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Review

Review on hygroscopic aging of cellulose fibres and their biocomposites

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ABSTRACT

This review presents critical literature on effects of humidity and temperature on the properties of natural fibres and its composites. The drawback of moisture absorption on the mechanical properties of natural fibre and its composites is evaluated. Numerous researchers have been working to address the moisture absorption issue, with specific attention paid to the surface treatment of fibres and refining the fibre–matrix interface. Because of the natural fibre's positive commercial and environmental outcomes, as well as their desirable properties such as high specific strength, natural fibre reinforced composites are displaying a good potential to be used in various applications such as automotive, aerospace and packaging. This review addresses a comprehensive survey on hygroscopic factors (long term environmental aging) affecting natural fibres and their performance as reinforcement in polymer composites. The effects of cellulose surface chemistry and topography on hydrophobicity are addressed. Furthermore, the review also addresses the progress in the development of superhydrophobic materials based on cellulose material for better moisture resistance. In addition, recent investigations dealing with bio-based coatings prepared from renewable resources are also discussed.

Contents

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1. Introduction

The use of natural fibres as reinforcement in polymer composite materials is constantly growing, especially in the automotive and aerospace industries, because of a need to produce environmental friendly products. It is likely that application of natural fibres as reinforcement in polymer matrices could expand their usage in the near future due to their offered advantages, which include low weight, high strength, low maintenance cost and corrosion resistance (Azwa, Yousif, Manalo, & Karunasena, 2013). Conversely, a major setback of natural fibres is their vulnerability to moisture absorption which results in poor mechanical performance when reinforced with polymers and therefore limits their application. Natural fibre composites undergo mechanical failure in humid conditions through water sorption resulting in delamination. When exposed to environmental conditions such as varying humidity and temperature, the composites are prone to moisture absorption leading to porosity, disbanding around filler, swelling, sorption in microcracks, and voids, which adversely affects the mechanical properties (Adroja, Koradiya, & Parsania, 2013; Azwa & Yousif, 2013; Cristaldi, Latteri, Recca, & Cicala, 2010; Sen & Reddy, 2013). Previous studies have reported that the factors such as, fibre volume fraction; temperature; humidity; matrix; fibre type and fibre–matrix adhesion influence the amount of moisture absorption, and therefore affect the composite properties. For instance, in wood fibre–polypropylene composites it was observed that the water absorption increases with increasing fibre content owing to the increased cellulose content (Bledzki & Faruk, 2004). The hydrophilic nature of natural fibres is obtained from lignocellulose, which contains strong polarized hydroxyl groups (Zafeiropoulos, 2011). This hydrophilic nature restricts compatibility with hydrophobic polymer matrix which results in poor interfacial interaction between a hydrophilic fibre and a hydrophobic polymer. In addition, the moisture absorption drawback could minimise the applications of natural fibres in advanced industrial sectors (aerospace and automotive); components in these sectors are exposed to a wide range of temperature and relative humidity and this affects the long-term strength and durability (Cristaldi et al., 2010; Zafeiropoulos, Williams, Baillie, & Matthews, 2002; Dhakal, Zhang, & Richardson, 2007; Zaki Abdullah, Dan-mallam, & Megat Yusoff, 2013).

Surface modification of natural fibres has served as an essential tool to improve the compatibility with the polymer matrix. Studies on surface modification of natural fibres leading to moisture absorption have been reported in literature (Alawar, Hamed, & Al-Kaabi, 2009; Cantero, Arbelaiz, Llano-Ponte, & Mondragon, 2003; Dixit & Verma, 2012; Hashim, Roslan, Amin, Zaidi, & Ariffin, 2012; John & Anandjiwala, 2008; Kalia, Kaith, & Kaur, 2009; Keener, Stuart, & Brown, 2004; Kumar, Obrai, & Sharma, 2011; Rout, Misra, Tripathy, Nayak, & Mohanty, 2001; Sgriccia, Hawley, & Misra, 2008; Xie, Hill, Xiao, Militz, & Mai, 2010; Zafeiropoulos et al., 2002). However, the long term effect of exposure of natural fibre composites to high relative humidity and temperature is problematic, further techniques such as nano-coatings, bio-based coatings and chemical modifications need to be exploited or optimised to enhance surface hydrophobicity of natural fibres. Emphasis has to be placed on the effects of cellulose surface chemistry and topography, both of which affect hydrophobicity. Interestingly, research on superhydrophobicity has stimulated much scientific and industrial interest because of applications in self-cleaning, friction reduction, water repellence and antifouling (Song & Rojas, 2013). In addition, bio-based polyurethane coatings with superior properties such as solvent resistance, hydrolytic stability, weatherability and acid–base resistance have been reported and show good moisture repellence properties. Another promising hydrophobic resin is poly(furfural alcohol) which holds excellent properties such as high heat distortion temperature, high chemical resistance, hydrophobicity and high chemical resistance (Deka, Misra, & Mohanty, 2013; Kumar, Kumar, & Anandjiwala, 2012). Reviews on effect of water sorption/diffusion on properties of natural fibres/composites are present in literature. However, this review addresses issues of moisture absorption as a result of relative high humidity and temperature and focuses on significant effects on chemical and physical properties of natural fibres as well as on final performance of composite structures especially in long-term application. The review also discusses the drawbacks of mechanical fatigue associated with long-term durability of natural fibre reinforced composites especially when moisture sorption is accompanied by high environmental variations of temperature and humidity. Furthermore, the review also highlights research work done on chemical treatment to reduce the inherent hydrophilicity of lignocellulosic fibres and retard moisture absorption behaviour. Emphasis is placed on possible solutions to bridge the gap between chemical treatments, bio-based coatings and developing superhydrophobic materials using nanoparticles to improve the long-term utilization of fibre reinforced composites, especially when exposed to water absorption accompanied by high hygroscopic factors. Therefore, a comprehensive survey in the development of superhydrophobic materials based on cellulose material for better moisture resistance as well as the potential of bio-based coatings to be used as suitable material for lowering moisture absorption in natural fibre composites is discussed.

2. Natural fibres

2.1. Structure and properties of natural fibres

Natural fibres are divided based on their origins, coming from plants, animals or minerals. All plant fibres are made-up of cellulose while animal fibres comprise of proteins (wool, hair, and silk). Natural fibres consist of bast fibres (or stem or soft sclerenchyma), hard or leaf fibres, seed, cereal straw, wood, fruit, and other grass fibres. In their natural form, fibres are composites made up of hollow cellulose fibrils fused together by hemicellulose and lignin matrix (Jayaraman, 2003; John & Anandjiwala, 2008; John & Thomas, 2008) (see Fig. 1). Each fibril consists of complicated layered structure comprised of a thin primary wall surrounding a thick secondary wall. This secondary wall is comprised of three layers of which the thick middle layer controls the mechanical properties of the fibre. The middle layer has a series of helically coiled cellular microfibrils created from long chain cellulose molecules; between the microfibrils and the fibre axis a microfibrillar angle which varies from one fibre to another is found.

The microfibrils are made up of 30–100 cellulose molecules with diameter of about 10–30 nm in extended chain conformation and offers mechanical strength to the fibre. The cell wall is very complicated and made-up of hemicellulose, lignin and in some circumstances wax and pectin. Hemicellulose molecules are held to cellulose by hydrogen bonds which act as cementing matrix between the cellulose microfibrils, to form a hemicellulose–cellulose network, which is seemingly the main structural constituent of the fibre. The stiffness of the hemicellulose/cellulose composite is increased by a network of a hydrophobic lignin which acts as a coupling agent in the fibre cell. The nature of cellulose and its crystallinity correlates to the reinforcing efficiency of natural fibres. The main constituents of natural fibres are hemicellulose; lignin; cellulose (Fig. 2) while pectin; wax; fat and water soluble substances are the minor components of the structure. These compositions may differ with test methods and with growing conditions even for the same kind of fibre (see Table 1)