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Polymer composites for thermal applications – A review

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ABSTRACT

Polymer composites are commonly used in industry and are used in various fields such as the aircraft industry, automobile industry, electronic industry and packaging industry, etc. due to their diverse versatility, low cost, light weight, and outstanding chemical consistency. For new technologies, especially in aerospace and aeronautics, thermal properties have become a significant parameter. A reference to a number of research studies is made in this paper and the role of fillers in polymers is studied. The main purpose of this analysis is to identify any possible patterns that control and dictate the thermal properties in polymeric composites.

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1. Introduction

There is an increasing demand and development in the field of material science since the last two decades and to fit the requirements of the out-dated products available in the market, material scientists have evolved the polymer composites to outperform their original functions that is being rigid and not buckling. Polymer composite has a large variety of industrial applications due to its many desirable properties ranging from high thermal conductivity to excellent chemical resistance. Polymer composites are mostly anisotropic in nature, these results in them having good mechanical, electrical and thermal properties. Compared to isotropic materials composite materials are much more effective and efficient.

There are many conventional filler materials that are using as a filler material in polymer composites for different applications [1–5]. The ever-alarming concern about the environment can also be put to rest by using the construction, industrial and animal waste as filler which is reinforced with the polymer matrix and enhances the mechanical, physical and thermal properties. However, epoxy polymeric composite despite having so many industrial applications, possess poor mechanical properties. Silica is one of the most ideal inorganic compounds that can be used as reinforcement material along with other inorganic materials. Research also indicates that plant fibres are often used as fillers because of their renewability and high availability. The main sources of natural fibres are both inexhaustible and non-sustainable for example sisal, palm oil and flax. These are then used to make composite material.

Presently the composites that are used in thermal fillers do not provide any electrical properties. Carbon Nanotubes (CNTs) and Graphene Nanotubes (GNTs) have excellent mechanical, thermal and electrical properties. CNTs and GNTs have a strong lattice which gives them good physical and thermal properties [6–8].

With these polymer composite materials integrating into the electronics industry, the developments in thermal properties, especially thermal dissipation heavily influences the performance, reliability and lifetime of these devices. Hence thermal conductivity of these polymer composite materials plays a huge role in a lot of industries. Exhaust heat affects the functioning and the properties of the equipment. A good thermal management system is necessary to protect the equipment from any heat related damages.

2. Filler materials

In the material science field, there is a constant surge to develop new, cheap and better material and this has accelerated the growth

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and development of fillers. Fillers are added to the composite to be reinforced with the matrix and change the properties of the composite. Fillers can be organic as well as inorganic.

Mainly, Natural fibre reinforces composite (NFRCs) are used when better thermal properties are required, glass fibre dominates the market with 95% of fibre composites being reinforce with glass fibre (as of 2015) but natural fibres are a suitable alternative because of their many desirable properties. Here are a few natural fibres that are commonly used in the industry.

2.1. Sisal fibre

Sisal fibre comes from the plant Agave Sisalana which is a native plant of Mexico and grows well in hot climate. Sisal plant is grown in some parts of India as well. A leaf of sisal plant has around 1000 fibres, out of which only 4% are used as fibres for industrial applications. It is extracted by the process of manual or mechanical decortication in which the leaves are crushed between the rollers and then the sisal leaf decortication residue (SLDR) is extracted leaving behind sisal fibre. This fibre becomes suitable to use after being cleaned and dried. This fibre is used to reinforce the polymer matrix due to its many desirable qualities like renewability, low cost, high specific strength, etc. In fact, in India Sisal fibre is used by leading manufactures in the Automobile industry [9] (Fig. 1).

Fig. 1. Sisal fibre [10].

2.2. Jute fibre

Jute is derived from jute plant; the fibre is derived from the stem and the outer skin of the jute plant. Polymer composite is made using jute as the reinforcement. Jute fibres are used in composites as they are easily available and are sustainably produced. Just like most natural fibres jute provides low density, biodegradability and good insulation. Just fibre is also non-toxic compared to the other available Petro-chemical based synthetic polymers [11] (Fig. 2).

Fig. 2. Jute fibre [12].

2.3. Oil palm boiler ash (OPBA)

Palm oil holds the title of being most consumed edible oil and it is largely produced in Malaysia and Indonesia. Palm oil industries produce two major solid waste palm oil boiler ash and palm oil fuel ash (palm kernel shell). Palm kernel shell can also be used as a fuel to generate electricity, but the disposal of the other solid waste by-product was a raising concern until they began being used as fillers. After the completion of palm oil production process, the waste in the lower compartment of boiler is the boiler ash [13,14] (Fig. 3).

Fig. 3. Oil palm boiler ash [15].

2.4. Hemp fibre

Hemp is a type of Cannabis Sativa plant. Hemp is specifically grown for industrial purposes. Hemp fibre is produced by the process of water retting. Hemp fibre is used to make ropes, sail canvases, textile etc. In polymer composites hemp is used as the reinforcement. Polymer composites made using Hemp have low density, provide good thermal insulation and have good mechanical properties. Hemp is produced naturally in plants as a result they are environmentally friendly, and non-toxic. Hemp based polymers are considered as promising material for manufacturing of electric vehicle as they have very less weight and very less environmental impact which is very important factor in case of electric cars [16] (Fig. 4).

2.5. Corn husk fibre

India's second largest produced crop is corn and its cultivation creates stover (stalk, husk and leaves) in huge amounts. Corn husk is a by-product of corn or maize. 14% of the fodder produced by corn cultivation is husk. Corn husk has is made up of high percentage of cellulose and small amounts of lignin and ash. Fibres are extracted from corn husk though the process of alkali treatment at high temperature then washed and finally require enzymatic

Fig. 4. Hemp fibre [17].

treatment to remove traces of hemicellulose and lignin. Corn husk fibres have twisted ribbon like shape. This agricultural by-product produces fibres that are typically used in textile industries producing fabric with qualities like durability, softness, elongation, etc [18] (Fig. 5).

2.6. Kenaf fibre

Kenaf is obtained from Hibiscus cannabinus. Kenaf fibre is similar to that of jute fibre and has similar characteristics. Kenaf fibre is mainly used to produce ropes, cloths and other textile products. The pulp obtained is also used to produce paper. Polymer composites made with kenaf generally use a kenaf-epoxy combination. Here kenaf is the reinforcement and epoxy is the matrix [20,21] (Fig. 6).

2.7. Areca husk fibre

Areca is an inexpensive and naturally abundant fibre extracted from the Aceraceae palm family. India grows a fairly large amount of Areca plant, nearly 40,000 tonnes annually with Karnataka being the major producer of the plant. It is composed of cellulose, hemicellulose, lignin, pectin and protopectin [23] (Fig. 7).

Fig. 5. Corn husk fibre [19].

Fig. 6. Kenaf fibre [22].

2.8. Flax fibre

Flax is a natural fibre obtained from the plant Linum usitatissimum. Flax fibre is collected from the bast beneath the surface of the flax plant stem. Coarse fibres are used to make ropes. Flax fibres are also used to make textile, it is known as linen. Flax fibres are extracted by the process of retting. Polymer composites made with flax are light in weight and have less environmental impact. They are biodegradable and are non-toxic. Flax fibres are used as reinforcement. They are also used to make geopolymer composites with fly ash. Flax based geopolymer composites are used in constructions as they are a more environmentally friendly option compared to the commonly used Portland cement [25,26] (Fig. 8).

2.9. Abaca fibre

Abaca is a natural fibre, it is also known as Manila Hemp. Abaca fibre is mainly used to make ropes and its pulp is used to make paper products such as tea bags and banknotes. Polymer composites made using abaca fibres are used in constructions and are also used in the automobile sector. They are used mainly because of their light weight, high tensile strength [28,29] (Fig. 9).

2.10. Henequen fibre

Henequen fibre is obtained from the leaves of the plant Agave fourcroydes. This species is mainly available in Mexico and Guate-

Fig. 7. Areca husk fibre [24].

Fig. 8. Flax fibre [27].

Fig. 9. Abaca fibre [30].

mala. Polymer composites that are made using Henequen fibre are mainly used in the automobile sector. These composites provide better thermal properties than traditional synthetic composites as a result they are much suited for making components in cars [31] (Fig. 10).

The most common natural fibres that are generally used in the industry, their composition and tensile strength are compiled in the table below (Table 1).

3. Thermal properties of polymer composites

Polymer composites are found nearly in all aspects in the modern world. They find vast uses in the automotive sector, construction and many more. Composites have low density which results in reduced weight. They have high tensile strength and have great thermal properties. Due to these great properties, they have a lot of applications in all sectors. Thermal properties of polymer composite are heavily dependent on the interfacial interactions between the polymer matrix and the filler. Lattice vibrations are the mode of heat transfer in the polymer composite materials [34].

The thermal applications of polymer composites depend a lot on the thermal properties of natural fibre. Thermal stability of natural fibres is a very important factor especially when one is comparing them with inorganic reinforcements. Poor thermal properties like low thermal conductivity and diffusivity makes the polymer composite less industrially suitable. Milling or other stress induced machining on natural fibre polymers may reduce their thermal stability [35].

Fig. 10. Henequen Fibre [32].

In case of Hemp fibre reduction in the length of the natural fibre of polymer composites results in the reduction of thermal stability. Although thermal stability mainly depend on the thermal behaviour of the composites. Degradation onset temperature reduces for shorter fibres when intense milling is performed [36–37,16].

Thermogravimetric analysis of flax fibres reveal that they degrade in three steps. The first degradation transition occurs somewhere between 25 and 240 °C. In this stage they release the free water that is stored in it. The second stage of degradation occurs in between 240 and 365 °C. In this stage the maximum weight loss occurs as the cellulose gets decomposed. The final stage of degradation occurs when the temperature is above 365 °C. In this stage the rate of weight loss is low as only volatile evaporates and the fibre starts to decompose. From this result it can be said that for applications below 250 °C Flax fibre composites work perfectly [38,25–26].

In case of treated abaca fibres thermal degradation occurred in two steps. In the first step about 8.4% of weight is lost. In the second step 72% of the weight is lost and the onset temperature for the degradation is around 253 °C. When abaca fibres are mixed with 1% high density Polythene and nano precipitated calcium carbonate thermal degradation takes place in four steps. In the first step about 1% of weight is lost. In the second step about 14.5% of weight is lost and about 78% of weight in the last step. The degradation onset temperature is around 336 °C. Another control setup was prepared for the experiment where thermal degradation of HDPE was found by adding HDPE with treated abaca. With increase in concentration of NPCC the weight reduction reduces but in a very small quantity and the degradation onset temperature doesn't have much of a change. The addition of NPCC can be said to increase thermal stability as it reduces degradation [39,29].

In the case of erythritol graphite composite the thermal degradation began somewhere around 200 °C. In the temperature between 200 and 300 °C the composite lost about 78% of its weight. Above 300 °C the reduction in weight was less as most of the erythritol had already degraded. Above 530 °C there was weight loss of around 25% as graphite starts to degrade [40].

On conducting tests to find out the specific heat of kenaf epoxy fibres it is found out that chemical treatment does not affect the specific heat capacity of kenaf fibres. In case of thermal diffusivity and conductivity, the chemically treated fibres performed much better than the untreated ones. Chemically treated kenaf epoxy fibres had shown an increase in overall thermal diffusivity and conductivity. The better thermal properties of the chemically trea-

Table 1
Fibres compositions and tensile strength [31,33].

Fibre	Composition (in %)							Tensile Strength (in MPa)
	Lignin	Cellulose	Moisture content	Hemicellulose	Pectin	Wax	Ash	
Jute	15–25	45–70	10–15	12–20	0.5	0.35	0.3–2	835
Hemp	3–15	55–75	5–12	13–23	1	0.9	0.7	35.17
Flax	2.5	75	7–13	16–21	2	1–3	–	10.45
Sisal	8–12	45–75	10–20	10–25	10	1	0.5	27
Kenaf	12–21	30–70	–	15–25	–	–	1–5	15.5
Abaca	7–10	55–65	6–10	14–19	–	–	2	24.81
Henequen	14	75	–	4–8	–	–	–	16

ted fibres could be attributed to the better interfacial contact between the fibre and its matrix [41].

Kenaf epoxy composite have gained much popularity due to its mechanical and thermal properties but there is an interfacial mismatch between fibre and polymer matrix which affects the adhesion, this reduction in adhesion reduces the thermal conductivity. So, on alkaline treatment of kenaf epoxy composite with 6% NaOH, the thermal conductivity and thermal diffusivity improve as a result of improved interfacial contact between fibre and matrix. Thermal diffusivity decreases with increase in temperature which shows the high-volume fraction in the polymer composite. This reduction in diffusivity also depicts an increase in phonon–phonon scattering at high temperature. The alkali treated composite shows improved thermal conductivity as well because of reduced thermal contact resistance which helps with the heat transfer through the epoxy composite. The effective thermal conductivity and thermal diffusivity of chemically (alkali) treated kenaf epoxy polymer is 0.232 W/mK at 28 °C and 0.234 W/mK at 200 °C respectively. Hence, due to such thermal properties and good mechanical properties they show a promising future in industrial applications [42,21].

Graphene aligned composites with graphene nanoplatelets (GNPs) as filler material has excellent thermal conductivity making them suitable for a lot of thermal applications. Thermal conduction is carried out by phonon- phonon scattering is reduced when there is good interfacial interaction between polymer matrix and filler and there is a large contact area. As a result of reduced scattering the thermal conductivity increases. The large contact area is provided by the high aspect ratio of GNPs. GNPs can be aligned in the polymer matrix through many methods like electric/magnetic alignment or mechanical stress aided alignment, this alignment defines the interfacial interactions between filler and matrix. With 5 wt% GNPs the thermal conductivity of GNP composite is 0.3 W/m/K however thermal conductivity with 20 wt% GNPs is 0.587 W/m/K, this depicts that low GNP content in polymer matrix significantly improves the thermal conductivity as compared to high content of GNP. This is because when GNP content is high, they contact each other in random and aligned composite reducing the functionality of the alignment. Graphene aligned composite exhibits an oriented thermal conduction also known as in-plane thermal conduction which is about 3000 W/mK whereas through plane thermal conductivity is 6 W/mK, hence parallel and perpendicular alignment of GNPs create a lot of difference [43,6].

The solder matrix nano polymer composite (SMNPC) is fabricated by liquid phase infiltration of a Sn-Ag-Cu into silver nanoparticle coated electro spun polyimide fibre. It shows promising thermal properties and could be used as an alternative for conventional solder. Xenon flash method is used to analyse the thermal properties of the fibre in the polymer matrix. The through plane thermal conductivity of SMNPC is nearly 22 W/mK which is roughly 35% of bulk conductivity of Sn-Ag-Cu matrix. These values are likely to change for thicker SMNPC because more thickness will lead to increase in number of continuous high conducting matrix paths, this will increase the thermal resistance. However, the total thermal resistance for SMNPC lies between 2.2 and 3.7 mm^2/W. The in-plane thermal conductivity is also measured by xenon flash method which was found to be 39 – 43 W/mK which is about 70% of bulk matrix value. This shows that in-plane thermal conductivity is almost double the through-plane conductivity for the composite. Reason behind this is the smaller conducting area exhibited by fibres running in parallel direction to heat. Thermo-mechanical reliability is also an important aspect to consider for industrial application of SMNPCs and to evaluate this reliability, thermal cycling under harsh conditions was carried on the composite to monitor the change in thermal resistance. So, for 1000 cycles the effective thermal resistance of SMNPC was unaffected indicating high thermo-mechanical reliability under thermal stress, thus making it an alternative for high-cost indium and die attach applications [44].

Epoxy polymer composite shows an improvement in mechanical and thermal properties when reinforced with oil palm boiler ash (OPBA) which contains around 53 wt% silica (Si). Using thermogravimetric analysis on the epoxy polymer, the maximum thermal degradation temperature, initial decomposition temperature and final decomposition temperature were found to be highest with 50 wt% OPBA filler loading and 50 μm particle size with values 364 °C, 435 °C, 389 °C respectively. Hence, with increasing silica content in the polymer matrix i.e., with increasing filler loading the thermal stability increased. The char residue also increased with increasing OPBA filler loading and particle size. The polymer composite with 30 wt% OPBA filler loading showed the highest mechanical and thermal properties for good interfacial adhesion between filler and matrix [45–46,13].

Fibre reinforced polymer (FRP) composites have emerged as one of the most promising developments in material science as they offer improved mechanical, electrical and thermal properties and therefore have many industrial applications. Most common fibres are glass, Kevlar and carbon, natural fibres like paper and wood are rarely used for reinforcement. Most common polymer matrix used in FRP is epoxy resin. Kevlar/glass reinforced polymer with modified epoxy resin (2 wt% of cloisite 30B and hardened) as matrix has many desirable mechanical and thermal properties. Differential scanning calorimetry (DSC) analysis was carried out on the Kevlar/glass fibre reinforced polymer matrix with nitrogen atmosphere, with heating rate of 0.3–2.6 °C/min and a flow rate of 50 mL/min to find out the glass transition temperature. Only Kevlar fibre possessed glass transition temperature at 122.5 °C after decomposition of fibre. Thermogravimetric analysis was carried out on Kevlar/glass reinforced polymer composite resulted in weight loss (due to matrix loss) when heated uniformly in stable environment. This weight loss indicated the thermal stability of Kevlar and glass fibres. So, when the Kevlar/glass fibre is heated close to 800 °C in nitrogen atmosphere, nearly 68% of the initial mass is lost. To observe the change in force and deflection of fibre with varying temperature dynamic mechanical analysis is conducted, it gives the loss modulus, dampening coefficient and storage modulus. With increase in temperature the storage modulus slightly increases with increase in volume fraction of glass fibre and then decreases. The melting peaks of kevlar and glass fibre also shift to higher temperatures. Loss modulus also increases at temperature range 0 to 160 °C. Hence reinforcement of epoxy polymer with Kevlar/glass fibre improves the thermal properties and increase gas transition temperature with altering the thermal stability [47–48].

4. Summary

In this paper we had conducted research on the thermal applications and the thermal properties of mainly natural fibre composites. From the research we conducted, we can conclude that:

1. Natural fibre composites have properties similar to that of a conventional composite material. They have low density which makes them light but have high tensile strength.
2. Unlike conventional composites, natural fibre composites are non-toxic.
3. Natural fibre composites are much more environment friendly.
4. Natural fibre composites find a lot of application in the automobile sector, and the construction sector.
5. Electric vehicle's main aim is to make travel more energy efficient and reduce the impact on the environment. Natural fibre composites are light and are environmentally friendly as a result there is a massive potential for future mainstream uses of natural fibre composites.

As we are shifting to a more carbon neutral world, we must embrace new materials which have the same properties that of the conventional materials but have less impact on the environment. Every single day more and more industries are trying to incorporate new materials into their system and natural fibre composites will find much more applications in the future.

CRediT authorship contribution statement

Sugeet Kharbanda: Conceptualization, Investigation, Writing - original draft. **Tanish Bhadury:** Conceptualization, Investigation, Writing - original draft. **Gaurav Gupta:** Supervision, Writing - original draft. **Devasri Fuloria:** Visualization, Writing - review & editing. **Pravat Ranjan Pati:** Visualization, Writing - review & editing. **Vijay Kumar Mishra:** Visualization, Writing - review & editing. **Abhishek Sharma:** Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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