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A review of recent research on the use of cellulosic fibres, their fibre fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering

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ABSTRACT

Environmentally-friendly monofilament cellulosic fibres have been widely used as alternatives for conventional steel reinforcement within concrete. Recently, the use of cellulosic fibre fabrics and their fabric reinforced polymer composites as reinforcement materials within and/or outside of construction materials (e.g. concrete) has gained popularity due to their inexpensive cost and favourable specific mechanical properties compared with synthetic fibre fabrics (e.g. E-glass). This review presents a summary of recent development on cellulosic fibre Fabric Reinforced Cementitious (FRC) and Fabric Reinforced Geopolymer (FRG) composites, as well as their cellulosic Fabric Reinforced Polymer (FRP) composites as reinforcements of concrete, masonry and timber structures for civil engineering applications. This review covers: (1) properties (i.e. chemical composition, microstructure, mechanical properties and cost) of monofilament cellulosic fibres and their comparison with synthetic fibres, the relationship between fibre chemical composition and fibre mechanical properties, parameters affect fibre properties; (2) properties (e.g. fabrication of monofilament fibres to fabrics and structures) of cellulosic fibre fabrics, properties of polymer matrices, and properties (i.e. flexural, tensile, impact, insulation and fire properties) of cellulosic fabric FRP composites; and (3) properties (compressive, flexural and tensile and impact properties) of cellulosic FRC and FRG composites, and the properties of cellulosic FRP composites reinforced concrete, masonry and timber structures. In addition, the degradation mechanisms of cellulosic FRC and FRP are discussed. Furthermore, the durability of FRC, FRG and FRP composites are reviewed and the methods to improve the durability of FRC, FRG and FRP composites from the aspects of fibre modification and matrix modification are reviewed and summarized.

1. Introduction

Because of ever-increasing environmental concern and a requirement for development of environmentally-friendly and energy-efficient materials, monofilament cellulosic fibres have been widely used as alternatives for steel or synthetic fibres as reinforcements within cementitious composites for decades [1–8]. These cellulosic fibres include flax, sisal, jute, hemp, coir, hibiscus cannabinus, eucalyptus pulp, malva, ramie, pineapple leaf, kenaf bast, sansevieria leaf, abaca leaf, vakka, bamboo, banana, and palm and sugarcane fibres, etc. Cellulosic fibres are widely available in most countries and cost-effectively with low density. They are biodegradable, renewable, non-hazardous and non-abrasive. In addition, their specific mechanical properties (i.e. specific strength and modulus) are comparable to those of synthetic fibres (e.g. E-glass) when used as reinforcement materials [9–11]. These advantageous make cellulosic fibres to be convenient materials as reinforcement of cement-based materials. The purpose of adding these monofilament cellulosic fibres is to enhance the mechanical properties (e.g. tensile, flexural and impact properties) of brittle building materials, such as cement, mortar or concrete, especially for improving ductility and post-cracking toughness of cement-

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based composite materials provided by the fibres after cracking started [12–16]. The embedded monofilament cellulosic fibres bridge the cracks of cement matrix and transfer the stresses. Moreover, the addition of monofilament cellulosic fibres can reduce free plastic shrinkage [17] and thermal conductivity [18], and improve sound absorption [19] and vibration damping properties of cementitious materials [20].

Although there are many aforementioned advantageous, several shortcomings in producing cellulosic fibre reinforced cementitious materials at industrial scale still exist: (1) **Suspect of durability**. One major obstacle which needs to be overcame for successful commercialization of cellulosic fibre reinforced cementitious materials is their durability. The lack of data related to the durability is a critical challenge that needed to be addressed prior to the widespread acceptance and implementation of these materials in engineering areas [21–24], (2) **use of small fibre fraction/content leads to relatively limited reinforcement effect**. In monofilament configuration, normally the amount of cellulosic fibre used within cementitious materials is relatively small, i.e. the fibre volume fraction is controlled within the range from 0.2 to 2.0% [2,16,23–28]. As well known, for monofilament cellulosic fibre reinforced cementitious composite, a large fibre content can cause difficulties in concrete mixing and distribution of fibre, and even a significant reduction in workability of the fresh concrete which possible results in large growth of porosity [25–28]. Thus, the improvement in mechanical properties of cementitious composites by adding the small amount of cellulosic fibre is positive but also relatively limited, and (3) **significant variations in fibre properties**. Cellulosic fibres have significant variations in chemical compositions, diameter, length and surface roughness resulting in the significant scattering in fibre mechanical properties [29–33]. Consequently, this may cause scattering in mechanical properties of these cellulosic fibre reinforced cementitious materials.

As the aforementioned reasons, in recent years, there is an increasing tendency to use cellulosic fibre fabrics and their fabric reinforced polymer (FRP) composites as reinforcement materials of conventional building materials. Polymer matrix, reinforced by woven fabrics, is the form of composites which have been used most commonly in structural applications such as aircrafts, boats and automobiles [34]. The advantageous to use cellulosic fibre fabrics and their FRP composites of construction materials (e.g. concrete) are as follows: (1) **Good stability in mechanical properties**. Fine and regular long monofilament cellulosic fibres are usually spun into yarns, and next, a number of fibre yarns are twisted into a continuous strand, and then these strand yarns are woven into fabrics with different yarn structures such as configuration, alignment and packing of constituent fibres in the yarn cross section [35,36]. With a standardized manufacturing process, cellulosic woven fabric allows the control of fibre orientation and quality, good reproducibility and high productivity. Consequently, the issues, such as significant variations in monofilament cellulosic fibre properties, hard to dispersion and random distribution of cellulosic fibres in cementitious matrix (i.e. which may be not along the loading direction and cannot provide effective reinforcement), can be overcame in the case of cellulosic fibre fabrics. Therefore, these fabrics and their FRP composites exhibit good stability in mechanical properties so as their reinforced structural materials, (2) **provide effective reinforcements in multi-directions**. Compared with monofilament cellulosic fibres in cementitious matrix which only provide reinforcement effect in the fibre longitudinal direction, the woven cellulosic fabrics can offer effective reinforcements for the matrix in multi-directions (e.g. bi-directional woven fabric in both weft and wrap directions), (3) **not only used within but also outside of cementitious matrix**. In monofilament cellulosic fibre reinforced cementitious composite, these fibres were embedded within the cement matrix only. But for cellulosic fibre fabrics and their FRP composites, these reinforcements can be used either within and/or outside of concrete members to retrofit/strengthen of existing concrete structures [e.g. Refs. [37–43]] and to create new hybrid composite concrete structures [e.g. Refs. [44–52]] or to be new fibre fabric reinforced geo-polymer (FRG) composites [53–64], and (4) **can be used with other conventional construction materials**. Unlike the monofilament cellulosic fibres normally embedded within cementitious matrix, the cellulosic fibre fabrics and their FRP composites can be used as reinforcement materials of other conventional construction materials, such as timber [e.g. Refs. [65–69]] and masonry [e.g. Refs. [70–75]].

Therefore, this study presents an overview of recent development on the use of cellulosic fibres, their fabric reinforced cementitious (FRC) composites, and cellulosic fabric reinforced geopolymer (FRG) composites and the cellulosic fabric FRP composite reinforced concrete, timber and masonry structures for civil engineering applications. Firstly, the physical and mechanical properties and cost of various cellulosic fibres were summarized and compared with the synthetic fibres such as glass, carbon and aramid. Next, the microstructures of several most commonly-used celluloses fibres (i.e. flax, sisal, hemp, cotton and jute) were presented. The relationship between chemical compositions and mechanical properties of monofilament cellulosic fibres were discussed. Then, the parameters which influent the mechanical properties of cellulosic fibres were summarized. After that, the properties such as fabrication of fabrics from monofilament fibres and structures of cellulosic fibre fabrics, properties of polymer matrices, and the mechanical properties of their FRP composites were discussed. Afterwards, the mechanical properties of fabric FRC and FRG composites, and those of FRP composite strengthened concrete, masonry and timber structures were reviewed. In addition, the degradation mechanisms of cellulosic FRC and FRP composites were discussed. Furthermore, the durability of FRC, FRG and FRP composites were reviewed and the methods to improve the durability of FRC, FRG and FRP composites from the aspects of fibre modification and matrix modification were reviewed and summarized.

2. Characteristics of cellulosic fibres

2.1. Chemical compositions of cellulosic fibres

Cellulosic fibres are natural fibres based on the classification according to their origin or botanical type, as shown in Fig. 1 [91]. Cellulosic fibre itself is a composite material which is consists of cellulose, hemicellulose, lignin, wax and pectin as main constituents and minor amounts of sugars, starch proteins in varying quantities. The properties of a cellulosic fibre are highly dependent on its chemical composition. The basic chemical components of a cellulosic fibre are cellulose, hemicellulose and lignin. In a cellulosic fibre, the cellulose is the stiffest and strongest organic component which provides the fibre with strength, stiffness and stability. Cellulose is a natural polymer and the cellulose molecules include glucose units linked together in long chairs, which in turn are lined together in bundles named micro-fibrils [22]. However, cellulose is semi-crystalline polysaccharide with a large amount of hydroxyl group. This hydrophilic nature causes a poor resistance of cellulosic fibre to moisture absorption and the poor interfacial bond when these fibres are used as reinforcement of hydrophobic matrix, such as polymer [22,76]. Hemicelluloses are polysaccharides bonded together in relatively short, branching chains. They are intimately associated with cellulose micro-fibrils, embedding the cellulose in a matrix [22]. Hemicellulose has an open structure and is fully