3 Lightweight Polymer–Nanoparticle-Based Composites

An Overview

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3.1 INTRODUCTION

A lot of research has been undergoing for a long time in coming up with composite materials. Different composites have different applications depending on their properties. It is, therefore, necessary to have a review of the literature to understand the existing gap especially in the construction industry. This chapter includes an overview of classification, applications, and properties of polymer-based composites, and theory of processing and manufacturing of polymer-based composites and products. Most importantly, it includes a detailed review of the research and progress on the polymer-based composites with an emphasis on polymer–silica nanoparticle-based composites.

3.2 CLASSIFICATION OF COMPOSITE MATERIALS

Composite materials refer to the class of materials that consist of two or more components that are diverse in their physical and chemical properties (Altenbach, Altenbach, & Kissing, 2018). The combination of two or more materials eventually results in a new material with different properties from the single composition (Nielsen, 2005). Individual materials used in the production of composite material components are discrete and separable within the final composite material configuration; however, composites have to strictly be differentiated from mixtures and solution of solids (Koniuszewska & Kaczmar, 2016). Studies carried out have documented many beneficial features of composite materials. First, they are stronger (Murr, 2014), and secondly, they are generally of lower density and less expensive compared to the original materials (Dawoud & Saleh, 2019). Composite materials are divided into three categories based on the matrix constituents: metal matrix composites, ceramic matrix composites, and polymer matrix composites. Composites are also classified according to the size and shape of the reinforcing material structure, for example, particulate or fibrous reinforced composite.

3.2.1 METAL MATRIX COMPOSITES

These are metals reinforced with other metals, organic compounds, or ceramic compounds (Casati & Vedani, 2014). The making of these composites involves the dispersion of reinforcement in the metal matrix basically to improve the properties of the base materials. The study carried out by Ramnath et al. (2014) on aluminum metal matrix composite reported an enhancement in terms of strength, strain, hardness, wear, and fatigue of the aluminum metal. However, the study reported a decline in tensile strength. A study conducted on reduced graphene oxide–metal composite for application in water purification (Sreeprasad, Maliyekkal, Lisha, & Pradeep, 2011) found that the graphene-based composite was efficient for the purification process. Besides, the study noted that the composites can also be used in a wide range of applications such as in catalysis and fuel cells. Another study (Casati & Vedani, 2014) on metal matrix composites enforced by nanocomposites showed remarkable results such as increased hardness, mechanical strength, wear resistance, creep behavior, and damping properties (Macke, Schultz, & Rohatgi, 2012). Although the composites were said to aid in the reduction of costs incurred on conventional monolithic alloys,

some aspects such as clustering of particles, the complexity involved in the fabrication process, and clarity on the reactions between ceramic nanoparticles or carbon nanotubes would require improvement and further research.

3.2.2 CERAMIC COMPOSITES

They consist of a ceramic matrix combined with a ceramic (oxides, carbides) dispersed phase (Porwal et al., 2013). They are particularly designed to enhance the toughness of conventional ceramic materials, which are naturally brittle (Walker, Marotto, Rafiee, Koratkar, & Corral, 2011). There are various studies that have been conducted on fiber ceramic composites. In the previous years, the focus was mainly on carbon nanotube (CNT)-reinforced glass and ceramic composites. The authors have documented enhanced properties such as toughness, strength, and electrical conductivity over original ceramic (Choi et al., 2018; Katoh & Nakagama, 2014). Similarly, Porwal et al. (2013) reported a significant enhancement in mechanical, electrical, and thermal properties under graphene ceramic matrix enhancement. Additionally, Walker et al. (2011) found that graphene ceramic composite has the potential to improve the mechanical properties of polymers.

3.2.3 POLYMER COMPOSITES

Polymers fall into two categories: thermoplastic and thermosetting (Altenbach et al., 2018). The most commonly used thermoplastic materials include polypropylene, polyethene, and polyvinyl chloride, while epoxy, polyester, and phenolic are the mostly used thermosetting matrices (Nielsen, 2005). Recently, natural fibers as polymer composite fillers have gained much interest due to their better physical and mechanical properties as compared to synthetic fibers, e.g., glass. Some of these natural fibers include hemp, sisal, jute, and flax, among others (Pickering, Efendy, & Le, 2016). Their advantages over conventional carbon and glass fibers include non-abrasiveness, low density, better tensile properties, low cost, and reduced health risk, among others (Sreeprasad et al., 2011). The main applications of polymer composites fall under construction, packaging, aerospace, automotive, and sports industries (Murr, 2014). Despite these advantages, these composites are limited by the incompatibility that exists between the hydrophobic thermoplastic and hydrophilic natural fiber matrices. There is significant research that has been undertaken on polymer–fiber composite focusing on specific applications, enhancements of properties, and optimization of performance. The use of natural fibers in polymers results in materials that are eco-friendly, less expensive, and excellent in tensile behavior and can be used as an alternative to conventional fibers such as glass (Wang et al., 2011). However, the limitation of these (polymer–fiber) materials is that the strength of the polymer is dependent on the fiber loading. This may not be advantageous since the increment in fiber weight results in decreased tensile strength.

A polymer–nanoparticle composite material is produced by incorporating synthetic or natural nanoparticles into a polymeric matrix. Silica nanoparticles may be obtained from sources of natural silica such as sand, clay, and quarry dust. The inclusion of silica nanoparticles into a polymeric matrix can improve the thermal, mechanical, and fire-retardant properties of the polymer material. A polymer–nanoparticle composite

is a material containing one of its phases (reinforcing material) in a nanometer-sized structure, and it is considered to be a nanocomposite; otherwise, the composite material is a micro-composite. It is worth emphasizing that the main features of polymer–silica nanoparticle composite material have close relationships with each phase's physical and chemical characteristic properties and also with the size of silica nanoparticles and their interfacial adhesion between the matrix and silica nanoparticles.

Nanocomposites are composites that contain one of the phases in nano-size (10^{-9}m). These composite materials started to be produced because of their superior physical, thermal, and mechanical properties in comparison with traditional composites and micro-composites. Besides, the preparation techniques and processing of these nano-composites show different challenges as a result of the stoichiometry in the nano-phased and elementary structure. Nano-phased filler materials are integrated into the matrix of the composite to enhance the properties of the nanocomposites (Asmatulu, Khan, Reddy, & Ceylan, 2015). Polymer nanocomposites are an interesting material category that exhibits distinct physical and chemical properties that cannot be achieved by individual components. Due to their exciting capabilities in many applications in environmental sustainability and addressing various environmental challenges, polymer nanocomposites have increasingly attracted thorough research attentions (Chowdhury, Amin, Haque, & Rahman, 2018). Some of the polymer nanocomposites include PLA/fumed silica/clay (PLA-fsi-clay) nanocomposites, PVA/silica/clay (PVA-si-clay) nanocomposites, PVA/fumed silica/clay (PVA-fsi-clay) nanocomposites, PF/fumed silica/clay (PF-fsi-clay) nanocomposites, and ST-co-GM/fumed silica/clay (ST-co-GMA-fsi-clay) nanocomposites (Rahman, Chang Hui, & Hamdan, 2018).

3.3 APPLICATION OF POLYMER COMPOSITES

3.3.1 Aerospace Industry

In order to improve the fuel economy, carrying capacity, and maneuverability of airplanes, there is the need to adopt the use of new materials that are low in weight and high in strength (Zhang, Chen, Li, Tian, & Liu, 2018). Composites materials exhibit these properties and are therefore attractive for aerospace applications. For instance, American Airlines, which constitutes a fleet of 600 planes, could immensely save on the fuel cost by reducing the aircraft weight (Morris, 2018). Several airplane manufacturers have opted for the application of natural fiber-based composites to minimize the cost of production and enhance the use of eco-friendly materials. Most of the components in aircraft are currently manufactured from polymer composites. These include aircraft body, wings, fuselage, doors, tail, and interior that are mostly manufactured from carbon fiber-reinforced plastic (CFRP) due to its high strength-to-weight ratio (Irving & Soutis, 2015). Sections of the wings and tail are manufactured from fiberglass (Maria, 2013).

3.3.2 Automotive Industry

There is pressure to manufacture light, fuel-efficient, low-cost, and green automobiles in modern society. The use of polymer-based composites on some components of an automobile has been shown to enhance the low-weight and green

manufacturing of cars (Witik, Payet, Michaud, Ludwig, & Månson, 2011). Some of the components in the automotive industry are extensively manufactured from polymer-composite bumper beams, battery boxes, and seatbacks produced from glass mat thermoplastics (GMT) (Witik et al., 2011); interior headliner, engine cover, underbody system, air intake manifold, deck lid, instrument panel, bumper beam, front-end module, load floor, air duct, airbag housing, and air cleaner housing produced from glass-reinforced plastics (GFRP) (Friedrich & Almajid, 2013; Holbery & Houston, 2006); roof, rear spoiler, trunk lid, side panels, floor panel, hood frame, chassis/monocoque, tailgate, hood, bumper, and fender produced from carbon fiber-reinforced composites (CFRP) (Mitschang & Hildebrandt, 2012).

3.3.3 MARINE INDUSTRY

Polymer composite materials have found a great application in building marine structures. This is attributed to better physical, mechanical, chemical, and thermal properties these composites possess. Some of the desirable properties include low weight, good long-term properties (no corrosion), and the ability to produce components with complex shapes with affordable tooling. The low weight of marine construction of the ship is important for low fuel consumption and effective performance. For instance, the speedboat revolver 42, which is a result of the collaborative work of Michael Peters Yacht Design and the Milan-based studio, is a remarkable example of the application of polymer composites (Neşer, 2017). The hull and deck are made from cystic vinyl ester resin and a core cell M-foam and enhanced with carbon fibers (Koniuszewska & Kaczmar, 2016). Despite the ship having a large mass, it can accelerate up to a speed of 68 knots. For a similar reason, sailboat wings are primarily fabricated from carbon spar. Additionally, there has been a lot of research aiming at improving the properties of polymer composite materials for the underwater application while prolonging their underwater life. The aim is to replace the old traditional glass composite with thermoplastic matrix composite for large submarine elements (Neşer, 2017).

3.3.4 MICROELECTRONICS

The electronics industry is growing rapidly, and polymer composite materials are increasingly finding great electronic applications. This is because of some desirable properties such as low thermal expansion, low/high electrical conductivity, low dielectric constant, high thermal conductivity, and/or electromagnetic interference (EMI) shielding effectiveness that is required in electronics applications. Some of the applications of polymer composites in microelectronics include thermal interface materials, photovoltaic device, interconnections, organic light-emitting diode (OLED), housings, actuator, sensors, connectors, substrates, encapsulations, electroluminescent device, heat sinks, printed circuit boards, die attach, lids, interlayer dielectrics, displays, electrodes, batteries, and electrical contacts (Wei, Hua, & Xiong, 2018). For example, the use of carbon fillers such as graphene, fullerene, and carbon nanotubes (CNTs) in the polymeric matrix

has proven to be appropriate for the detection of various kinds of molecules, e.g., gases, heat, biomolecules, temperature, and pH (Rahaman, Khastgir, & Aldalbahi, 2019).

3.3.5 MEDICAL APPLICATIONS

Polymer-reinforced composites play an important part in the science of polymers because of their typical properties, e.g., solvent resistance, strong viscoelastic properties, stability at high temperatures, and high mechanical strength. Thermosetting polymers cannot be melted or reshaped once they have been produced, and as a result, they are found to be suitable in various applications that require these properties. Polymer composites show biodegradability, high cell adhesion, low inflammatory response, and biocompatibility when implanted for applications of tissue engineering (Ramakrishna, Mayer, Wintermantel, & Leong, 2001). They find great application in biomedical fields, such as in replacement of hardened tissue, preparation of dental materials, wound dressing, polymeric heart valves, medical devices such as electrocardiographs, bone formation, and prosthetic sockets (Zafar et al., 2016). For example, polyolefins cross-linked with poly(styrene-block-isobutylene-block-styrene) can be used as a heart valve (Madhav, Singh, & Jaiswar, 2019). Properties of polymer matrices can be modified by the addition of metal fillers; e.g., GO-modified epoxy polymer matrix displays an increase in mechanical and thermal properties, whereas Ag nanoparticles enhance dielectric and antimicrobial properties (Qi et al., 2014). Polymer composites, however, have certain disadvantages including poor cell affinity and the release of acidic by-products (Zagho, Hussein, & Elzatahry, 2018).

3.3.6 CONSTRUCTION INDUSTRY

In the past 30 years, innovative polymer composites have become appealing in the construction industry as new structural materials and there has been an increase in their usage in the reconstruction of existing bridges and buildings. The research and development strategies for polymer composites for application in the construction industry are continuously underway, and the advancement accomplished on this exciting material has continued to increase to satisfy the construction industry demands. Some of the applications include the use of composites in the rehabilitation and repair of wood, steel, concrete, and masonry structures and all-composite applications in constructing structures, which include the construction of bridges and buildings (Medina et al., 2018). For example, the usage of fiber-reinforced polymer composites (FRPC) increases energy absorption efficiency and load-carrying capability of slabs made up of FRPC. Generally, stress transmission throughout the crack improves by self-strengthening, which slows the formation of cracks, and therefore, FRPC reinforcement is capable of achieving its entire capability to strengthen the slabs (Mosallam, 2014). Additionally, pultruded fiber-reinforced polymer (PFRP) composites exhibit the electromagnetic transparency and radio wave reflection properties. These non-magnetic properties of PFRP composites are desirable in applications requiring construction of

facilities containing delicate instrumentation (Alberto, 2013; Gand, Chan, & Mottram, 2013). However, not much has been reported on the applicability of polymer–silica in the construction industry.

3.4 PROCESSING OF POLYMER-BASED COMPOSITES

The processing of polymer-based composites involves two major steps: melting and forming in a mold (die). For composites with thermoplastic matrix, the consolidation process is achieved by cooling; on the other hand, for thermoset matrix, consolidation is achieved by curing (Baran, Cinar, Ersoy, Akkerman, & Hattel, 2017). Concerning the thermoset matrix composite, the curing can be conducted at room temperature although it can be quickened through the application of heat typically through an oven in vacuum conditions (Singh, Chauhan, Mozafari, & Hiran, 2016). Notably, curing, which enhances successful cross-linking and polymerization process of the hydrocarbon chains, can be enhanced by other forms of energy, besides the heat, and these may include X-ray, electron beam, ultraviolet, and microwave curing (Abliz et al., 2013).

There are various methods used in the processing of polymer composites, and some of the common ones include autoclave molding, out-of-autoclave Quickstep molding, liquid molding, and filament winding processing.

3.4.1 AUTOCLAVE MOLDING

Autoclave molding is among the open molding techniques in which vacuum, pressure, and heat of the inert gases are used to cure the molded component. Figure 3.1 shows a schematic diagram showing the autoclave molding process setup. In terms of operation, the molded component is put in a plastic bag containing a vacuum created by a vacuum pump. The presence of a vacuum prevents the molded component from
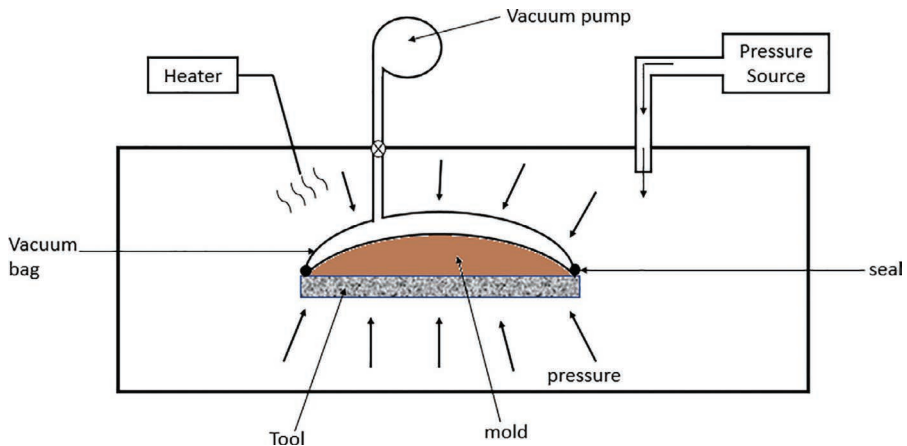

FIGURE 3.1   Schematic diagram showing the autoclave molding process setup.

coming into contact with volatile materials and air inclusions. Then, curing and densification of the part are done by the application of heat and pressure of the inert gas in the autoclave. Eventually, autoclave curing allows the production of uniform homogeneous components due to heating from both sides (Ouarhim, Zari, Bouhfid, & Qaiss, 2018). According to Ghori, Siakeng, Rasheed, Saba, & Jawaid (2018), curing times can be automated using the controller according to a specific cure profile to pressurize and heat the unconsolidated laminate stack. Before placing a vacuum bag above the entire assembly of tools, layers of breather and release film are first put in place (Alagirusamy, 2010). The sealed air is drawn out of the assembly basically to pressurize it for maximum fiber reinforcement and minimum creation of voids in the cured composite part, requiring minimal finishing. The technique is comparatively expensive, and it is applied in the production of high-quality aerospace components. Additionally, this method has some benefits; for example, the applied pressure helps in binding the composite materials by increasing the density of the lining and strength of the bond making them more compact, the ability to produce composites with high-fiber load, and the production of high-quality components.

3.4.2 Out-of-Autoclave Quickstep Molding

The applications of out-of-autoclave technique have increased in popularity over the last decade due to the ability to cure autoclave-quality materials/components in vacuum-bag-only (VBO). To achieve high-dimensional tolerance and low porosity, VBO prepregs rely on particular processing techniques and microstructural features. The Quickstep technique of producing components made of fiber-reinforced composites depends on the conduction heating principle. During processing, glycol-based heat transfer fluid (HTF) is used to transfer heat and pressure to the processed component that is uncured. According to Drakonakis, Seferis, & Doumanidis (2013), the high thermal conductivity and heat capacity of HTF as compared to those of the air enable the processing temperature to be controlled effectively than in an autoclave or oven. It uses a conventional layup sealed in vacuum bag processed in a pressure chamber that has the HTF (Khan, Khan, & Ahmed, 2017). Afterward, the processed component is sandwiched between two flexible membranes in the pressure chamber by which the HTF supplies the necessary heat and pressure to consolidate and cure the matrix–fiber interface. Under this process, the temperature is maintained by circulating the HTF in the pressure chamber, thereby enhancing the rapid cooling and heating rates and the control of resin viscosity in relation to the findings of Hernández, Sket, Molina-Aldareguı́a, González, & LLorca (2011). The quick heat energy transfer into the curing fiber is the main technique in this process. Figure 3.2 shows a typical out-of-autoclave Quickstep molding process.

3.4.3 Liquid Molding

Liquid composite molding (LCM) comprises several composite production methods, for example, Seemann composite resin infusion molding process (SCRIMP), resin transfer molding (RTM), injection compression molding (ICM), and vacuum-assisted RTM (VARTM) processes. Such a technique can produce complex-shaped,
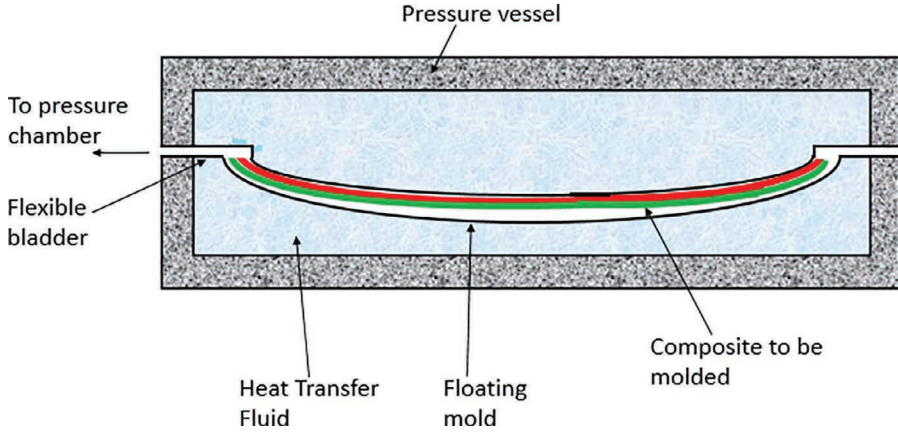
FIGURE 3.2   Schematic diagram showing the out-of-autoclave Quickstep molding process (Ogale & Schlimbach, 2011).

high-quality fiber-reinforced composite and is therefore predominantly used in the automotive, aerospace, civil, and marine industries. It is the most commonly used processing technique for polymer matrix, and this is because of its low cost (Finkbeiner, 2013). RTM is the primary method that has given rise to most of the variations. Figure 3.3 demonstrates a flow diagram of the steps of a typical RTM method. The preform is first formed and put in the mold compartment. Once the mold is closed, a polymeric resin is introduced into the mold chamber, which saturates the preform and ejects the existing air in the mold chamber (Walbran, Bickerton, & Kelly, 2013). A curing process is triggered causing the cross-linking of the thermoset resin, either during or after mold injection, to produce a solid piece.
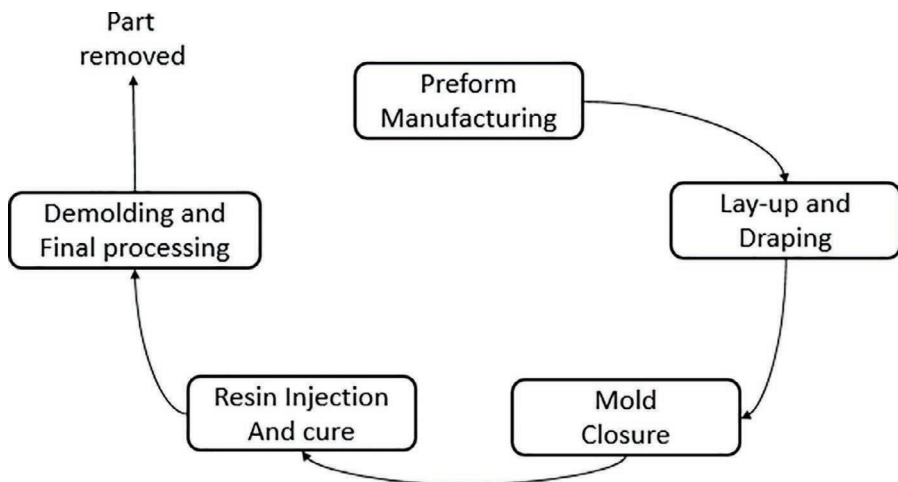

FIGURE 3.3   Flow diagram of the steps of a typical RTM method.

After the component has been cured enough, it can then be taken out of the mold. The advantage of LCM is that it is used in the production of larger and more complex parts and has short cycle times and rejection rates. The process is labor-intensive, and the quality of composite depends on the skill of the operator (Hamidi & Altan, 2017).

3.4.4 FILAMENT WINDING PROCESS

Filament winding is a method by which composite components are produced by continuously winding fibers on a specially oriented rotating mandrel. This method of polymer composite production is the most economical in the processing of symmetric composite components in areas requiring mass production (Abdalla et al., 2007). This technique is mainly used with circular or oval hollow, sectional parts, e.g., tanks and pipes. This offers a wide range of applications, from small hollow products such as gas cylinders to huge products such as cryogenic tanks. The fibers are first passed through a bath of resin where the fibers are moistened before they are winded. The desired properties of the composite components can be achieved by varying the winding thicknesses and the number of layers. The fibers are supplied with enough tension to compact them on the mandrel. Varying the revolution of the mandrel and movement of the carriage produces a variety of winding patterns. This entire process normally is carried out at room or high temperatures. After curing, the mandrel is removed from the produced composite part for reuse (Mack & Schledjewski, 2012). The advantages of filament winding include excellent mechanical properties achieved by the use of constant fibers, process speed, better fiber and material control, good interior finish, good thickness control, and high intensity of the strengthening procedure. The main disadvantages of this technique are as follows: the difficulty of winding complex profiles which may require the use of complex equipment, limitations on convex-shaped components, poor external finish, low-viscosity resins, and high cost of the mandrel. Some of the applications of filament winding include the production of open-ended products, such as gas cylinders and tube systems, and closed-end products, such as chemical tanks and pressure vessels (Minsch, Herrmann, Gereke, Nocke, & Cherif, 2017).

3.5 STATE-OF-THE-ART REVIEW OF POLYMER– NANOPARTICLE COMPOSITES

An extensive literature on studies involving plastic–nanoparticle composites is available. The focus of such studies has been on the enhancement of properties and optimization of the performance of the composites. The emphasis has been on the polymer matrix–reinforcement adhesion, strength, and matrix–reinforcement ratios. A critical review of the literature review revealed that polymer-based composites can be classified based on the size of the reinforcement particles with an emphasis on mixture ratios. This is the focus of this research. As such, the review in this subtopic is analyzed under micro- and nanoparticle composites for comparison purposes.

3.5.1 MICRO-COMPOSITES: SAND–PLASTIC COMPOSITE

In polymer–sand composites, the effect of the ratio of matrix to reinforcing sand particles plays an important role in the properties and performance of the composites. For instance, Sultana et al. (2013) investigated sand–polyester composite prepared at varying weights of 10, 20, 30, 40, 50, and 60 wt.% of sand. The tests conducted were water absorption rate, comprehensive strength, flexural strength, hardness, and thermal conductivity tests. It was found that the percentage of water absorbed increased as the time of immersion increased. Additionally, the water absorption rate increased with an increase in sand composition. A similar result was reported by Bajuri, Mazlan, & Ishak (2018) who investigated the effect of micro-silica concentration on epoxy. The water absorption rate for the composite increased with an increase in the concentration of micro-silica particle due to the hydrophilic nature of silica. Moreover, the compressive strength and the flexural strength of the composite decreased with an increase in the amount of sand. Similar results were reported by Herrera-Franco, Valadez-Gonzalez, & Cervantes-Uc (1997) where the flexural and tensile properties of the HDPE–sand composite decreased as the amount of silica sand was increased beyond 30% wt. composition. This was attributed to the poor adhesion between the polymer and the silica sand interfaces. However, high flexural strengths were exhibited, indicating that the composite was brittle as a result of poor adhesion between the matrix and the fiber. When the Vickers hardness test was conducted, it was noted that the hardness of the composites increased with an increase in sand composition. The thermal conductivity decreased with an increase in the sand content.

In another study, Seghiri, Boutoutaou, Kriker, & Hachani (2017) mixed sand dune and r-HDPE to form sand dune–plastic composite in 30, 40, 50, 60, 70, and 80 wt.% HDPE. The tests that were conducted included flexural rigidity test, impermeability test, and density test. It was found that the density varied from 1.379 to 1.873 g/cm^3. The composite exhibited good impermeability as compared to clay tile. Additionally, the flexural rigidity of all the composite mixes was lower than that of tile made up of clay. The results are comparable to those of the studies conducted by Bajuri et al. (2018) in which silica particles were used as filler material to enhance the properties of composite reinforced with kenaf. For 10 min, the silica particles were deposited into the epoxy matrix using a homogenizer at a speed of 3,000 rpm before being injected into the fibers. It was found that the addition of silica particles typically decreased the mechanical properties of the composite. However, better mechanical properties were achieved with the addition of 2 vol.% of silica with the flexural strength, flexural modulus, compressive strength, and compressive modulus of 43.8 MPa, 3.05 GPa, 40 MPa, and 1.15 GPa, respectively.

Similarly, Aghazadeh Mohandesi, Refahi, Sadeghi Meresht, & Berenji (2011) produced polyethene terephthalate (PET)–sand composite by blending recycled PET waste plastic in the form of molten polymer with silica sand particles at 5%–40% sand particle weight concentrations. The average diameter of sand particles in the form of particulate composites ranged from 0.062 to 0.35 mm. The produced composites were tested with three bending points and compression at varying temperatures of 20°C, 25°C, 40°C, 60°C, and 80°C. For comparison purposes,

the related compression strength analyses were numerically modeled to approximate the cohesive strength between the fine particles defining the structure of the composite materials evaluated. The results indicated that the tested composites exhibited the maximum pseudo-cohesive strength and mechanical strength at 25°C. Further, composite compressive strength increased with an increase in the percentage weight of the sand particles by up to 10%, and it decreased with further increase in percentage weight (i.e., 20% and 40% sand).

Additionally, Abdel-Rahman, Younes, & Yassene (2018) investigated the effect of varying composition of clay (silica) in 0%, 3%, 5%, and 10% weight concentrations in the unsaturated polyester polymer matrix and varying gamma irradiation at 30 and 50 kGγ on the polyester–clay composite's mechanical properties. The results revealed that there was an improvement in the compressive strength as the composition of the clay content in unsaturated polyester matrix was increased up to 5 wt.%. These observations under the influence of γ-irradiation were attributed to the adhesion between and unsaturated polyester matrix and clay additive within the composite structure. The results obtained in TGA also showed that the composite's thermal stability improved as the composition of clay increased. The use of 50 kGγ radiation showed good thermal stability as compared to the use of 30 kGγ radiation.

The chemistry of the matrix material has also been shown to influence the characteristics of polymer–sand composites. In a study, Slieptsova, Savchenko, Sova, & Slieptsov (2016) produced plastic–sand composite using recycled plastic and sand as a reinforcement additive. A comparison based on characterization techniques was made between the composites made from polyolefin (low-density polyethene (LLDPE) and polyethylene (PE)) and polyester (PET) matrices. Various composition alteration methods were used, such as the addition of compatibilizers, filler surface treatment, and the production of polymer blends. The effect of varying the composite constituents in its structure on the mechanical composite properties was determined. The produced composite comprising PET–polycarbonate (PC) mixture displayed improved thermal and mechanical properties than the composites comprising polyolefin. These composites find application where there is a need to use thinner and lighter materials having excellent thermal stability and high rigidity.

3.5.2 Nanocomposites: Plastic–Silica Nanoparticle Composites

A lot of research exists on the influence of the reinforcement ratios of silica nanoparticles on the plastic composites. In a study by Ahmed & Mamat (2011), HDPE–silica nanoparticle composite was produced containing silica nanoparticles with an average size of silica nanoparticle of less than 100 nm. The silica nanoparticles were generated in several steps in ball mills and combinations of heating. The HDPE–silica nanoparticle composite was produced by mixing HDPE with silica nanoparticles while varying the concentration of silica nanoparticles by 5, 10, 15, and 20 wt.% and then through compression molding. The nanocomposite was evaluated based on the physical properties, thermal properties, mechanical properties, and microstructure. It was found that there was an improvement in the physical properties with the addition of silica sand nanoparticles as a reinforcement additive in HDPE. Additionally, there was an improvement in the mechanical properties of HDPE–silica nanoparticle

composite with an increase in silica nanoparticles with an optimum value of 15 wt.%. DSC results showed that the crystallinity of silica sand nanoparticles decreased.

In a research conducted by Krasucka, Stefaniak, Kierys, & Goworek (2015), cross-linked copolymer resins were used in different chemical compositions to prepare silica gel and polymer–silica nanoparticle composite. In order to study the formation of porosity in different polymer templates, the structure of calcined pellets and nanocomposite pores was studied using the typical adsorption process. Based on their hydrophobicity and geometric structure, examination of the porosity parameters describing the studied materials within meso- and micropores displayed a varying degree of silica nanoparticle portion penetration into the polymer matrix. It has been reported that the adsorption–desorption process can be affected by the pore blockage and cavitation effects (Reichenbach, Kalies, Enke, & Klank, 2011; Thommes, 2010). The addition of silica nanoparticles in the polymer matrix allows swelling in solvents to be eradicated and the entire matrix structure to be reinforced. Therefore, the interaction between the polymer matrix and an inorganic additive plays an important role in the formation of pores inside a composite which correlates with the swelling of a polymer composite. A difference in the polymer structure leads to a different interaction between the polymer and an inorganic additive. Ji et al. (2003) conducted a similar study by reacting tetraethoxysilane (TEOS) with propyl methacrylate to form a silica–polymer nanocomposite. The results indicated an improvement in thermal and mechanical properties. Therefore, the addition of silica nanoparticles in the polymer matrix significantly changes the porosity and morphology of the original particles as well as influencing the mechanical and thermal properties of the polymer.

Similarly, Peng & Kong (2007) prepared a nanocomposite made up of polyvinyl alcohol/silica nanoparticles using a combination of two methods: self-assembly and solution compounding methods. The findings indicated that the intense interaction of the particle with the matrix is completely inhibited and that the homogeneity of spherical silica nanoparticle dispersion in the polyvinyl alcohol (PVA) matrix is achieved. Atomic force microscopy height profiles showed heterogeneity in the surface of the nanocomposite which is influenced by the concentration of silica nanoparticles. The values of roughness assessed indicated that an increase in silica nanoparticle content leads to a rougher surface. Therefore, structural changes occur with an increase in silica nanoparticles into the composite polymer matrix.

Moreover, Younes et al. (2019) studied the effect the amount and type of binder have on the thermal and porous properties in a silica gel composite. A selection of four binders was made: polyvinylpyrrolidone (PVP), polyvinyl alcohol (PVA), gelatin, and hydroxyethylcellulose (HEC). It was found that silica gel powder (SGP) containing 2 wt.% of PVP composite demonstrated improved thermal and porous properties. Higher thermal conductivity of 32% more than that of SGP was found for PVP 2 wt.% composite. By comparison, the adsorption of water uptake for both SGP and PVP 2 wt.% of the composite remained the same, while there was a 12.5% increase in the volumetric uptake for the composite. The composites evaluated were considered to be appropriate for high-performance adsorption cooling system designs.

Furthermore, Kalambettu, Venkatesan, & Dharmalingam (2012) produced polymethacrylate–silica composite membrane and polyvinyl alcohol–silica composite membranes using the sol–gel method and studied their suitability in medical

applications. The results from SEM revealed that the homogeneity of the surface of the membranes relies on the amount and fusion between the two polymers. The development of microcracks in all composite samples was apparently regulated by changing the composition in the polymer ratios. FTIR verified the mixing interaction of polymers in both composites. Composite bioactivity studies showed that the highest bioactivity in these two environments existed at higher concentrations of PVA and sulfonated poly(ether ether ketone) (SPEEK). The MTT method of in vitro cytotoxicity analysis involving epithelial cells (HBL-100) revealed that excellent cell viability was depicted in all samples.

Similarly, Meer, Kausar, & Iqbal (2016) studied polymer microsphere and silica nanoparticles as effective polymer composite reinforcement additives. The focus was on their methods of production, properties, and application based on their properties. Silica is commonly used as an enhanced surface mediator, as a nucleating agent, and as cores and templates. Under the polymer–silica composites, different categories such as polypyrene, rubber, polystyrene, polyaniline, acrylate polymers, and epoxy were extensively discussed. It was found that silica nanoparticles tend to improve the mechanical properties and overall performance of polymer–silica composites. Similarly, silica-carbon nanotube composites have good mechanical and electrical properties. They are important in the application such as nanomedicines, nanoelectronic devices, and protection.

In addition, Guyard, Persello, Boisvert, & Cabane (2006) prepared a cast film composite using an aqueous solution of the polymer having silica nanoparticles. The polymer matrices used were hydroxypropyl methylcellulose (HPMC), polyvinyl alcohol (PVA), and a mixture of PVA and HPMC polymers. The polymer–silica nanoparticle interphase was investigated by adsorption isotherms in the aqueous dispersion. From the results, a high affinity for silica nanoparticles and a high adsorption coverage were observed in HPMC; in contrast, PVA had a low affinity and could adsorb at low coverage. In films, silica nanoparticle structure was observed by small-angle neutron scattering (SANS) and transmission electron microscopy (TEM). All analyses indicated that the nanoparticles of silica in HPMC films were well dispersed and aggregated in PVA films. Composite mechanical properties were assessed by tensile strength tests. In both cases, the polymers had high elastic modulus (291 MPa for PVA and 65 MPa for HPMC) and low-maximum break elongation (4.12 mm for PVA and 0.15 mm for HPMC). The inclusion of silica nanoparticles in HPMC matrix resulted in increased modulus of elasticity and decreased breaking stress. When silica nanoparticles were added in the PVA matrix, the modulus of elasticity decreased and the breaking stress increased. The polymer–silica interface modifications can be used to change the mechanical properties of these composite materials.

In a research conducted by Kierys, Dziadosz, & Goworek (2010), the monodisperse polymer–silica composite was produced by a two-stage method, with the polymer as a matrix and hydrophilic silica gel as the filler element. In the first step, Amberlite XAD7HP particle swelling was done in tetraethoxysilane (TEOS). Some amount of the TEOS-impregnated XAD7HP particles was subsequently transferred to an acidic, aqueous solution to enhance the silica precursor sol–gel process. This method is evaluated as a prospective route toward obtaining a core-shell morphology composite material. Microscopic images of scanning electron microscopy (SEM)

and 29Si MAS NMR showed that silica nanofibers were formed on the polymer matrix. The silica nanoparticles were attached to the matrix of polymers. The silica shell had significantly higher mechanical properties. The polymer swelling and silica phase formation significantly altered the porosity of the original polymer material. Surprisingly, the produced composite showed much more homogenous porosity.

Additionally, Fu, Feng, Lauke, & Mai (2008) researched on the effects of the adhesion of particles, particle size, and the loading of particles on the toughness, strength, and stiffness of a variety of composites containing additives in both micro- and nano-sizes with a small aspect unit ratio. Composite toughness and strength were found to be significantly affected by all three factors, in particular particle/matrix adhesion. This could be because strength relies on an effective transmission of stress between the reinforcement additive and the matrix, noting that adhesion controls brittleness and toughness. The relationship that exists between these three factors, which in most cases coexist, has shown several trends in the influence particle loading has on the toughness and strength of the composite. The composite toughness, however, significantly varies with particle loading, not particle/matrix adhesion, because the additives have much greater modulus than the polymer matrix. The vital size of the particle, normally in nanometer, was also established, below which the stiffness of the composite is greatly improved because of the significant impact of the size of the particle, possibly caused by a "nano" effective surface area.

In a study conducted by Hussain (2018), it was reported that nanostructured particles, due to their processability, tunable properties, and low cost, are the best suited flexible materials for polymer matrix–reinforcement. Similarly, Huang, Yeh, & Lai (2012) reported that a nanocomposite containing a polymeric matrix can particularly act as an effective coating as it improves substrate surface characteristics for specific purposes. For example, a nanocomposite of polymers having an inorganic layered filler that is coated on the steel surface can greatly slow down corrosion. Besides their inherent material behavior, the simplicity and efficiency in incorporating them on substrates are the main parameters for defining effective polymer nanocomposite coatings.

3.6   CONCLUSION

Most researches have been concerned with the hydrophilic nature of polymer–silica composites. Moisture absorption is an undesirable property in most engineering applications because water causes swelling and bulking of materials, especially composites. Swelling causes dimensional changes, and it greatly affects the mechanical and thermal properties of a composite material. A lot of focus has been shifted to the nanocomposite technology with various researchers trying to lower the hydrophilicity of polymer–silica nanocomposites. A lot of research is currently being conducted to explore a wider range of naturally available silica sand or related materials to improve the hydrophilicity performance of such composites, especially for green construction materials. The currently reported research on polymer–silica composites has not been directed toward green construction application. Therefore, there is a need for researching more silica materials to reinforce polymers for green construction applications.

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