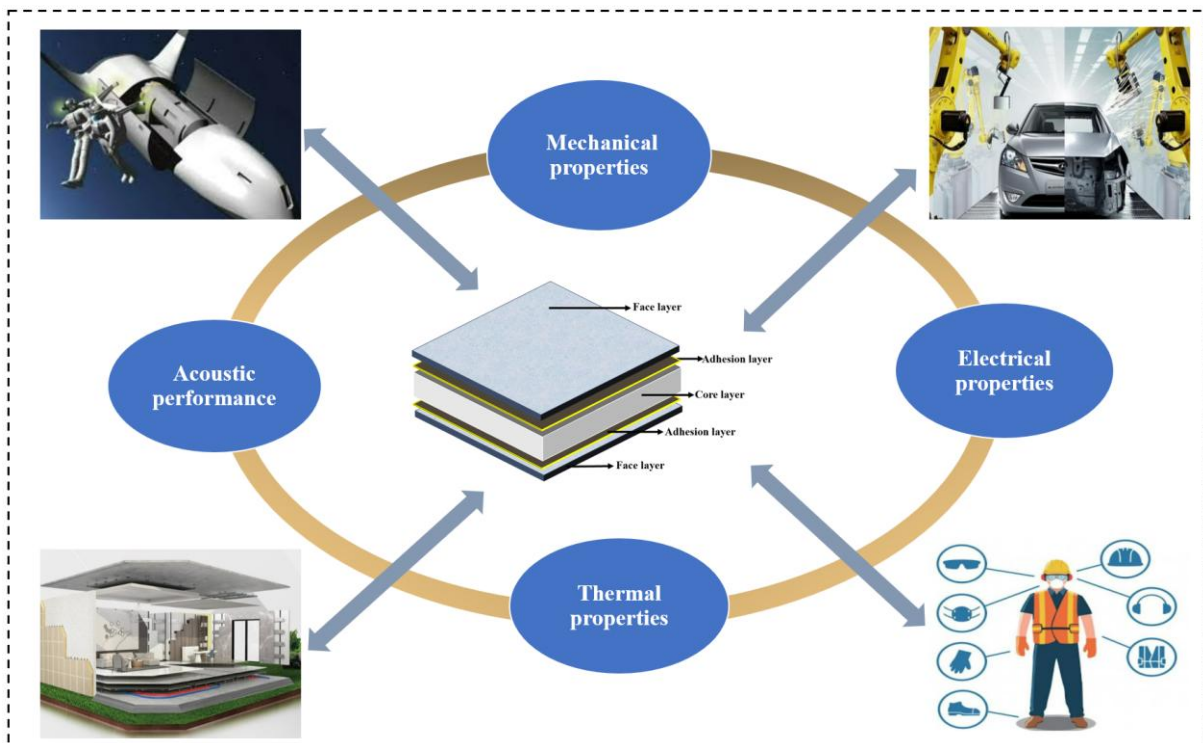
**$\int_{f_1}^{f_2} \alpha(f) \times df$** : Area under the absorption curve over the frequency range from *f<sub>l</sub>* to *f<sub>h</sub>*

# Content

1.Introduction.....	1
2.State of art.....	3
2.1 Soft-textured sandwich materials.....	3
2.2 Rigid-textured sandwich composites.....	4
2.3 Multifunctional sandwich structures.....	5
3.Motivation of thesis.....	6
4.Soft-textured sandwich materials.....	7
4.1 Materials and fabrication.....	7
4.2 Basic physical and morphological characterization.....	8
4.3 Electromagnetic interference (EMI) shielding performance.....	10
4.4 Thermal properties.....	12
4.5 Ohmic-heating performance.....	14
4.6 Acoustic absorption coefficient.....	16
5. Rigid-textured sandwich composites.....	19
5.1 Materials and fabrication.....	19
5.2 Basic physical and morphological characterization.....	20
5.3 Electromagnetic interference (EMI) shielding performance.....	21
5.4 Thermal properties.....	24
5.5 Ohmic-heating performance.....	24
5.6 Mechanical properties.....	26
6.Conclusion.....	27
7.Reference.....	28
8.List of publication.....	33
9.Appendix-Full texts of commented articles.....	36
10.Curriculum vitae.....	37
11.Recommendation of the supervisor.....	38
12.Opponent’s reviews.....	40

## 1. Introduction

Sandwich-structured textile materials are a type of high-performance composite material combined at least of two layers of high-strength fiber-reinforced surface layers and an intermediate functional core layer. Its basic structure imitates the "sandwich" form and achieves the optimal balance between performance and weight through the scientific superposition of structural layers and functional synergy [1]. In recent years, with the development of advanced manufacturing technology and high-performance fiber materials, this type of material has been rapidly promoted and widely concerned in many high-end application fields such as aerospace, automotive lightweighting, building energy conservation, and protective equipment [2]. Its core advantage lies in its light weight, high strength, high stiffness, and excellent energy absorption performance. At the same time, its structural design is flexible and suitable for application scenarios with complex forces and multi-functional requirements [3].



**Figure 1. Main application and properties of Sandwich-structured textile materials**

In the field of aerospace, sandwich structural materials are widely used in components such as fuselage skins, internal partitions, and radar covers to reduce the weight of the structure, improve fuel efficiency, and enhance its vibration, impact resistance and fatigue performance [4]. In automobile manufacturing, sandwich structures are used in door inner panels, luggage compartment covers, floor systems, and other parts, which not only meet the requirements of lightweight design but also effectively absorb energy in collisions and enhance the safety protection of occupants [5]. In terms of green buildings, this type of material, as part of the exterior wall sandwich panels, roof panels, or insulation systems, can simultaneously meet the requirements of structural support and multiple functions such as heat insulation, sound insulation, and fire prevention, effectively improving the overall energy saving and safety performance of the building [6]. In personal protection and military and police equipment, the safety performance of materials is enhanced by integrating aramid fibers and 3D three-dimensional fabrics, further improving their anti-puncture, bulletproof, and explosion-proof capabilities to meet the

functional needs in harsh environments [7].

The core advantage of sandwich structural materials lies in their unique layered composite design, which can provide excellent mechanical properties under extremely low deadweight conditions, such as high strength, high stiffness, and good bending rigidity, while also having excellent buffering and energy absorption capabilities and natural anti-interference capabilities against impact loads [8] [9]. With the development of materials science and textile engineering, advanced molding technologies such as three-dimensional weaving and three-dimensional braiding have enabled the core layer structure to gradually evolve from traditional foam and honeycomb structures to high-performance three-dimensional fabric structures, significantly improving the surface-core bonding strength, anti-delamination ability, and overall impact resistance [10] [11]. At the same time, researchers continue to expand their functionality, making the material more intelligent and adaptable to the needs of extreme environments by introducing a variety of functional fibers and core materials such as flame retardant, bulletproof, puncture-proof, sound insulation, and heat insulation [12] [13]. In terms of sustainable development, more and more research focuses on using natural fibers as core materials or using bio-based resins and recyclable structural designs to respond to the trend of green manufacturing and circular economy [14].

Although sandwich-structured textile materials have significant advantages such as light weight, high strength, flexible structure, and multifunctional integration, they still face many challenges in the process of research and application [15]. First, the interface bonding strength between the surface layer and the core layer is insufficient, which is prone to delamination and instability, especially under impact or cyclic loads, affecting the safety of the structure. Secondly, the complex manufacturing process, low degree of automation, long molding cycle, and high cost limit its promotion in large-scale industrialization. In addition, there are difficulties in matching the material structure design with the multi-performance requirements, and multifunctional integration also faces the challenges of process compatibility and interface control [16] [17] [18]. Finally, due to the use of multi-layer composite structures and thermosetting matrices, this type of material still has significant deficiencies in recyclability and environmental protection, and it is difficult to meet the growing requirements of sustainable development [19].

This work proposes targeted solutions to address the previously discussed limitations of sandwich-structured textile materials, including insufficient interfacial bonding, complex manufacturing processes, and limited adaptability. Firstly, to simplify the complex core structure, the approach involves vertically stacking textile layers with different functional properties and bonding them using commercially available textile adhesives. This technique not only enhances the bonding strength between the face and core layers but also reduces process complexity, shortens production cycles, lowers costs, and facilitates automation. To address diverse application requirements, two types of sandwich-structured textile materials with different levels of stiffness were developed. For personal protective equipment and construction materials, a soft texture material with sandwich-structured was designed, featuring electromagnetic shielding, thermal insulation, ohmic heating, and soundproofing capabilities. For applications in automotive or aerospace products, a rigid sandwich-structured composite was created, combining electromagnetic shielding, thermal management, ohmic heating, and mechanical performance. These tailored designs significantly expand the functional versatility of sandwich structures and provide broader possibilities for application-specific customization. Furthermore, this study also addresses recyclability and environmental sustainability. Material selection prioritizes not only functional performance but also safety and eco-friendliness. During sample preparation, energy

consumption and material waste were minimized, aligning with the goals of green manufacturing and sustainable development. It will elaborate on the aforementioned contents in detail below.

## **2. State of art**

### *2.1 Soft-textured sandwich materials*

The development of protective equipment is essential for ensuring the safety and performance of individuals working in professional and high-risk environments. Recently, numerous researchers have conducted extensive studies aimed at enhancing the electromagnetic interference shielding effectiveness (EM SE) of various textile materials. For instance, Yao et al. [20] fabricated an EMI shielding textile by incorporating MXene into a polymer network based on polydimethylsiloxane. The resulting fabric demonstrated multifunctionality, including electromagnetic shielding, pressure sensing, and conversion of electrical energy into thermal or photothermal energy. Notably, samples without MXene exhibited minimal EMI shielding in the X-band, whereas those subjected to 3–9 cycles of dip-coating with MXene achieved shielding effectiveness exceeding 30 dB across the entire X-band, primarily due to increased absorption. Similarly, Hong et al. [21] developed an EMI shielding textile by first oxidizing the surface of cellulose fibers, converting hydroxyl groups to carboxyl groups, and subsequently generating silver nanoparticles in situ on the oxidized substrate. The resulting materials exhibited high shielding effectiveness, with a single-layer textile achieving 47 dB and a three-layer system reaching up to 69 dB. In parallel, other studies have investigated the comfort properties of EMI shielding textiles. Tunakova et al. [22] utilized a woven fabric composed of a blend of conventional fibers and ultra-fine stainless-steel filaments. This substrate was subjected to digital printing to produce garments suitable for everyday wear while offering electromagnetic protection. The study confirmed the feasibility of using digital printing to modify the color and pattern of metal-fiber-containing textiles. However, repeated washing negatively affected both the EMI shielding performance and the printed appearance. Overall, the majority of current research focuses either on enhancing EMI shielding performance or on evaluating the comfort properties of single-layer shielding materials. However, there remains a significant research gap concerning the development of sandwich-structured textile materials that simultaneously optimize thermal comfort and electromagnetic shielding effectiveness, highlighting an important direction for the studies.

Currently, a growing number of researchers and experts are dedicated to the study of thermal insulation materials and the development of energy-efficient structural systems for construction materials. In a study conducted by Hamza Alahmad et al. [23], it was concluded that the most commonly used building insulation materials in Turkey include extruded polystyrene, expanded polystyrene, glass wool, rock wool, rigid polyurethane foam, and phenolic foam. Yuan et al. [24] conducted a comparative analysis of engineering test data for thermal insulation materials in six cities across various climatic regions of Japan. Their research assessed the efficacy of four varieties of insulation materials in conjunction with four types of fuel sources. The findings indicated that rock wool and liquefied natural gas constitute the most effective combination for thermal efficiency in the various climate zones. In a separate review, Dong Yitong et al. [25] summarized recent advancements in innovative building insulation materials, including transparent insulation materials, aerogels, closed-cell foams, vacuum insulation panels, and reflective insulation materials. In contrast, research on construction materials with electromagnetic shielding effectiveness remains relatively limited. Among the currently available solutions, cement-based electromagnetic shielding composites and EMI shielding coatings are the most commonly used.

Aylin Akyildiz et al. [26] investigated the enhancement of EM SE in cement-based mixtures through the incorporation of carbon nanomaterials. Their findings indicated that the highest shielding effectiveness, particularly at 2 GHz, was achieved with the addition of 1% carbon nanotubes. Similarly, Yue Li et al. [27] examined both the mechanical properties and EM SE of cement paste modified with fly ash and slag. The study compared a control group of pure cement paste with experimental groups incorporating 10%, 20%, and 30% replacements of cement with fly ash and slag. The best performance in both mechanical strength and electromagnetic shielding was observed with a combination of 20% fly ash and 30% slag. Simultaneously, increasing attention is being directed toward the acoustic performance of buildings, particularly in terms of soundproofing and noise control. Numerous studies have demonstrated that prolonged exposure to noise pollution can significantly disrupt sleep, hinder verbal communication, reduce work efficiency, and induce negative psychological responses such as irritation, anxiety, and frustration [28] [29]. In the context of residential environments, research on acoustic insulation and sound-absorbing materials is relatively well-established. Commonly studied materials include a range of sound-absorbing and soundproofing solutions, such as resonant absorbers, panel absorbers, acoustic membranes, and decoupling materials. These materials function through various mechanisms—such as resonance, impedance mismatch, and energy dissipation—to mitigate the transmission of airborne and structure-borne noise, thereby enhancing indoor acoustic comfort [30]. In summary, there is a notable lack of research integrating thermal insulation, electromagnetic shielding, and acoustic insulation functionalities within a single building material or structural system. The simultaneous consideration of these three performance criteria remains an underexplored yet highly promising area for future investigation.

## *2.2 Rigid-textured sandwich composites*

As the pursuit of sustainable solutions continues to accelerate, researchers and engineers are increasingly focused on advancing various aspects of automotive and aerospace design to improve performance, enhance energy efficiency, and reduce environmental impact. Among new materials, carbon fiber reinforced composites (CFRCs), composed of carbon fibers embedded in polymer resin matrices, have attracted significant attention due to their exceptional mechanical strength and low density. These properties enable substantial weight reduction while maintaining structural integrity, thereby improving fuel efficiency and lowering emissions. Consequently, CFRCs are regarded as highly promising materials for the development of next-generation sustainable transportation systems [31].

Wang and others [32] studied carbon fiber-reinforced polymer sandwich structures that were cured at high temperatures for use in car bodies, using aluminum honeycomb as the core material. The results demonstrated that increasing the core density or thickness generally enhanced the overall material strength. However, the bending stiffness was maximized at intermediate values of density and thickness, indicating an optimal design trade-off. Furthermore, stiffness was found to be more sensitive to variations in core density and thickness than strength. Among the experimental configurations, samples with an aluminum honeycomb core of 101 kg/m<sup>3</sup> density and 20 mm thickness exhibited a favorable balance of high strength and stiffness while maintaining relatively low weight. Additionally, improving the interfacial bonding between the face sheets and the core significantly enhanced the panel peeling strength, highlighting the importance of interface optimization in sandwich structure design. As the automotive industry increasingly transitions toward electrification, the demand for advanced materials capable of addressing the specific structural, thermal, and electromagnetic challenges associated with electric vehicle (EV) battery casings has become increasingly critical. Despite the growing interest in

EV technologies, there remains a significant lack of comprehensive research focused on evaluating the suitability and performance of carbon fiber-reinforced composite materials for battery enclosure applications. In a related study, M. S. Santhosh [33] investigated the feasibility of employing an E-glass fiber/phenolic resin/ammonium polyphosphate laminate composite as a candidate material for electric vehicle battery casings. A series of mechanical performance tests including tensile, flexural, low-velocity impact, and quasi-static indentation tests were conducted to assess its structural integrity. However, the study did not address key performance parameters such as electromagnetic interference shielding effectiveness and thermal conductivity, which are essential for a comprehensive evaluation of materials intended for EV battery protection.

Inspired by the structural efficiency of interchange bridges which allow vehicles to travel swiftly in multiple directions, Song et al. [34] developed a simple yet effective method for fabricating bidirectionally oriented carbon fiber (CF)/silicone rubber composites featuring an interchange-bridge-like architecture. The high aspect ratio of the carbon fibers, combined with their bidirectional orientation, plays a critical role in establishing continuous thermal and electrical conduction pathways within the composite matrix. Notably, the bidirectional alignment of the CF arrays significantly enhances the tensile strength of the composites in both vertical and horizontal directions, owing to the cross-arranged reinforcement structure. The composite exhibited a high tensile strength of 6.18 MPa at a filler loading of 62.3 wt%. In addition, the material demonstrated excellent thermal conductivity, reaching 25.3 W/(m·K), and an outstanding electromagnetic interference shielding effectiveness of 61.6 dB. Qiu et al. [35] determined that the intrinsically inadequate interfacial characteristics of carbon fiber-reinforced polymers considerably restrict their utilization in high-performance domains, including the aerospace sector. To address this limitation, magnetic graphene oxide (MGO) was synthesized and uniformly applied to the surface of carbon fibers to improve the interfacial interactions between the fiber and matrix. The integration of Fe<sub>3</sub>O<sub>4</sub> nanoparticles into the MGO framework significantly reduced the agglomeration propensity of graphene oxide, facilitating swift, regulated surface sizing while preserving superior dispersion of MGO in a magnetic field. Experimental results indicated significant enhancements in the mechanical interfacial properties of MGO-treated CFRPs, with interlaminar shear strength, interfacial shear strength, and transverse fiber bundle tensile strength augmented by 56.04%, 46.73%, and 82.00%, respectively, in comparison to untreated composites. The MGO-modified CFRPs demonstrated significant multifunctionality, attaining an electromagnetic interference shielding effectiveness of up to 46.33 dB within the X-band frequency range. In summary, there is a significant deficiency of research that amalgamates thermal insulation, electromagnetic shielding, and mechanical functionalities within a unified structural system. The simultaneous consideration of these three performance criteria remains an underexplored yet highly promising area for future investigation.

### *2.3 Multifunctional sandwich structures*

The development of protective clothing is essential for safeguarding individuals in professional settings against electromagnetic radiation. While existing studies mainly focus on the performance of single-layer EMI shielding materials, this work emphasizes a composite approach to integrating EMI shielding layers with other textile materials to form a multifunctional sandwich structure that balances multiple properties [36] [37]. The proposed sandwich-structured materials consist of an EMI shielding layer positioned between two thermal insulation layers. This multilayered architecture ensures effective electromagnetic shielding while simultaneously enhancing thermal comfort by providing insulation and regulating heat transfer between the body and the external environment.

With the continuous improvement of living standards, the functional requirements for building materials are becoming increasingly stringent. Given that buildings account for approximately 30–40% of global energy consumption, enhancing the energy efficiency of construction materials is of significant importance [38]. Additionally, acoustic comfort is gaining attention, as prolonged exposure to noise has been shown to cause both psychological and physiological stress, potentially leading to various health issues [39]. Furthermore, the proliferation of electronic devices in daily life has increased concerns about electromagnetic radiation exposure, reinforcing the demand for materials that can effectively shield against such radiation [40].

Another sandwich-structured composite that was used in automotive or aerospace products was also systematically investigated through its EMI shielding properties, thermal insulation performance, ohmic heating effect, and mechanical properties. In automotive applications, they contribute to vehicle weight reduction and improved energy efficiency while offering excellent mechanical resistance, thermal insulation, and the ability to integrate functionalities such as electromagnetic shielding and heating, meeting the growing demands for intelligent and sustainable manufacturing [41] [15]. In the aerospace sector, these materials fulfill stringent requirements for extreme lightweight design, high strength, and stiffness, making them ideal for use in components such as wings, cabin doors, and satellite structures. Additionally, they offer advantages in thermal protection, electromagnetic compatibility, and radar stealth [42] [43]. As a result, sandwich composites have become a key enabling material technology for achieving the combined goals of structural performance, functional integration, and weight reduction in modern transportation systems.

Although extensive research has been conducted on mechanical properties, thermal insulation, soundproofing, ohmic heating effect and EMI shielding individually, there remains a notable gap in the development of materials that integrate all these functionalities.

### **3. Motivation of thesis**

In this thesis, the EMI shielding properties, thermal insulation performance, ohmic heating effect, mechanical properties, and sound absorption performance of the sandwich-structured materials were systematically investigated. The two basic types of composites were primarily investigated for two application domains: soft-textured sandwich materials for the wearable protection and smart building application (A) and rigid-textured sandwich composites for the automotive and aerospace sectors (B).

The main aims of the research were:

(A) design, creation, and complex characterization of a novel sandwich structure by using polyester nonwoven fabrics: one layer coated with an acrylic binder exhibiting high spectral absorbance and another layer plated with copper to provide EMI shielding and ohmic heating functionality. These materials demonstrate a combination of desirable characteristics—lightweight, thermally insulating, acoustically absorbent, and effective at electromagnetic interference shielding—making them promising candidates for both wearable protection and smart building application.

(B) design, creation, and complex characterization of a novel sandwich structure to address the current challenges in multifunctional material design by developing a carbon fiber composite material treated with a water-soluble resin to ensure uniform resin distribution throughout the matrix. To enhance EMI shielding effectiveness and optimize thermal conductivity, copper-coated polyester nonwoven fabrics were strategically integrated into the sandwich structure composite. Additionally, to meet thermal

insulation requirements, a melamine-formaldehyde foam board was inserted between two layers of the carbon fiber composite, significantly improving the overall thermal resistance of the structure. These sandwich structures are suitable for the automotive and aerospace sectors.

The main research results are only presented here. The experimental details, measurement techniques, and comparison with other solutions are described in the full text of four articles ([A1] to [A4] in Appendix 1). By balanced integration of mechanical strength, electromagnetic shielding, and thermal management, these multifunctional composites will present a promising new solution for the evolving demands of high-performance, lightweight materials in next-generation transportation systems.

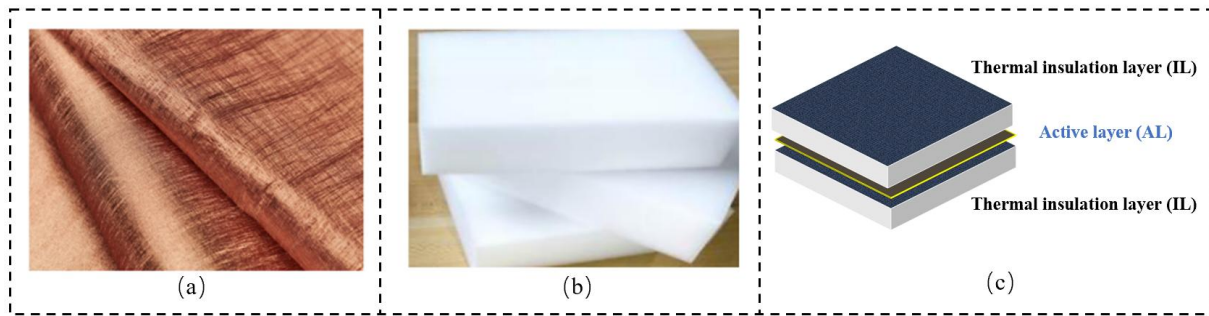
## 4. Soft-textured sandwich materials

### 4.1 Materials and fabrication

The sandwich-structured materials investigated in this part (A) consists of two distinct types of nonwoven fabrics. The first is referred to as the active layer (AL) material named “MefTex” produced by the Boehmie company, which is a polyester nonwoven substrate modified with three different loadings of copper nanoparticles via a patented chemical deposition method. The electromagnetic shielding performance of this material primarily results from the uniform surface deposition of conductive copper, which effectively attenuates electromagnetic radiation. Additionally, the surface-distributed copper nanoparticles enable the AL material to exhibit an ohmic heating effect when subjected to an electric field, thereby expanding its functional potential. This material is therefore suitable for use as the middle layer in sandwich-structured materials. The second material is referred to as the insulation layer (IL) material, which consists of a polyester nonwoven fabric impregnated with an acrylic binder. Due to its high spectral absorbance and low thermal conductivity, the IL is primarily used for thermal insulation and heat retention. This type of nonwoven is generally employed in multilayer systems rather than as a standalone layer. In this research, three different thicknesses of the IL material were selected for comparison. The detailed physical and compositional properties of both AL and IL materials are summarized in Table 1. Spray adhesive (3M Super 77) finally bonds active layer material and insulation layer material together to create the sandwich-structured materials. Table 4 is presented the basic information of sandwich-structured materials with different combination and Figure 2 (c) is shown the schematic diagram of sandwich-structured materials with three layers.

**Table 1. Basic information of AL and IL materials [Adopted from publication A2]**

Sample code	Sample details	Fabrication method
AL10 (MefTex10)	10g/m <sup>2</sup> polyester nonwoven with 3g/m <sup>2</sup> copper coating	Point Thermal bonding
AL20 (MefTex20)	100% polyester nonwoven with copper coating 20g/m <sup>2</sup> polyester nonwoven with 5g/m <sup>2</sup> copper coating	
AL30 (MefTex30)	30g/m <sup>2</sup> polyester nonwoven with 7g/m <sup>2</sup> copper coating	
IL100	100% polyester nonwoven with acrylic binder	Chemical bonding
IL150		
IL200		



**Figure 2. Schematic diagram of active layer material (a), insulation layer material (b), and sandwich-structured materials with three layers (c) [Adopted from publication A2]**

#### 4.2 Basic physical and morphological characterization

The fundamental physical properties and Fourier transform infrared spectrometer (FTIR) test results of the AL and IL materials are presented in Tables 2 and 3. The AL materials are relatively thin and lightweight. Specifically, samples AL10, AL20, and AL30 exhibit areal densities of 12.13 g/m<sup>2</sup>, 24.81 g/m<sup>2</sup>, and 36.47 g/m<sup>2</sup>, with corresponding thicknesses of 0.06 mm, 0.08 mm, and 0.11 mm, respectively. A key distinction among these three samples lies in their copper deposition levels: 3 g/m<sup>2</sup>, 5 g/m<sup>2</sup>, and 7 g/m<sup>2</sup> of copper were chemically plated onto greige polyester fabrics with base weights of approximately 10 g/m<sup>2</sup>, 20 g/m<sup>2</sup>, and 30 g/m<sup>2</sup>, respectively. In contrast, the IL materials are significantly thicker and denser. The areal densities of IL100, IL150, and IL200 are 79.94 g/m<sup>2</sup>, 130.56 g/m<sup>2</sup>, and 228.08 g/m<sup>2</sup>, with thicknesses of 4.21 mm, 8.11 mm, and 12.93 mm, respectively. As shown in Table 3, the spectral reflectance, transmittance, and absorbance of both AL and IL materials were measured at a wavelength of 10 μm. The AL samples demonstrated higher spectral reflectance, particularly AL10, which reached 18% reflectance at 10 μm. The enhanced reflectance suggests improved resistance to radiative heat transfer due to reduced infrared absorption. Moreover, the absorbance increased with the areal mass of the greige fabric. And the IL samples exhibited extremely high absorbance, with values exceeding 97%, confirming their suitability for thermal insulation applications in multilayer sandwich structures. In addition, the SEM pictures of all AL materials are shown in Figure 3. According to the pictures, it can be observed that the copper particles on the surface of the active layer material gradually evolve from a sparse point distribution to dense coverage and aggregation into a mesh structure. This change will improve the electromagnetic shielding performance and ohmic-heating ability of the material, but may have a certain impact on its comfort performance. Therefore, the function and structural performance should be weighed in the application.

**Table 2. Basic physical properties of AL and IL materials [Adopted from publication A2]**

Sample code	Areal mass (g/m <sup>2</sup> )	Thickness (mm)	Volume porosity (%)
<b>AL10</b>	12.13±0.02	0.06±0.01	85.47±0.02
<b>AL20</b>	24.81±0.13	0.08±0.01	77.54±0.02
<b>AL30</b>	36.47±0.41	0.11±0.01	75.91±0.01
<b>IL100</b>	79.94±1.59	4.21±0.02	98.66±0.04
<b>IL150</b>	130.56±3.41	8.11±1.09	98.82±0.02
<b>IL200</b>	228.08±2.56	12.93±0.17	98.79±0.03

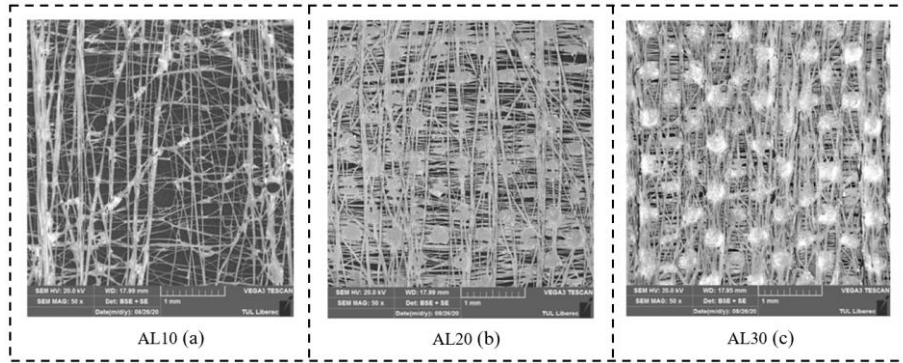


Figure 3. Scanning electron microscope (SEM) picture of active layer (AL) materials

Table 3. Reflectance, transmittance, and absorbance of AL and IL materials at a wavelength of 10  $\mu\text{m}$  [Adopted from publication A2]

Sample code	Reflectance (%)	Transmittance (%)	Absorbance (%)
AL10	18	26	56
AL20	6	7	87
AL30	3	2	95
IL100	0.5	2	97.5
IL150	0.5	0.6	98.9
IL200	0.5	0.2	99.3

Table 4 presents the basic physical properties of the sandwich-structured materials composed of various combinations of AL and IL materials. The areal mass of the sandwich-structured materials went up steadily as both the IL materials' thickness and AL materials' copper content increased, starting at 172.01  $\text{g}/\text{m}^2$  for sample 100/10/100 and reaching 492.63  $\text{g}/\text{m}^2$  for sample 200/30/200. The overall thickness showed a similar trend, increasing from 8.21 mm to 27.31 mm throughout the sample series. Notably, the active layer material had a modest influence on thickness, and the insulation layer material was the dominant factor determining the overall structural dimension. Despite these changes, all samples maintained a high volume porosity between 98.5% and 98.9%, indicating a lightweight and highly porous structure. This combination of tunable density and thickness with consistently high porosity makes these multilayer materials suitable for multifunctional applications such as thermal insulation, electromagnetic shielding, and low-voltage ohmic heating.

Table 4. Basic information and physical properties of sandwich-structured materials [Adopted from publication A2]

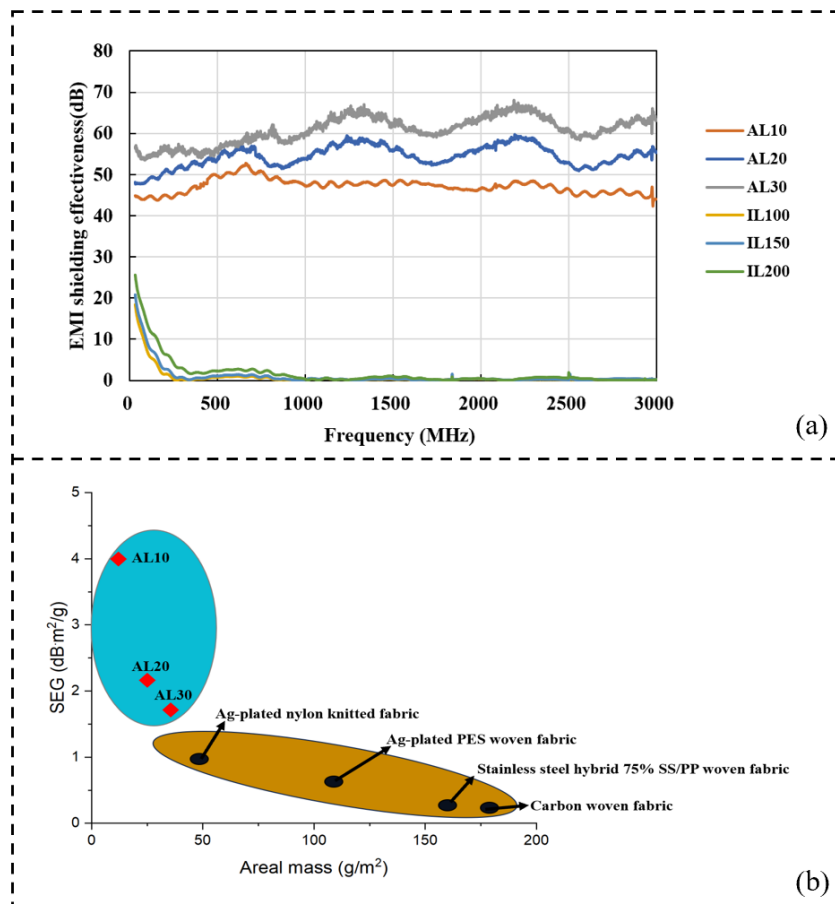
Sample code	Sample configuration	Areal mass ( $\text{g}/\text{m}^2$ )	Thickness (mm)	Volume porosity (%)
100/10/100	IL100+AL10+IL100	172.01 $\pm$ 1.28	8.21 $\pm$ 0.23	98.59 $\pm$ 0.02
100/20/100	IL100+AL20+IL100	184.69 $\pm$ 0.49	10.47 $\pm$ 0.26	98.72 $\pm$ 0.02
100/30/100	IL100+AL30+IL100	196.35 $\pm$ 0.21	10.51 $\pm$ 0.11	98.68 $\pm$ 0.03
150/10/150	IL150+AL10+IL150	273.25 $\pm$ 2.74	17.33 $\pm$ 0.91	98.92 $\pm$ 0.01
150/20/150	IL150+AL20+IL150	285.93 $\pm$ 1.23	18.91 $\pm$ 0.49	98.97 $\pm$ 0.03
150/30/150	IL150+AL30+IL150	297.59 $\pm$ 0.88	18.81 $\pm$ 0.34	98.91 $\pm$ 0.04
200/10/200	IL200+AL10+IL200	468.29 $\pm$ 1.29	26.61 $\pm$ 0.29	98.74 $\pm$ 0.04
200/20/200	IL200+AL20+IL200	480.97 $\pm$ 0.24	27.17 $\pm$ 0.07	98.73 $\pm$ 0.03
200/30/200	IL200+AL30+IL200	492.63 $\pm$ 0.82	27.31 $\pm$ 0.27	98.73 $\pm$ 0.03

### 4.3 Electromagnetic interference (EMI) shielding performance

With the widespread adoption of electronic devices and wireless communications, the issue of electromagnetic interference has become increasingly significant. Shielding materials can effectively block electromagnetic waves, ensure the stable operation of equipment, and prevent the leakage of sensitive information. They are widely used in military, government, and high-end communication systems. At the same time, electromagnetic shielding can also reduce the potential harm of electromagnetic radiation to the human body. The EMI shielding effectiveness test was performed using the coaxial transmission line method, and it presumes a plane wave impact on a shielding material in the frequency band from 30 MHz to 3 GHz. The calculation is shown in Equation (1):

$$SE = -10 \log \frac{P_1}{P_2} \quad (1)$$

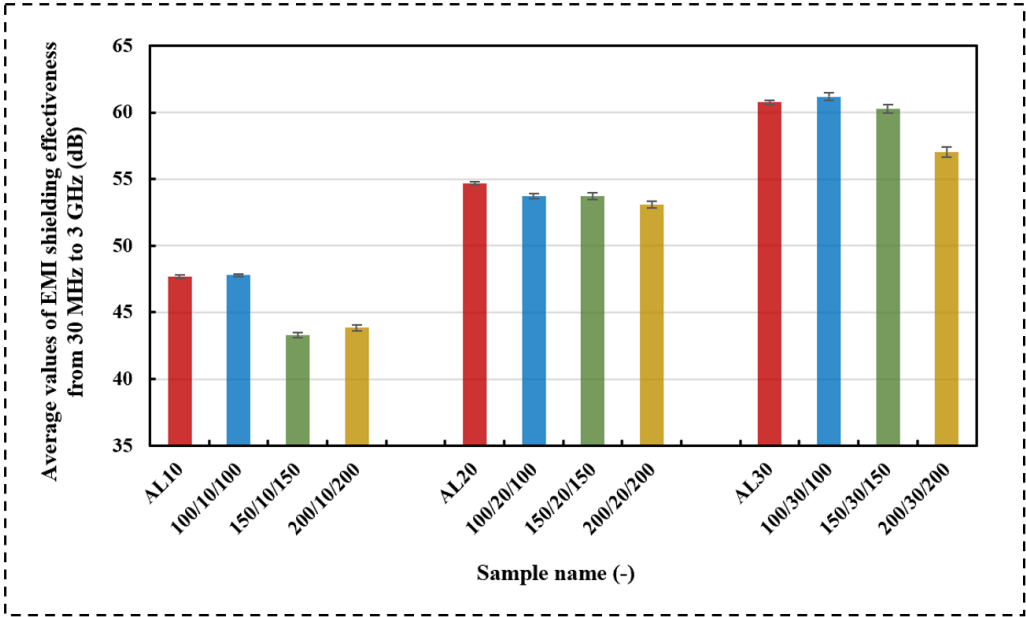
Where,  $P_1$  is the received power without the shielding material, and  $P_2$  is the received power with the shielding material present.



**Figure 4. EM SE for all AL and IL materials (a) [Adopted from publication A2], relative SE according to areal mass performance compared with other metalized textiles (b)**

This part compares the electromagnetic interference shielding effectiveness (EM SE) of various active layer and insulation layer samples across the frequency range of 30 MHz to 3 GHz. As shown in Figure 4(a), the EM SE of samples AL10, AL20, and AL30 was approximately 48 dB, 55 dB, and 61 dB, respectively. According to the FTTS-FA-003 standard for the classification of professional EMI shielding textiles, all three active layer materials fall within the category of "very good" shielding

performance [44]. In the context of various EMI shielding applications, the areal mass of the shielding material is a critical factor. To comprehensively evaluate the performance of shielding materials, the specific electromagnetic shielding effectiveness (SEG, expressed in  $\text{dB}\cdot\text{m}^2/\text{g}$ ) based on areal mass is often employed. A higher SEG value is preferred, as it reflects a superior balance between shielding effectiveness and material areal mass [44]. In this study, the SEG values of the AL materials were calculated and compared with those of other metallized or carbon-based fabrics [45]. As illustrated in Figure 4(b), the AL materials exhibit superior SEG values, ranging from 1.7 to 4, significantly outperforming conventional metallized or carbon-based textiles, whose SEG values typically fall between 0.25 and 1. These results highlight the AL materials' advantageous combination of low mass and high shielding performance, underscoring their promising potential for lightweight and efficient EMI shielding applications.



**Figure 5. Average value of EM SE from 30MHz to 3 GHz for samples AL10, AL20, AL30 and all sandwich-structured samples**

Previous studies have demonstrated that EM SE is primarily governed by the electrical conductivity and porosity of the shielding material [46] [47]. In general, shielding effectiveness increases with conductivity and decreases with porosity. The experimental results presented are consistent with this trend: a positive correlation is observed between the copper content in the active layers and their EM SE, while a negative correlation exists with respect to porosity. Furthermore, the insulation layer materials exhibited negligible EMI shielding within the measured frequency range, indicating that the overall EMI performance of the sandwich-structured materials is predominantly contributed by the active layer components. The EM SE of sandwich-structured materials with different active layer materials is shown in Figure 5. It can be observed that there is no big difference in the electromagnetic interference shielding effectiveness between the sandwich-structured materials and the active layer material they contain. The primary determinants of electromagnetic interference shielding efficiency are the conductivity, thickness, and porosity of the shielding layer [48]. So, simply increasing the thickness of the non-conductive layer does not impact the overall electromagnetic interference shielding performance of the sandwich material.

#### 4.4 Thermal properties

Thermal performance is one of the core indicators to measure the availability, reliability, and safety of materials. It plays a vital role in aerospace, energy engineering, building materials, and other fields. The thermal conductivity, thermal resistance, thermal expansion coefficient, thermal stability, and other parameters of the material determine its adaptability and functionality in different environments. Thermal conductivity and thermal resistance tested by Alambeta under 200 Pa in this part, and were selected to characterize the thermal properties of the samples.

**Table 5. Thermal conductivity and resistance of AL and IL materials [Adopted from publication A2]**

Sample code	Thermal conductivity (W/m·K)	Thermal resistance (K·m <sup>2</sup> /W)
AL10	0.0358±0.0004	0.0018±0.0002
AL20	0.0411±0.0005	0.0019±0.0003
AL30	0.0466±0.0013	0.0022±0.0001
IL100	0.0367±0.0004	0.1147±0.0024
IL150	0.0466±0.0024	0.1733±0.0157
IL200	0.0534±0.0009	0.2423±0.0053

Table 5 summarizes the thermal conductivity and thermal resistance of all AL and IL materials. A slight increase in thermal conductivity is observed with increasing copper content in the AL materials and increasing thickness in the IL materials. This trend can be attributed to the high intrinsic thermal conductivity of copper, which enhances heat transfer as its content rises in the AL materials with higher areal mass of its greige fabric [49]. Similarly, the increase in IL materials' thickness corresponds to a higher content of acrylic binder, which possesses a thermal conductivity of 0.19 W·m<sup>-1</sup>·K<sup>-1</sup>, thereby contributing to the overall thermal conductivity of the IL materials [50]. The measured thermal resistance values of AL10, AL20, and AL30 are 0.0018 K·m<sup>2</sup>/W, 0.0019 K·m<sup>2</sup>/W, and 0.0022 K·m<sup>2</sup>/W, respectively, indicating relatively low thermal resistance due to their thin structure and high thermal conductivity. In contrast, the IL materials exhibit significantly higher thermal resistance values. When the thermal conductivities are relatively comparable, the thermal resistance increases primarily as a function of thickness. Specifically, the thermal resistance values for IL100, IL150, and IL200 are 0.1147 K·m<sup>2</sup>/W, 0.1733 K·m<sup>2</sup>/W, and 0.2423 K·m<sup>2</sup>/W, respectively, confirming their effectiveness as thermal insulation layers.

**Table 6. Thermal conductivity and resistance of the sandwich-structured materials [Adopted from publication A2]**

Sample code	Thermal conductivity (W/m·K)	Thermal resistance (K·m <sup>2</sup> /W)
100/10/100	0.0398±0.0011	0.2603±0.0075
100/20/100	0.0398±0.0015	0.2631±0.0118
100/30/100	0.0433±0.0008	0.2427±0.0024
150/10/150	0.0521±0.0011	0.3327±0.0235
150/20/150	0.0531±0.0006	0.3553±0.0056
150/30/150	0.0539±0.0016	0.3493±0.0151
200/10/200	0.0622±0.0004	0.4281±0.0089
200/20/200	0.0624±0.0008	0.4353±0.0058
200/30/200	0.0629±0.0014	0.4271±0.0136

Table 6 presents the thermal conductivity and thermal resistance values of the sandwich-structured materials with varying configurations of active and insulation layers. Specifically, thermal conductivity increases gradually from 0.0398 W/m·K in sample 100/10/100 to 0.0629 W/m·K in sample 200/30/200, which can be attributed to the combined effects of increasing copper nanoparticle content in the active layer and a higher acrylic binder ratio in thicker insulation layers. Despite this moderate increase in conductivity, thermal resistance shows a more substantial rise, ranging from 0.2603 K·m<sup>2</sup>/W (sample 100/10/100) to 0.4353 K·m<sup>2</sup>/W (sample 200/20/200), indicating enhanced thermal insulation performance. This is consistent with the principle that thermal resistance is positively correlated with material thickness, provided that thermal conductivity remains within a similar range [51] [52].

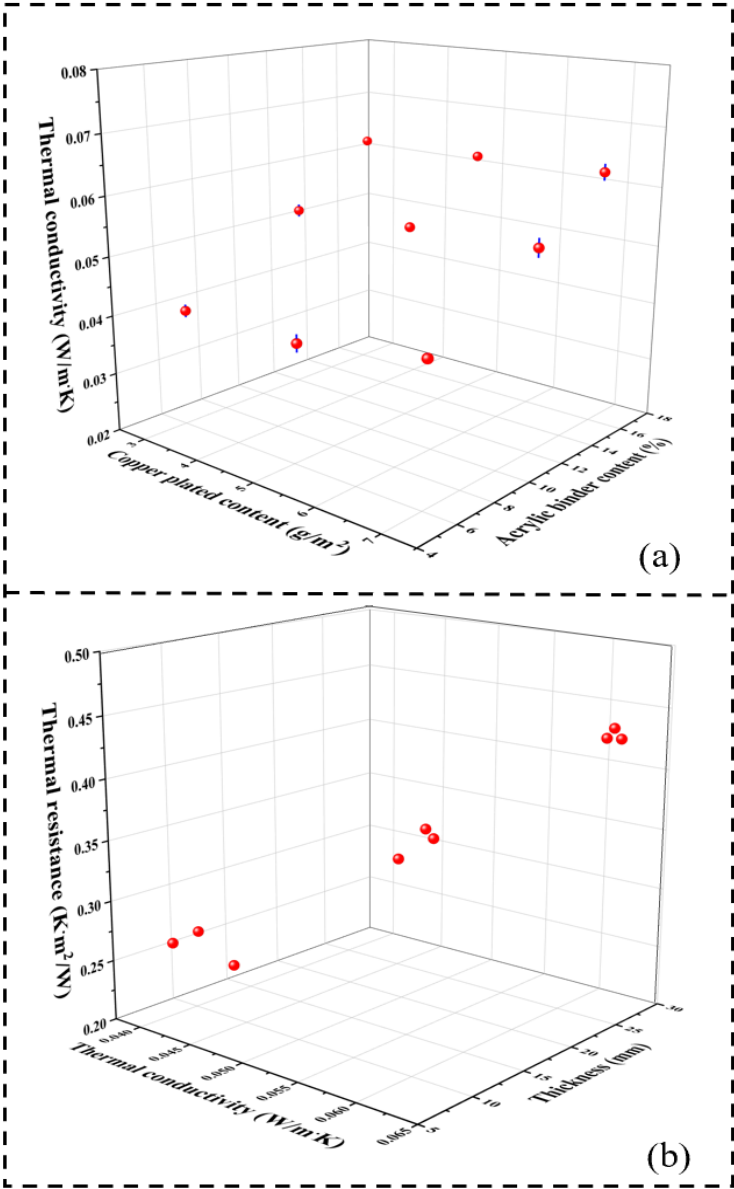


Figure 6. Relationship between the thermal conductivity of the sandwich-structured materials and their copper plated and acrylic binder content (a), and relationship between the thermal resistance of the sandwich-structured materials and their thermal conductivity and thickness (b) [Adopted from publication A2]

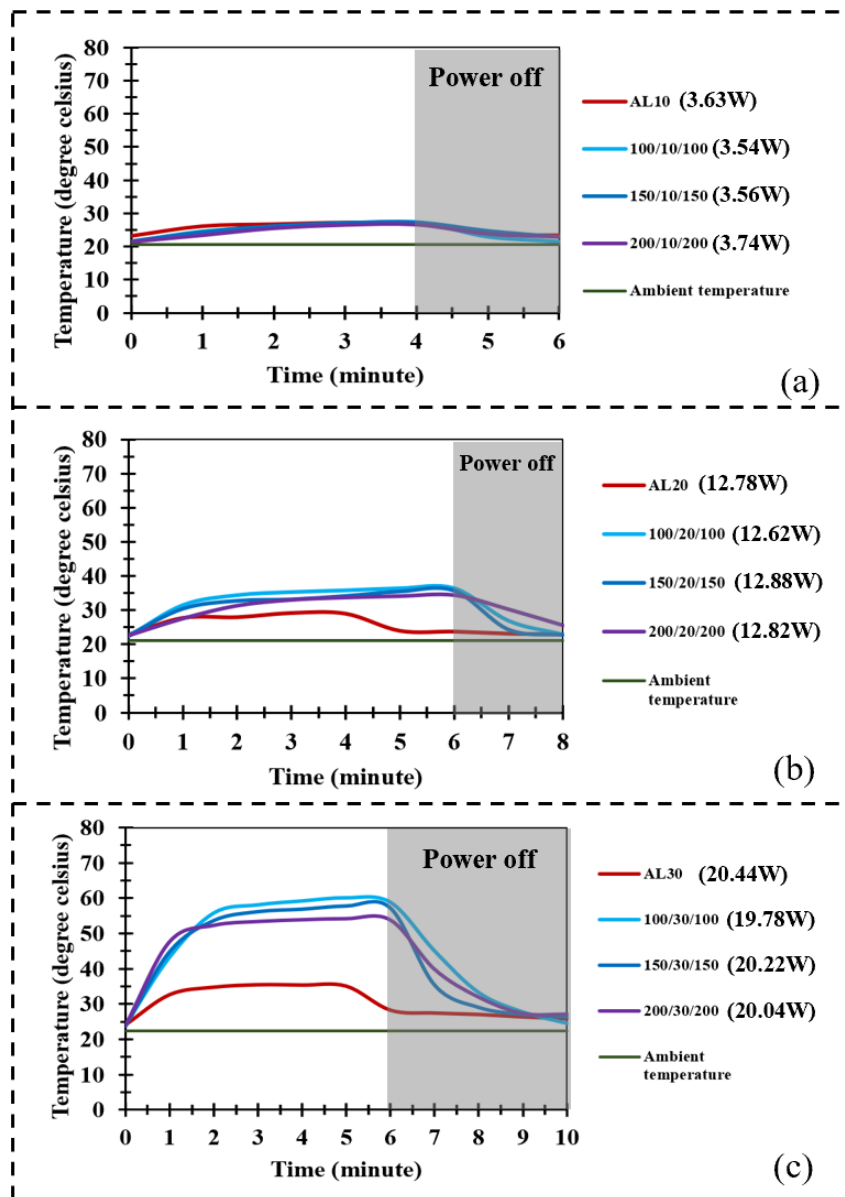
The 3D plots in Figure 6 further validate these trends: Figure 6(a) illustrates that thermal conductivity is influenced by both the copper content of the active layer and the acrylic binder content of the insulation layer, and Figure 6(b) confirms that thermal resistance increases with the material's thickness. Collectively, these results suggest that the designed sandwich-structured materials can achieve a balanced thermal management performance that allows for some degree of heat conduction via the copper-enhanced active layer material while maintaining strong insulation capability through the highly porous insulation layer components. Such tunable thermal properties are beneficial for multifunctional applications requiring both heat retention and heat dissipation control.

#### 4.5 Ohmic-heating performance

Ohmic heating refers to the generation of heat as an electric current passes through a conductive material [53]. Owing to the surface distribution of copper nanoparticles, the AL materials in this study exhibit a measurable ohmic heating effect. As shown in Figure 7, samples AL10, AL20, and AL30 were subjected to low-voltage loading in the heating test: 1.5 V for AL10 and 2.0 V for both AL20 and AL30. The applied voltages were intentionally limited to prevent thermal degradation or burning of the samples due to excessive heat generation. Based on the above-mentioned loaded voltage, three samples (AL10, AL20, and AL30) were subjected to ohmic-heating tests at power conditions of 3.63 W, 12.78 W, and 20.44 W, respectively. At the lowest input power of approximately 3.63 W, sample AL10 exhibited negligible temperature rise, with the surface temperature remaining below 25 °C throughout the 4-minute heating cycle. For sample AL20, which was subjected to medium power, the thermal response did not show a significant increase compared to AL10. The surface temperature steadily increased to approximately 28 °C within 4 minutes of power application, followed by a gradual cooling phase after the power was shut off. In contrast, sample AL30-tested under the highest power input of 20.44 W-demonstrated a rapid thermal response, reaching peak temperatures close to 35 °C within two minutes. This indicates that sample AL30 was capable of moderate and stable heating, with improved conductivity and heat generation compared to samples AL10 and AL20. This modest temperature rise can be attributed to the minimal thickness of the AL materials, which results in rapid heat dissipation into the surrounding air. Consequently, these materials alone are insufficient for effective thermal management. However, when integrated within a multilayer sandwich structure, they are expected to perform more effectively by simultaneously generating and retaining heat, thereby enhancing the overall thermal performance of the composite system.

To evaluate the ohmic-heating behavior of the sandwich-structured materials, temperature–time profiles under varying power inputs were recorded, as shown in Figure 7. At a low power level of approximately 3.6 W [Figure 7(a)], all tested samples exhibited minimal temperature increases, with maximum surface temperatures remaining below 30 °C after 4 minutes of continuous power supply. In contrast, samples subjected to a moderate power level of approximately 12.8 W [Figure 7(b)] demonstrated noticeable temperature increases, with peak surface temperatures ranging from 35 to 40 °C. The heating curves reached a plateau within 5 minutes and displayed a gradual decline after power-off, indicating effective yet moderate heating behavior. Notably, the heating performance among different samples remained relatively consistent, confirming the material's stability under intermediate power conditions. At a high power input of approximately 20.2 W [Figure 7(c)], the samples exhibited a rapid and pronounced rise in surface temperature, reaching values exceeding 60 °C within 2 to 3 minutes. After the power was turned off, the temperature dropped quickly, showing satisfactory thermal responsiveness. A comparison of the results shown in the corresponding figures reveals that the ohmic heating temperatures of the

sandwich-structured materials with AL20 and AL30 were substantially higher than those of the standalone AL20 and AL30 materials. This finding underscores the effectiveness of the sandwich configuration in enhancing heat retention.

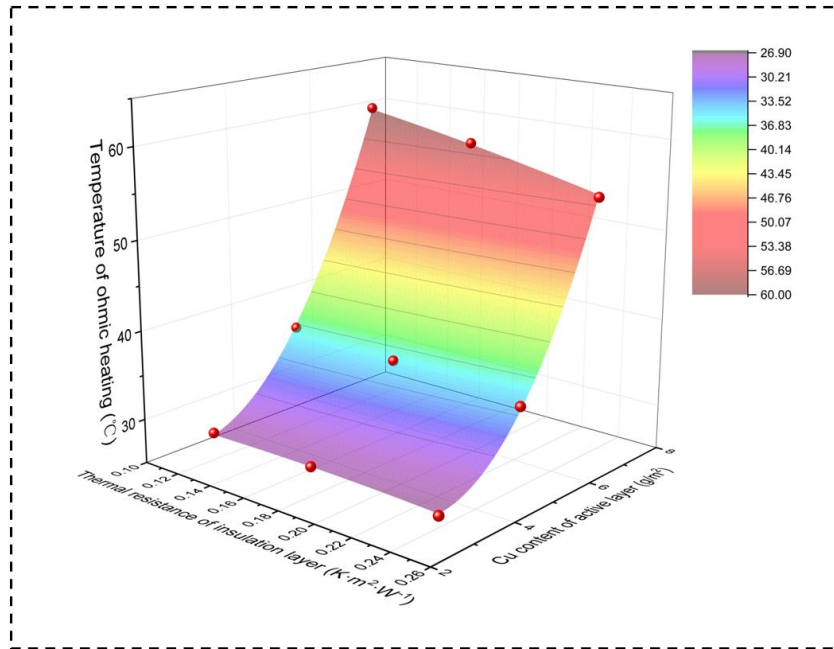


**Figure 7. Ohmic-heating test results for sample AL10 and sandwich-structured materials with sample AL10 (a), sample AL20 and sandwich-structured materials with sample AL20 (b), sample AL30 and sandwich-structured materials with sample AL30 (c) [Adopted from publication A2]**

Furthermore, Table 7 and Figure 8 highlight the synergistic influence of the thermal resistance of the insulation layer and the copper content in the active layer on the resulting ohmic heating temperatures. Specifically, sandwich samples combining low thermal resistance in the insulation layer (i.e., improved heat retention) with a higher copper nanoparticle content in the active layer (i.e., enhanced heat generation) demonstrated superior heating performance. Collectively, these results confirm that the active layer materials can fully realize their ohmic heating potential when embedded within a sandwich structure, where heat generation and retention are effectively balanced.

**Table 7. Thermal resistance of insulation layer, copper plated content of active layer, and maximum temperature of ohmic heating for sandwich-structured materials [Adopted from publication A2]**

Sample code	Thermal resistance of insulation layer ( $K \cdot m^2/W$ )	Copper plated content of active layer ( $g/m^2$ )	Maximum temperature of ohmic heating ( $^{\circ}C$ )
100/10/100	0.1147	3	27.4
100/20/100	0.1147	5	36.4
100/30/100	0.1147	7	60.1
150/10/150	0.1733	3	27.3
150/20/150	0.1733	5	35.6
150/30/150	0.1733	7	57.8
200/10/200	0.2423	3	26.7
200/20/200	0.2423	5	34.4
200/30/200	0.2423	7	54.2



**Figure 8. Relationship between the thermal resistance of the insulation layer, the copper-plated content of the active layer, and the maximum temperature of ohmic heating for sandwich-structured materials [Adopted from publication A2]**

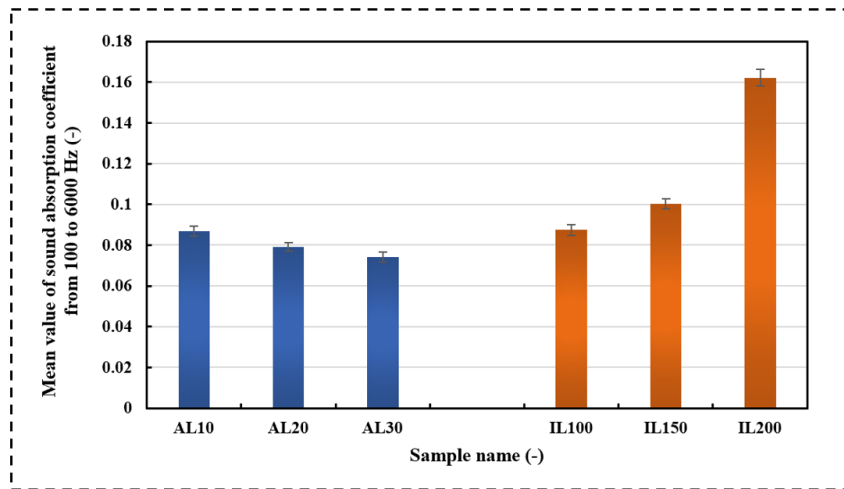
#### 4.6 Acoustic absorption coefficient

The sound absorption coefficient is a key parameter used to quantify a material's capacity to absorb acoustic energy. Defined as the ratio of absorbed sound intensity to incident sound intensity, it ranges from 0 to 1. Materials with higher values demonstrate superior performance in minimizing sound reflections and controlling reverberation, thereby enhancing acoustic comfort and noise reduction in various applications [54] [55]. In this part, the two-microphone impedance tube device was utilized to ascertain the sound absorption coefficient of circular samples in a laboratory setting. The method is based on assessing the sound absorptive characteristics of materials at a normal incidence of sound waves. The mean value of sound absorption coefficients from 100 to 6000 Hz of the AL and IL samples can be observed in Figure 9. And the calculation for the mean value of sound absorption coefficients is

shown in Equation (2):

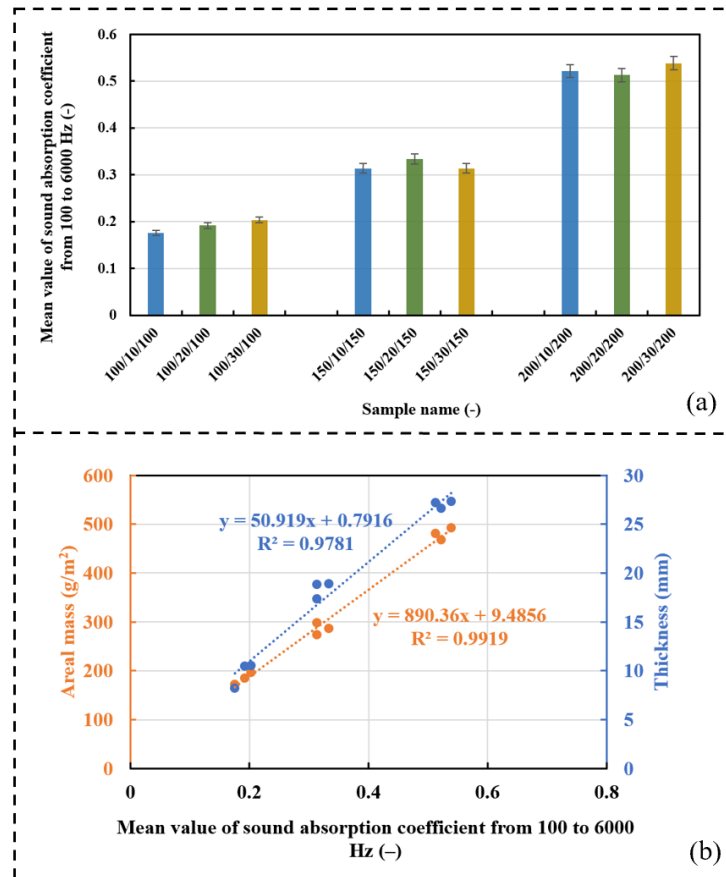
$$\alpha_{mean} = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} \alpha(f) \times df \quad (2)$$

Where,  $f_2$  is the upper frequency (6000Hz),  $f_1$  is the lower frequency (100Hz), and  $\int_{f_1}^{f_2} \alpha(f) \times df$  is the area under the absorption curve over the frequency range from  $f_1$  to  $f_2$ . The mean value of sound absorption coefficients of the samples AL and IL from the 100 to 6000 Hz range are all below 0.2. Based on the findings of other researchers, it is shown that materials with sound absorption coefficients greater than 0.2 can be used as acoustic absorbers [56]. Therefore, the materials used in this experiment do not have sound-absorbing properties alone, but their sound absorption coefficients can be greatly improved by combining them and changing their structures.



**Figure 9. The mean value of sound absorption coefficient from 100 to 6000 Hz of the AL and IL samples**

Figure 10(a) presents the mean sound absorption coefficients of sandwich samples within the frequency range of 100 to 6000 Hz. A clear upward trend is observed, indicating a progressive improvement in acoustic performance across the sample series. Sandwich samples with IL100 exhibit relatively low mean absorption coefficients, approximately 0.15-0.20, suggesting limited capability to dissipate sound energy. In contrast, sandwich samples with IL150 show a marked enhancement, reaching values around 0.30-0.35. Notably, sandwich samples with IL200 demonstrate the highest performance, with mean sound absorption coefficients approaching 0.50-0.55, representing a two to threefold increase compared to other samples. The superior sound absorption of samples with IL200 may result from the optimized multilayer configuration, which enhances energy dissipation mechanisms across a broad frequency range. Figure 10(b) further illustrates strong positive correlations between the mean value of sound absorption coefficient from 100 to 6000 Hz and both areal mass and thickness. Linear regression analysis yielded an  $R^2$  value of 0.9919 for areal mass and 0.9781 for thickness, suggesting that areal mass plays a more dominant role in enhancing acoustic absorption. These findings confirm that optimizing the thickness and density of sandwich-structured materials is an effective strategy for improving their sound absorption performance, especially for applications requiring efficient mid-to-high frequency noise mitigation.



**Figure 10. The mean value of sound absorption coefficient from 100 to 6000 Hz of sandwich-structured materials (a) and the relationship between the areal mass, thickness, and mean value of sound absorption coefficient from 100 to 6000 Hz for sandwich-structured materials (b)**

As shown in Table 8, sample 200/30/200 exhibits a maximum sound absorption coefficient of 0.78, which is comparable to other widely used acoustic materials such as melamine-formaldehyde foam and polyester fiber panels. More importantly, unlike traditional materials like glass wool or PU foam that pose environmental and health risks due to microplastic release or flammability, sample 200/30/200 is recyclable, non-toxic, and free from dust or microplastic hazards. These advantages make sample 200/30/200 a promising eco-friendly alternative for sound-absorbing applications.

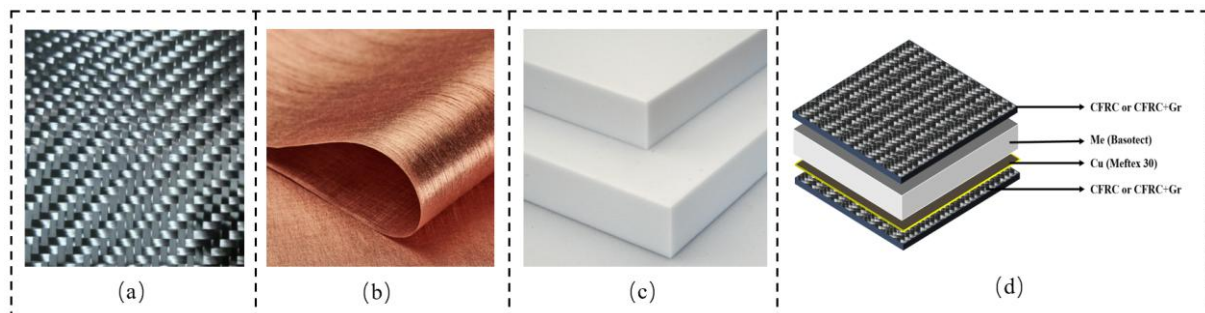
**Table 8. The maximum sound absorption coefficient and features of sample 200/30/200 compared to that of other leading research materials [57] [58]**

Sample name	Maximum sound absorption coefficient	Pros and Cons
Rock wool	0.85 – 0.95	Non-degradable; Generate fiber dust; Health hazards
Melamine-formaldehyde foam	0.75 – 0.95	Non-degradable; Microplastic pollution
PU foam	0.3 – 0.7	Non-degradable; Flammable; Health hazards
Polyester fiber acoustic panel	0.4 – 0.8	Non-biodegradable; Recyclable; Non-toxic
Sample 200/30/200	0.78	Non-biodegradable; Recyclable; Non-toxic

## 5. Rigid-textured sandwich composites

### 5.1 Materials and fabrication

A range of materials with distinct structural and functional properties was selected for the preparation of rigid-textured sandwich composites in this part (B). The carbon fabric (Havel Composite) is a plain-weave textile with high surface density and moderate thickness, providing both mechanical strength and electrical conductivity. Meftex 30 (Bochemie) is a copper-coated nonwoven polyester (PET) fabric that enhances EMI shielding effectiveness and ohmic heating performance. Basotect (BASF), a lightweight melamine-formaldehyde foam, was used for thermal insulation due to its extremely low density. Graphite particles (Sigma Aldrich) with a size less than 45  $\mu\text{m}$  were incorporated to enhance electrical conductivity. CHS Epoxy 200 (Havel Composite), a low molecular weight water-dispersed epoxy resin, served as the binding matrix. This water-dispersible epoxy resin matrix exhibits a highly positive effect on the wetting of carbon fabric. Under catalytic conditions, it can undergo crosslinking at a specific temperature without the need for a curing agent. Additionally, due to its relatively low viscosity, the new matrix is more suitable for dispersing doped particles. The fundamental physical properties of the untreated samples are summarized in Table 9 and the schematic diagram of materials are presented in Figure 11.



**Figure 11. Schematic diagram of Carbon fabric (a), Meftex 30 (b), Basotect (c), and sandwich-structured composites with four layers (d) [Adopted from publication A4]**

**Table 9. Basic information of carbon fabric, Meftex 30, Basotect, graphite particle, and CHS Epoxy 200 [Adopted from publication A4]**

Sample Name	Description	Areal mass ( $\text{g}/\text{m}^2$ )	Thickness (mm)	Density ( $\text{kg}/\text{m}^3$ )	Supplier
<b>Carbon woven fabric</b>	Plain weave carbon fabric	245.01 $\pm$ 1.21	0.43 $\pm$ 0.04	570	Havel Composite
<b>Meftex 30</b>	Cu coated nonwoven PET fabric	34.88 $\pm$ 0.94	0.14 $\pm$ 0.01	250	Bochemie
<b>Basotect</b>	Melamine-formaldehyde foam	68.87 $\pm$ 1.26	5.94 $\pm$ 0.02	10	BASF
<b>Graphite particle</b>	Particle size < 45 $\mu\text{m}$	-	-	8940	Sigma Aldrich
<b>CHS Epoxy 200</b>	Water dispersion of a low molecular weight epoxy resin	-	-	-	Havel Composite

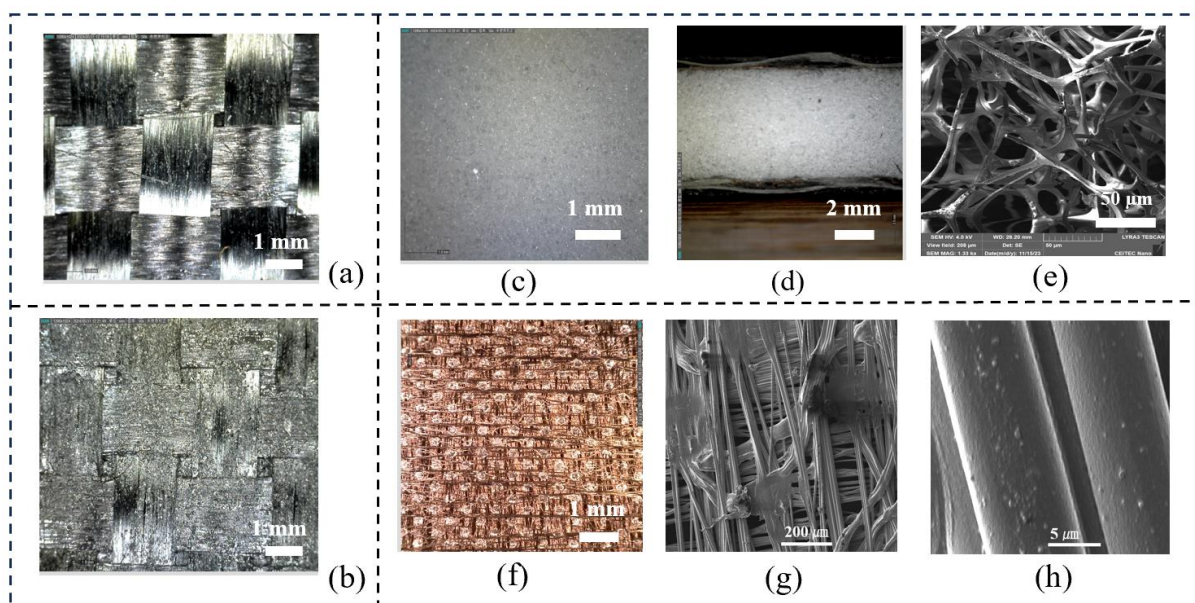
The carbon fabric-reinforced composite (CFRC) was fabricated using a hot press molding technique. Initially, the epoxy resin matrix was prepared by incorporating 10 wt% of the catalyst potassium thiocyanate (KSCN). To ensure comparability of composite properties, the carbon fabric (CF) content was maintained at approximately 60 wt% across CFRC. The prepared resin matrix was manually applied onto the pre-arranged CF layers using a hand lay-up method. Excess resin was subsequently expelled from the fiber layers using a hand-rolling tool to ensure uniform impregnation. The resulting preform laminates were allowed to rest at ambient conditions for 24 hours to facilitate stabilization and water evaporation. And then the samples were subjected to a preliminary curing step in an oven at 80°C for 1 hour. Finally, the semi-cured composites were hot-pressed at 140°C for 30 minutes using a heated hand press to complete the curing and consolidation process. To enhance the electrical conductivity of the matrix, 10 wt% graphite particles were mixed with the matrix system via magnetic stirring for 30 min. For the samples with graphite particles, the prepared matrix system was applied onto a single layer by the same procedure as in the other samples. Spray adhesive (3M Super 77) finally bonds the finished carbon fiber reinforced composite, Meflex 30 and Basotect together to create the sandwich-structured composites. Table 10 is presented the basic information of sandwich-structured composites with different combination and Figure 10(d) is shown the schematic diagram of sandwich-structured composites with four layers.

**Table 10. Basic information of sandwich-structured composites with different combinations [Adopted from publication A4]**

Sample Name	Description	Areal mass (g/m <sup>2</sup> )	Thickness (mm)	Density (kg/m <sup>3</sup> )	Structure
<b>CFRC</b>	Carbon fabric-reinforced composite	613.15	0.81±0.08	760	Two layers
<b>CFRC/Cu</b>	Carbon composite with Cu-coated PET as the middle layer	717.89	0.77±0.11	920	Three layers
<b>CFRC/Me</b>	Carbon composite with melamine-formaldehyde foam as the middle layer	787.57	7.02±0.21	110	Three layers
<b>CFRC/Cu/Me</b>	Carbon composite integrated with Cu-coated PET and melamine-formaldehyde foam in the middle	828.83	8.11±1.21	110	Four layers
<b>CFRC+Gr</b>	Carbon fabric-reinforced composite with the graphite particles-mixed matrix	651.24	0.98±0.11	670	Two layers
<b>CFRC+Gr/Cu</b>	Carbon composite with the graphite particles-mixed matrix and Cu-coated PET as the middle layer	718.74	0.78±0.06	920	Three layers
<b>CFRC+Gr/Me</b>	Carbon composite with the graphite particles-mixed matrix and melamine-formaldehyde foam as the middle layer	735.07	7.73±0.21	100	Three layers
<b>CFRC+Gr/Cu/Me</b>	Carbon composite with the graphite particles-mixed matrix and Cu-coated PET and melamine-formaldehyde foam in the middle	824.05	7.62±0.03	110	Four layers

## 5.2 Basic physical and morphological characterization

The basic physical and morphological characteristics of the sandwich-structured composites are detailed in Table 10 and Figure 12. Figures 12(a and b) depict an even distribution of the epoxy matrix on the fiber surfaces following the fabrication process. The CFRC+Gr samples had physical characteristics similar to those of no-particle-mixed samples. However, the microscope picture revealed an increase in surface roughness compared to the CFRC samples. Due to the limited number of mixed graphite particles, the change in density of the CFRC+Gr group samples was not significant compared to that of the no-particle-mixed samples. The surface and cross-section structures of Basotect is shown in Figures 12(c and d). Figure 12(f) illustrates the structure of Meftex 30, which displays a typical nonwoven fabric configuration. It produced horizontal and vertical filaments as nonwoven structured fabrics by employing a thermal bending method. The coated Cu particles on the PET filament were also evident in the SEM images of Figure 12(h).



**Figure 12. Schematic diagram of surface morphology: CFRC surface (a), CFRC+Gr surface (b), Basotect surface structure (c), Basotect cross-section structure (d), SEM picture of Basotect with fiber distribution (e), Meftex 30 surface structure (f), SEM picture of Meftex 30 with fiber distribution (g), Cu particle distribution on PET fibers of Meftex 30 (h) [Adopted from publication A4]**

The sandwich-structured composites demonstrated significant variations in thickness, density, and areal mass depending on the type and number of intermediate layers. The hot-pressing process of the CFRC series yielded a comparatively thin composite material. Using graphite particles in the mix slightly raised the areal mass while keeping the densities low, providing a good balance between being lightweight and improving functionality. Samples incorporating Basotect exhibited substantial thickness and low density, making them suitable for thermal insulation applications. In contrast, the inclusion of Meftex 30 led to higher density and areal mass, suggesting enhanced structural compactness. Overall, all samples exhibited densities below  $1 \text{ g/cm}^3$ , signifying a density less than that of water. It means the tailored combination of intermediate layers allowed precise control over the composite architecture and physical properties.

### 5.3 Electromagnetic interference (EMI) shielding performance

In the fields of aerospace, electric vehicles, etc., high-performance composite materials are realizing the integration of structure and shielding functions, becoming an important material to support key technologies and information security [59]. Therefore, the EMI shielding performance of the composite material was rigorously evaluated and presented in the Figure 13. Carbon fabric materials exhibit commendable electrical conductivity, enabling the unprocessed carbon fabric to achieve an EMI shielding effectiveness of approximately 60 dB. After integration with a resin matrix, the EMI shielding performance of the carbon fiber-reinforced composite remained largely unchanged at around 60 dB. This stability in shielding effectiveness is attributed to the preservation of the conductive network formed by the carbon fabric during composite fabrication. Previous studies have also shown that Meftex 30 possesses excellent EMI shielding capabilities, with a performance of approximately 53 dB. When two layers of CFRC and a single layer of Meftex 30 or Basotect were configured into a sandwich structure, a significant enhancement in EMI shielding effectiveness was observed. Specifically, the sample CFRC/Cu showed an average shielding effectiveness of 83.66 dB from 30 MHz to 3 GHz, which is a 25.1% increase compared to sample CFRC. The sample CFRC/Me also demonstrated superior EMI shielding, with an average shielding effectiveness of approximately 87.47 dB. In the complex multilayered structure comprising CFRC/Cu/Me, the highest shielding effectiveness value reached 88.27 dB. After adding the graphite particles to the mix, the sample CFRC only improved slightly by 1.57 dB compared to the sample CFRC+GR, and the shielding effectiveness improvement in all the other samples was not significant. The zigzag waveform observed in the signal of Figure 13 can be attributed to the interference and diffraction of electromagnetic waves, leading to the superposition of wave crests and troughs. This phenomenon is a direct result of multiple internal reflections within the sandwich structure, where the introduction of an intermediate layer between conductive materials increases the spacing and thus promotes multilayer internal reflection [60].

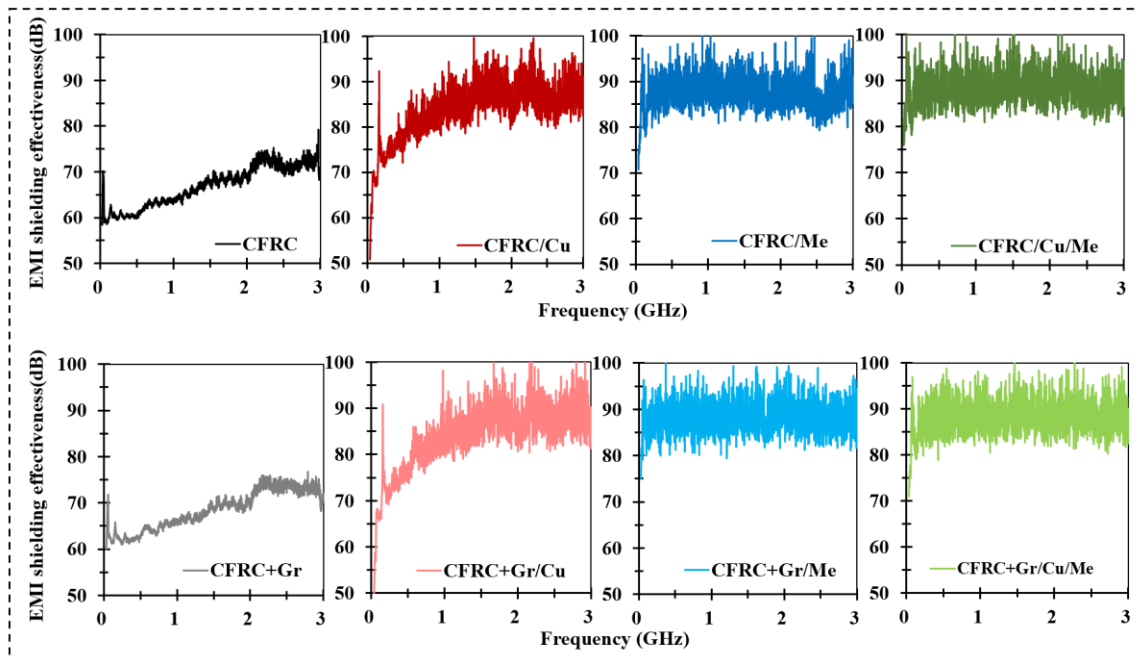
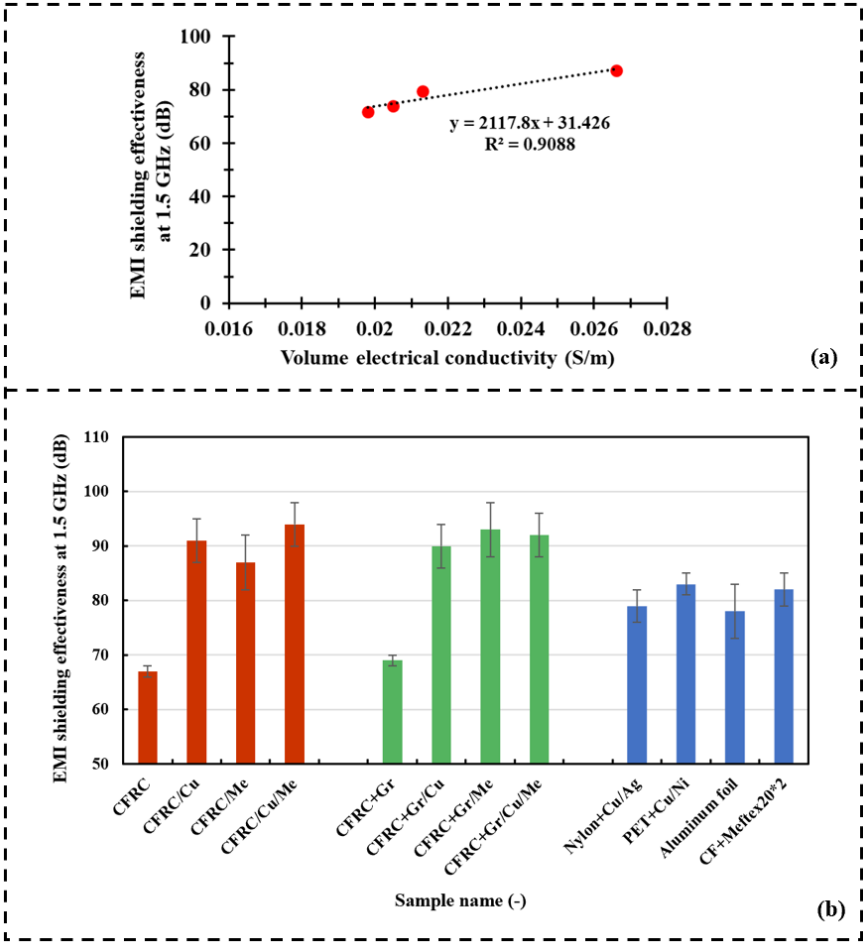


Figure 13. EMI shielding effectiveness of sandwich-structured composites from 30 MHz to 3 GHz  
[Adopted from publication A4]

Several studies have confirmed that enhancing electrical conductivity can lead to increased EMI shielding effectiveness values [46]. However, due to the high electrical resistivity of Basotect ( $>10^6 \Omega \cdot m$ ), the electrical conductivity of samples CFRC/Me and CFRC+Gr/Me was not measured. In comparison, the EMI shielding effectiveness values of CFRC, CFRC/Cu, CFRC+Gr, and CFRC+Gr/Cu samples increased significantly, and this increase was directly related to their electrical conductivity. Notably, the EMI shielding effectiveness was found to have a positive relationship with electrical conductivity, as illustrated in Figure 14(a). The EMI shielding effectiveness of various sandwich-structured composite and other leading research materials was compared at 1.5 GHz and shown in Figure 14(b) [45]. This part analysis selects the value at 1.5 GHz for comparison because this frequency of the electromagnetic spectrum is most commonly exposed in daily life and work environments. Notably, the CFRC/Cu/Me composite achieved the highest shielding effectiveness of 94 dB, indicating a strong synergistic effect between copper and melamine-formaldehyde foam in enhancing electromagnetic attenuation. Other multilayer structures, such as samples CFRC+Gr/Me and CFRC+Gr/Cu/Me, also demonstrated excellent EMI shielding performance (above 90 dB). In contrast, other leading research materials showed moderate EMI shielding effectiveness values (78–83 dB), all lower than the optimized CFRC-based composites.



**Figure 14. The relationship between EMI shielding effectiveness and volume electrical conductivity (a) [Adopted from publication A4] and the EMI shielding effectiveness at 1.5 GHz of sandwich-structured composites compared to that of other leading research materials (b)**

## 5.4 Thermal properties

In this part, thermal conductivity and thermal resistance are selected to characterize the thermal properties of the samples. As can be seen from Figure 15(a), the addition of material with copper coating significantly improves the thermal conductivity of the composite material, among which the CFRC/Cu and CFRC+Gr/Cu samples exhibit the higher thermal conductivity (around  $0.18 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ), indicating that it has excellent thermal conductivity. As mentioned in the last part, copper is the preferred material for many heat dissipation and thermal conduction applications. On the contrary, composites containing Basotect (Me) have significantly reduced thermal conductivity, showing excellent thermal insulation capabilities. They exhibited a thermal conductivity around  $0.05 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , which classifies it as an effective thermal insulation material. According to commonly accepted standards, materials with thermal conductivity values below  $0.1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  are generally considered suitable for insulation purposes. Although it isn't as low as the thermal conductivity of vacuum insulation panels ( $0.02\text{-}0.04 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ), this level of thermal performance is good enough for thermal protective layers and energy-efficient composite structures. The thermal resistance results in Figure 15(b) are inversely proportional to the thermal conductivity, further verifying this trend. In general, composites with Meflex 30 are suitable for structures with high requirements for heat dissipation performance, while composites with Basotect are more suitable for thermal insulation scenarios. In addition, adding graphite particles resulted in only marginal changes in thermal conductivity and thermal resistance. These limited variations may be attributed to the relatively low concentration and inhomogeneous distribution of the graphite particles within the matrix.

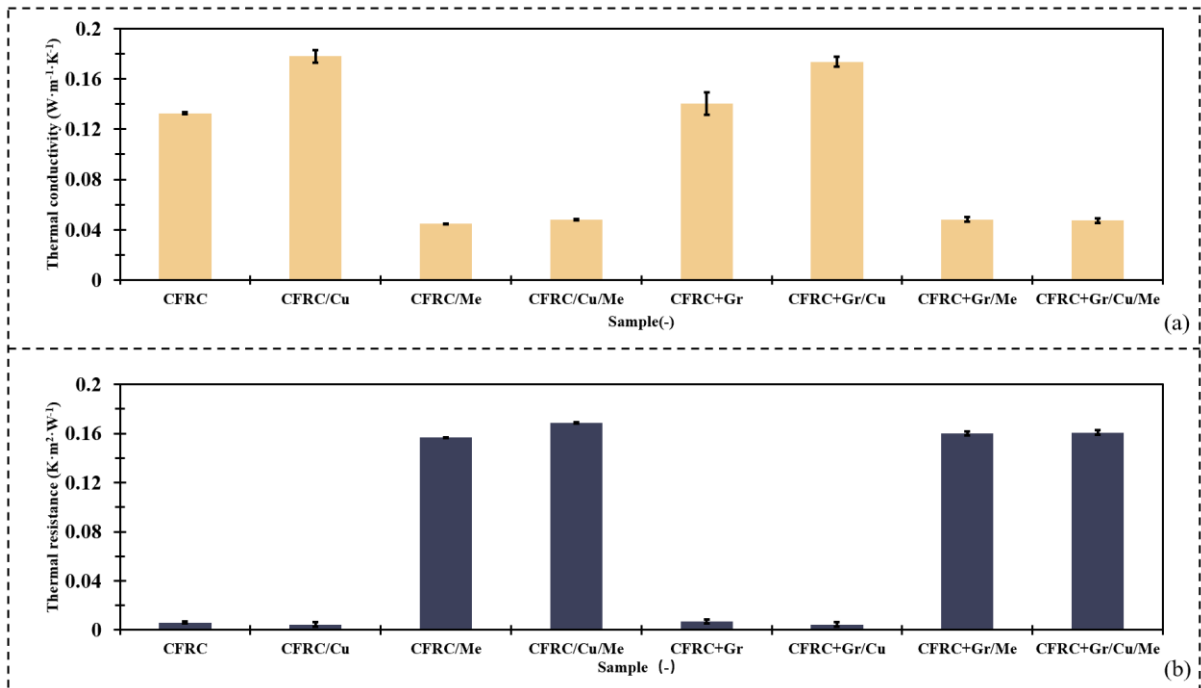
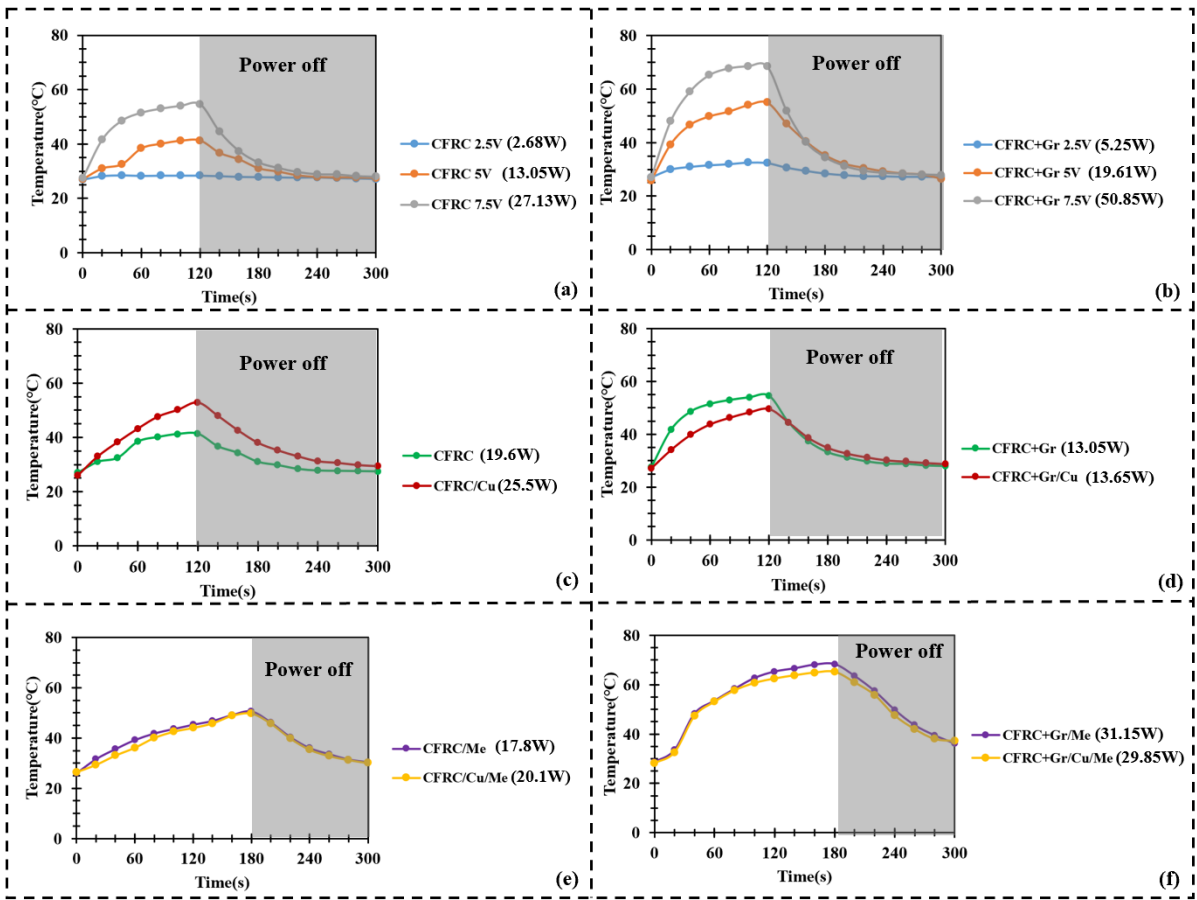


Figure 15. Thermal conductivity (a) and thermal resistance (b) of sandwich-structured composites  
[Adopted from publication A4]

## 5.5 Ohmic-heating performance

The conventional carbon fabric-reinforced composites possess limited electrical conductivity due to the presence of insulating resin, rendering them less effective for the ohmic heating effect [53]. By

incorporating conductive graphite particles into the resin matrix, the electrical conductivity of the composite can be significantly enhanced and enabling higher Joule heat output at relatively low voltages. Experimental results (refer to Figure 16a and 16b) demonstrated that the surface temperature of CFRCs increased with applied voltage. At 2.5 V, the temperature rise was minimal and deemed insufficient. Upon increasing the voltage to 5 V, the surface temperature of the CFRC sample reached 41.3°C after 120 seconds of electrification, while the CFRC+Gr sample showed a notably higher temperature of 55°C under the same conditions. When the voltage was further increased to 7.5 V, the temperatures rose to 54.6°C for CFRC and 68.5°C for CFRC+Gr, respectively. Based on the dynamic mechanical analysis results in previous research, all composites started to lose their mechanical properties at about 55°C, and their glass transition temperature was around 70°C. Therefore, a working voltage of around 5 V is considered optimal, as it ensures sufficient heat generation for temperature regulation without exceeding the thermal limits of the composite material, thus preserving its mechanical integrity.



**Figure 16. Ohmic-heating test results under different voltages for CFRC samples (a) and CFRC+Gr samples (b), CFRC series' (c and e) and CFRC+Gr series' (d and f) temperature changes after 300 s under a 5 V direct current [Adopted from publication A4]**

The ohmic-heating performance of the sandwich-structured composites was evaluated under different configurations shown in Figure 16(c, d, e and f). At an applied voltage of 5 V, the temperature of the CFRC sample stabilized at around 120 s, reaching a peak of approximately 41 °C. The CFRC/Cu composite exhibited a faster temperature rise and achieved a higher peak temperature of 52.8°C. For samples containing Basotect (melamine-formaldehyde foam), the temperature stabilization time was extended to approximately 180 s due to enhanced thermal resistance. Additionally, after the power

supply was cut off, the heat dissipation process in melamine-formaldehyde foam-containing composites was slower than in those without melamine-formaldehyde foam, confirming the melamine-formaldehyde foam's superior thermal insulation properties. When conductive graphite particles were incorporated, the peak temperature of all composites increased, particularly in foam-integrated samples. Notably, CFRC+Gr/Me reached 68.3 °C and CFRC+Gr/Cu/Me reached 65.2 °C after 180 s of electrification, both exceeding the threshold temperature (55 °C) at which mechanical degradation begins. Therefore, to ensure sufficient ohmic heating while avoiding damage to the material's mechanical integrity, an operating voltage range between 2.5 and 5 V is recommended. These results highlight the improved electrical conductivity of the composites, especially after the addition of graphite, and the beneficial thermal insulation effects of melamine-formaldehyde foam.

## 5.6 Mechanical properties

The mechanical properties of composite materials are crucial as they determine the material's strength, stiffness, and durability under various loading conditions. Therefore, mechanical performance is a key criterion for evaluating and applying composite materials effectively [61]. The tensile test was applied to the developed composite material to compare it with commonly used metal materials, and the results are presented in Table 11. For CFRCs without melamine-formaldehyde foam incorporation, the tensile strength ranged from 197.6 to 295.1 MPa, and the tensile modulus ranged from 2.7 to 5.5 GPa. Upon integrating melamine-formaldehyde foam, a significant increase in cross-sectional area was observed. However, due to the markedly lower mechanical strength of melamine-formaldehyde foam compared to carbon fiber composites, the tensile strength of the melamine-formaldehyde foam-integrated composites was substantially reduced compared to that of pure CFRCs or CFRCs reinforced with graphene. The inclusion of graphite particles was also found to significantly enhance the tensile properties of the composites. When comparing CFRC with CFRC+Gr and CFRC/Cu with CFRC+Gr/Cu, the tensile strength increased by 12.2% and 49.3%, respectively. According to previously published studies, this improvement can be attributed to the incorporation of graphite particles into the resin matrix, which improves the interfacial bonding between the carbon fibers and the matrix. Enhanced interfacial bonding promotes more efficient stress transfer, thereby contributing to the overall increase in composite strength.

**Table 11. Tensile test results of sandwich-structured composites compared with those of metal materials**

Sample Name	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at break (%)
CFRC	207.1±11.4	3.8±0.03	2.86
CFRC/Cu	197.6±20.6	2.7±0.3	2.05
CFRC/Me	18.3±1.3	0.4±0.03	2.61
CFRC/Cu/Me	17.6±0.3	0.3±0.03	2.95
CFRC+Gr	232.4±7.7	4.2±0.2	4.35
CFRC+Gr/Cu	295.1±32.2	5.5±0.3	4.06
CFRC+Gr/Me	17.8±1.4	0.3±0.01	3.32
CFRC+Gr/Cu/Me	14.1±2.1	0.3±0.05	3.21
6061-T6 Aluminum alloy	310-350	68-70	8-12
Stainless steel (304)	520-750	190-200	45-55
Ti-6Al-4V Titanium alloy	880-950	110-120	8-15
Ultra-high-strength steel	1000-1750	190-220	4-12

The sample CFRC+Gr/Cu exhibited a tensile strength of  $295.1 \pm 32.2$  MPa, which is comparable to that of 6061-T6 aluminum alloy (approximately 310–350 MPa) [62]. When compared with other common structural metals, such as stainless steel (520–750 MPa), titanium alloy (880–950 MPa), and ultra-high-strength steel (1000–1750 MPa), the composite materials exhibit lower absolute tensile strength and much lower stiffness. However, their advantages in terms of lightweight design, multifunctionality (e.g., thermal insulation, ohmic heating, EMI shielding), and design flexibility make them promising candidates for mid-load applications in automotive, aerospace, and structural shielding systems where functional integration is prioritized over maximum mechanical strength.

## 6. Conclusion

This dissertation presents a comprehensive comments and synthesis of my first-author publications in scientific journals, all of which are closely aligned with the core subject of my Ph.D. research. These journals are indexed in the Journal Citation Reports and hold Q1 or Q2 quartile rankings. This study systematically developed and characterized two types of multifunctional sandwich-structured textile materials tailored for applications in personal protection, construction, automotive, and aerospace industries. By adopting a modular design strategy and integrating functional components into layered textile or composite systems, the research addressed several critical challenges faced by traditional sandwich structures, including limited multifunctionality, complex fabrication, poor recyclability, and insufficient structural integration.

The sandwich-structured materials with soft textures (A) developed in this study exhibited a highly effective combination of functional properties, including EMI shielding, thermal insulation, ohmic heating, and sound absorption. Specifically, the copper-coated polyester nonwoven fabrics served as both an EMI shielding layer and a conductive medium for ohmic heating, while the acrylic-bonded polyester nonwovens provided a porous and thermally resistive outer shell. Experimental results demonstrate that the sample ALs exhibit excellent shielding effectiveness from 48 to 61 dB, with EMI performance in sandwich structures dominated by the EM SE of sample AL. In terms of thermal behavior, increasing the copper content of sample AL will raise its conductivity. The thickness of the sample IL determines its thermal resistance, with a thicker layer providing superior insulation. This combination allows the composites to achieve both efficient heat conduction and strong insulation, making them promising for thermal management applications. Ohmic heating performance is also significantly improved in the sandwich configuration, with composites combining the higher copper content of sample AL and the higher thermal resistance of sample IL achieving surface temperatures up to  $60^{\circ}\text{C}$  under low voltage. Acoustic characterization further reveals that while individual AL and IL samples show poor sound absorption, the sandwich structures exhibit marked improvements in the mid-to-high frequency range, where thicker and heavier samples achieve higher absorption coefficients. This synergistic layering strategy ensured that the material could deliver multiple performance benefits without sacrificing flexibility or adding significant weight, making these materials suitable for wearable protection or smart architectural solutions.

In contrast, the sandwich-structured composites with rigid textures (B) were engineered to meet the demands of structural applications in the automotive and aerospace sectors. This design integrates carbon fiber-reinforced composite to provide superior mechanical strength and rigidity, melamine-formaldehyde foam as a lightweight and thermal insulation core, and copper-coated polyester fabric to achieve EMI shielding and ohmic heating functions. The study demonstrated that the electromagnetic

shielding tests revealed excellent performance, with the CFRC/Cu/Me configuration achieving an average shielding effectiveness of 88.27 dB across the 30 MHz–3 GHz frequency range, surpassing that of conventional metal materials. Thermal assessments indicated that CFRC/Cu composites offered the highest thermal conductivity, facilitating efficient heat dissipation. In contrast, composites containing melamine-formaldehyde foam offered greater thermal resistance, which is beneficial for insulation in cold environments. Furthermore, composites that contain graphite particles demonstrated effective Joule heating. And incorporating copper-plated polyester nonwoven significantly enhanced the stiffness and internal friction of the composites, while graphite addition improved electrical conductivity despite a reduction in initial modulus. Collectively, these results confirm that the sandwich-structured carbon fiber composites integrate mechanical strength, superior EMI shielding, tunable thermal management, and Joule heating capability, making them strong candidates for the automotive and aerospace sectors.

Overall, the results highlight that sandwich-structured textile materials can be effectively designed to provide tailored combinations of electrical, thermal, acoustic, and mechanical functions. The use of commercially available materials and scalable fabrication methods supports potential industrial applications. This work contributes a novel and sustainable pathway for next-generation textile-based composites, offering a foundation for further innovation in intelligent and eco-friendly material systems.

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## 8. List of publication by author

### 8.1 Journal articles

1. **Wang D**, Hu S, Kremenakova D, et al. The electromagnetic shielding effectiveness of the copper plated nonwoven fabric and its' related comfort properties. *Journal of Engineered Fibers and Fabrics*, 2022, 17: 15589250221133462. (Q1, IF:2.9)
2. **Wang D**, Hu S, Kremenakova D, Militky J. Evaluation of the wearing comfort properties for winter used electromagnetic interference shielding sandwich materials. *Journal of Industrial Textiles*. 2023;53. doi:10.1177/15280837231159869 (Q1, IF:3.2)
3. **Wang D**, Hu S, Kremenakova D, Militky J. Influence of washability treatment on the electromagnetic interference shielding material's comfort properties. *Journal of Engineered Fibers and Fabrics*. 2023;18. doi:10.1177/15589250231186940 (Q2, IF:2.9)
4. **Wang, D.**, Hu, S., Vecernik, J., Kremenakova, D., Militky, J., & Novotna, J. (2024). Impact of different matrix systems on mechanical, thermal, and electrical properties of carbon fiber reinforced epoxy resin matrix composites. *Polymer Composites*. (Q1, IF:4.8)
5. **Wang D**, Venkataraman M, Hu S, et al. Multifunctional sandwich materials with ROTIS structure for improved thermal and electrical properties in construction application. *Journal of Industrial Textiles*. 2024;54. doi:10.1177/15280837241271786 (Q1, IF:3.2)
6. Hu, S.; **Wang, D.**; Periyasamy, A.P.; Kremenakova, D.; Militky, J.; Tunak, M. Ultrathin Multilayer Textile Structure with Enhanced EMI Shielding and Air Permeable Properties. *Polymers* 2021, 13, 4176. <https://doi.org/10.3390/polym13234176> (Q1, IF:5)
7. Hu S, **Wang D**, Kyosev Y, et al. The novel approach of EMI shielding simulation for metal coated nonwoven textiles with optimized textile module[J]. *Polymer Testing*, 2022, 114: 107706. (Q1, IF:5.1)
8. Hu S, **Wang D**, Křemenáková D, Militký J. Washable and breathable ultrathin copper-coated nonwoven polyethylene terephthalate (PET) fabric with chlorinated poly-para-xylylene (parylene-C) encapsulation for electromagnetic interference shielding application. *Textile Research Journal*. 2023;0(0). doi:10.1177/00405175231168418 (Q2, IF:2.3)
9. Hu S, **Wang D**, Venkataraman M, et al. Enhanced electromagnetic shielding of lightweight copper-coated nonwoven laminate with carbon filament reinforcement. *Journal of Engineered Fibers and Fabrics*. 2023;18. doi:10.1177/15589250231199970 (Q1, IF:2.9)
10. Hu S, **Wang D**, Křemenáková D, et al. Mathematical modeling for electromagnetic shielding effectiveness characterization of metalized nonwoven fabrics. *Journal of Industrial Textiles*, 2023, 53: 15280837231219504. (Q1 IF:2.2)
11. Hu, S., **Wang, D.**, Vecernik, J., Křemenáková, D., & Militký, J. (2024). Electromagnetic Interference (EMI) Shielding and Thermal Management of Sandwich-Structured Carbon Fiber-Reinforced Composite (CFRC) for Electric Vehicle Battery Casings. *Polymers*, 16(16), 2291. (Q1, IF:5)
12. Hou Wang, Veronika Tunakova, Hu Shi, **Wang Dan**, et al. Sustainable Recycling of PET/Cotton Mixed Waste Fabrics: Mechanical Decomposition and Efficient Component Separation for Reuse [J]. *Polymer Testing*, 2025, 149: 108874. (Q1, IF:5.1)

### 8.2 Conference papers

13. **Dan Wang**, Shi Hu, Dana Kremenakova, Jiri Militky. Factors Influencing the Heat Transfer Performance of the Fabrics [C]. *Textile Bioengineering and Informatics Symposium Proceedings*

- (TBIS 2022). (DOI: 10.3993/tbis2022)
14. **Dan Wang**, Shi Hu, Dana Kremenakova, Jiri Militky. EFFECT OF ANTI-WASH TREATMENT ON THE WEARING COMFORT PROPERTIES OF THE EMI SHIELDING MATERIAL [C]. Strutex2022.
  15. **Dan Wang**, Shi Hu, Yordan Kyosev, Dana Křemanáková, Jiří Militký. ANALYSIS OF THE HEAT TRANSFER PROPERTY WITH THE SANDWICH FABRICS BASED ON ANSYS WORKBENCH AND ALAMBETA [C]. AUTEX 2022 Conference Proceedings, 978-83-66741-75-1. (DOI: 10.34658/9788366741751.90)
  16. **Dan Wang**, Shi Hu, Dana Kremenakova, Jiri Militky. Study on Modification of Carbon Fiber Reinforced Epoxy Resin Matrix Composites: A Review. [C]. Textile Bioengineering and Informatics Symposium Proceedings (TBIS 2023). (DOI: 10.3993/tbis2023)
  17. **Wang D**, Hu S, Venkataraman M, Kremenakova D, Militky J. Influence of ROTIS structure on sandwich material's thermal property for construction application[C], Autex 2024. Liberec,2024.
  18. Hu S, **Wang D**, Yang K, et al. Copper coated textiles for inhibition of virus spread[C]//13th Textile Bioengineering and Informatics Symposium, TBIS 2020. 2020: 84-91.
  19. S. Hu, **D. Wang**, et al., : Impact of Morphology and Content of Fly Ash Filler on the Mechanical Properties of Epoxy Resin Composites [C]//Proceedings of the 14th Textile Bioengineering and Informatics Symposium (TBIS 2021), 2021: 326-330.
  20. S. Hu, **D. Wang**, et al., : ID127 | Anti-microbial property and ohmic heating effect of copper loaded acrylic fabrics and fiber slivers [C]// Autex 2021 - Unfolding the Future, book of abstracts, (AUTEX 2021), 2021: 199-200.
  21. Shi HU, **Dan WANG**, Yordan KYOSEV, Ann-Malin SCHMIDT, Dana KREMENAKOVA. Statistical Fiber-Level Geometrical Model of Thin Non-Woven Structures [C]. TTPF 2021 IASIRO.(<https://doi.org/10.2478/9788366675735-017>) (Online publication on 01.2022)
  22. Shi Hu, **Dan Wang**, Dana Kremenakova, Jiri Militky, Yuanfeng Wang. Electromagnetic Interference Shielding Simulation of Copper Coated Polyester Non-Woven Fabric And Pore Size Adjusting[C]. Strutex2022.
  23. Hu S, **Wang D**, Vecernik J, et al. Sandwich structured carbon fiber composites with enhanced EMI shielding performance[C]//62nd International Conference of Machine Design Departments (ICMD 2022). Atlantis Press, 2024: 305-314.
  24. Shi Hu, **Dan Wang**, Mohanapriya Venkataraman, Dana Křemanáková<sup>1</sup>, Jiří Militký. Parylene-C encapsulated Cu coated nonwovens for thermotherapy application [C]. Autex 2024. Liberec,2024.
  25. Hou Wang, Veronika Tunáková, Jiří Militký, Shi Hu, **Dan Wang**. A Review of Chemical Recycling Methods for Waste Polyester [C]//17th Textile Bioengineering and Informatics Symposium, TBIS 2024. 2024: 170-176.

### 8.3 Book chapters

26. **Dan Wang**, Shi Hu, Dana Kremenakova, and Jiri Militky. Influence of fabric structure parameters on its heat transfer performance [M]. Selected topics in fibrous materials science. (Volume VI 2022-Book chapter 10) ISBN 978-80-7494-607-3
27. **Dan Wang**, Shi Hu, Dana Kremenakova, Jiri Militky and Guocheng Zhu. Effect of Textile Structure on Heat Transfer Performance [M]. Advanced Multifunctional Materials from Fibrous Structures, Book chapter 8, page 163-198. DOI: 10.1007/978-981-99-6002-6\_8.
28. Shi Hu, **Dan Wang**, Dana Křemanáková, Jiří Militký. Characterization and application of EMI shielding textiles [M]. Selected topics in fibrous materials science. (Volume VI 2022-Book chapter

- 9). ISBN 978-80-7494-607-3.
29. Hu S, **Wang D**, Kremenakova D, Militký J, et al. Copper-Coated Textiles for Viruses Dodging[M]//Textiles and Their Use in Microbial Protection. CRC Press, 2021: 235-250.
30. Hu, S., **Wang, D.**, Křemenáková, D., Militký, J. (2023). Characterization and Multifunction Application of Metalized Textile Materials. In: Militký, J., Venkataraman, M. (eds) Advanced Multifunctional Materials from Fibrous Structures. Advanced Structured Materials, vol 201. Springer, Singapore. [https://doi.org/10.1007/978-981-99-6002-6\\_7](https://doi.org/10.1007/978-981-99-6002-6_7)

## **9. Appendix-Full texts of commented articles**

*A1 The electromagnetic shielding effectiveness of the copper plated nonwoven fabric and its' related comfort properties*

*A2 Multifunctional sandwich materials with ROTIS structure for improved thermal and electrical properties in construction application*

*A3 Impact of different matrix systems on mechanical, thermal, and electrical properties of carbon fiber reinforced epoxy resin matrix composites*

*A4 Electromagnetic Interference (EMI) Shielding and Thermal Management of Sandwich-Structured Carbon Fiber-Reinforced Composite (CFRC) for Electric Vehicle Battery Casings*

## 10. Curriculum vitae

# Dan Wang

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### Education

Bachelor 09.2008-06.2012	Tiangong University, Faculty of Textile Science and Engineering Clothing Design and Engineering
Master 09.2012-02.2015	Hochschule Niederrhein, Faculty of Textile and Clothing Technology Management of Textile Trade and Technology
Master 09.2016-06.2018	Ghent university, Faculty of Engineering and Architecture Textile Engineering
PhD 10.2019-now	Technical University of Liberec, Faculty of Textile Engineering Textile Engineering

### Research Experience

05.2021-12.2025	Research Assistant Department of Material Engineering (KMI), Faculty of Textile Engineering, Technical University of Liberec
09.2021-02.2022	Research Intern Institut für Textilmaschinen und Textile Hochleistungswerkstofftechnik (ITM), TU Dresden

### Research Project

03.2021-12.2021	SGS-2021-6025, Effect of geometry and concentration of fly ash and laponite on impact and dynamic mechanical properties of filled epoxy matrix
05.2021-12.2022	HyHi project - Hybrid Materials for Hierarchical Structures (Reg. No. CZ.02.1.01/0.0/0.0/16_019/0000843)
03.2022-12.2022	SGS-2022-6012, Permeable and washable copper loaded nonwoven fabrics processed with Parylene encapsulation technology
03.2023-12.2023	SGS-2023-6375, Impact of different matrix systems on selected properties of carbon filaments reinforced composites
03.2024-12.2024	SGS-2024-6422, Mechanical decomposition of polyester textiles
03.2025-12.2025	SGS-2025-6544, Epoxy composites filled with mechanically decomposed waste textiles
01.2024-12.2025	GACR project - Advanced structures for thermal insulation in extreme conditions (Reg. No. 21-32510M)

### Additional Skills

**Computer skills:** Python, MATLAB, MS Office

**Language:** English (B2, IELTS 6), Chinese (Native speaker)

## 11. Recommendation of the supervisor

### Opinion of the supervisor on Ph.D. thesis of Dan Wang MSc.

Thesis title: **The Multifunctional Sandwich - structured Textile Materials**

Doctoral student Dan Wang submitted a dissertation for defense in the form of annotated published scientific articles in high-impact journals.

In the dissertation, two types of multilayer structures were designed and systematically investigated. One type of multilayer structure was a light, breathable and flexible sandwich consisting of an inner reflective active layer shielding electromagnetic radiation, which also allows heating (Meflex Bohemia s.r.o.), and outer insulating layers (acrylate-bonded nonwoven fabrics). Various combinations of sandwiches were created using different areal density of the mentioned layers so that they could be used both for clothing purposes and, for example, for interior panels. The influence of individual layers on the properties of the sandwich in terms of electromagnetic radiation shielding, heating possibilities, thermal conductivity and thermal resistance was shown.

Furthermore, the student designed eight different types of new multifunctional composites, which contained a reflective active layer (Meflex Bohemia s.r.o.), a conductive and mechanically reinforcing carbon fabric (Havel Composites) and an ultra-light, porous melamine-formaldehyde foam with increased acoustic and thermal insulation properties (BASF). From the combinations of the above layers, the student produced four-layer composites, for which she used a matrix of epoxy resin with carbon particles to further increase electrical conductivity. The student investigated the influence of the properties of the individual layers on the resulting properties of the composites. In this way, new very light, sufficiently mechanically resistant composites were created, which, as needed, shield electromagnetic radiation, allow heating and have suitable acoustic properties for use in the automotive or aerospace industry.

Overall, I evaluate the PhD student's dissertation as comprehensive, dealing with the necessary problems, making it possible to construct optimal multifunctional structures with increased efficiency of electromagnetic shielding, thermal and acoustic property for various fields of application in practice.

The language proficiency exhibited in the thesis is commendable and satisfies the standards expected at the doctoral level. Her exceptional abilities are evidenced by his publication record in journals with high-impact factors. Throughout his research tenure at TUL, she has presented her findings through the publication of 25 papers in journals with high-impact factors Q1, Q2, 5 book chapters, and 13 articles in conference proceedings. Throughout his academic pursuits, he demonstrated a high level of diligence and competency.

The findings of the dissertation are valuable, innovative, and readily applicable in practical settings. For the reasons stated, I recommend that the dissertation be submitted for the final defense of the doctoral

thesis.

During the plagiarism check, 8% similarities was found with Shi Hu's habilitation. He used similar EMI shielding measurement methods, but this information does not affect the original results of Dan Wang's dissertation. These are formal matters, declarations that are the same for all works (copyright, acknowledgement of projects), identification of authors of publications, citations of publications, projects, standards, patents, names of quantities, technologies, chemicals, fibers and statistical characteristics. The same is the case in other similarities of 2 % and smaller.

Liberec February 22, 2026

Doc Dr. Ing. Dana Křemenáková  
Supervisor

## 12. Opponent's reviews

### Assessment of PhD Thesis

<b>Aspirant:</b>	Dan Wang, M.Sc.
<b>Thesis title:</b>	The Multifunctional Sandwich-structured Textile Materials
<b>Specialization:</b>	P0723D270003 Textile Engineering
<b>Supervisor:</b>	doc. Dr. Ing. Dana Křemenáková
<b>Reviewer:</b>	doc. Ing. Antonín Potěšil, CSc.

<b>Topicality of the thesis</b>									
Comment:									
The topic of the submitted dissertation is topical and respects current and future innovative trends that are moving towards the use of sandwich textile material structures focused on multifunctionality in the areas of electromagnetic shielding, thermal insulation, and resistance heating. The aim is to apply and use them in consumer and industrial sectors with demanding environmental and climatic conditions.									
excellent <sup>1</sup>	<input checked="" type="checkbox"/>	above standard	<input type="checkbox"/>	standard	<input type="checkbox"/>	substandard	<input type="checkbox"/>	weak	<input type="checkbox"/>

<sup>1</sup> Mark selected with a cross

<b>Meet the objectives of the thesis</b>									
Comment:									
The submitted dissertation has a well-written descriptive section and explains the approaches to the preparation and testing of two types (A, B) of the sandwich textile material structures in question. The thesis has good factual content, listing the laboratory experimental technologies used, which are focused on increasing functionality in "A-interiors in the consumer industry" and "B-exterior in technical industries." Chapter 9 is conceived as an appendix, consisting of the full text of four articles published in leading journals.									
After reviewing the dissertation as a whole, it can be concluded that the defined objectives and intentions of the doctoral student have been fulfilled.									
excellent	<input type="checkbox"/>	above standard	<input checked="" type="checkbox"/>	standard	<input type="checkbox"/>	substandard	<input type="checkbox"/>	weak	<input type="checkbox"/>

<b>Methods and solutions</b>									
Comment:									
A number of physical testing methods and procedures were used to characterize the properties of the textile structures prepared and tested by the dissertation author, using the experimental equipment listed. Both the dissertation itself and related publications clearly demonstrate the author's team-based approach to the experimental activities used.									
excellent	<input type="checkbox"/>	above standard	<input checked="" type="checkbox"/>	standard	<input type="checkbox"/>	substandard	<input type="checkbox"/>	weak	<input type="checkbox"/>

Results of the Thesis - specific benefits of the student					
Comments: The main contribution of the dissertation is the identification and comparison of the properties of the studied textile structures under various conditions of their use in reality, both in interior and exterior applications. The results of the experimental findings are statistically processed and provide useful information for practical use.					
excellent	above standard	<input checked="" type="checkbox"/>	standard	substandard	weak

Significance for practice and for the development of the scientific branch					
Comments: This work provides a good basis for further research and development activities in the field of using these textile structures in various industrial applications. I recommend that follow-up work focus more deeply on the theoretical areas of the physical properties of composite materials, both with regard to follow up processing technologies in product manufacturing and their specific applications in industrial practice.					
excellent	<input checked="" type="checkbox"/>	above standard	standard	substandard	weak

Formal layout of the Thesis and its language level					
Comments: The work has a logical structure, the English text is comprehensible, and the Czech version of the abstract has no editing errors.					
excellent	<input checked="" type="checkbox"/>	above standard	standard	substandard	weak

Comments, questions, recommendations
<p>1. As stated in the thesis, the mechanical properties of the tested sandwich textile material structures were identified using the DMA method in the temperature range of approximately 25-130-280-250 °C. As part of your thesis defense, characterize the significance of the evaluated variables "storage modulus" and "loss modulus" and their practical applicability. Also indicate the dynamic modes under which the DMA experiments were performed and the reasons for such decisions.</p> <p>2. For possible predictive CAE/FEM simulations, which are commonly required in practice, composite structures must be considered as anisotropic or orthotropic material continua. Using which relationships given in solid continuum mechanics are the relationships between stress and strain described in such cases, which are the result or response to the loading conditions of the relevant manufactured product during its use? Give examples.</p>

Final evaluation of the Thesis
Based on the above review I recommend submitting thesis for defense in front of the scientific committee for the defense of doctoral thesis.

I recommend after a successful defense of the dissertation grant Ph.D. <sup>2</sup>	yes	<input checked="" type="checkbox"/>
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<sup>2</sup> Delete where applicable

Place and Date: In Liberec 15.12.2025

Signature: Antonín Potěšil

## Opponent review of PhD Thesis

**Opponent:** Ing. Karel Kupka, PhD.&PhD.

**Dissertation Thesis:** *The Multifunctional Sandwich-structured Textile Materials*

**Author:** Dan Wang, M.Sc.

**Study programme:** P0723D270003 Textile Engineering

**Thesis Supervisor:** doc. Dr. Ing. Dana Křemenáková, Department of material engineering

### Summary

This thesis investigates **multifunctional sandwich-structured textile materials** designed to combine multiple performance domains within a layered architecture. Two material families are developed and evaluated:

1. **Soft/flexible textile sandwiches** aimed at applications such as wearables, PPE, and building-related textile structures, integrating **thermal insulation, electromagnetic interference (EMI) shielding, and Joule (ohmic) heating**, with additional attention to **acoustic performance**.
2. **Rigid sandwich composites** aimed at transportation/aerospace contexts, combining composite skins with an insulating core and conductive textile layers to integrate **mechanical load-bearing, thermal control/insulation, EMI shielding, and electrical heating**.

Overall, the work is positioned as an engineering-oriented thesis emphasizing **design, fabrication, and experimental characterization** of layered textile-based systems capable of delivering multiple functions simultaneously.

### Strengths

**Clear architectural approach:** The thesis uses a coherent “sandwich” concept to integrate functions and demonstrates this across both flexible and rigid constructions.

**Relevance and applicability:** The targeted functions (EMI shielding, thermal insulation/management, and heating) are practically relevant across several sectors, and the material choices appear broadly compatible with scalable manufacturing pathways.

**Experimental breadth:** The thesis covers a wide set of properties (electrical, thermal, EMI shielding, heating behavior, and (for rigid systems) mechanical performance), enabling a multi-criteria view rather than single-metric optimization.

**Useful design trade-off narrative (potentially):** The work suggests relationships between conductive layer content/continuity and shielding/heating, and between insulating layer thickness/composition and heat retention (and acoustic performance). With clearer consolidation, these could form transferable design guidelines.

**Integration across domains:** The rigid composite studies are particularly valuable in demonstrating how conductive textile layers and structural components can be combined without treating EMI/heating as add-on features.

### Major concerns

1. **Novelty and generalizable contribution**

The thesis integrates known functional layers (conductive shielding/heating + insulation + structural skins). The key opponent question is: **what is the primary new contribution** beyond integration and characterization? The defense should articulate one or two **generalizable design principles** (e.g., rules linking layer architecture to shielding/heating/thermal resistance) rather than presenting outcomes as case-specific.

## 2. Data analysis and graphical presentation

There is missing sample size/sampling frequency information for figures 3, 4, 7, 9, 10, 14. It is not stated what the +/- intervals in the tables mean: sigma? 2sigma? 95% confidence? In figure 6 there should be a projection (eg. a vertical line) onto the horizontal plane, otherwise it is not clear where the red points are in space. On Fig. 7, the measured dots should be plotted rather than somewhat confusing artificial smooth spline, why the AL20 and AL30 curve drops long before Power-off?

## 3. Self-contained scientific argument

If detailed methods reside mainly in appended papers, the main thesis must still allow an informed reader to assess validity. Key missing elements (if not explicitly stated in the thesis body) often include **test standards, sample conditioning, replicates (n), uncertainty/statistical dispersion, and failure criteria.**

## 4. Durability and real-use robustness

**For soft systems:** performance under bending/flex fatigue, abrasion, moisture/sweat exposure, washing/cleaning, and copper-layer retention is critical for wearable/PPE claims. **For rigid systems:** interfacial stability and performance under thermal cycling, vibration, humidity aging, and potential delamination are key for transport/aerospace relevance.

## 5. Joule heating engineering realism

Heating demonstrations are promising, but application readiness depends on **power density (W/m<sup>2</sup>), efficiency, temperature uniformity, hotspot control, contact resistance/connectors, control electronics, and safety limits.** A defense should explicitly connect heating behavior to realistic scenarios (panel size, required wattage, target temperature rise, allowable local surface temperatures).

## 6. Safety, compliance, and hazard considerations

Conductive particle/coating systems raise questions about **particle release**, skin contact safety (wearables), corrosion/oxidation behavior, and end-of-life handling. Electrically heated multilayers require safety discussion: **overheating, shorting, fire behavior**, and relevant standards for target domains (PPE/building/transport).

## 7. Benchmarking and comparability

EMI shielding results should be framed with careful benchmarking: consistent **frequency bands, methods/standards, areal-mass normalization**, and ideally some mechanism interpretation (reflection vs absorption). Mechanical benchmarking of rigid composites vs metals must be carefully contextualized: strength comparisons may be meaningful, but **stiffness (modulus) differences** can dominate design acceptability.

## Conclusion - Recommendation

### ***Acceptable for defense.***

Rationale: The thesis presents a coherent and practically relevant exploration of multifunctional sandwich textile materials with substantial experimental work. The principal improvements needed are largely positioning and consolidation (clear statement of novelty and design rules), plus stronger framing of robustness/safety and benchmarking. These can typically be addressed through defense discussion and/or minor thesis revisions, assuming the appended papers contain sufficient methodological detail. I recommend that the candidate is allowed to defend her dissertation thesis.

### Question list for the defense

1. What is the single most important new insight of this thesis beyond “combining layers combines functions”? State it as a transferable design rule.
2. Which results are most sensitive to fabrication variability (adhesive amount, copper continuity, dispersion, press conditions), and how did you control it?
3. What are your replicate counts (n) and uncertainty for the headline claims (EMI shielding, heating, thermal resistance, mechanical properties)? Explain why the uncertainty bars in Fig 14b are much wider than those on Fig 5. Did you attempt to suggest any quantitative relationship (mathematical model) based on the measurement (eg. dependence of ohmic heating parameters on Cu areal density)?
4. Your EMI range is 30 MHz–3 GHz: how does this align with intended applications, and what do you expect at higher GHz bands? Can you interpret shielding mechanisms: what portion is reflection vs absorption, and which layer dominates each? What device was used for measurement?
5. For Joule heating, what is the achieved power density ( $W/m^2$ ) under safe operating conditions, and how does it scale to a real panel size? How uniform is the heating field? Where do hotspots occur, and what design changes reduce them? What is the limiting factor for higher temperature: electrical resistance, heat loss, oxidation/degradation, or safety limits?
6. For soft systems: how would washing/abrasion/moisture affect copper retention and performance, and what qualification tests would you run first? For rigid systems: what do you expect under thermal cycling (e.g.,  $-20$  to  $+60^\circ C$ ) regarding interfacial bonding and shielding continuity?

Pardubice, 5.2. 2026

Reviwer: Karel Kupka, PhD.&PhD.