



## Review Article

# Advancements in thermal management of polymer composites and sandwich structures: Insights and innovations

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## ABSTRACT

This paper presents an inclusive review of recent developments in the thermal-mechanical endurance of composites made of polymers and sandwich structures. The large number of literatures are studied on phase change materials, smart materials, nanofiller based polymer composites, and natural fiber based composites. These combinations or materials provides the improved capabilities for energy storage, more supportable material, and good thermos-mechanical properties. It also discusses the use of this information in various fields such as construction, energy storage, thermal management of electronic equipment, etc. This review suggests potential for future research directions to improve the thermal stability and performance of polymer materials and panels.

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## INTRODUCTION

The pursuit of innovative solutions for effective thermal management in structural composite structures (like polymer or sandwich) has been a driving force in various fields, like aerospace and locomotive/automobile engineering to renewable energy systems and building materials. The considerable research is going on on composite structural composites to enhance the performance in terms of long lasting performance, and efficiency and durability [1-3]. In this comprehensive review, we delve into the latest insights and innovations shaping the landscape of thermal management in polymer composites and sandwich structures.

Polymer composites finds its application in variety of applications as they as comparably light weights as

compared to metal and ceramic matrix composites, also they are easy to fabricate as compared to others [4]. But the polymers used in this case have lesser glass transition temperature, and this forms the critical challenge in the thermal management filed where the dissipation of heat and sustainability in high temperature becomes dominant [5,6].

Simultaneously, when light weight core inserted between the two surrounded sheets, it will act as a thermal insulation or thermal barrier. Also this kind of sandwich structural composites provide good strength to weight ratio. Overall whenever required to utilise these both structural composites (layered composites and sandwich composites) in diversified applications, need to improve their thermal stability.

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Current investigation has rigorous on developing progressive materials and manufacturing practices to meet the sophisticated thermal management requirements of structural composites (layered composites and sandwich composites). A key area of examination encompasses integrating phase change materials (PCMs) into these materials to apply their latent heat storage capacity and regulator temperature variants [7-9]. Graphene-based phase change composites (PCCs) have attracted considerable interest due to their greater temperature conductivity and energy stowing properties, proposing promising methods to progress the thermal recital of polymer composites and sandwich structures [10,11]

To improvise the thermos-mechanical properties of structural (layered and sandwich) composites, researchers were investigated modern method and processes of fabrications [12]. During working on this improvising researchers were found that carbon nanotubes (CNTs), fullerene, graphene oxide, Nano cellulose suitable after integration with regular composite for improving thermal capacities in terms of conductivity and mechanical property enhancement as well [13,14], and further precession in product development can be achieved with the help of 3D printing additive manufacturing technologies [15].

As observed from the previous literatures, layered composite are better in inplane loading, but sandwich composite are shows superior in transverse loading applications. In this sandwich composites, core plays an important load [16,17]. The face sheet is transmitting the applied load over core, and core is the member who actually takes that load, transmit it into its channel uniformly. In this regard, phase change metal foam core offers good thermos-mechanical collaborative gain [18-21]. Under dynamic loading conditions also these sandwich structures found suitable [22-25].

The structural sandwich and polymer composites are found suitable in civil engineering works because of easy and fast installing, efficient energy, and improved strength to weight ratio [26]. As sandwich composites are light in weight, also ability of core to provide insulation capacity, such structures find its applications in cold storage, building blocks and bricks [27-29].

Besides, there is a countless transaction of potential for refining thermal controlling competences in polymer composites and sandwich structures by the corporation of smart materials and compliant structures [30].

Shape memory materials are stimulating materials which can be utilised in the electronics, transportation containers, aerospace, automobile, medical, space antenna, and temperature regulating mechanism or applications [31,32].

### THERMAL ANALYSIS

Whenever dealing with the chemical (organic/inorganic), food, drugs, petrochemicals, thermal analysis is important [33], because it makes simple to study heat flow, dissipation, any kind of dimensional or mechanical changes occurred [34]. This technique is indispensable for characterizing properties such as decomposition, crystallization, melting, molecular structure, viscoelastic behavior, glass transition temperature ( $T_g$ ), cross-linking, oxidation, volatilization, coefficient of thermal expansion (CTE), tensile modulus, composition, processing, stability, and mobility.

A comprehensive array of TA techniques is currently well-established, which includes various methods as shown in Figure 1.

All of these techniques are suitable and useful for the investigation of various properties and what kind of basic material under study.

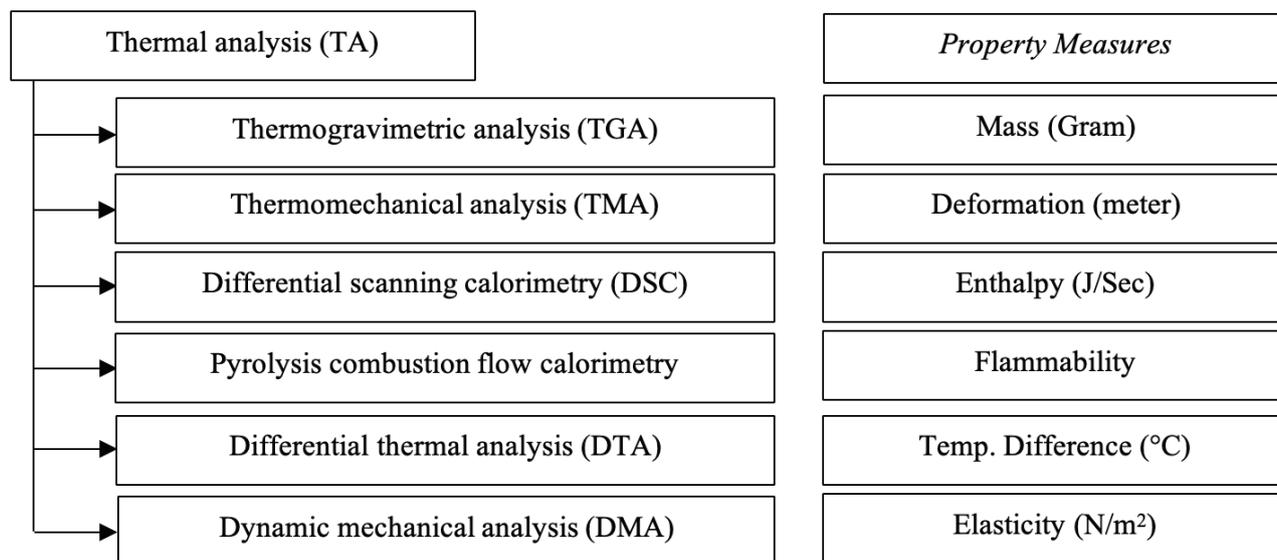


Figure 1. An inclusive arrangement of TA procedures.

To study the resistance against temperature, heat, durability, researchers were focused on temperature stability of the materials, and whenever thinking industry point of view, developments are going on for improvement in polymer composites [35]. These polymers generally show significantly higher melting or softening temperatures ( $T_m$ ), superior resistance to thermal decomposition, larger remaining mass fraction and little changes in physical, mechanical and chemical properties even after long-term exposure at an elevated temperature compared with other common biopolymers [36]. Further, these polymers may have a higher heat deflection temperature under load and so possess greater stability. This emphasis on thermal stability underscores the significance of materials capable of withstanding demanding thermal environments across diverse industrial applications [37,38].

As technology advances, there is a rising demand for multifunctional, smart, lightweight, flexible, and cost-effective materials, rendering traditional options like metals inadequate for modern industries [37,39]. However, polymers, abundant and versatile, boast enticing attributes such as low specific weight, high corrosion resistance, affordability, ease of molding, smart optical properties, and excellent electrical and thermal insulation [40]. Polymer composite obviously found suitable in widespread industry utilization, because of thermo-mechanical, electrical limitations of amorphous structures [27,28].

## POLYMER COMPOSITES

PMCs are widely used in engineering, such as aerospace, marine, automotive and civil engineering. Nevertheless, the practical applications are limited by the glass transition temperatures of polymer matrix which is usually about 78 °C for epoxy concurrently [41]. Indeed, > also results in some structural changes of which defending (64) or improving the system's level even involving carbon black with graphene nanoplatelet addition could be useful for avoiding damage caused by heat effects [42].

Notwithstanding the above, it is important to understand the PMC behavior at elevated temperatures. Current research focuses on determining the mechanisms of degradation during exposure to high temperatures, as well

as the mechanical properties of composite forms. Till the temperature reaches to 250 °C, slow process of degradation occurs, but after that decay rapidly occurs shows nonlinearity in process [43]. The aging period in different literature survey is different, and temperature also. Like, in [44] the samples of matrix fiber composites were heated till 150 °C for different time, [45] done it for 4800 hours at 50 °C, and [46] performed it for 2000 hours for temperature range of 210 °C to 250 °C. This shows that with reducing the range of working temperature, the chemical or physical changes apperaded in material will reduce down.

In addition to thickness, the layer arrangement and reinforcement type significantly influence composite behavior at elevated temperatures. For example, in reference [47], researchers examined four composite variants as shown in Figure 2:

Another study, as discussed in reference [48], focused on the thermo-oxidative aging behavior of carbon fiber-reinforced polymer (CFRP) CF/PA6 composites and glass-fiber reinforced composites (Ultramid® B3WG7). Additionally, reference [49,50] investigated accelerated aging of carbon-epoxy (carbon/EP) and carbon-vinyl (carbon/VE) composites.

PMCs may encounter additional environmental stresses like UV contamination, salt sprig, or water exposure [51]. Moreover, elevated pressure can be a contributing factor, as illustrated in reference [52,53], where pressures of 1.7 bar and 5 bar were applied alongside high air temperatures.

Numerical modeling plays a pivotal role in comprehending the behavior of Polymer Matrix Composites (PMCs), particularly regarding thermal degradation. In reference [54], researchers devised a specialized numerical modeling tool integrated into the commercial software ABAQUS to model the thermo-oxidative responses of fiber-matrix composite cells that are microscopically appropriate. Similarly, reference [55] employed NOVA-3D code with custom finite element analysis, to model decline in unidirectional composite samples exposed to thermo-oxidative aging at 300 °C. Delamination phenomenon was simulated by micromechanical a viscoelastic cohesive layer model. Such methods or modeling practices supports researchers for creating and improving the complex behaviour of multiphase polymer

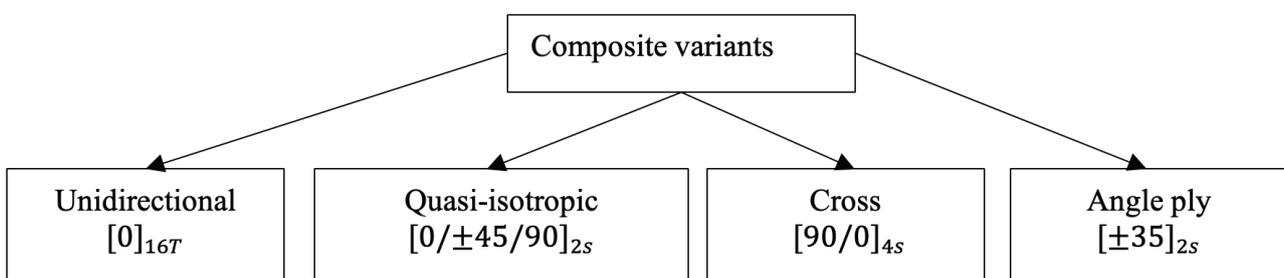


Figure 2. Composite variants.

composite which were worked in variety of thermal conditions [56], [57].

In some cases it is observed that minor surface damage to matrix comes out with constructive results which includes electromagnetic (EM) radiation absorption designing systems [58].

Thermo-oxidative aging induces surface irregularities, cracks, and voids in composites, which can scatter incident EM waves. However, controlled aging is imperative, and the effects must be assessed using non-destructive methods.

Various factors influence the shape and frequency of natural vibration, including structural defects, composite internal structure (e.g., shape memory fibers, nano additives, hybrid composites), manufacturing techniques (e.g., material property scattering, residual stresses, imperfections), contact with composite bolted joints, and hygrothermal effects during aging processes [59,60].

Up to the temperature of 250°C, polymer thermoset composites are effectively get utilised as pristine material, but above 300°C, the deterioration due to temperature will get start, which possibly leads to disengagement of contact between matrix and fiber. The bonding between these two phases will start damaging significantly, which simultaneously reduces the material properties like modulus of elasticity and rigidity, Poisson's ratio, decrement in load carrying capacity, strength etc

#### Carbon Fiber Reinforced Polymer/Plastic (CFRP)

Research work introduces that, CFRP are well known for its strength, durability, good thermo-mechanical properties, resistance against deterioration, radiation barrier, so these materials are found to be most suitable in aerospace, defense, automobile, and many more industries [61]. However, machining CFRP components, such as those found in aircraft wings and automobile panels, presents considerable challenges, particularly in hole processing for connections, which significantly impacts connection strength [62].

Various material combinations can be used to prepare structural composite sheets based on user needs and

application. Some of them are referred to here. Graphite/carbon/Kevlar fiber reinforced sheets, matrix-based sheets, nanofillers reinforced sheets, Aluminum alloys, glass-vinyl ester are common types of face and bottom sheets used in sandwich structures. [63] conducted a comparison of the strength properties between steel plate and aluminum plate sandwich structures, and glass fiber reinforced plastic (GFRP) plate sandwich structures. In the research by [64], FRP materials like CFRP ([65,66]; and GFRP [67]) were applied to enhance the bending characteristics of sandwich panels. ((Liu et al., 2015; Markad and Lal, 2021a, 2023) conducted tests on carbon/epoxy fabric composite sandwich panels and carbon/epoxy unidirectional prepreg panels. Below is Table 1 which shows the mechanical characteristics of various popular face materials [68].

Due to its heterogeneous and anisotropic nature, CFRP poses greater challenges in achieving high-quality cuts compared to homogeneous materials [70]. Currently, the CFRP manufacturing methods are generalized and their mechanical processing also. But whenever working with these CFRP composites, like drilling, cutting that time vulnerable delamination results formation of tears or removal of fiber or formation of burrs [71]. Whenever these delamination or fiber breakage occurs, these creates the defects which ultimately creates the adverse effect. So this is the time consuming and cost increasing phenomenon [72]. Also, whenever traditional methods are get utilised to machining the CFRP parts, the possibility of melt the matrix/polymer from CFRP which will open the fiber to atmosphere. To avoid such dramatic situations, different methods are utilised for machining the CFRP parts which include the abrasive water jet machining, lesser cutting, and electrical discharge machining (EDM) [73-75]. As we know, the purpose of matrix material is to protect the fiber from environment. But sometimes it is observe that, during the abrasive water jet machining (AWJ) excess water causes the submerging the water molecules into fiber which may starts the corrosion or degradation in performance of CFRP [76]. Similar to that in harsh environment, EDM processed CFRP samples are also were not performed well

**Table 1.** The mechanical parameters of some common sheet materials

Face material	Poisson's ratio	Longitudinal modulus (GPa)	Transverse modulus (GPa)	Shear modulus (GPa)	Density (kg/m <sup>3</sup> )	Reference
FRP	0.33	--		24.8	1600	[63]
Aluminum	--	72	72	27	2700	[69]
USN [0]Ns	0.28	130	10.5	5.06	1540	[69]
USN [90]Ns	0.30	51.7	51.7	19.94	1540	[69]
Stycast epoxy resin	--	2.1	2.1	0.81	1200	[69]
CFRP	0.3	54	---	---	---	[31,56]
GNPRC	0.3	65	---	---	---	[57]

because of hygroscopic characteristics form due to introduction of water into samples. Contrariwise, because of higher processing flexibility, and minor cutting force lesser cutting find advantageous. However the effect of temperature can cause formation of co2 emission, and burnt gases due to fiber, which may cause ablation damage of samples of CFRP.

To tackle all these machining process challenges, new methods are introduced. Ultrafast layers introduces the femto-and-pico-second lasers which is cold work processing technique promising for CFRP processing. These technique is reduces or avoid the thermal damage, but having lower cutting efficiency. Due to all facts, researchers are now focusing on parameter variation in lesser cutting so as to develop the innovative method which ultimately perform efficiently on CFRP machining operation.

### FRP with Nanofillers

Over the last decade, considerable attention has been directed towards experimental and numerical investigations aiming to predict the influence of dual nanofillers (DNFs) and multiscale fillers (MSFs) in polymers. Polymer composites reinforced with DNFs and MSFs exhibit remarkable mechanical and thermomechanical properties, achieved through meticulous design and control of material and process parameters [77]. This article presents an overview of the latest advanced manufacturing methods, key factors, micromechanical models, and simulation approaches to analyse the mechanical properties of hybrid polymer composites under static and dynamic conditions.

It is a well-established fact that further progress in the direction of using laminated and sandwich composite materials as an alternative to the conventional materials in various applications largely depend on better understanding of thermo-mechanical nonlinear flexural, buckling and vibrational response under various loading conditions using finite element analysis. There are tremendous literature can be observed which worked over CFRP or individually over polymer, but it is essential to study the effect of utilization of the shape memory behaviour of the shape memory polymer (SMP) utilised in CFRP or can called as shape memory polymer composite (SMPC). It is important to found the effect of dynamic temperature variation in SMP over nonlinear transverse central deflection (TCD), buckling, and post-buckling of the laminated SMPC beam under constant and varying loads in a glass transition region

Table 2 clearly differentiate between performance of SMPC and SMP hybrid composite beam with the utilization of SWCNT, MWCNT for different lamination or stacking sequence of layups [56,62]. From the obtained results, it was observed that as compared to carbon fibre reinforced polymer or SMPC, SMP hybrid composites effectively increase the performance of the structural composites, and these results were motivated to work and analyse the SMP hybrid composites.

Nanomaterials are integrated into raw materials, becoming an integral, non-invasive part of the structure. These in-situ sensors enhance mechanical performance without compromising structural integrity, providing improved toughening and interfacial conformability, unlike traditional sensors [78]. They respond to external stimuli by disturbances in conductive paths formed by nanomaterial flakes. Irfan et al. [79] conducted recent research that thoroughly examined the use of these sensors in monitoring the manufacturing processes and structural health of polymer composites. A notable example is carbon-based reduced Graphene Oxide (rGO), which is highly regarded for its exceptional conductivity and flexibility. Number of research were conducted to improve the structural health monitoring of the nanocomposites materials. The abilities of rGO nanocomposites find its application in sensors to improve health of structures and manufacturing characteristics [80-82] and find applications in biomedicine, flexible electronics, and energy storage applications [83].

However, most of these tests have been conducted in static or dynamic modes at fixed temperatures [80] explored the impact of temperature on the piezoresistivity of rGO-coated glass fiber sensors embedded in epoxy/glass fiber composites, noting a noticeable enhancement in piezoresistivity with increasing temperature.

Carbon-based nanoparticles, such as carbon nanotubes (CNTs) and their derivatives—single-walled carbon nanotubes (SWCNTs), multi-walled carbon nanotubes (MWCNTs), graphene, and graphene oxide—are widely recognized for their exceptional properties. Problems associated with high cost and the processing of CNTs notwithstanding, owing to their remarkable mechanical properties which include a very high intrinsic strength, relative lightness and extremely large aspect ratio, they have emerged among the most sought nanofillers. These properties make them highly effective in numerous advance applications

**Table 2.** Effect of number of walls of CNT and lamination scheme over central deflection of SMPC beam

No. of walls of CNT	Lamination scheme	TCD of two phase SMPC ( $N_w=0$ )	TCD of three phase composite
$N_w=0$	0/90	0.02807	-----
$N_w=1$	0/90	-----	0.0227
$N_w=2$	0/90	-----	0.02554
$N_w=3$	0/90	-----	0.02643

[84]. These nanofillers have been shown to greatly improve the properties of composites even at low wt %. Nevertheless, this improvement varies depending on filler functionalization, aspect ratio, filler loading and polymer matrix nature, dispersability of fillers in the polymer matrix and processing methods. Despite these high cost and processing issues with carbon nanoparticles, the superior mechanical, electrical and thermal properties of carbon-based nano particles demonstrate great promise toward advanced compositing [85].

The improved performance is recorded with the incorporation of graphene nanofillers in a jute fiber composites. With this combination notable improvement is observed. As compared to two phase jute fiber reinforced composite, the multiphase composite shows 110% and 324% improvement in tensile strength and elastic modulus. This combination shows the suitability of this modified nanocomposite based jute fiber composite in many synergetic application and ability of replacement of untreated jute fiber composite, along with this it is eco-friendly too [86].

Zhang et al. embedded the graphene oxide (GO)-and polyhedral oligomeric silsesquioxanes (POSS) into carbon fiber composites for the formation of multiphase composites. With this, improvement is observed in interfacial adhesion and mechanical characteristics. In the similar manner, Sharma et al. also studied the effect of incorporation of 2-dimensional GO, 1-dimensional MWCNT, 3-dimensional graphene-carbon nanotube hybrids in aramid fiber-reinforced polycarbonate composites, and proposed that with just 0.2% addition of nanofiller significantly improves the mechanical properties like tensile strength, elastic modulus. The overall performance improvement is noted with the addition of graphene-based nanofillers [87].

Bulut et al. also investigated the effect of addition of nanoclay into the basalt fiber-reinforced polymer (BFRP) composites, and shows that 29% improvement in bending strength, and 7.6% improvement in tensile strength, and 16.8% improvement in impact resistance as compared to pristine basalt fiber-reinforced polymer (BFRP) composites [88].

## METHOD OF DEVELOPMENT OF POLYMER COMPOSITES

The studied literatures clearly reveal that the addition of nanofillers into fiber reinforced composites significantly shows the improvement as compared to base composites. But some literatures also highlight the effect of addition of nanofillers after certain percentage creates the aggregation. Because of van der Waals force of attraction in CNT or any nanofiller, the aggregation arises. This particularly happens because nonhomogeneous or poor dispersion of nanofillers into the base matrix. This directly reduces the capabilities of the nanocomposites. This difficulty can be overcome with proper dispersion and aligning the CNTs unidirectional into the polymer matrix.

With this process of development of polymer composites, one can improve the thermo-electrical characteristic of the composite materials [89,90]. Traditionally, three main techniques are utilized for preparing CNT/polymer composites:

### Standard Approaches

#### Solution collaborating

Solution collaborating / mixing stands as an adaptable technique widely utilized for the large-scale production of nanocomposites, including CNT/polymer composites, while preserving the desirable properties of nano-sized fillers. In a solvent epoxy and CNTs are mixed separately, for increasing solubility for further mixing. After that both the mixtures are added into each other, and for homogeneous mixing purpose and ultra-sonication, magnetic stirring, or high-speed homogenization can be performed [90]. During the degassing process this solvent will get vaporise.

Alternatively, CNTs can be directly mixed into the polymer solution, followed by intense ultra-sonication and shear homogenization. Surface-functionalized CNTs, on the other hand, offer improved dispersal and interfacial attachment with the polymer matrix, leading to improvements in mechanical, thermal, and electrical properties [91].

The choice of solvent is crucial in this method, with low-boiling-point solvents typically favoured due to the complexities involved in evaporating high-boiling-point solvents, which may result in trapped solvent during composite solidification, causing structural defects. Low-viscosity solvents facilitate better dispersion [92]. While solution mixing offers the advantage of potentially de-bundling CNTs to achieve quality dispersion, it also has drawbacks, such as the possibility of leaching of added constituents, potential environmental contamination due to the large amount of solvent used, and the inability to dissolve insoluble polymers [93].

#### Melt blending

For the insoluble thermoplastic polymers, melt blending approach is eco-friendly, cost effective and simple to prepare composite material. Thermoplastic matrix is reusable, means they can be remoulded after heating at transition temperature. In melted condition of granules of polymers, nanofillers are added like CNT, GnP, and using banbury mixers and extruders mixture is homogeneously mixed, the cooling it till solidifies, and further it can cut into required shape and size [94]. The melt blending offers the high speed which found it suitable for industrial applications, along with that it doesn't require the solvent too. But this technique has some disadvantages also. High shear forces and temperatures during processing can potentially disrupt both the CNTs and polymer chains, leading to a reduction in their intrinsic properties [95]. Therefore, Process parameters must be carefully controlled in order to minimise any negative influence on the final composite qualities.

### ***In situ* polymerization/reaction processing**

Reaction processing offers an effective approach for achieving even dispersal of CNTs in insoluble and uneven polymers, which may not be feasible with solution blending and melt treating methods. The process involves initially dispersing CNTs in a monomer solution, followed by the polymerization process under specific conditions [96]. For thermosetting materials like epoxy or unsaturated polyester (PET), polymerization is initiated by a curing agent or hardener acting as a catalyst. In the case of thermoplastics, polymerization occurs either through temperature elevation or by adding an initiator.

This technique facilitates the homogeneous distribution and compatibility of the filler-matrix, leading to strong interface between the CNTs and the polymer matrix. However, there are some drawbacks associated with this method [97]. It typically requires expensive equipment and involves the use of a large volume of solvent, which can increase production costs and may pose environmental concerns.

### **Graphene-Based Composite**

Due to its  $sp_2$ -hybridized structure, graphene, a two-dimensional (2D) hexagonal or tile-like single layer of graphite, has attracted much attention since its discovery in 2004 [96]. Due to its structure, graphene has important properties such as electrical conductivity, physicochemical stability, excellent optical transparency and excellent structural strength. As a result, graphene and its derivatives have found applications in various fields, including tissue engineering, optoelectronics, biosensors and catalysis [97-99]. Various carbonised nanoparticles are displayed in Figure 3.

Graphene can be synthesized using numerous methods, containing mechanical exfoliation of graphite, decline of graphene oxide (GO), chemical vapour deposition (CVD), and epitaxial progress [100-102]. With a thermal conductivity reaching from 3000 to 5000 W/(m·K), graphene surpasses other materials like carbon nanotubes (CNTs) and copper in thermal conductivity. As a result, graphene becomes a perfect filler for phase change materials (PCM), providing better mechanical, electrical and thermal conductivity (PCC) to PCM composites.

However, when incorporating graphene into PCMs, it is essential to consider its large specific surface area. Exceeding the optimum amount of graphene filler may negatively impact the natural convection thermal conductivity of PCMs. Additionally, the thickness and geometry of graphene nanofillers significantly influence the whole thermal conductivity of PCCs. Therefore, careful consideration of these factors is crucial when designing PCCs to ensure optimal thermal enhancement and energy storage capability.

### **Graphene oxide (GO)**

Graphene oxide, or GO, is an oxidised version of graphene with a basal structure like a hexagon or honeycomb,

but with additional oxygen groups like hydroxyl, carboxyl, and epoxy on the base and edges. This alteration results in a wider separation between layers of 6–9 Å, as compared to 3.34 Å for graphene, and enhances its capacity to form bonds with other molecules, hence improving its mechanical and tribological properties [103]. Chemical and electrochemical methods can be used to produce graphene oxide from graphite; the Hummers and modified Hummers procedures are the most widely used [104].

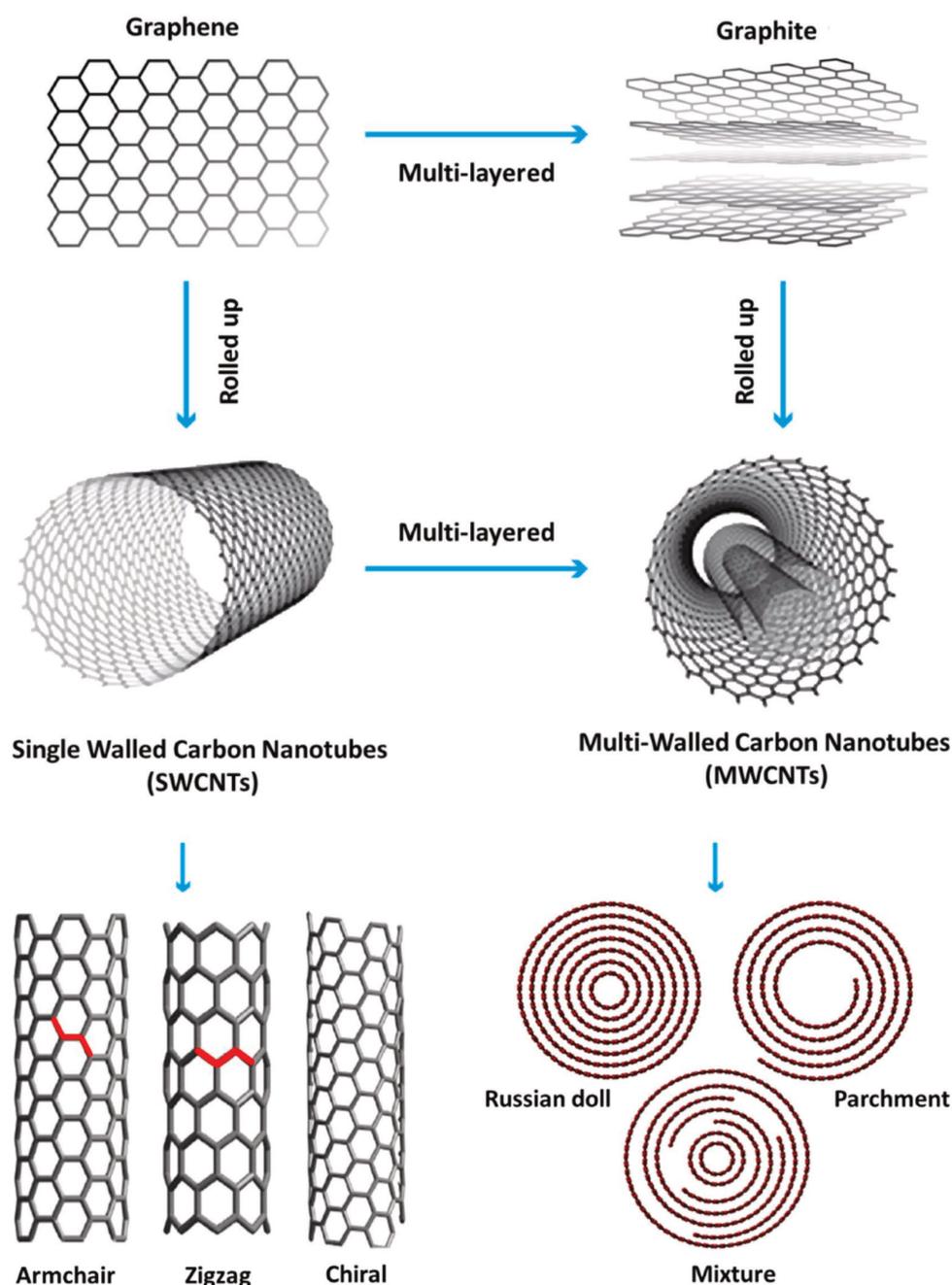
Graphene oxide (GO) exhibits remarkable qualities that make it highly versatile for various applications, including sensors, energy storage, and catalysis [105,106]. A notable example involves the work of Huang et al., who combined GO with molten DHPD, an inorganic phase change material (PCM), to create a shape-stabilized PCM (ssPCM) [107]. This mixture was then incorporated into expanded vermiculite (EV), a porous mineral that enhances structural stability. The inclusion of a minor amount (0.2 wt%) of GO resulted in an increase in the latent heat of the combination from 167 J/g to 229 J/g. Additionally, the contact angle between molten DHPD and EV decreased from 56 to 45 degrees, indicating improved DHPD volume containment due to GO's ability to reduce interface tension.

In another approach, Cao et al. [108] utilized free radical polymerization to covalently attach hexadecyl acrylate (HDA) to GO, creating a ssPCM (GO-g-PHDA). Microscopic and spectroscopic analyses confirmed the successful grafting of PHDA onto the surface of GO. This modification significantly increased the encapsulation volume of DHPD, as evidenced by the reduced interfacial tension between DHPD and EV. Furthermore, the carboxyl and hydroxyl groups on GO facilitated the formation of hydrogen bonds with water molecules, thereby enhancing its thermal properties.

### **Diminished graphene oxide**

From the GO, rGO is get extracted using the decline method which remove major portion oxygen-enclosing functional groups, characterizes a partially abridged material with partially restored  $sp_2$  hybridization of carbon atoms, regaining electrical and mechanical properties akin to graphene. Reduction methods involve chemical processes utilizing agents such as hydrazine or hydriodic acid, as well as thermal treatment at high temperatures [109-111]. Much like graphene and GO, rGO has undergone extensive examination as a thermally sensitive and structurally supportive pitch material in PCCs. For instance, Zhou et al. explored the utilization of a chromium-based metal-organic framework (MOF) adorned with rGO as an adsorption material and structural backing for a shape-stabilized phase change material (ssPCM).

Melt infiltration, akin to vacuum impregnation, stands as a prevalent technique for producing ssPCMs, seeking to resolve the problem of liquid PCM leakage by infusing the PCM into a mesoporous matrix that delivers structural support. However, a drawback of this method lies in the



**Figure 3.** A evaluation of the preparation of SWCNTs and MWCNTs, and the diversity of each kind of CNT [Open Access]

potential weakness of the physical interaction between the matrix and PCM, which could lead to desorption problems following multiple thermal cycles [112].

Chemical modification techniques, such as grafting, offer an alternative approach where the PCM material is covalently committed to the matrix, enhancing thermal reliability and chemical stability. For instance, a novel PCC exhibited a remarkable 472% enhancement in thermal conductivity [112].

### Functionalized nanofillers and its compound

Graphene and its derivatives offer valuable possessions such as dispersion, stability, reactivity, and solubility, making them highly desirable for various applications [113]. These properties can be tailored using various functionalization methods, which include covalent, noncovalent, and hybrid approaches. With the Covalent functionalization the functional groups are directly attached to carbon-covering graphite network with utilising reduction, oxidation, click chemistry, and diazonium chemistry. Opposite to that,

with the noncovalent functionalization outside molecules and nanoparticles enriched into the carbon-rich network through connections like hydrogen bonds, van der Waals forces,  $\pi$ - $\pi$  interactions, hydrophobic, and electrostatic interactions [114]. Additionally, texture processing can combine functional and non-functional approaches, which is particularly useful when multiple features need to be incorporated into graphene materials. These functionalization methods can be implemented either during the assembly of the raw material (in situ) or as a separate process after the material has been obtained (ex situ).

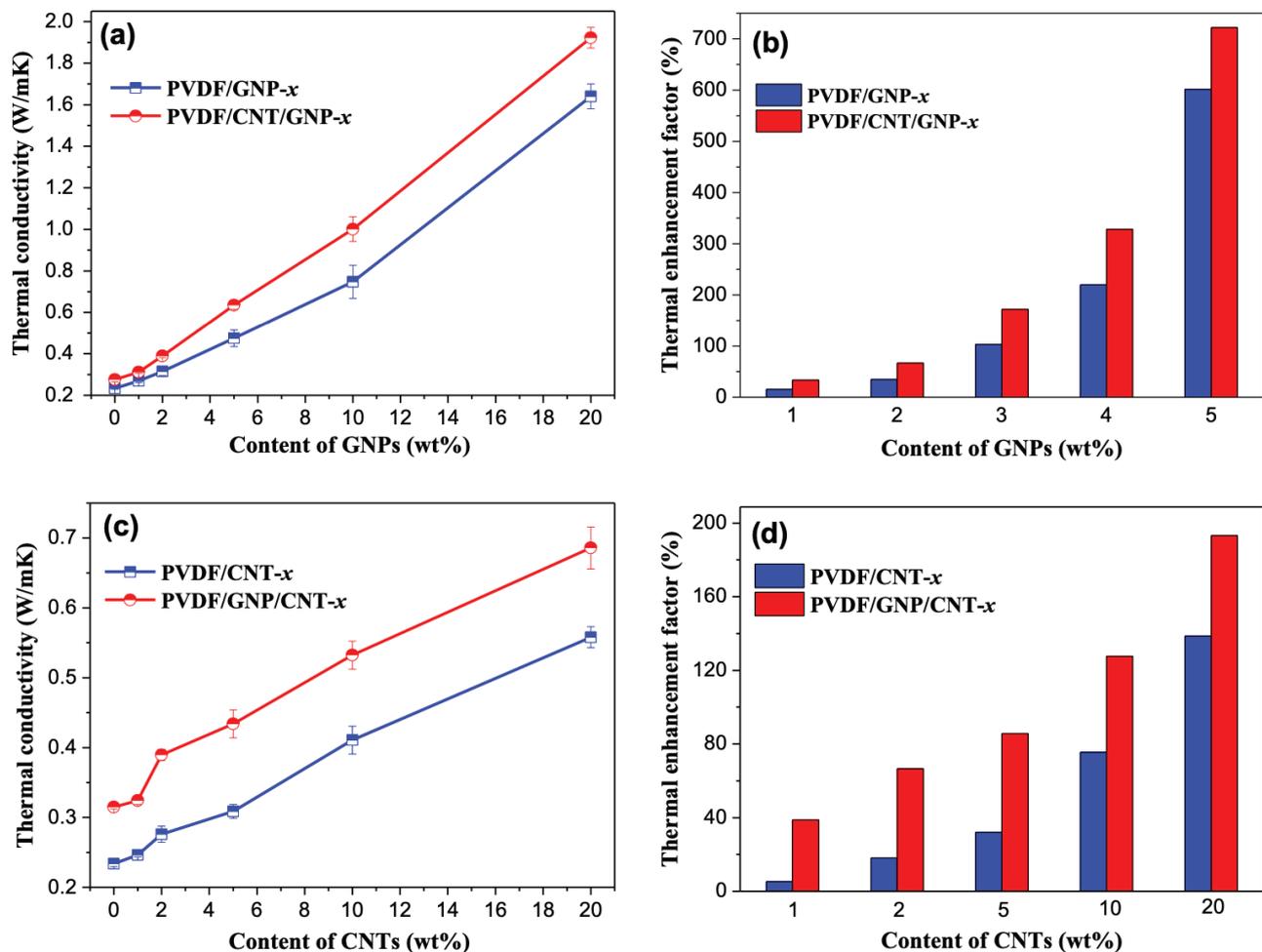
Considering the fluctuation in air source temperature with operation load and duration, researchers have examined the impact of initial phase change material (PCM) temperature ( $T_{int}$ ) on casting performance. They found that increasing the temperature from 2°C to 10°C without graphene nanoplatelet (GnP) functionalization increased the off time by 23.9%. However, the difference in fusion process time decreased to 22.1%, 20.3%, 19.2%, and 17.6% as the working GnP volume increased from 0.1% to 0.5%.

Notably, the total thermal conductivity and melting process delay were reduced as the volume fraction of thermally activated GnP in PCM composite (PCC) was increased. The PCC containing 0.5 vol% GnP exhibited faster melting at both 10°C and 2°C dye levels [115].

### CNTs Inserted Polymer Composites

Carbon nanotubes (CNTs) present significant potential for crafting polymer composites due to their outstanding attributes like high strength, modulus, surface area, stiffness, porosity, corrosion resistance, mechanical-chemical stability, and impressive thermal and electrical properties [116,117]. The important characteristics and nanostructure makes CNTs as an ideal base for wide applications in materials, metals, and ceramics [118]. However only relying on the CNTs as a primary fillers make it financially incorrect therefore need of secondary fillers to alternative costs.

Despite their advantageous qualities, the nano-scale structure and reactivity of CNTs pose potential health hazards during the manufacturing and handling of



**Figure 4.** (a and c) Changes in thermal conductivity and filler content of PVDF composites and (b and d) the comparison of thermal enhancement coefficients between binary and binary composites.

nanocomposites. The disposal of CNTs mostly affect the human health if it get improperly dispose. It may lead to cause lung cancer, respiratory ailments [119]. To overcome these harmful effect caused by CNTs, it is necessary to modify the surface of CNTs.

Secondary fillers are often used for the preparation of hybrid filler systems. The different secondary fillers used are silica, graphene oxide, zinc oxide, carbon black, conductive carbon black, nano-clay, and graphite [120-124]. The many significant qualities are present in these fillers such as fire resistance, lightweight, flexibility, electrical and thermal conductivity, high modulus, and strength. Most favourable results were produced by the combination of CNTs with the graphene particles. Comparative to composite consist of solely graphene and CNTs, a combination of both shows the good performance in modulus and thermal stability [125].

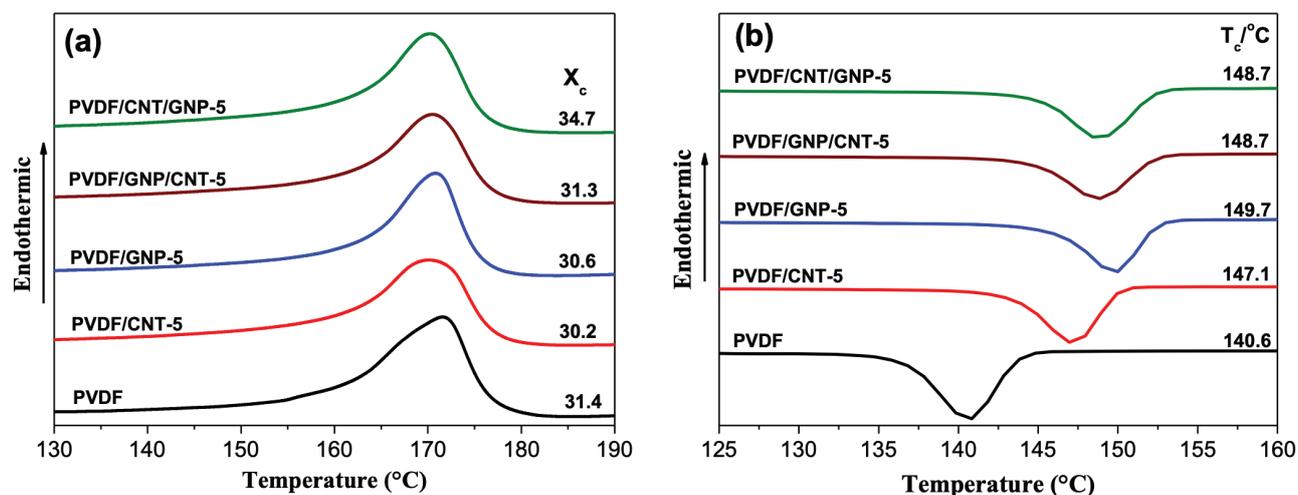
In addition to improving thermal performance, it is important to consider the long-term stability and aging effects of CNT hybrid composites. . To overcome these challenges the composites are prepared with desired material combination by considering various parameters such as material selection, controlled CNT loading, optimized process parameters. The various qualitative methods are used to analyse the behavior and performance of the composite material. The various methods used are thermogravimetric analysis (TGA), infrared spectroscopy (FTIR), dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC). The TGA method is used to determine the decomposition temperature, aging performance of the compounds, and weight loss. The various mechanical and thermal properties are gets affected such as tensile strength, impact strength, thermal conductivity, and ductility. The present study also carried the investigation of environmental, UV rays, humidity, and chemical reaction. Figure 4

shows the nature of heat conduction behaviour with nano-fillers percentage variations [126].

For graphene nanoplatelet (GNP) content below 10 wt%, there is only a slight increase in thermal conductivity in the samples, ranging from  $0.27 \text{ W / mK}$  (with 1 wt% GNPs) to  $0.48 \text{ W / mK}$  (with 5 wt% GNPs). During lower concentration, The GNP dispersed randomly and do not create saturated network structure, which causes ineffective thermal conductive regions. Thermal conductivity increases from  $0.75 \text{ W / mK}$  and  $1.64 \text{ W / mK}$  with the variation of GNP content from 10 wt% and 20 wt% respectively. The recorded thermal conductivity enhanced bt 220% and 602% respectively, indicating the formation of GNPs network structures. Interestingly, all PVDF/CNT/GNP-x models demonstrate greater thermal sensitivity compared to PVDF/GNP-x samples at the same GNP content. For example, the thermal sensitivity of the PVDF/CNT/GNP-1 sample is  $0.31 \text{ W / mK}$ , while that of the PVDF/CNT/GNP-20 sample is significantly higher at  $1.92 \text{ W / mK}$ .

Comparisons of thermal conductivities for PVDF/CNT-x and PVDF/GNP/CNT-x samples with increasing CNT concentration reveal that the PVDF/CNT-20 sample has a thermal conductivity of approximately  $0.56 \text{ W / mK}$ , which is substantially lower than the  $1.64 \text{ W / mK}$  observed in the PVDF/GNP-20 sample. However, the PVDF/GNP/CNT-20 sample, which includes a small quantity of GNPs (2 wt%) in the PVDF/CNT-x composites, exhibits a thermal conductivity of  $0.69 \text{ W / mK}$ . Nonetheless, the thermal conductivity of the PVDF/GNP/CNT-20 sample ( $1.92 \text{ W / mK}$ ) is still lower than that of the PVDF/CNT/GNP-20 sample.

Both carbon nanotubes (CNTs) and graphene nanoparticles (GNPs) have shown to be successful in promoting the crystallization of semi-crystalline polymers as nucleating agents as observed in Figure 5 [126]. Nevertheless, if



**Figure 5.** The graph displays the melting and crystallisation behaviours of the typical samples as represented by the DSC heating curves (a) and cooling curves (b). (created by authors [126])

filler content reaches a certain point and creates a compact interconnected structure, it may impede the movement of polymer chains. This obstacle hinders the development of spherulites, leading to a decrease in crystallinity. The crystalline structures of semicrystalline polymers are widely recognized as determining their conductive properties. Improving the thermal conductivity has been proven by enhancing the crystallinity of the polymer matrix.

DSC was utilized to assess the melting and crystallization behaviors of the samples. All samples, as depicted in Figure 5a, exhibit lower melting temperatures ( $T_m$ ) in comparison to the pure PVDF sample. This implies that the lamella thickness in the composites made with PVDF matrix is slightly smaller than in the pure PVDF sample. Additionally, Figure 5b indicates that there is minimal variation in crystallinity among the samples. The crystallization temperature ( $T_c$ ) of the pure PVDF sample is 140.6 °C. This indicates the nucleation of the PVDF matrix at the crystallisation.

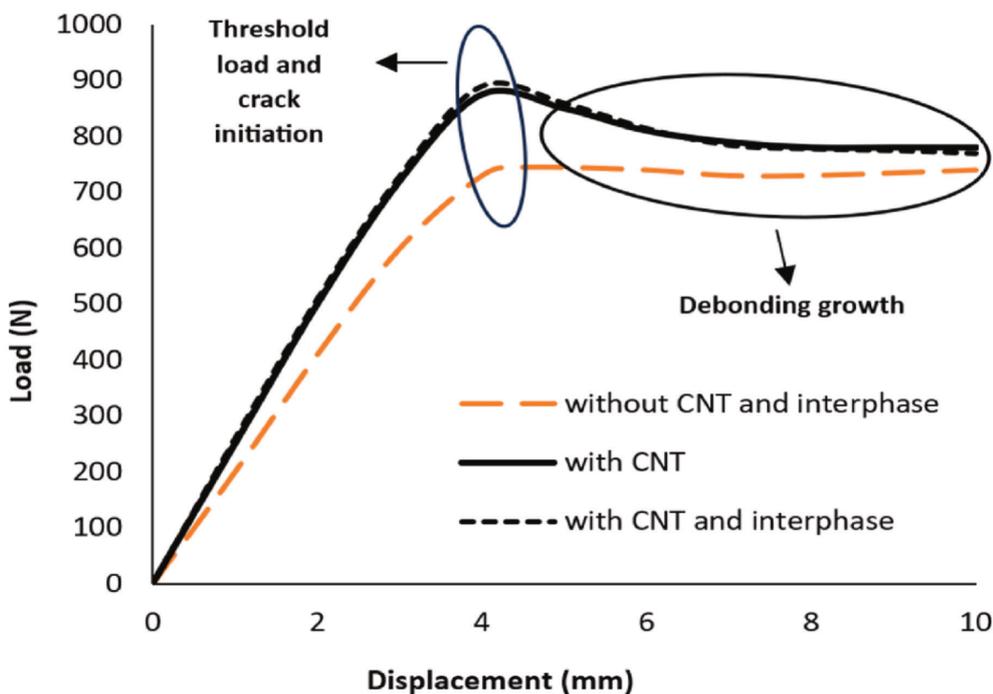
## REINFORCED POLYMER SANDWICH STRUCTURE

In the various industries like marine, aerospace where it is necessary to have a high strength to weight ratio and proper flexural stiffness need to construct the composite structure [127,128]. The technical needs of these application can be achieved by the thick light weight face sheet and lighter core material. In this arrangement, the face plates

endure the  $\sigma_c$ ,  $\sigma_t$  from bending, while the core disperses the impact and stress from transverse shear and normal loads. Hence, it is crucially important to ensure the reliability of sandwich composites [129].

The boundary between the outer layer and the inner core of a bimaterial sandwich composite forms a transition region that is often seen as the least strong part of the structure. This region causes the primary failure like skin cracking, shearing of core, delamination of skin and core, and core crushing [130-132]. Therefore to create the high performance sandwich structure, it is necessary to do research on various factors such as delamination of skin and core. The face sheet and core delamination happens due to the bending force exerted on the multi-layered systems. The high shear stress developed between the face sheet and core. Multiple research were carried for precise characterization of the bending phenomenon for sandwich structures [133-137]. For example, the superposition principle calculates the parameters required for mixed-mode bending, including compliance and strain energy release rate, given the appropriate kinematic relationship of sample deformation [138].

Examination at the microstructural level has shown that enhancing the proportion of carbon fiber and CNT in the volume greatly enhances the  $E_p$ ,  $E_p$  correspondingly. Both the stiffness and thickness of the contacting region, resulting from the bonding of CNTs with the polymer, contribute to improving the  $E_p$ ,  $E_t$  of fuzzy carbon fiber-reinforced composites throughout the entire 0-90° range [139].



**Figure 6.** Impact of CNT addition and CNT/polymer phase development on the FFRC/PVC sandwich structural composite's load-displacement diagram. (created by authors [144])

Efforts have been concentrated on examining flexural properties and skin/core separation of sandwich constructions to determine the effectiveness of nano-additives in enhancing mechanical characteristics at low volume (or weight) concentration [140-142]. A drawback of fiber-reinforced composites, essential in sandwich constructions, is their limited transverse elastic properties. Several studies have shown that enhancing the transverse modulus and bending strength of the composite can be achieved by growing CNTs radially on the circumferential surfaces of fibers [143]. To improve our comprehension of the impact FFRC skins have on bending stiffness and FFRC skin/PVC foam core separation, we will use the current numerical assessment framework.

In Figure 6, addition of 2 volume% CNT, while keeping a constant volume fraction of 30% for E-glass fiber and an interphase region thickness of 0.5 nm, on the bending nature of FFRC skins/PVC core sandwich composite is depicted [144]. It's apparent that the inclusion of CNTs results in a notable improvement in the limiting force and flexural stiffness, attributed to the enhancement of the transverse assets of the FFRC outer layer. Moreover, with the increase in bending stiffness, crack propagation occurs at a steeper rate. The influence of interphase development on the flexural behavior of the sandwich structure seems insignificant based on Figure 5 [145].

Traditionally, honeycomb structures have been the preferred choice for manufacturing sandwich-type composites, as shown in Figure 7 [145]. However, alternative core materials such as aluminum foam have gained popularity due to their exceptional arrangement of physical-mechanical possessions, particularly in withstanding impact and blast loading. For example, the Airbus A340 incorporates composite sandwich structures throughout its vertical tail, which consists of Nomex® honeycomb core along with

the combination of glass fiber reinforced prepreg [146]. Furthermore, polymer foam materials like polyethylene terephthalate (PET) foam and polyvinylchloride (PVC) foam were found application in sandwich composites, as evidenced by models such as the Mercedes-Benz A series automobiles [147,148]. These foam materials offer advantages in terms of lightweight construction and impact absorption, rendering them suitable for various automotive applications [149].

Enhancing impact absorption and improving the interfacial strength between skin and core layers are pivotal challenges in sandwich composite production [56]. Researchers have devised a simple technique involving fabric surface brushing and abrading to bolster the interfacial adhesion between carbon fiber reinforced polymer (CFRP) and core materials. This method has shown notable enhancements in delamination resistance without significant loss in in-plane tensile strength [150]. Another innovative strategy involves employing magnetorheological elastomer (MRE) tapering composite structural sandwich plates to fortify the interfacial structure of sandwich composites [151].

Efforts have also been concentrated on adding nanoparticles to strengthen foam mechanical properties and improve impact absorption through altering specimen thickness. Furthermore, researchers have explored the utilization of modified polymer structural foams with diverse compositions to amplify the properties of sandwich composite materials [152]. These studies aim to optimize the mechanical steadiness of structural composites by augmenting connexion between the skin and core material and leveraging suitable design technologies tailored to specific application conditions [153]. Moreover the sandwich structure exhibits the versatility and structural stability improvement. The sandwich structures are effectively deployed in various applications such as vibration damping, electromagnetic

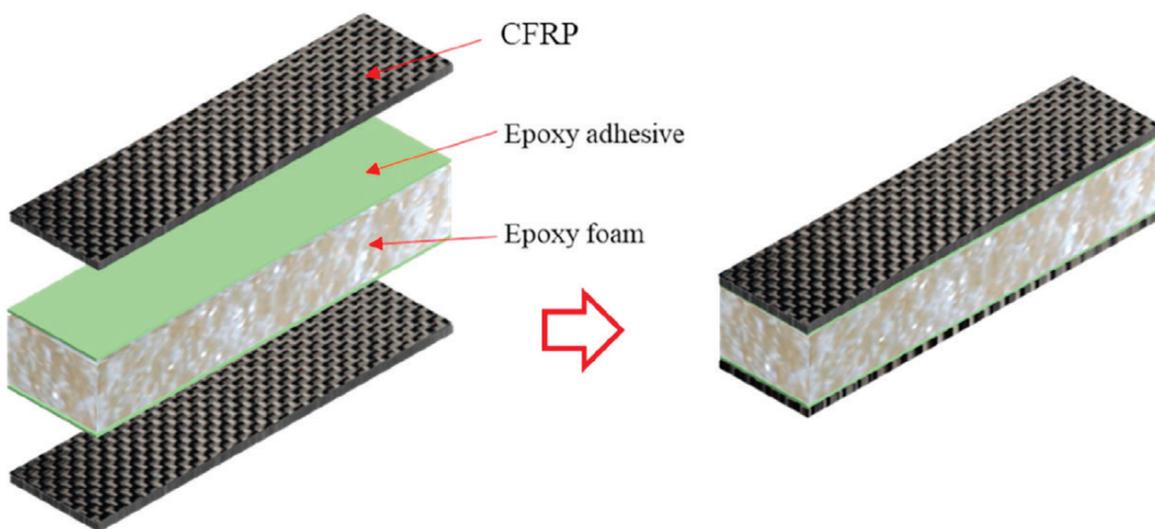


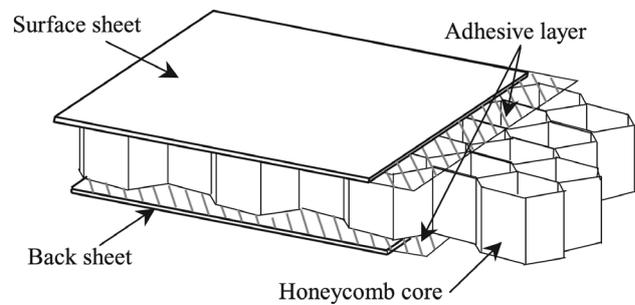
Figure 7. Representation of the sample manufacturing process. (cretaed by authors [145])

shielding, noise cancellation etc. at various industrial applications [154,155]. In the manufacturing of sandwich composite to enhance the mechanical strength the core type reinforcement is generally preferred [156].

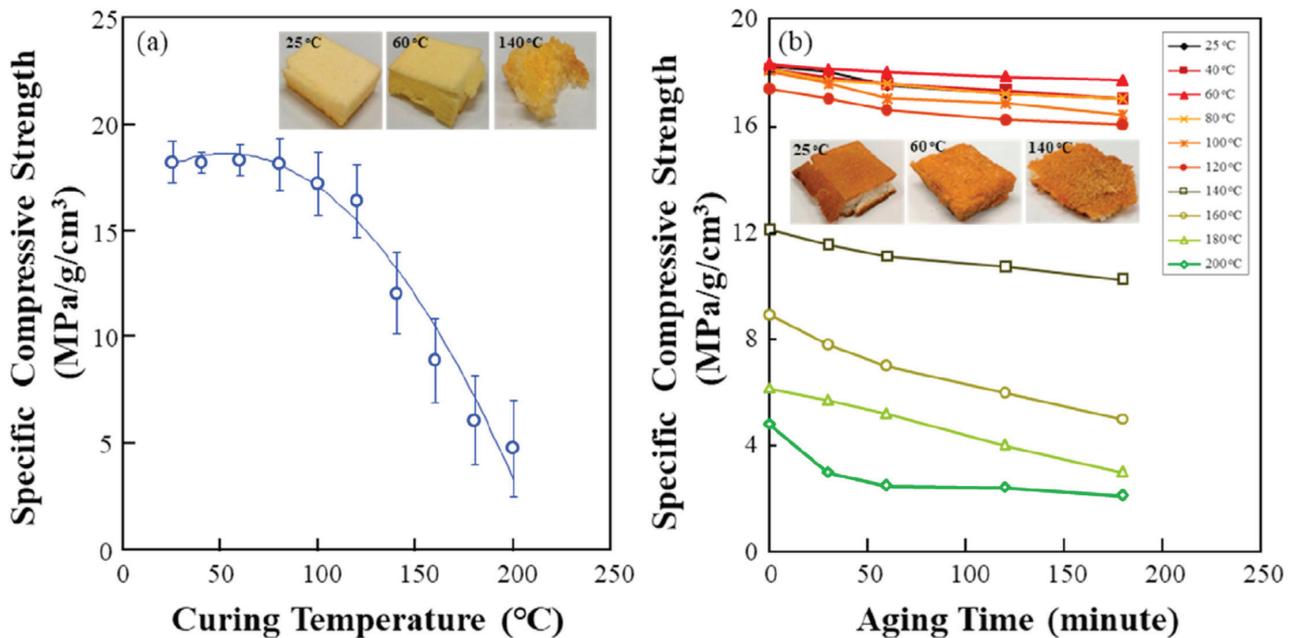
The foam type reinforcement has the advantages such as lesser specific gravity as compared to core reinforced sandwich composite, also the foam type reinforcement material is environmental friendly raw materials. Therefore foam material can be tailored to enhance the functionality of the sandwich composite. The multifunctional properties can be achieved by reinforcement of the CNT [157,158]. These concepts open the large opportunities sandwich composite in the perspective of the mechanical strength improvement, widening the application range.

Figure 8 shows the compressive strength of epoxy foams (EF) at different curing temperatures and times. In Figure 7a, it is evident that EF specimens molded at temperatures of 140°C or higher experienced fractures during compression testing, indicating a decrease in specific compressive strength attributed to increased cell size. The changes in specific compressive properties over time for EF specimens cured at different temperatures and aged for 180 minutes are displayed in Figure 8b. At curing temperatures of 100°C and higher, the curing process rapidly progresses near the foam's surface, leading to a continuous increase in cell size within the EF. This phenomenon is possibly due to the thick crosslinked layer of the skin despite unstable foaming, resulting in a higher degree of crosslinking at the EF surface. Both the glass transition temperature ( $T_g$ ) and density tend to increase with higher cure temperatures [149]. Moreover,

specific compressive property at a 180°C curing temperature as a function of time is shown in Figure 7b. EFs formed at higher curing temperatures exhibited higher compressive strengths due to more stable foaming. The specific compressive strength continued to increase even after 120 and 180 minutes of aging at 180°C. Additionally, the brown color depth on the surface of 40 mm thick foam specimens after 120 and 180 minutes of aging at 180°C was found to be only 0.691 mm and 0.716 mm, respectively. Unlike other types of foams, EF surfaces mainly degraded through thermal aging, resulting in relatively small decreases in foam strength with increased aging time. Unlike materials like polylactic acid (PLA), PU, and PVC foams, structural epoxy foams are preferred in applications requiring high heat resistance and rigidity [160]. A schematic of honeycomb sandwich is demonstrated in Figure 9 [160].



**Figure 9.** Structure of honeycomb structure. (created by authors [160])



**Figure 8.** Differences in compressive strength of epoxy foam are examined through variations in curing and aging temperatures.

## PHASE CHANGE COMPOSITE

Utilization of solar energy usually revolves around the capture of sunlight for heat. Phase-change material (PCM) in use for thermal energy storage can store large amounts of heat without significant change in phase-transition temperature [161]. But there are some shortcomings in the current PCMs regarding thermal conductivity being relatively low, resulting in lower heat transfer rate and storage efficiency [6,8,9]. Furthermore, as a result of most PCMs are liquid or semiliquid and their inherent instability makes its application in various industrial conditions limited [162,163]. Various approaches have been found to upgrade the thermo-stability properties of PCMs.

One approach involves improving the thermal conductivity of PCMs by incorporating exterior fillers such as carbon compounds, metal foams, and nanoparticles [164]. For instance, [165] demonstrated an 80% enhancement in the thermal characteristics of palmitic acid by adding 5 wt %  $\text{TiO}_2$ . [166] produced exfoliated graphite by exposing graphite flakes and amorphous graphite to sunlight and microwave radiation, resulting in improved thermal properties of PCMs. [167] studied thermal properties of pure paraffin influenced by silicon nitride ( $\text{Si}_3\text{N}_4$ ) nanoparticles. Their measurement showed a 33.9% increase in the thermal conductivity of paraffin when 2 wt %  $\text{Si}_3\text{N}_4$  was mixed. Similarly, [168] examined the thermal properties of paraffin with the inclusion of nanoparticles and observed significant improvements.

Pressing demand for sustainable and eco-friendly energy systems has been drawn attention to, by the increase of greenhouse gas emission, depletion of non-renewable energy source and the rise in global energy consumption that have occurred over last year's [169]. Wind and solar power, being renewable energy sources, have almost infinite potential. However, their intermittent availability, contingent on factors like wind patterns, cloud cover, and sunlight, presents challenges [170]. For the decreasing the percentage of carbon emission, the technologies related to energy storage are quite improving and facilitating the continuous supply of energy/power though there is a fluctuation in energy get happens. In this case as requirement

supplying required energy by reducing or eliminating fluctuation, so out of the glob there is a interesting demand of these tech which includes increasing span of battery, optimising charging and discharging cycle, improving loading capacity. This underscores the significance of advancing energy storing materials [170].

Considerable research has been dedicated to PCMs in this context. PCMs can absorb and release large amounts of heat energy when they undergo phase changes [171]. The phase transition temperature is a critical characteristic that establishes their suitability for various uses. PCMs find widespread use in buildings, solar energy systems, thermo-electric materials, textiles, and electronics. PCMs can be classified into four types as shown in Figure 10.

While SGPCMs and LGPCMs boast greater latent heat loading abilities, their volumetric changes during phase transitions limit their practical application. SSPCMs, although experiencing minimal volume changes, have relatively lower latent heat capacities and are still being explored for potential future applications. SLPCMs, with their great latent heat loading ability, minimal volume change, and good chemical and thermal stability, remain one of the most widely used types of PCMs [172].

Inorganic PCMs comprise crystalline hydrated salts and metals, offering extraordinary energy storing density, non-flammability, cost-effectiveness, and superior thermal conductivity compared to organic PCMs. However, they are susceptible to issues like phase separation and supercooling [39]. Conversely, organic PCMs, including paraffin wax (PW), alcohols, fatty acids, esters, and polymer materials, boast high latent heat capacity, minimal supercooling, and non-corrosiveness [173]. Nonetheless, they suffer from inherently low intrinsic thermal conductivity. To tackle this challenge, researchers have explored nanomaterials addition will rise thermal conductivity after addition into the PCM matrix [174]. Despite progress in this area, the low thermal conductivity of SLPCMs and the potential leakage of the liquid phase present hurdles to their practical application [38].

One promising strategy involves using  $\text{sp}^2$ -rich carbon-based nanomaterials as filler materials. These

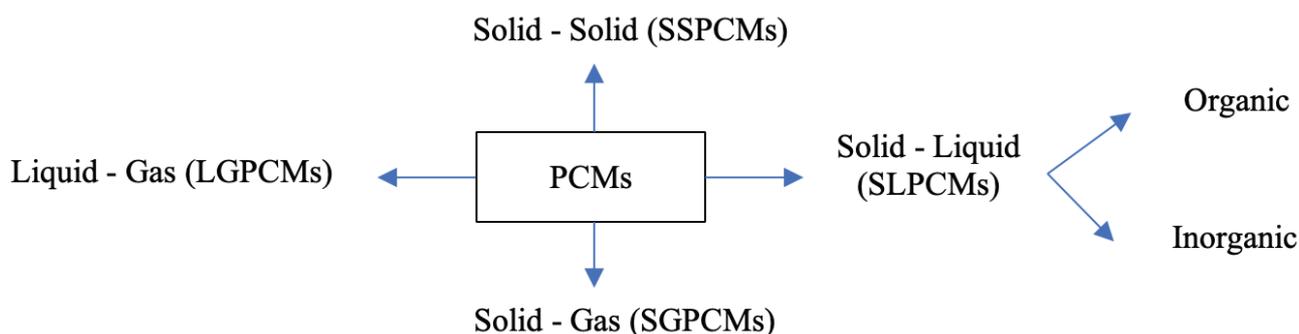


Figure 10. Classification of PCM.

nanomaterials exhibit great thermal conductivity and harmony with organic PCMs [175]. By directly adding them to PCMs, phase change composites (PCCs) with enhanced total heat transfer efficiency can be developed. Enhancing the thermal conductivity of PCMs is crucial for maintaining an even temperature dispersal, thus reducing hotspots and confined overheating [176]. This improvement facilitates faster charging and discharging rates, leading to more well-organized storage and consumption of thermal energy. Among sp<sup>2</sup>-rich carbon nanomaterials like graphene, carbon nanotubes (CNTs), expanded graphite (EG), and graphite nanoplatelets (GNPs), graphene and its derivatives have garnered significant attention for enhancing PCM systems [177].

Graphene-PCCs have several advantages compared to other systems, e.g., nanofiller-enriched PCCs and MOF-based PCCs. The features include high thermal conductivity, low density, the reinforced structural quality and a high surface area that make them perfect for application requiring a fast heat diffusion with low mass. Graphene and rGO exhibit higher thermal conductivities than GO as they possess no or fewer impurities that disturb the pathways of heat carrier transfer [178]. Due to the oxygen functionalization, GO is more easily dispersed in PCMs; however, graphene and rGO are relatively easy to prepare. Graphene aerogels and foams have low densities and high specific surface areas, creating a porous and conductive structure that improves thermal conductivity when combined with PCMs. Furthermore, these three-dimensional nanostructures endow PCCs with shape persistence to avoid leakage during phase transition and enable applications integration [179]. Besides being used as fillers, carbonaceous nanomaterials can encapsulate PCMs in a core-shell manner. By adopting such core-PCM and the phase change material with high thermal conductivity, it is possible to effectively control latent heat and phase change temperature of the core-PCM so as to improve thermal conductivity property and shape stability. On the whole, recent progress of graphene-based PCCs offer tremendous potential in raising the performance levels for TES in a wide range of applications.

## PERCEPTION USES

### Claim in Shape Memory Material

From the early 1980's the material which gets stimulated by external or internal sources shows remarkable affinity by research community and industrial uses [180]. The researchers were found shape memory polymers (SMPs) more suitable in many applications over shape memory wires (SMA), as these kind of polymers possess remarkable unique properties than that of SMA. These include bio-degradation ability, low cost, easily available, lower density, easy production, variety in transition temperature, good recoverable strain, multiple time shape regain ability

just by modifying minor chemical changes [181]. Notably, SMPs can achieve strains of up to 200%, a significant improvement over the limited strains exhibited by SMAs, shape memory ceramics, and glasses [182].

A range of functional shape memory polymers (SMPs) with remarkable shape memory effects (SME) have been established over time. Notable examples include epoxy-based SMPs cyanate, polyurethane (PU), and styrene which stand out as enhanced smart materials. Cyanate is the thermoset matrix, for instance, boasts exceptional thermal stability with a high  $T_g$  of up to 400°C. Its small dielectric loss and minimal hygroscopicity make cyanate-based polymers ideal for applications in electronic PCB, coating of dielectrics, aerospace, and wave transmission [183]. In contrast, styrene-based SMPs find utility in low-temperature applications due to their low  $T_g$ . Polyurethane SMPs typically have a constricted  $T_g$  limits nearby room temperature, making them suitable for molding into desired shapes via injection, extrusion, and blowing processes, particularly valued in biomedical applications owing to their low deformation temperatures [184]. Epoxy-based resins, chosen for their higher mechanical properties, excellent thermal stability, ease of processing, and outstanding chemical resistance, offer promising potential for SMP development [185].

Despite the intelligent behaviors exhibited by SMPs compared to conventional materials, their inherent poor mechanical properties remain a significant drawback. The limited structural integrity of neat SMPs poses challenges in effectively integrating them into structural applications. Consequently, there has been a surge in research interest surrounding shape memory polymer composites (SMPCs). These composites incorporate reinforcing fillers such as particulates, short fibers, long or continuous fibers, and fiber fabrics [186], aiming to overcome the weaknesses of SMPs and enhance their structural, electrical, thermal, and shape memory properties for structural applications.

Later exploratory thoughts about and explanatory approaches have highlighted the potential of basalt fiber-reinforced materials for basic applications in respectful designing. Basalt offers various amazing properties, counting tall quality, electrical separator, erosion resistance, affect resistance, and a tall dissolving temperature [187]. Outstandingly, basalt shows predominant physical, mechanical, and warm properties compared to glass fiber, with the next Young's modulus and pliable quality, as well as a most extreme benefit temperature of 650°C compared to 460°C for glass fiber. Whereas manufactured carbon fiber has been broadly utilized in polymer composites due to its surprising mechanical properties, counting tall quality and modulus, it has been a conspicuous building fabric since the 1960s [188].

In addressing modern construction challenges, engineers are exploring novel methods to expedite and simplify construction processes. Modular construction has emerged as a solution, particularly in congested urban areas where traditional construction methods face limitations because

of the longer building durations and the limited space. This approach involves fabricating different construction parts in a factory as modules, which are subsequently delivered to the building location for assembly. Modular construction offers advantages such as enlarged construction rapidity, safer manufacturing, reduced on-site labour, and minimized resource expenditure. However, transportation of large-sized modules remains a key challenge, especially in congested cities.

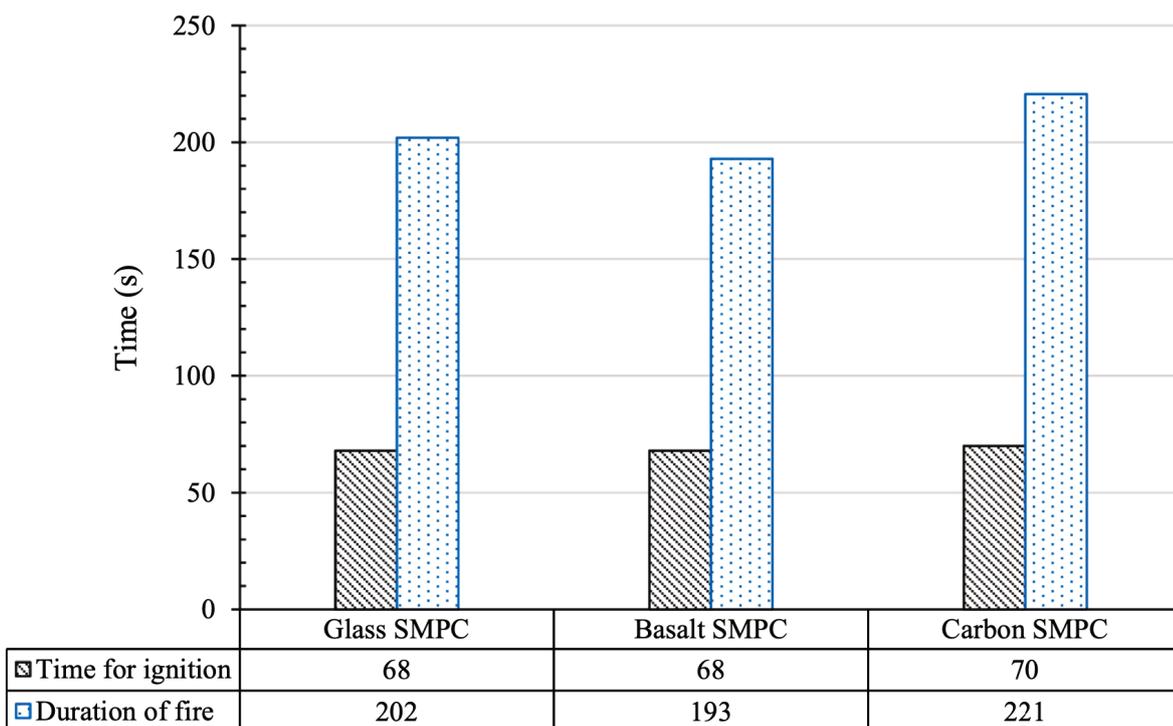
**Fire Retardation**

The characteristics of SMPCs under fire exposure remain largely unexplored as shown in Figure 11 [189]. Additionally, while carbon fiber reinforcement significantly enhances mechanical properties, it renders designs costly and unsuitable for mass production [190]. Utilizing natural fiber reinforcement with an SMP matrix offers a cost-effective solution to broaden current limitations and achieve significant improvements in integrating SMPCs into civil engineering applications [191]. Furthermore, prolonged exposure to sunlight could harm the polymer matrix, necessitating investigation into the light absorbance properties of SMPCs as a construction material. Similarly, the effects of water or solvent exposure on construction materials, considering phenomena like rain and humidity, warrant future research to understand potential degradation of strength and stiffness.

In civil engineering applications and buildings, protection against fire is of utmost importance. Building

regulations provide strict design specifications and material performance expectations. Fire safety encompasses prevention, containment, detection, and evacuation [192]. The evaluation of building materials’ appropriateness and application during fire crises is generally focused on factors such as ignition, flame spread, emission of heat, and smoke emission. Smoke production is one of these variables that poses the greatest risk since it can cause fatalities owing to impaired sight and breathing difficulties caused by the poisonous compounds in smoke. It can also impede evacuation attempts. Therefore, analyzing smoke generation is essential when introducing a new material for construction or structural purposes [193].

The warm oxidative deterioration components of epoxy tars include oxygen assaulting the methylene gather, oxidizing tertiary carbons within the aliphatic parcel of the chain, and oxygen assaulting nitrogen in epoxies cured with amine-based hardeners. Glass and basalt SMPCs stood up to start for 68 s, whereas carbon fiber-reinforced SMPCs stood up to for 70 s. Figure 12 portrays the decay behavior of shape memory polymer composites (SMPCs) at hoisted temperatures. The temperature at which a 5% weight misfortune happens is considered the warm deterioration temperature of the fabric [189]. Up to 380°C, all three SMPCs show comparable behavior, starting warm decay at an indistinguishable temperature of 345°C. This demonstrates that the sort of fortification fabric does not essentially impact the warm deterioration temperature of the chosen SMPCs. In any case, past 380°C, exceedingly thermally steady basalt



**Figure 11.** The amount of time that SMPCs need to start and finish a fire while being tested. (created by authors [189])

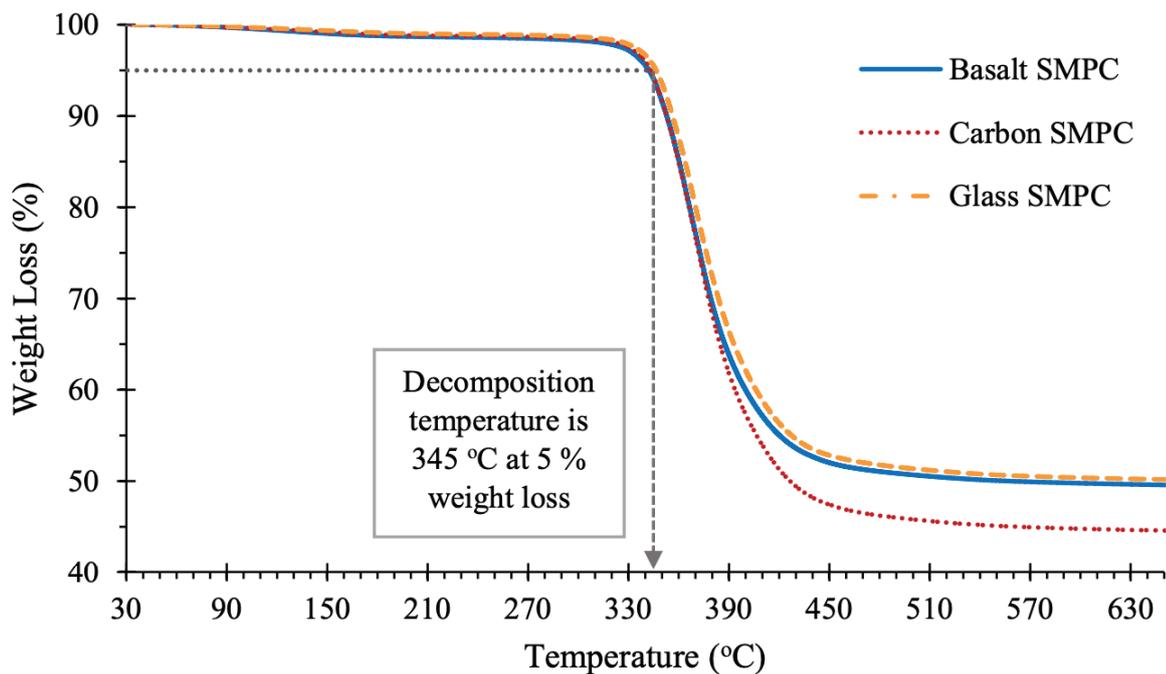


Figure 12. SMPC weight reduction as a result of thermal degradation.

and glass fiber-reinforced composites show about indistinguishable behavior. In differentiate, the less thermally steady carbon fiber SMPC appears a better decay in weight. This error can be ascribed to the lower decay temperature of carbon fiber. Subsequently, when uncovered to higher temperatures, carbon fiber is more inclined to burning in barometrical oxygen, driving to assist weight misfortune.

### Hygrothermal Stability

Fiber-reinforced polymeric composites have revolutionized various industries due to their exceptional properties, including corrosion resistance, high strength-to-weight ratios, and versatility in shaping intricate structures with enhanced mechanical performance [194]. However, exposure to moist environments can pose significant challenges to FRP, leading to water absorption and subsequent degradation of mechanical properties [195]. This degradation, characterized by phenomena such as microcrack formation, fiber/matrix debonding, and delamination, necessitates thorough investigation and assessment of FRP performance in hygrothermal conditions [196].

Tests for hygrothermal decaying are frequently used to mimic the long-term performance of FRP in maritime settings. These tests involve subjecting FRP samples to elevated temperatures until saturation is reached. The performance of FRP in hygrothermal environments is influenced by various aspects, comprising fabric architecture, polymer matrix, environmental conditions, and manufacturing techniques, all of which influence nearly steady, vibrant, and qualities that tolerate harm [197].

Sophisticated numerical modelling models, including CLPT and CDM, and analytical methods, play a crucial role in predicting mechanical property degradation in FRP. CDM, operating at multiple scales, offers insights into crack propagation and damage evolution, leading to more accurate predictions of mechanical behavior. CLT, although simpler in its assumptions, provides valuable information about laminate behavior, albeit with some limitations in handling complex microstructures. Analytical modeling complements numerical simulations by offering theoretical insights into material behavior and facilitating the development of predictive models for mechanical property degradation [198-200].

Understanding the interplay between temperature, moisture, and mechanical properties is necessary for safeguarding the dependability and toughness of FRP in real-world applications [201]. By leveraging advanced simulation techniques and experimental validation, researchers can improvement prised insights into the degradation mechanisms of FRP and develop strategies to mitigate their adverse effects, thereby advancing the development of more resilient and sustainable composite materials for diverse engineering applications [202].

### Solar Energy Harvesting Systems

Solar energy is a promising renewable resource, offering abundant and environmentally friendly power. However, the alternating nature of sunlight necessitates efficient energy storage solutions to bridge the gap between energy demand and supply. Among these solutions, graphene-based PCCs have emerged as a cutting-edge technology for enhancing the

reliability, efficiency, and performance of solar thermal systems. In recent research, Wang et al. developed solar-driven PCCs by incorporating magnesium nitrate hexahydrate, carboxymethyl cellulose, and graphene. This innovative approach demonstrated significant improvements in performance of photothermal conversion and preservation of energy [203]. By adding carboxymethyl cellulose as a thickening mediator and 5 wt % graphene to enhance thermal conductivity, they achieved a remarkable 191.18% increase in thermal conductivity without compromising latent heat capacity. Moreover, graphene's exceptional optical absorption capacity and photothermal conversion properties contributed to a substantial increase in thermal absorption capacity and photo-thermal conversion efficiency.

Similarly, Cui et al. devised a cost-effective and stable PCC utilizing sodium acetate trihydrate (SAT) as the phase change material (PCM). Xanthan gum and GO@SiO<sub>2</sub> were incorporated to remove the issues related to phase segregation and address supercooling [204]. Also to improve the solar energy charging, latent heat and thermal conductivity, silicon carbide foam, GO and wood powder (WP) were utilised. PCC can be utilised as photothermal conversion with the use of PEG-based PU [205,206].

## FUTURE SCOPE

The review focused on many encouraging paths those are helpful in the development of the materials, specifically phase change composites (PCCs) with their applications in different field. Summary of various applications in the perspective of future scope is enlisted below;

### Improved Thermal Management in Textiles

The innovation of graphene based PCCs into textiles gives a confident future growth. The heat dissipation rate can be improved by optimizing the composition and structure of PCC coatings. Furthermore the production rate and cost effectiveness methods PCC-coated textiles would be important for practical use.

### Thermal Regulation by Innovative Materials

The integration of PCCs with the thermally prompted flexible wood generates the possibilities of the novel materials with the improved flexibility and thermal properties. Future investigation might focus on enhancing the range of PCC composition and wood species to improve the latent heat storage and thermal conductivity for specific applications like structural components useful in building materials.

### Advanced cold Chain Solutions

The improvement in the temperature control and energy efficiency could be achieved by incorporating PCCs into cold chain distribution boxes. Thermal conductivity, durability, and reliability under different environmental conditions could enhance by optimized the structure and composition of the PCC.

### Heat Dissipation in Electronics

To improve thermal management efficiency by enhancing cooling of electronic components it is necessary to investigate the effect of combination of phase change materials (PCMs) and heat pipes. Furthermore the research could focus on design and integration of PCM based heat sinks with heat pipes to attain the good quality of heat dissipation performance by overcoming the challenges such as PCM leakage and agglomeration of nano particles. Furthermore by exploring alternative PCM composition and nano fillers to enhance the thermal conductivity and stability.

### Novel PCC Compositions and Structures

The innovative phase change compositions like aerogels or graphene-based skeletons incorporated in PCM which offers lot off opportunities to enhance thermal energy storage and control technologies. Furthermore the investigation can be carried for novel synthesis methods, performance evaluations, and characterization techniques.

### Scalability and Commercialization

It is found that many of the research in PCC shows the good results at laboratory level, furthermore it is important address the commercialization and scalability challenges. Furthermore investigation could focused on various production scaling methods, optimizing the material cost. The collective efforts between industry, academia will be crucial for translating research innovations for practical solutions.

## CONCLUSION

The study of the polymer composite, fiber reinforced polymers and shape memory polymers highlights its respective significance across different industries. Researcher have investigated the significant properties of shape memory polymer composites like shape memory effects and the transition temperatures which can be used for various structural applications. Furthermore the shape memory polymer with enhanced properties like cyanate and styrene-based shape memory polymers, shows the versatility in various applications from engineering to medical field.

The limitation of mechanical properties in shape memory polymer are addressing this by the use of developing the shape memory polymers composites. The structural integrity, thermal stability, and mechanical strength could be increased by incorporating the various nano fillers in the shape memory polymer. The various reinforcement used are carbon fibers, glass fibers, basalt fibers. The advancement in the SMPCs is useful for various applications like structural applications, and also where reliability and high performance are important.

The incorporation of basalt fiber as a reinforced materials for civil engineering applications proves their strength for facing modern challenges. Now modern construction method is coupled with the use of SMP composites which

gives the advantages such as high construction speed, lesser labor costs, and high structural performance. Furthermore the application of natural fibers reinforcement with the SMP gives a cost optimized product for various applications.

The study on phase change composites focused their importance in facing challenges in the perspective of thermal energy storage and its control. Graphene based phase change composites shows the important properties such as energy storage density, thermal conductivity, and heat transfer efficiency. The combination of material shows the application in diverse fields like battery technologies, textiles, solar energy systems, and electronic cooling which shows the potential for strengthening energy efficiency and sustainability.

Furthermore research also focused on the optimization of composition of the phase change composites with its commercialization and scaling up the production rate. The research also focused the technical challenges for its adoption. Collective efforts of industry, academia and various agencies will enhance the research of polymer composites and sandwich structures for practical solutions.

The research shows the remarkable advancements and strength of sandwich and polymer composite structure in various applications. By investigating the various advanced material, manufacturing techniques causes sustainable, high performance and functional materials for the benefit of environment and society.

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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