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Review Article

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Properties and potential applications of polymer composites containing secondary fillers

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Abstract: Polymer composites are custom-made materials created by compounding a polymer matrix with various fillers to improve their mechanical, thermal, and electrical properties. The integration of secondary fillers in polymer composites provides fresh possibilities for material improvements and functional diversification. This brief review categorizes some polymer matrices, primary fillers, and secondary fillers utilized in polymer composites. It briefly highlights the impact of secondary fillers on the mechanical, thermal, and electrical properties of the composites. Furthermore, this review summarizes the potential applications of polymer composites containing secondary fillers. Overall, numerous studies indicate that incorporating secondary fillers usually enhances the mechanical, thermal, and electrical properties of polymer composites, irrespective of the type of polymer matrix or primary filler used. These enhancements are due to the bridging effect of secondary fillers, which creates continuous paths for heat and electron flow. Additionally, the formation of conductive networks by secondary fillers improves electrical conduction and stress distribution. The mechanical interlocking of secondary fillers within the matrix increases resistance to mechanical stresses. Moreover, the high thermal and electrical conductivity of secondary fillers improves heat and electron transfer. The synergistic effect with primary fillers also improves load transfer and thermal conductivity. Typical potential applications of thermoset composites containing secondary fillers include thermal management systems, fuel cell technologies, and electronics. Thermoplastic composites containing secondary fillers are potentially applied in packaging, electronics, and fuel cells. Elastomer composites containing secondary fillers are potentially employed in flexible electronics and wearable sensors.

Keywords: secondary filler, polymer composite, mechanical, thermal, electrical

1 Introduction

Polymer composites are fabricated materials made by incorporating a polymer matrix with a variety of fillers to enhance their mechanical, thermal, and electrical properties. The polymer matrix acts as a continuous phase that binds the fillers and imparts to the composite its appearance and bulk characteristics [1]. This matrix can be either a thermoset that cures irreversibly, a thermoplastic that remains processable after initial production, or an elastomer that exhibits significant elasticity and can return to its original shape after deformation [2,3]. The choice of polymer matrix used is critical for defining the composite's final characteristics, including its resistance to mechanical stress and environmental factors [4]. The fillers, dispersed throughout the matrix, can be either fibers or particulates [5,6], each selected based on the desired property enhancements. Fiber fillers, such as glass, carbon, or natural fibers, are particularly popular for their ability to significantly increase tensile strength and stiffness [7,8]. On the other hand, particulate fillers, such as silica, calcium carbonate, or graphite, are used to improve thermal properties, dimensional stability, and electrical properties [9]. The unique ability of polymer composites to be customized for specific applications makes them vital in diverse fields ranging from aerospace to consumer products, where tailored material properties are necessary for performance.

Polymer composites have seen remarkable advancements in their applications across various industries, driven

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by innovative research on their mechanical, thermal, and electrical properties. Studies characterizing pyrolyzed carbon black (CB) from waste tires in reinforced epoxy nanocomposites reveal potential in coating applications by leveraging enhanced tensile and compressive strengths [10]. These composites demonstrate significant improvement in hardness, which contributes to their robust performance in protective coatings, mitigating environmental impact by utilizing waste tires. Recently, a comprehensive review highlighted the versatility of conductive filler-based polymer nanocomposites (CFPNCs) and conducting polymeric nanocomposites (CPNCs) in multifaceted sensing applications [11]. The review focused on CFPNCs, CPNC membranes, and insulative polymers with conductive filler-based CPNCs (IPCFCPNCs). These materials are particularly noted for their application in strain sensors to detect pressure, gas, humidity, and other variables. The review also highlights the advantages of incorporating specific nanofillers, such as graphene or carbon nanotubes, into the CPNC membrane matrix and insulative polymeric matrices. This enhancement aims to improve their mechanical stability, enabling their use in high-performance sensing applications. Additionally, the review highlights the possibility of creating thin, flexible CPNC membranes using advanced fabrication techniques like electrospinning. These membranes exhibit high sensitivity and stability toward target analytes, making them highly effective for precise and reliable sensing applications.

The mechanical properties of polymer composites are notably enhanced by the incorporation of fillers, which increase flexural strength, tensile strength, impact strength, and hardness. These improvements are crucial for applications requiring durable materials that can withstand heavy loads and resist wear over time [12,13]. For instance, Kevlar-reinforced polymer composites are renowned for their exceptional specific mechanical properties, making them indispensable in the automotive, aerospace, and defense industries [14]. Thermal properties are also significantly influenced by the choice of fillers. Polymer composites can be engineered to possess high thermal stability and thermal conductivity, which are essential for maintaining structural integrity under varying thermal conditions as well as for efficient heat transfer [15,16]. Fillers like alumina nanoparticles and boron nitride nanosheets are often incorporated to enhance thermal conductivity [17,18], allowing the composites to dissipate heat more effectively, which is important in electronic packaging and heat sink applications [19]. Furthermore, electrical properties such as conductivity and dielectric strength can be designed through the incorporation of conductive fillers like carbon nanotubes, graphene, conductive CB, or metal particles [20]. This adaptability enables the creation of polymer composites that can serve not only as insulators but also as conductive materials in electrical and electronic components, offering versatility across various technological applications.

2 Motivation and the objective of the review

The integration of secondary fillers into polymer composites presents a significant opportunity for material advancement and functional diversification, motivating the exploration of their enhanced properties and applications. These fillers, ranging from whiskers and microparticles to nanoparticles, are strategically incorporated and synergistically improve the composite's properties and performance [21,22] while also reducing material costs and promoting sustainable production practices [23]. This motivation is driven by the need to extend the application range of polymer composites and foster the development of innovative solutions tailored to meet specific industry challenges. Historically, there has been a notable absence of brief reviews that specifically focus on the use of polymer matrices, primary fillers, and secondary fillers in influencing polymer composites, especially their mechanical, thermal, and electrical properties. The objective of this brief review is to address this gap by detailing the various polymer matrices used alongside primary and secondary fillers in composites and discussing their common types. It also aims to investigate the assortment of primary fillers employed with secondary fillers in polymer composites, emphasizing their prevalent applications. Furthermore, this review intends to provide insights into the strategic selection of different secondary fillers, examine their impact on the fundamental properties of polymer composites, and explore the potential applications of these advanced materials.

3 Polymer matrices in composites

Table 1 shows polymer matrices used in composites containing secondary fillers. It indicates that various polymer matrices are categorized based on their type, specifically thermosets, thermoplastics, and elastomers, each serving specific roles in composite materials due to their unique properties. Thermoset polymers, once cured, become irreversibly hard. Epoxy resin (ER) is prominent among them, favored for its excellent adhesive qualities and mechanical strength [24,25], making it suitable for aerospace and automotive applications where durability is predominant. Polyester resin is another thermoset that is less expensive

Table 1: Polymer matrices used in composites containing secondary fillers

Polymer matrix	Abbreviation	Ref.
Thermoset		
Epoxy resin	ER	[1,14,15,17,19,21,24,25,32–38]
Polyester resin	PER	[8,26,39]
Waterborne epoxy	WEP	[40]
Waterborne polyurethane	WPU	[27]
Thermoplastic		
High-density polyethylene	HDPE	[23]
Low-density polyethylene	LDPE	[9,41]
Linear low-density polyethylene	LLDPE	[42]
Polyamide 12	PA12	[43]
Polylactide	PLA	[44]
Polyphenylene sulfide	PPS	[29,45]
Polypropylene	PP	[4,28,46,47]
Poly(vinylidene fluoride)	PVDF	[30,48]
Thermoplastic polyurethane	TPU	[49]
Ultra-high molecular weight polyethylene	UHMWPE	[6]
Elastomer		
Acrylonitrile butadiene rubber	NBR	[22]
Natural rubber	NR	[12,31,50,51]
Polydimethylsiloxane	PDMS	[2,52]
Polymethylvinylsiloxane	PMVS	[53]

than epoxy and is commonly used in bulk applications due to its good mechanical properties and water resistance [26]. Waterborne variants like waterborne epoxy and waterborne polyurethane represent advancements, offering environmental benefits while maintaining performance in protective coatings [27]. Thermoplastic polymers can be remelted and remolded, providing versatility in manufacturing and recycling. Polypropylene (PP) is widely used for its chemical resistance and fatigue handling, particularly in automotive parts [28]. High-density polyethylene and low-density polyethylene are noted for their excellent toughness and chemical resistance, which are suited to household appliances and packaging [23]. Linear low-density polyethylene offers enhanced ductility over its counterparts. Specialized polymers like polyphenylene sulfide and poly(vinylidene fluoride) are selected for specific applications requiring high performance in engineering tasks due to their superior mechanical and thermal properties [29,30]. Elastomers are highly elastic, making them essential in applications needing flexibility and resilience. Natural rubber (NR) is typically used in automotive and industrial applications for its ability to absorb shocks and vibrations [31]. Polydimethylsiloxane and polymethylvinylsiloxane are silicone-based elastomers utilized for thermal stability and flexibility [2], often in medical devices. Figure 1

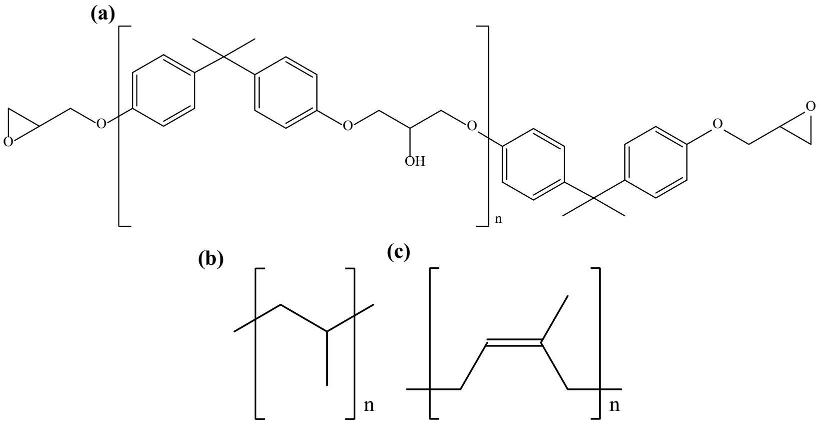

Figure 1: Chemical structures of (a) ER, (b) PP, and (c) NR.

shows the chemical structures of ER, PP, and NR. Generally, the selection of polymer matrices in composites is tailored to achieve desired properties such as mechanical strength, thermal stability, chemical resistance, and elasticity, catering to various applications.

4 Primary fillers in polymer composites

Table 2 shows primary fillers employed with secondary fillers in polymer composites. It demonstrates that these fillers are crucial for enhancing the structural and mechanical properties of the composites. Primary fillers are generally categorized as carbon-, inorganic-, and organic-based materials, each offering unique benefits to the polymer matrices. Carbon-based fillers are highly valued for their exceptional strength-to-weight ratios and electrical conductivity [17]. Multi-walled carbon nanotubes (MWCNTs) and graphite are widely used for their ability to improve thermal and electrical properties, making them ideal for electronics and energy storage [45,49]. Graphene nanoplatelets are at the forefront of nanotechnology, enhancing barrier properties, mechanical strength, and conductivity [22]. CB and exfoliated graphene nanoplatelets provide significant reinforcement, increasing tensile strength and durability [47,51]. Inorganic-based fillers are chosen for their thermal stability and mechanical robustness. Silica improves tensile and tear strength, which is useful for tire tread applications [12,31]. Alumina is noted for its excellent thermal conductivity, which is essential in heat dissipation applications [35]. Glass fibers are traditional reinforcements that provide composites with improved impact resistance, tensile and flexural strength [32], and they are widely used in construction and automotive fields. Organic-based fillers such as kenaf core fiber and woven coconut sheath are increasingly popular due to their environmental benefits and biodegradability [23,39]. They are primarily used in lightweight applications where sustainability is a key concern, such as biodegradable packaging and eco-friendly automotive components. In general, the choice of primary fillers in polymer composites is strategic, driven by the need to meet specific technical requirements such as strength, conductivity, and environmental sustainability.

5 Secondary fillers in polymer composites

Table 3 shows secondary fillers utilized in polymer composites. It shows that the selection of secondary fillers is influenced by the desired enhancements in the mechanical, thermal, and electrical properties of the composites.

Table 2: Primary fillers employed with secondary fillers in polymer composites

Primary filler	Abbreviation	Ref.
Carbon-based		
Carbon black	CB	[50,51]
Carbon fiber	CF	[34]
Exfoliated graphene nanoplatelets	xGNP	[24,47]
Graphene nanoplatelets	GNP	[21,22,33]
Graphite	C	[25,37,38,45,47]
Milled carbon fibers	MCF	[1]
Multi-walled carbon nanotubes	MWCNTs	[2,27,28,30,40,42–44,48,49,52,53]
Reduced graphene oxide	RGO	[17]
Inorganic-based		
Alumina	Al_2O_3	[15,35]
Boron nitride	BN	[29]
Glass fibers	GF	[32,36]
Nanoclay	Nc	[46]
Silica	SiO_2	[12,31,51]
Silver nanoparticles	AgNP	[19]
Zinc oxide nanoparticles	ZnONP	[6]
Organic-based		
Banana fiber	BF	[8]
Kenaf core fiber	KCF	[9,23,41]
Kevlar	Kev	[14]
Mixed textile fleece	MTF	[4]
Woven coconut sheath	WCS	[26,39]

Table 3: Secondary fillers utilized in polymer composites

Secondary filler	Abbreviation	Ref.
Carbon-based		
Carbon black	CB	[1,12,22,25,31,43,44,47,49]
Conductive carbon black	CCB	[50,53]
Graphene	Gra	[27]
Graphene oxide	GO	[36,40]
Graphite	C	[32]
Milled carbon fibers	MCF	[37]
Multi-walled carbon nanotubes	MWCNTs	[1,14,22,29,38,45,47,50]
Inorganic-based		
Alumina	Al_2O_3	[35]
Alumina nanoparticles	Al_2O_3NP	[17]
Barium titanate nanoparticles	$BaTiO_3NP$	[30,48]
Boron nitride	BN	[35]
Boron nitride nanoparticles	BNNP	[21,33]
Calcium carbonate	$CaCO_3$	[9]
Copper nanoparticles	CuNP	[24]
Dolomite	Dol	[41]
Glass fiber	GF	[6]
Organomodified montmorillonite	OMMT	[12,26,39]
Potassium titanate whisker	PTW	[32]
Redmud	RM	[8]
Sepiolite	Sep	[49]
Silica	SiO_2	[2,52]
Silicon carbide	SiC	[34,35]
Silver microparticles	AgMP	[19]
Silver nanopowder	AgNP	[23]
Silver nanowires	AgNWs	[15]
Stainless steel fiber	SSF	[28]
Talc particles	TP	[6,9,42]
Organic-based		
Bagasse fiber ash	BFA	[51]
Oil palm empty fruit bunch	OPEFB	[46]
Wood fibers	WF	[4]

These fillers are grouped mainly into carbon-, inorganic-, and organic-based categories, each offering specific functional improvements to the polymer composites. Carbon-based fillers such as CB and conductive CB are widely used to improve the mechanical properties and electrical conductivity of composites [31,53]. They are particularly valued in the automotive and electronics industries for creating conductive pathways and enhancing the durability of materials. MWCNTs significantly improve the mechanical strength, electrical conductivity, and thermal stability of the polymer composites. Their tubular nanostructure provides a high aspect ratio [38], which is ideal for creating networks within the polymer that lead to improved properties [47]. Graphene oxide is used for its exceptional mechanical strength. It also enhances the thermal conductivity of composites [40] due to its high surface area and functional groups that facilitate better interaction with the polymer matrix [36]. Inorganic-based fillers like organomodified montmorillonite (OMMT) are utilized to improve the mechanical properties and barrier resistance against gases and liquids [26]. This makes OMMT a popular choice for packaging materials [39]. Talc particles (TP) are employed to increase the stiffness and heat resistance of the polymer composites [9,42]. Barium titanate and boron nitride nanoparticles are utilized for their high dielectric properties, making them ideal for electronic applications where high insulation is required [33,48]. Silica and silicon carbide are important for improving mechanical strength and wear resistance [2,34]. They are often used in composites that operate under high-stress conditions and require enhanced abrasion resistance. Overall, each of these secondary fillers is chosen based on its ability to impart specific characteristics to the composite, such as enhanced functional properties, increased durability, and improved performance under extreme conditions. Their strategic use in polymer composites highlights their vital role in tailoring material properties to meet industrial needs.

6 Properties of polymer composites containing secondary fillers

6.1 Properties of thermoset composites containing secondary fillers

Table 4 shows the mechanical, thermal, and electrical properties of thermoset composites containing various types of secondary fillers. The incorporation of AgMP in ER/AgNP composite at 25 vol% enhances both thermal and electrical conductivity due to the significant bridging effect between filler particles in the composite [19]. Moreover, incorporating AgNWs at a low content of 0.5 vol% in ER/Al_2O_3 composite increases flexural strength and thermal conductivity while decreasing electrical resistivity because of the bridging effect of the well-dispersed high aspect ratio AgNWs between the primary spherical particles [15]. Additionally, the incorporation of SiC in ER/Al_2O_3 composite at a high content of 57 vol% enhances thermal conductivity and decreases dielectric strength, as SiC possesses higher thermal conductivity and lower electrical volume resistivity [35]. Furthermore, incorporating CB at 10 vol% in ER/C composite increases flexural strength, degradation temperature, and electrical conductivity because CB's

Table 4: Mechanical, thermal, and electrical properties of thermoset composites containing secondary fillers

Thermoset composite	Secondary filler	Content	Properties			Ref.
			Mechanical	Thermal	Electrical	
ER/AgNP	AgMP	25 vol%	N/A	$k\uparrow$	EC ↑	[19]
ER/Al_2O_3	AgNWs	0.5 vol%	FS ↑	$k\uparrow$	ER ↓	[15]
ER/Al_2O_3	SiC	57 vol%	N/A	$k\uparrow$	DS ↓	[35]
ER/C	CB	10 vol%	FS ↑	$T_d\uparrow$	EC ↑	[25]
ER/C	MCF	2 wt%	FS ↑	N/A	EC ↑	[37]
ER/C	MWCNTs	5 wt%	FS ↑	$T_d\uparrow$	EC ↑	[38]
ER/GNP	BNNP	0.02 vol%	FS ↑	$k\uparrow$	EC ↑	[21]
ER/Kev	MWCNTs	0.3 wt%	FS ↑	$T_d\uparrow$	N/A	[14]
ER/MCF	MWCNTs	6 wt%	FS ↑	N/A	EC ↑	[1]
ER/RGO	Al_2O_3NP	20 wt%	TS ↑	$k\uparrow$	EC ↑	[17]
ER/xGNP	CuNP	35 wt%	N/A	$k\uparrow$	EC ↑	[24]
PER/WCS	OMMT	3 wt%	N/A	$k\downarrow$	DS ↓	[26]
WEP/MWCNTs	GO	4 wt%	TS ↑	$k\uparrow$	N/A	[40]
WPU/MWCNTs	Gra	3 wt%	TS ↑	$k\uparrow$	EC ↑	[27]

N/A = not available, k = thermal conductivity, EC = electrical conductivity, FS = flexural strength, ER = electrical resistivity, DS = dielectric strength, T_d = degradation temperature, TS = tensile strength, ↑ = increase in the properties, and ↓ = decrease in the properties.

small diameter allows it to form conductive networks that fill the voids between the graphite and ER matrix [25]. The incorporation of MCF in ER/C composite at 2 wt% enhances flexural strength and electrical conductivity due to the high mechanical strength of MCF and increased bulk density, which leads to better conductivity since the compaction improves network formation [37]. In addition, incorporating MWCNTs at 5 wt% in ER/C composite enhances flexural strength, degradation temperature, and electrical conductivity because MWCNTs have a smaller diameter and a tubular geometry, which forms conducting networks between the C/MWCNTs and ER matrix [38]. Furthermore, the incorporation of BNNP in ER/GNP composite at a low content of 0.02 vol% enhances flexural strength, thermal conductivity, and electrical conductivity because BNNP creates additional contacts with GNP, resulting in a new three-dimensional network [21].

MWCNTs at a low content of 0.3 wt% in the ER/Kev composite enhance both flexural strength and degradation temperature due to the high mechanical interlocking of the MWCNTs with the ER matrix and bridging action between Kev and ER interface [14]. The utilization of MWCNTs in ER/MCF composite at 6 wt% increases flexural strength and electrical conductivity, attributable to the high aspect ratio and small size of the MWCNTs, minimizing the gaps between MCF, and enhancing the conductive path [1]. Al_2O_3NP at 20 wt% incorporated into ER/RGO composite boosts tensile strength, thermal conductivity, and electrical conductivity because the intercalation of Al_2O_3NP between the RGO sheets not only suppresses the electron transfer but also reduces the agglomerations of RGO sheets [17]. CuNP in ER/xGNP composite at 35 wt% improves thermal and electrical conductivity as the CuNP acts as a bridge between the large xGNP sheets, creating highly conductive xGNP networks [24]. OMMT in PER/WCS composite at 3 wt% reduces the thermal conductivity and dielectric strength due to the randomly disordered dispersion; OMMT acts as a barrier, creating a complicated path for conductivity [26]. GO in the WEP/MWCNT composite at 4 wt% increases tensile strength and thermal conductivity due to the synergistic reinforcement with MWCNTs, and GO increases the synergic effect of MWCNTs by reducing their agglomeration [40]. Finally, Gra at 3 wt% in WPU/MWCNT composite also increases tensile strength, thermal conductivity, and electrical conductivity because micro-scale Gra creates excluded volumes that improve MWCNT dispersion and form a more continuous conductive network [27].

From the properties of thermoset composites containing secondary fillers, it can be seen that each type of secondary filler plays a critical role in enhancing specific properties of the composites based on their physical and chemical characteristics. AgMP enhances thermal and electrical conductivity due to the bridging effect between filler particles. Similarly, AgNWs increase flexural strength and thermal conductivity, attributed to their ability to bridge between primary spherical particles. Furthermore, SiC enhances thermal conductivity while decreasing dielectric strength, as SiC possesses higher thermal conductivity and lower electrical volume resistivity. CB increases flexural strength, degradation temperature, and electrical conductivity since its small diameter allows for the formation of conductive networks. MCF enhances flexural strength and electrical conductivity through increased bulk density, improving the formation of conductive networks. MWCNTs raise flexural strength, degradation temperature, and electrical conductivity; their tubular geometry and smaller diameter create effective conducting networks. BNNP also enhances flexural strength, thermal conductivity, and electrical conductivity, as BNNP creates additional contact points, forming a new three-dimensional network. MWCNTs improve flexural strength and degradation temperature through mechanical interlocking and bridging across the composite's interface. Additionally, Al_2O_3NP boosts tensile strength, thermal conductivity, and electrical conductivity by moderating electron transfer and agglomeration of primary fillers. CuNP improves thermal and electrical conductivity by acting as bridges among large primary fillers, creating highly conductive networks. OMMT reduces thermal conductivity and dielectric strength due to its barrier properties, obstructing conductivity paths. GO also increases tensile strength and thermal conductivity through synergistic reinforcement with primary fillers. Finally, Gra enhances tensile strength, thermal conductivity, and electrical conductivity, as Gra improves filler dispersion and forms a more continuous conductive network. Hence, each of these findings reflects a strategic incorporation of secondary fillers to exploit their unique properties for improving specific characteristics of the thermoset composites, demonstrating a complex interplay between the composite matrix, filler type, and content.

6.2 Properties of thermoplastic composites containing secondary fillers

Table 5 shows the mechanical, thermal, and electrical properties of thermoplastic composites containing various types of secondary fillers. The incorporation of AgNP at 10 wt% in the HDPE/KCF composite notably improves tensile strength and degradation temperature due to AgNP's nano-chain structure, high nano-mechanical performance, excellent thermal stability, and high volume ratio [23]. Similarly, in the LDPE/KCF composite, Dol is incorporated at 18 wt% and elevates tensile strength and degradation temperature due to Dol's abrasive nature, which provides mechanical interlocking and enhances stiffness, and Dol possesses high thermal decomposition characteristics [41]. The utilization of TP at 30 wt% in the LLDPE/MWCNT composite enhances tensile strength and crystallization temperature while decreasing electrical volume resistivity due to an increased interfacial area between TP and the LLDPE matrix, and TP boosts the matrix's strength and rigidity [42]. CB at 3 wt% in the PA12/MWCNT composite leaves the crystallization temperature unchanged and improves electrical conductivity, as CB enhances MWCNT dispersion and particularly reduces the size of large primary nanotube agglomerates [43]. The incorporation of MWCNTs at 5 wt% in PP/C composite boosts flexural strength and electrical conductivity because the MWCNTs bridge across adjacent graphite particles, which forms an extended network of filler particles in direct contact [47]. However, incorporating SSF at 1 vol% in the PP/MWCNT composite decreases tensile strength and crystallization temperature while improving electrical conductivity due to SSF's high aspect ratio and rigid nature, which facilitate effective network formation even at a low loading [28]. Finally, the incorporation of MWCNTs at 2.5 wt% in the PPS/C composite significantly increases flexural strength, leaves the crystallization temperature unchanged, and enhances electrical conductivity; this is because the MWCNTs, due to their high aspect ratio, act as bridges between graphite particles, filling the gaps between them [45].

From the properties of thermoplastic composites containing secondary fillers, it can be observed that each filler

Table 5: Mechanical, thermal, and electrical properties of thermoplastic composites containing secondary fillers

Thermoplastic composite	Secondary filler	Content	Properties			Ref.
			Mechanical	Thermal	Electrical	
HDPE/KCF	AgNP	10 wt%	TS ↑	T_d ↑	N/A	[23]
LDPE/KCF	Dol	18 wt%	TS ↑	T_d ↑	N/A	[41]
LLDPE/MWCNTs	TP	30 wt%	TS ↑	T_c ↑	EVR ↓	[42]
PA12/MWCNTs	CB	3 wt%	N/A	T_c ↕	EC ↑	[43]
PP/C	MWCNTs	5 wt%	FS ↑	N/A	EC ↑	[47]
PP/MWCNTs	SSF	1 vol%	TS ↓	T_c ↓	EC ↑	[28]
PPS/C	MWCNTs	2.5 wt%	FS ↑	T_c ↕	EC ↑	[45]

TS = tensile strength, T_d = degradation temperature, N/A = not available, T_c = crystallization temperature, EVR = electrical volume resistivity, EC = electrical conductivity, FS = flexural strength, ↑ = increase in the properties, ↓ = decrease in the properties, and ↕ = unchanged in the properties.

plays a specific role in enhancing the composite's structural and functional characteristics. AgNP improves tensile strength and degradation temperature due to its nanochain structure, exhibiting high nano-mechanical performance and excellent thermal stability. Similarly, Dol elevates both tensile strength and degradation temperature, as its abrasive nature provides mechanical interlocking and promotes high thermal decomposition. Additionally, TP boosts both tensile strength and crystallization temperature, attributable to the increased interfacial area between TP and the polymer matrix. CB effectively improves electrical conductivity by enhancing primary filler dispersion and reducing the size of agglomerates. Moreover, MWCNTs increase both flexural strength and electrical conductivity by bridging adjacent primary particles, forming an extensive network. Conversely, SSF decreases both tensile strength and crystallization temperature while improving electrical conductivity, as its high aspect ratio and rigid nature aid effective network formation. Finally, MWCNTs enhance both flexural strength and electrical conductivity, as they act as bridges between primary particles. Thus, these secondary fillers perform critical functions in improving and modifying the physical properties of the base thermoplastic composites, enabling their tailored application across various industrial uses, each improvement driven by specific characteristics imparted by the fillers.

6.3 Properties of elastomer composites containing secondary fillers

Table 6 shows the mechanical, thermal, and electrical properties of elastomer composites containing various types of secondary fillers. The incorporation of CB at 10 phr in the NBR/GNP composite significantly enhances tensile strength, degradation temperature, and electrical conductivity because CB particles aid in the exfoliation of GNP layers, which act as a delaminating agent by entering between individual layers [22]. MWCNTs at 2 phr in the NR/CB composite increase tensile strength and thermal conductivity while decreasing electrical volume resistivity due to the greater reinforcement provided by MWCNTs. This also leads to better CB dispersion and a higher cross-link density [50]. In the NR/SiO_2 composite, the incorporation of CB at 10 phr markedly improves tensile strength and tangent delta because of the increased physical interactions of NR molecules with the CB surface. Additionally, CB's high surface area leads to the formation of a SiO_2-CB filler network [31]. In PDMS/MWCNT composite, the utilization of SiO_2 at 50 wt% elevates tensile strength and electrical conductivity due to the SiO_2-dominated volume in the composite, leading to an increased concentration of MWCNTs around SiO_2, which establishes more electrically conductive networks [2]. Similarly, the PMVS/MWCNT composite containing CCB at 10 phr shows increased tensile strength and electrical conductivity because CCB effectively improves the dispersion of MWCNTs by the effect of excluded volume, forming more conductive paths and ensuring efficient stress transmission [53].

From the properties of elastomer composites containing secondary fillers, it can be perceived that each filler distinctly enhances specific mechanical, thermal, and electrical properties. CB boosts tensile strength, degradation temperature, and electrical conductivity by acting as a delaminating agent to help exfoliate primary fillers. MWCNTs increase tensile strength and thermal conductivity since they improve filler dispersion and cross-link density within the rubber matrix. Additionally, CB further improves tensile strength and tangent delta, as its high surface area forms a robust filler–filler network. SiO_2 elevates tensile strength and electrical conductivity, with these improvements attributed to the SiO_2-dominated volume that creates more extensive conductive networks. Similarly, CCB enhances tensile strength and electrical

Table 6: Mechanical, thermal, and electrical properties of elastomer composites containing secondary fillers

Elastomer composite	Secondary filler	Content	Properties			Ref.
			Mechanical	Thermal	Electrical	
NBR/GNP	CB	10 phr	TS ↑	T_d ↑	EC ↑	[22]
NR/CB	MWCNTs	2 phr	TS ↑	k ↑	EVR ↓	[50]
NR/SiO_2	CB	10 phr	TS ↑	tan δ ↑	N/A	[31]
PDMS/MWCNTs	SiO_2	50 wt%	TS ↑	N/A	EC ↑	[2]
PMVS/MWCNTs	CCB	10 phr	TS ↑	N/A	EC ↑	[53]

TS = tensile strength, T_d = degradation temperature, EC = electrical conductivity, k = thermal conductivity, EVR = electrical volume resistivity, tan δ = tangent delta, N/A = not available, ↑ = increase in the properties, and ↓ = decrease in the properties.

conductivity by improving the dispersion of primary fillers, forming more effective conductive pathways. Therefore, these enhancements are essential for extending the practical range of the elastomer composites. They are directly attributable to the unique integrations between the secondary fillers and the composites' components, heightening their mechanical, thermal, and electrical properties.

7 Potential applications of polymer composites containing secondary fillers

7.1 Potential applications of thermoset composites containing secondary fillers

Table 7 shows the potential applications of thermoset composites containing various types of secondary fillers and their specific components. The ER/AgNP composite containing AgMP is ideal for use in thermal management systems as a thermal interface material because of its super-high thermal conductivity [19]. The ER/Al_2O_3 composite with AgNWs is suitable as an electronic packaging material in high-performance electronic applications due to its good mechanical performance and high thermal conductivity [15]. Similarly, the same composite containing SiC is potentially used as a thermally conductive material for thermal management due to its high thermal conductivity and low dielectric strength [35]. The ER/C composite incorporated with CB is particularly suitable as a bipolar plate material in low- and high-temperature polymer electrolyte membrane fuel cells because of its high electrical conductivity and good thermal stability [25]. When MCF or MWCNTs are incorporated into the same composite, they are also appropriate for use as bipolar plate materials due to their high mechanical, thermal, and electrical properties [37,38]. For ER/GNP composite containing BNNP, applications extend to thermal management as a thermal interface material because of its ultrahigh thermal conductivity [21]. The incorporation of MWCNTs in ER/Kev composite makes it ideal for the defense sector as a ballistic protection material due to its superior mechanical and thermal properties [14]. The ER/MCF composite incorporating MWCNTs is utilized in fuel cell applications as a bipolar plate material because of its excellent electrical conductivity and mechanical properties [1]. The ER/RGO composite containing Al_2O_3NP can be used as an electronic packaging material in high-performance electronics because of its outstanding mechanical and thermal properties [17]. When CuNP is incorporated into the ER/xGNP composite, it finds potential applications in thermal management as a thermal interface material due to its high thermal conductivity [24]. The OMMT in the PER/WCS composite makes it suitable as a thermal insulation material in automobile industries due to its low thermal conductivity and dielectric strength [26]. Additionally, the GO in the WEP/MWCNT composite can be used in smart materials as a shape memory composite because of its exceptional mechanical strength, thermal conductivity, and thermal response speed [40]. Finally, the incorporation of Gra in the WPU/MWCNT composite can be applied as an electromagnetic interference shielding material in the electromagnetic shielding area due to its high electrical conductivity, good mechanical properties, and high thermal conductivity [27].

Table 7: Potential applications of thermoset composites containing secondary fillers and their specific components

Thermoset composite	Secondary filler	Potential application	Specific component	Ref.
ER/AgNP	AgMP	Thermal management	Thermal interface	[19]
ER/Al_2O_3	AgNWs	High-performance electronic	Electronic packager	[15]
ER/Al_2O_3	SiC	Thermal management	Thermal conductor	[35]
ER/C	CB	Fuel cell	Bipolar plate	[25]
ER/C	MCF	Fuel cell	Bipolar plate	[37]
ER/C	MWCNTs	Fuel cell	Bipolar plate	[38]
ER/GNP	BNNP	Thermal management	Thermal interface	[21]
ER/Kev	MWCNTs	Defense	Ballistic protector	[14]
ER/MCF	MWCNTs	Fuel cell	Bipolar plate	[1]
ER/RGO	Al_2O_3NP	High-performance electronic	Electronic packager	[17]
ER/xGNP	CuNP	Thermal management	Thermal interface	[24]
PER/WCS	OMMT	Automobile	Thermal insulator	[26]
WEP/MWCNTs	GO	Smart material	Shape memory	[40]
WPU/MWCNTs	Gra	Electromagnetic shielding	Electromagnetic interference shield	[27]

Table 8: Potential applications of thermoplastic composites containing secondary fillers and their specific components

Thermoplastic composite	Secondary filler	Potential application	Specific component	Ref.
HDPE/KCF	AgNP	Packaging	Food packager	[23]
LDPE/KCF	Dol	Packaging	Food packager	[41]
LLDPE/MWCNTs	TP	Electronic	Electrical conductor	[42]
PA12/MWCNTs	CB	Electronic	Electrical conductor	[43]
PP/C	MWCNTs	Fuel cell	Bipolar plate	[47]
PP/MWCNTs	SSF	Electromagnetic shielding	Electromagnetic interference shield	[28]
PPS/C	MWCNTs	Fuel cell	Bipolar plate	[45]

Each of these applications is directly related to the unique functions of the secondary fillers, which enhance the base properties of thermoset composites, effectively meeting specific industrial demands.

7.2 Potential applications of thermoplastic composites containing secondary fillers

Table 8 shows the potential applications of thermoplastic composites containing various types of secondary fillers and their specific components. The HDPE/KCF composite containing AgNP is particularly suited for packaging applications, especially as a food packaging material, because of its strong mechanical, thermal, and antimicrobial properties [23]. When incorporated with Dol, the LDPE/KCF composite is also potentially used as a food packaging material due to its enhanced mechanical properties, high thermal stability, and low cost [41]. The LLDPE/MWCNT composite with TP can be utilized in electronic components as an electrically conductive material because of its low electrical resistivity and high mechanical properties [42]. In the PA12/MWCNT composite, the incorporation of CB offers potential applications in electronics that benefit from improved electrical conductivity [43]. The PP/C composite containing MWCNTs is ideal for bipolar plate material needed in polymer electrolyte membrane fuel cells because of its elevated electrical conductivity and good mechanical properties [47]. Moreover, the PP/MWCNT composite with SSF can be used in electromagnetic shielding applications as an electromagnetic interference shielding material due to its improved electrical conductivity and lightweight [28]. Finally, the PPS/C composite incorporated with MWCNTs finds use as a bipolar plate material in fuel cells because of its high electrical conductivity and good mechanical stability [45]. Each of these applications leverages the exceptional enhancements provided by the secondary fillers to meet specific conductivity, stability, and mechanical performance requirements of thermoplastic composites in various engineering contexts.

7.3 Potential applications of elastomer composites containing secondary fillers

Table 9 shows the potential applications of elastomer composites containing various types of secondary fillers and their specific components. The NBR/GNP composite containing CB is ideal for flexible electronic applications as a stretchable conductive material due to its enhanced electrical conductivity and flexibility [22]. The NR/CB composite incorporated with MWCNTs can be used as a thermally conductive material in thermal management applications because of its excellent thermal conductivity and low electrical resistivity [50]. In the NR/SiO_2 composite, the incorporation of CB suggests potential applications in the automobile industry, such as a tire tread compound, due to its good mechanical strength and improved abrasion

Table 9: Potential applications of elastomer composites containing secondary fillers and their specific components

Elastomer composite	Secondary filler	Potential application	Specific component	Ref.
NBR/GNP	CB	Flexible electronic	Stretchable conductor	[22]
NR/CB	MWCNTs	Thermal management	Thermal conductor	[50]
NR/SiO_2	CB	Automobile	Tire tread	[31]
PDMS/MWCNTs	SiO_2	Wearable sensor	Piezoresistive material	[2]
PMVS/MWCNTs	CCB	Flexible electronic	Stretchable conductor	[53]

resistance [31]. The PDMS/MWCNT composite with SiO_2 can be utilized as a piezoresistive material in wearable sensor technologies due to its increased electrical conductivity and flexibility [2]. Finally, the PMVS/MWCNT composite containing CCB can be used in flexible electronic devices as a stretchable conductive material due to its high electrical conductivity and strain sensitivity [53]. Each application demonstrates how secondary fillers significantly enhance the performance characteristics of elastomer composites, thereby improving their usability and functionality in various fields.

8 Conclusions and future scopes

In this review, commonly used polymer matrices include thermosets (notably ER), thermoplastics (specifically PP), and elastomers (particularly NR). Typically, secondary fillers like carbon-based (CB and MWCNTs) and inorganic-based fillers (OMMT and TP) are incorporated into these composites. Primary fillers such as MWCNTs and C are also widely used. Overall, the incorporation of secondary fillers generally improves the mechanical, thermal, and electrical properties of polymer composites, regardless of the polymer matrix or primary filler types involved. These improvements are attributed to the bridging effect of secondary fillers, helping to form continuous paths for heat and electron flow, thereby enhancing the thermal and electrical conductivity of the composites. Moreover, the conductive network formation of secondary fillers leads to an improved path for electrical conduction and a more uniform distribution of stress, increasing the electrical conductivity and mechanical properties of the composites. The mechanical interlocking of secondary fillers within the matrix makes them more resistant to mechanical stresses, thereby enhancing the mechanical properties of the composites. Additionally, the inherent high thermal and electrical conductivity of secondary fillers enhances heat and electron transfer, thus improving both the thermal and electrical properties of the composites. Finally, the synergistic effect of secondary fillers with primary fillers contributes to enhanced load transfer and better thermal conductivity, improving the mechanical and thermal properties of the composites. The most common potential applications of thermoset composites containing secondary fillers are in thermal management systems, fuel cell technologies, and electronic industries. In addition, the most prevalent potential applications of thermoplastic composites containing secondary fillers include packaging, electronics, and fuel cells. Furthermore, the predominant potential applications of elastomer composites containing secondary fillers are flexible electronics and wearable sensors. Future scope could focus on the development of novel secondary fillers with enhanced functionalities to address specific industrial needs. Innovations in filler technology may include the synthesis of hybrid fillers that combine the benefits of different materials or the exploration of bio-based fillers for environmentally friendly solutions. Additionally, advanced fabrication techniques could be explored to create composites with customized properties and rapid production tailored to specific applications. Continued investigation into the interactions between fillers and polymer matrices may lead to composites with extraordinary performance, opening up new possibilities in high-tech applications such as aerospace, advanced robotics, and smart textiles. Further studies are needed to assess the long-term durability and recyclability of these composites to promote sustainable development in the field of materials science.

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