



THE INFLUENCE OF COMPOSITE MATERIAL COMPONENTS ON MECHANICAL AND THERMOELECTRIC PROPERTIES

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Abstract: *This paper presents an overview of the properties of composite materials and their potential use in thermoelectric systems. Applications in which conventional materials did not fully meet structural requirements have made composite materials an alternative worth considering. This category of materials is often used because they allow control over the desired properties, which are influenced by the matrix and reinforcement elements. For applications where the objectives focus on certain mechanical properties, the polymer matrix is often used. Likewise, in order to achieve these same properties, various fibers are used to control the range of values of these properties. The field of composites has also influenced thermoelectric materials, with specialized studies demonstrating interest in converting a temperature gradient into electrical energy and vice versa.*

Key words: *polymer composites, fiber architecture, thermal gradient conversion, tensile strength, Seebeck coefficient.*

1. INTRODUCTION

Composite materials represent a class of materials that emerged from the desire to overcome the limitations of conventional materials. This type of material is characterized by the combination of at least two distinct types of materials whose structure provides superior properties compared to the elements used individually. In developments carried out over the years, a composite material consists of a continuous matrix and a reinforcement element dispersed or oriented in a certain manner [1]. The matrix has the role of holding the component elements together, transferring mechanical loads, and protecting the reinforcement against external factors, while the reinforcement material mainly contributes to increasing strength and stiffness [2].

Depending on the nature of the matrix, composite materials can be classified according to this element, resulting in composite materials with polymer matrix [3], metal matrix [4], or ceramic matrix [5]. As for reinforcement materials, these may consist of synthetic fibers, such as glass fibers, carbon fiber, or aramid fibers [6], natural fibers [7], fabrics [8], nanotubes [9], and nanofibers [10].

One of the main reasons why composite materials have attracted interest for the development of studies is related to their mechanical performance. Due to their strength-to-weight ratio, high stiffness, and the possibility of optimizing properties through the orientation and distribution of the reinforcement, these materials have become attractive for industrial applications [11].

In addition to their use in structural applications, composite materials have increasingly begun to be developed as multifunctional materials, capable of providing not only mechanical strength but also electrical responses under various external stimuli. In this context, composites with thermoelectric



properties represent a direction of interest, since they allow the conversion of a temperature gradient into an electrical signal through the Seebeck, Peltier, or Thomson effect [12], being used in sensing systems [13], wearable systems [14], or flexible devices [15].

This paper examines the influence of reinforcement materials on the mechanical or thermoelectric properties of composites integrated into various polymer matrices. The analysis comparing different types of matrices, reinforcement elements, and composite architectures makes it possible to highlight how these components control the final performance of the material. In this context, mechanical properties and thermoelectric behavior are correlated, since the structural parameters that influence mechanical strength can also affect heat and electrical transport within the material. The conversion of a temperature difference into electrical energy is based on the Seebeck effect, through which a thermal gradient generates an electrical potential difference. Mechanical properties do not directly determine the occurrence of this effect, however they are essential for evaluating the material's potential for use in practical applications. Thus, a flexible thermoelectric composite material can be integrated into wearable textile applications, where the analysis of thermoelectric and mechanical properties is essential.

2. INFLUENCE OF REINFORCEMENT MATERIALS ON THE PROPERTIES OF COMPOSITE MATERIALS

To summarize the influence of matrices and reinforcement elements on the resulting composite materials, Fig. 1 illustrates a simplification of the analyzed elements. The literature used in this paper was identified through searches on ScienceDirect and MDPI, using keywords such as polymer matrix, glass fiber, carbon fiber, thermoelectric composite, mechanical properties, and Seebeck coefficient. Sources were selected thematically in three stages: composite materials and their general classification, mechanical performance of fiber-reinforced composites, and thermoelectric composites combining mechanical and thermoelectric properties, with preference given to experimental works reporting quantitative data.

Composite materials	Influence on mechanical properties	Matrix	Epoxy resin Polyester resin
		Reinforcement material	Glass fibers Kevlar fibers Carbon fibers Flax fibers
	Influence on thermoelectric properties	Matrix	Epoxy resin PEDOT:PSS PVDF SEBS PVA
		Reinforcement material	Carbon Fibers Glass Fibers Tellurium nanofibres Bi_2S_3 , Bi_2Te_3 , Sb_2Te_3

Fig. 1 – Matrix and reinforcement materials analysed for mechanical and thermoelectric properties



2.1 Influence on mechanical properties

Rout et al. [16] produced various composite material samples using bidirectional woven fabrics based on Kevlar fibers (K), glass fibers (G), and carbon fibers (C), with an epoxy matrix. The authors produced five material samples in the form of $[G_2K_3G_2]$, $[KG_2CKG_2]$, $[CKGCGKC]$, $[CGKCKGC]$, $[CK_2CK_2C]$, as well as three samples made from the base materials $[G_7]$, $[C_7]$, $[K_7]$. From the designation of the samples, the seven-component layered structure can be observed. These samples were tested by preparing specimens corresponding to each configuration, and the mechanical properties were evaluated using hardness, flexural, and impact tests.

The results showed that mechanical performance strongly depends on the laminate architecture. Among all the analysed variants, the $[CGKCKGC]$ configuration showed the best overall results, reaching a flexural strength of approximately 380 MPa, a flexural modulus of about 36 GPa, a hardness of 59 BHN, and an impact strength of approximately 80 kJ/m². The authors attributed this behavior to the positive effect of combining rigid carbon fibers with Kevlar and glass fibers, as well as to a stacking sequence favorable to load distribution and energy dissipation. Moreover, for the previously mentioned configuration, the SEM analysis revealed active fiber involvement in the deformation and failure mechanism, indicating efficient load transfer at the matrix–reinforcement interface. Unlike the specimens in which fiber sliding or pull-out from the matrix predominated, in this case fiber fracture and the maintenance of local adhesion with the polymer phase were observed, confirming their direct contribution to the improvement in mechanical performance.

Cao et al. [17] focused strictly on the influence of glass fibers on the properties of the composite material under tensile loading, but it provides further insight by testing different matrices and different compounds added to them that improve the fiber–matrix interface. The research team created various samples based on E51 epoxy resin, together with other improvement agents such as a silane coupling agent, nano-TiO₂, or nano-SiO₂. For the different experiments, specimens were made from samples based on: EPA-650 (E51+PA650 at 1:1), EPA-650-Md (E51+PA650+modified SiO₂/TiO₂ at 50:50:1:1), EPAA (E51+ PAA–phenolic amine curing agent at 2:1), and EAA (E51+AA – alicyclic amine curing agent at 2:1).

In the tensile tests carried out by the authors, for the tensile test performed on the EPA650- Md specimen, a significant elongation exceeding 7.5% was observed, but it did not reach maximum stress values close to 40 MPa as in EPAA and EAA. For additional validation, tests were carried out with 2, 4, and 8 layers. Among all the analysed variants, the 4-layer EPAA system showed the best combination of strength, stiffness, and deformation, being highlighted by the authors as the optimal variant. The microstructural analysis supports these results, showing that improving adhesion at the interface limits fiber sliding and promotes their active participation in load bearing, which leads to an overall increase in the tensile performance of the composite. It is worth noting that, with the increase in the number of layers to 8, all configurations showed inferior results compared to four layers.

The two studies show that mechanical performance depends on two distinct aspects: how the fiber layers are arranged and combined, as shown in [16], and how the matrix is formulated and how well it bonds to the fibers, as shown in [17]. This indicates that improving a composite for a given application requires attention to both aspects, since acting on only one of them may not lead to the expected results.

Islam et al. [18] presented a study on the influence of woven fabrics with carbon and flax fibers as warp and weft yarns, as well as a hybrid configuration. The composite materials had INF-114 epoxy resin and INF 211 curing agent as the matrix. Two architectures were produced, namely inter-ply, with layers $[CF_2CF_2C]$, and intra-ply with 14 layers of that hybrid fabric. The experimental evaluation



included both static tensile tests and tensile fatigue tests, carried out at 70% of the ultimate tensile strength and at a frequency of 3 Hz. The results showed that the ultimate tensile strength of the two configurations is relatively close, with an average value of approximately 805.26 MPa for the inter-ply composite and 765.46 MPa for the intra-ply composite, which indicates small differences under static loading, however, the intra-ply configuration provided a linear behavior compared to the other configuration, which showed fluctuations after leaving the elastic domain. In contrast, the fatigue differences were very pronounced: the inter-ply composite recorded an average fatigue life of approximately 17,034 cycles, while the intra-ply composite reached approximately 365,939 cycles, which corresponds to an increase of over 2000% in fatigue life. Under cyclic loading, the material sample showed a scattered structure of failed fibers, this aspect being due to the failure of the first layer of carbon fibers, while the other configuration showed a more orderly behavior of the failed fibers.

The results of [18] show that the two architectures perform similarly under static loading, but differ significantly under cyclic loading, where the intra-ply configuration reached over 2000% more fatigue cycles. This suggests that the choice of fiber arrangement should take into account the type of loading expected in the application, since an architecture that appears comparable under static conditions may behave very differently under repeated loading.

2.2 Influence on thermoelectric properties

Rodrigues-Marinho et al. [19] investigated flexible thermoelectric composite materials based on two polymer matrices, poly(vinylidene fluoride) (PVDF) and styrene-ethylene/butylene-styrene (SEBS), loaded with thermoelectric ceramics (Bi_2S_3 , Bi_2Te_3 , Sb_2Te_3) and multiwalled carbon nanotubes (CNTs), comparing thermoelectric performance against mechanical flexibility. In the tensile tests, PVDF composites showed tensile strengths of approximately 20–35 MPa, while SEBS composites exhibited strains up to 750% in pure form and 470% for the SEBS/50 Bi_2S_3 sample. The addition of 1 wt.% CNT led to a strong increase in conductivity, up to 32.9 (Ωm^{-1}) for PVDF/CNT/ Bi_2S_3 . With increasing Bi_2S_3 concentration, the Seebeck coefficient reached 36 $\mu\text{V}/\text{K}$ for PVDF/80 Bi_2S_3 . For a device made from PVDF/50 Bi_2S_3 and PVDF/50 Bi_2Te_3 , the generated voltage reached 3.5 mV for a single thermocouple and 5.1 V for two thermocouples at $\Delta T = 100$ °C.

Kong et al. [20] proposed a flexible TPP-type thermoelectric hydrogel composed of PEDOT:PSS and polyvinyl alcohol (PVA), into which tellurium nanowires (Te-NWs) were introduced to improve the thermoelectric properties. From a structural point of view, the system was based on a PEDOT:PSS/PVA matrix, with tellurium nanowires dispersed throughout the network that contributed to both charge-carrier transport and the optimization of thermoelectric performance. In terms of mechanical behavior, the TPP hydrogel showed the best results among the analyzed variants, reaching a tensile strength of approximately 0.905 MPa and a maximum strain of nearly 400%, which highlights high elasticity that can be exploited in wearable applications. From the thermoelectric point of view, the optimal composition was obtained at a content of 1.5 wt.% Te-NWs, for which the authors reported a maximum Seebeck coefficient of 787 $\mu\text{V}/\text{K}$. At a thermal gradient of 30 K, the hydrogel generated a voltage of approximately 23.8 mV, and a wearable module made up of 20 TPP units reached an output voltage of 138.5 mV when applied to the arm, demonstrating the potential of this material for low-temperature thermal energy harvesting in wearable applications.

Karalis et al. [21] proposed carbon-epoxy composite laminates capable of functioning as thermoelectric generators through the thickness direction, by integrating a functional layer based on glass fiber coated with a thermoelectric layer. The laminate matrix consisted of epoxy resin, and the reinforcement elements were represented by carbon fibers and glass fibers. The functional layer was obtained by depositing, on the glass fiber fabric, a thermoelectric paste formed from tellurium nanowires (Te NWs) dispersed in a PEDOT:PSS matrix, the optimal variant being the one with a 1:1



mass ratio, which showed an in-plane Seebeck coefficient of $189 \mu\text{V/K}$. Based on this layer, unidirectional (UD) and cross-ply laminates with 10 layers were fabricated, and the UD configuration provided the best thermoelectric results, generating a voltage of 8.4 mV at $\Delta T = 100 \text{ K}$, while the cross-ply laminate reached approximately 7.9 mV . From the mechanical point of view, the integration of the thermoelectric function caused only a moderate reduction in flexural performance, of approximately 10%.

The three studies approach thermoelectric composites from different directions. In terms of generated voltage, [19] reached 5.1 V at $\Delta T = 100^\circ\text{C}$ through thermocouple stacking, while [20] generated 23.8 mV at $\Delta T = 30 \text{ K}$ for a single element, reaching 138.5 mV for a 20 unit module. Study [21] reports 8.4 mV at $\Delta T = 100 \text{ K}$, a lower value but obtained within a structural laminate. From a mechanical standpoint, the hydrogel in [20] offers the highest deformability with strains up to 400%, while [21] maintains flexural performance with only a 10% reduction compared to a standard carbon-epoxy laminate, and [19] sits between the two with tensile strengths of 20–35 MPa. This shows that the three systems target different application contexts, and the choice between them depends on whether the priority is thermoelectric output, mechanical flexibility, or structural integration.

3. CONCLUSIONS

The analyzed studies demonstrate that reinforcement materials influence the performance of composites, both mechanically and thermoelectrically. In laminated systems intended for integration into structures, optimizing the type of fiber, the stacking sequence, and the matrix–reinforcement interface leads to improved strength, stiffness, and fatigue resistance under static or cyclic loading.

The integration of thermoelectric phases into polymer matrices or functional laminates demonstrates the potential to extend the use of composites to applications where converting a temperature gradient into electrical energy is desired. Therefore, composite materials represent a feasible alternative for particular applications, and configurations can be developed to meet structural requirements.

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