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Flax fibre and its composites – A review

Libo Yan [a,*], Nawawi Chouw [a], Krishnan Jayaraman [b]

[a] Department of Civil and Environmental Engineering, The University of Auckland, Auckland Mail Centre, Private Bag 92019, Auckland 1142, New Zealand
[b] Department of Mechanical Engineering, The University of Auckland, Auckland Mail Centre, Private Bag 92019, Auckland 1142, New Zealand

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ABSTRACT

In recent years, the use of flax fibres as reinforcement in composites has gained popularity due to an increasing requirement for developing sustainable materials. Flax fibres are cost-effective and offer specific mechanical properties comparable to those of glass fibres. Composites made of flax fibres with thermoplastic, thermoset, and biodegradable matrices have exhibited good mechanical properties. This review presents a summary of recent developments of flax fibre and its composites. Firstly, the fibre structure, mechanical properties, cost, the effect of various parameters (i.e. relative humidity, various physical/chemical treatments, gauge length, fibre diameter, fibre location in a stem, oleaginous, mechanical defects such as kink bands) on tensile properties of flax fibre have been reviewed. Secondly, the effect of fibre configuration (i.e. in forms of fabric, mat, yarn, roving and monofilament), manufacturing processes, fibre volume, and fibre/matrix interface parameters on the mechanical properties of flax fibre reinforced composites have been reviewed. Next, the studies of life cycle assessment and durability investigation of flax fibre reinforced composites have been reviewed.

1. Introduction

In recent years, the use of bio-fibres to replace glass fibres as reinforcement in composites for engineering applications has gained popularity due to an increasing environmental concern and requirement for developing sustainable materials [1,4]. Approximately 43,000 tonnes of bio-fibres were utilised as reinforcement in composites in the European Union (EU) in 2003 [2]. The amount increased to around 315,000 tonnes in 2010, which accounted for 13% of the total reinforcement materials (glass, carbon and natural fibres) in fibre reinforced composites. It is forecasted that about 830,000 tonnes of bio-fibres will be consumed by 2020 and the share will go up to 28% of the total reinforcement materials [3]. The United States (US) Department of Agriculture and the US Department of Energy had set goals of having at least 10% of all basic chemical building blocks be created from renewable and plant-based sources in 2020, increasing to 50% by 2050 [4]. The explosive growth in bio-composites is indicative of their wide application in the future as the next generation structural materials. Bio-fibres are cost-effective with low density. These are biodegradable and non-abrasive. In addition, they are readily available and their specific mechanical properties are comparable to those of glass fibres used as reinforcement [5,6].

* Corresponding author. Tel.: +64 9 373 7599x84521; fax: +64 9 373 7462.
E-mail address: lyan118@aucklanduni.ac.nz (L. Yan).

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2. Flax fibres

Flax (*Linum usitatissimum*) is one of the most widely utilised bio-fibres. Flax is also one of the first to be extracted, spun and woven into textiles. Flax in textile use was found in graves in Egypt dating back to 5000 BC [7]. Kvavadze et al. [8] have recently reported finding twisted wild flax fibres indicating that prehistoric hunter–gatherers were making cords for hafting stone tools, weaving baskets, or sewing garments around Dzudzuana Cave (Georgia) up to 30,000 years ago.

Flax grown for fibre and linseed grown for seed oil are cultivars (varieties of the same plant species bred with an emphasis on the required product) [9]. Canada is the largest producer and exporter of flax in the world since 1994. In 2005/06, Canada produced about 1.035 million-tonnes and currently ships 60% of its flax exports to the EU, 30% to the US, and 4% to Japan [10]. Other leading producers of flax are France, Belgium and the Netherlands, with nearly 130,000 acres under cultivation annually. In 2007, the EU produced 122,000 tonnes of flax fibres [11]. Climatic conditions in the regions are perfect for growing flax, and increasing worldwide demand for linen makes it an important cash crop. The growing cycle of flax is short, with only 100 days between sowing in March and harvesting in July in the Western European region [12].

Fine and regular long flax fibres are usually spun into yarns for linen textiles. Linen fabric maintains a strong traditional niche among high quality household textiles, such as bed linen, furnishing fabrics and interior decoration accessories. Shorter flax fibres produce heavier yarns suitable for kitchen towels, sails, tents and canvas. Lower fibre grades as reinforcement and filler in composites are used in automotive interior substrates and furniture [11].

2.1. Structure

Flax fibres are produced in the stems of flax bast plant. Like cotton, flax fibre is a cellulose polymer, but its structure is more crystalline, making it stronger, crisper and stiffer to handle, and more easily wrinkled. A schematic view of the multi-scale structures of flax from stem to the cellulosic fibrils is given in Fig. 1 [13,15]. Flax plant ranges in length up to 90 cm which possesses strong fibres all along its stem, and average 12–16 μm in diameter [11]. At the macroscopic level, a flax stem is composed, from the outer towards the inner part, of bark, phloem, xylem and a central void. At the meso-scopic level, the cross-section of a bundle contains between 10 and 40 fibres which are linked together mainly by pectin [13]. The microstructure of a flax fibre is extremely complex due to the hierarchical organisation at different length scale and the different materials present in variable proportions [14]. At the microscopic scale, each elementary fibre is itself made of concentric cell walls, which differ from each other in terms of thickness and arrangement of their constitutive components. At the centre of the elementary fibre, the concentric cylinders with a small open channel in the middle called the lumen, which contributes to water uptake as displayed in Fig. 1. The outer cell wall designed as the primary cell wall is only 0.2 μm thick [16]. On the outer side, the thin primary cell wall coats the thicker secondary cell wall which is responsible for the strength of the fibre and encloses the lumen. Each layer is composed of microfibrils of cellulose which run parallel one to another and form a microfirilar angle with the fibre direction; this angle is minimum in the secondary cell wall [13]. The bulk of the fibre is essentially constituted by the layer S2 of the secondary cell wall (dominating the cross section), as shown in Fig. 2. This thickest cell wall (S2) contains numerous crystalline cellulose micro-fibrils and amorphous hemicellulose which are oriented at 10° (see Fig. 2) with the fibre axis and give fibre its high tensile strength [14,17]. At the nano-scale, a microfibril is constituted of cellulose chains (crystalline zones) embedded in an amorphous matrix mainly made of pectins and hemicelluloses [13]. The cellulose crystallites in the secondary cell wall are laid down in oriented, highly crystalline microfibrils which are glued together by the amorphous hemicellulose/pectic matrix [14]. These micro-fibrils represent about 70% of the weight of a flax fibre and are likely to act as the reinforcement material within the fibre [18]. The angle between the axis and the fibrils of the fibre could affect the strength of the fibres. Generally, a fibre is more ductile if the micro-fibrils have a spiral orientation or the fibre axis.

2.2. Chemical composition

The chemical composition and location of constituents within the flax stem define the properties of flax fibre. Table 1 lists the compositions of flax fibres reported by different authors [20–24,64]. The main constituents of a flax fibre consist of cellulose, hemicellulose, wax, lignin and pectin, in varying quantities. Cellulose, hemicellulose and lignin are basic components which determine the physical properties of the fibres. Cellulose is the stiffest and the strongest organic constituent in the fibre. However, cellulose is a semicrystalline polysaccharidewith a large amount of hydroxyl group, giving hydrophilic nature to natural fibre when used to reinforce hydrophobic matrices. The result is a very poor interface and poor resistance to moisture absorption [108]. In the composite materials, bio-fibres adhere poorly to hydrophobic matrices, often to the point that the composite is mechanically inferior to either the bio-fibres or the matrix material on their own. This calls for the fibre or matrix modification to improve the mechanical properties of the composite. Hemicellulose is strongly bound to cellulose fibrils presumably by hydrogen bonds. Hemicellulosic polymers are branched, fully amorphous and have a significantly lower molecular weight than cellulose. Because of its open structure containing many hydroxyl and acetyl groups, hemicellulose is partly soluble in water and hygroscopic. Lignin and pectin act mainly as bonding agents [25]. Lignins are amorphous, highly complex, mainly aromatic, polymers of phenylpropane units but have the least water sorption of the natural fibre components [108]. The waxy substances of flax fibres affect the fibre wettability and adhesion characteristics. As shown in Table 1, flax fibre is rich in cellulose which accounts for about 70% of the total chemical composition. This enables flax to be widely considered as reinforcement in composite. In Table 1, the variation of proportions of the

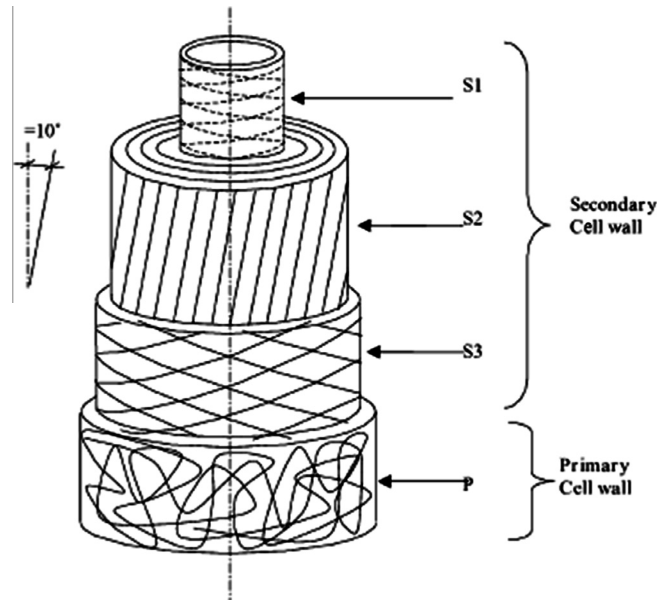

Fig. 2. The micro-structure of a flax fibre cell (reproduced with permission from [14]).

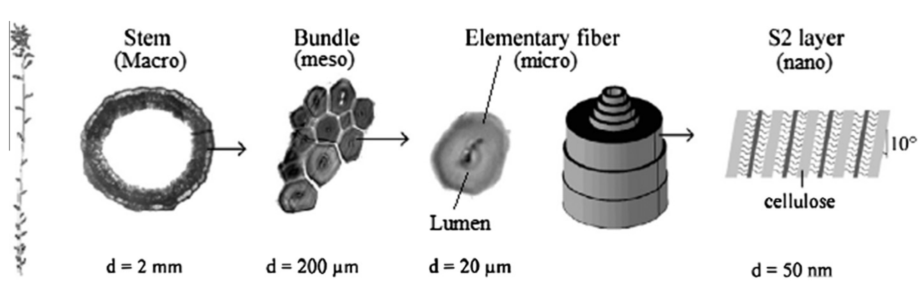

Fig. 1. Flax structure from the stem to the cellulosic fibrils (reproduced with permission from [13,15]).