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Plant-based natural fibre reinforced cement composites: A review

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ABSTRACT

The quest for sustainability in construction material usage has made the use of more renewable resources in the construction industry a necessity. Plant-based natural fibres are low cost renewable materials which can be found in abundant supply in many countries. This paper presents a summary of research progress on plant-based natural fibre reinforced cement-based composites. Fibre types, fibre characteristics and their effects on the properties of cement-based materials are reviewed. Factors affecting the fresh and hardened properties of cement-based composites reinforced with plant-based natural fibre are discussed. Measures to enhance the durability properties of cement-based composites containing plant-based natural fibres are appraised. Significant part of the paper is then focused on future trends such as the use of plant-based natural fibres as internal curing agents and durability enhancement materials in cement-based composites. Finally, applications and recommendations for future work are presented.

1. Introduction

Sustainability was defined by the World Commission on Environment and Development (WCED) as meeting the needs of the present without compromising the ability of future generations to meet their own needs [1]. One major problem facing mankind is the increasing world population and the associated pressure on the built environment. Demands for built infrastructure have caused significant waste generation, energy and material consumption by the construction industry. According to Melchert [2], the building construction industry is not only a major consumer of energy, raw materials and land; it also contributes immensely to environmental pollution, especially greenhouse gas (GHGs) emission. To improve sustainability in construction materials usage, the construction industry must embrace the reuse of industrial by-products and renewable materials in construction.

Presently, because of their proven performance, the use of synthetic fibres in cement composites is becoming increasingly popular. Cement research literature is replete with studies showing that the ductility, tensile strength, toughness, fatigue strength, impact resistance and absorbed energy of cement-based materials could be enhanced significantly through the addition of steel and polymeric fibres [3–6].

There are three types of natural fibres available for concrete reinforcement: animal-based, mineral-derived and plant-based. Animal fibres, comprising specific proteins, include silk, wool, and hair fibre. Mineral-derived fibres include asbestos, wollastonite and palygorskite. Finally, plant-based fibres include cotton, hemp, jute, flax, ramie, sisal, bagasse, specialty fibres processed from wood and etc.

Significant enhancement in the properties of cementitious materials is also possible by reinforcing them with plant-based fibres described above. Opportunely, such fibres are obtained from renewable sources and are readily available at relatively low cost compared to man-made fibres. The benefits from large scale utilization of plant-based natural fibres as raw materials for cement-based composites are immense in terms of environmental, energy and resource conservation.

Several investigations on plant-based natural fibre reinforced cement composites have been undertaken by researchers in the past three decades. This paper will present the current state-of-the-art knowledge on the use of short and pulp fibres from plant sources as reinforcement for cement paste and mortar. Emphasis will be on fibre characterization, fresh and hardened properties of composites. The mechanical and durability performance of plant-based natural fibre reinforced cement composites will be discussed. Information on recent developments, future trends and applications for cement-based materials reinforced with plant-based natural fibres will also be presented.

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2. Types of plant-based natural fibres

2.1. Bast fibre

Bast fibres are usually extracted from the outer bark of plant stems. Some examples of bast fibres are jute (*Corchorus olitorius*/*Corchorus capsularis*), flax (*Linum usitatissimum*), abaca (*Musa textilis*), and kenaf (*Hibiscus cannabinus*). Retting is the process through which these bast fibres are extracted, and is accomplished through biological or chemical degradation of cut plant stems. Long fibre bundles with high tensile strength is the typical characteristics of bast fibres, hence they are traditionally used in making yarn, textile, rope, sack, etc.

2.2. Leaf fibre

Leaf fibres are coarse and hard fibres obtained from leaf tissues by hand scraping after beating/retting process or mechanical extraction. Owing to the relatively high strength, leaf fibres are typically used for the production of ropes, fabrics, carpets and mats. Some examples of leaf fibres are sisal (*Agave sisalana*), caroa (*Neoglaziovia variegate*), henequen (*Agave fourcroydes*) and pineapple (*Ananas comosus*).

2.3. Seed fibre

Coir fibre is a typical example of seed fibre, and it is extracted from the coconut husk. These lightweight and strong fibres are mainly used in the production of ropes, mats, sacks, brush, geotextile and etc. Another set of seed fibres are also extracted from the pod or boll of some plant seeds. Examples are cotton, kapok (*Ceiba pentandra*), and milkweed floss which are widely used in textile, water safety equipment, insulation, upholstery and mattress products as a result of their softness and buoyancy.

2.4. Stalk fibre

These are fibres from plant stalks, and are typically extracted from plants such as sugarcane, corn, eggplant, sunflower, wood and the straw of various grain crops such as barley, wheat, rice and etc. Pulp from some of these fibres has been utilized in paper and paperboard products.

2.5. Grass and other fibre crop residue

Widely available tall grasses such as ryegrass (*Lolium perenne*), elephant grass (*Pennisetum purpureum*), switchgrass (*Panicum virgatum*) and bamboo (*Bambusa vulgaris*) are important sources of fibres. Furthermore, The Food and Agriculture Organization of the United Nations (FAO) estimated a 55% increase in world crop cultivation over the period from 1997/99 to 2030 [7]. Hence, fibrous crop residues such as pulse seed coat, peanut shell, hazelnut husk, corn husk, millet stover, and etc. can potentially be used as fibre reinforcements in cement-based composites.

2.6. Wood and specialty fibres

Wood fibres are sourced from a wide variety of trees. Hence, they are in abundant supply across the world. Wood fibres are broadly divided into two groups, softwood and hardwood. The major difference between these two groups is that while softwood fibres are generally longer than hardwood fibres, the number of fibres in a given gram of pulp is significantly higher for hardwood pulp. On the other hand, specialty cellulose fibres are industrially processed plant-based natural fibres with unique attributes such as bond enhancement and alkali resistance features. Furthermore, quality controlled manufacturing of these type of fibres ensure that the huge variability in dimensional and mechanical properties associated with unprocessed plant-based fibres is significantly reduced.

3. Fibre extraction processes

After the retting process, single fibres from plant-based strand fibres are mostly obtained by manual mechanical separation or the use of a decorticator. On the other hand, pulping procedure is used to reduce strand fibres or wood chips to individual fibres. In mechanical pulping, fibre strands or wood chips are ground in three different ways; without steaming, with steaming (thermo-mechanical pulping) and chemical/steam pre-treatment (chemithermo-mechanical pulping). Conversely, in chemical pulping, heat and chemicals (kraft and sulfite process) are utilized in removing lignin from strands and wood chips thereby individualizing bundled fibres. Although chemical pulping yields lower quantities of pulp, the produced fibres are longer, stronger and brighter. Depending on application, further post-pulping processing of fibres such as bleaching and mechanical beating are also performed.

4. Hygric, chemical and mechanical structure

Micrographs of some non-woody fibre bundles [8] are shown in Fig. 1. From the longitudinal view of these fibres, the surface of coir fibre did not only contain significant number of small indentations, it appears to be rougher compared to the surfaces of the other fibres. Cross-sections through these fibres also indicate that while the cell walls of the abaca fibre were thicker than those of coir and sisal fibres, the lumen diameter of all the fibres varied from 3 to 15 μm. Hence, given the open lumen of these fibres and the existence of pores on the cell walls, plant-based fibres could absorb significant quantity of water. Symington et al. [9] reported moisture absorption variation of 70%–164% in several plant-based fibres they investigated. Their findings indicated that coir and abaca fibres recorded the lowest and highest moisture content, respectively. The poor water absorption of coir fibre was attributed to the existence of air entrapping indentations on its surface as shown in Fig. 1a. In a related study, Ramadevi et al. [10] observed 135%–200% increase in the moisture content of untreated abaca fibre immersed in different types of water solution.

Plant-based natural fibres consist of cellulose, hemicellulose, lignin, extractives and ash. The concentrations of these components depend on factors such as fibre type, growth condition, dimension, age, location on plant, extraction and processing method. Table 1 shows the variations in chemical composition of some selected fibres [11–13]. These natural fibres are also very hydrophilic, and this is traceable to the presence of hemicelluloses and the hydroxyl group in the cell walls. Alvarez et al. [14] were of the opinion that the high content of hydroxyl group in cellulose increases moisture absorption properties of plant-based fibres. Hence, the cumulative effect of open lumen, cell wall pores and the presence of hydroxyl group makes plant-based fibres susceptible to moisture sorption induced dimension instability. Faruk et al. [15] suggested that the moisture content of plant-based fibres has a tremendous effect on their mechanical properties and performance in composites.

Previous studies have shown that the chemical composition of plant-based fibres has a great influence on its mechanical properties. This is because cellulose, hemicellulose and lignin are mainly responsible for the bond behavior and degradation of natural fibres in composites. According to Li et al. [16], the strength and stiffness of natural fibres depends on the cellulose content and the orientation of microfibrils in the cell wall. The chemical composition and