Development of Vegetable Fibre-Mortar Composites of Improved Durability

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1 Introduction

To resist propagation of cracks and to improve the ductility behaviour in cement mortar,fibres are used as reinforcement. Fibres are thread like substances which can improve the strength of cement composites, reduce the crack growth, and result to a better strain capacity of the cement composites.

The main types of fibre that have been used in cement-composites are natural and synthetic fibres. These fibres are derived from different materials, for example, natural fibres are gotten from animal, mineral, and plant. However, due to cost and environmental pollution that is associated with the use and production of synthetic fibres, natural fibres have been considered as viable alternative [31]. Being a very cheap and locally sourced material, their application in construction for improving the quality of cement composites will costs a very little and can lead to sustainable development.

Therefore, the utilization of natural fibers is technically beneficial being a material that can be promoted in construction industry [19]. One of such natural fibre that has potentially increased the durability of cement composites is the vegetable fibres (plant based fibres).

Vegetable fibres are bio-based fibres from vegetable origin (plants and wood). These bio-based fibres have continued to generate growing interest due to their

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potential as possible replacement for their synthetic counterparts [20]. Their chemical composition plays a vital role in their performance, cellulose and lignin being the major constituents have tremendous impact on the hydration process and ultimately on strength development in cement composites. Vegetable fibres are readily available, possess low weight and are energy and cost efficient. They require merely a small amount of industrialization for their processing and in contrast with an equivalent weight of nearly all regular synthetic reinforcing fibres, the energy required for their production is small and hence making them to be employed effectively in cement-composite components for weight reduction, strength improvement and crack reduction at low cost [40].

Also, their utilization in cement composites will result in significant reduction in the volume of agro-forestry residues generated by agro-industrial activities, as they have been previously considered as biodegradable waste. This implies that there could be a significant increase in the adoption of vegetable fibre as cementitous material, and this could be achieved by obtaining a material with properties comparable with the conventional construction materials.

2 Relevance of Vegetable Fibre as Reinforcement in Cement-Mortar Composites

The utilization of vegetable-fibres in cement composites has attracted great interest due to the following:

i. The application of vegetable fibre in cement-mortar composites will contribute to the decline of the environmental challenges caused by waste disposal. Vegetable fibres form major proportion of waste produced from agricultural sector, for instance, each tonne of commercially used sisal fibers resulted in three (3) tonnes of residual fibers, whose disposal have created environmental hazards in the neighbouring community [34]. Therefore, their utilization in cement composites will greatly help in addressing the problems of waste management faced in developing nations [27].
ii. They are abundantly available (they are produced in nearly all countries) [45] (Table 1). Due to various countries involvement in different agricultural practices such as growing plants and fruits which are used as raw materials for industries, the supply of vegetable fibres resources are unlimited, freely available and comparatively cheap [8]. More so, vegetable fibres originated from the environment (that is, they grow naturally in the environment), thereby making them to be abundantly available.
iii. Their use in cement composites will help in achieving sustainable construction materials which will support sustainable development, especially in emerging economies. Since, construction sector is a key contributor to climate change and the usage of sustainable materials in this industry have been a key focus

Table 1 Global production of vegetable fibres [42]

Fibres	Quantity (Million tons)	Country of production
Cotton	25	India, China, USA, Pakistan
Jute	2.5	Bangladesh, India
Kapok	0.03	Indonesia
Kenaf	0.45	Thailand, India, China
Flax	0.50	France, China, Belarus, Belgium, Ukraine
Hemp	0.10	China
Ramie	0.15	China
Abaca	0.10	Ecuador, Philippines
Sisal	0.30	Brazil, Kenya, China, Tanzania
Henequen	0.03	Mexico
Coir	0.45	India, Sri Lanka
Wool	2.2	China, Australia, New Zealand
Silk	0.10	China, India

over the years, the utilization of vegetable fibres in construction will drastically reduce the environmental impact caused by the industry [23].

iv. Vegetable fibers are non-hazardous, renewable, and biodegradable, permitting the development of more sustainable construction materials. In a study conducted by [21], it was reported that the process of extraction of vegetable fibers is pollution free and environmentally sustainable. The study further stated that their utilization as fibers-reinforced cement composites as a substitute of asbestos cement composites, would eradicate the dangers of exposure of human lives to infectious diseases like asbestosis, cancer, malignant pleural disease and tumors.

v. Vegetable fibres are as stronger as their synthetic fibres counterpart, cost-effective and above all environmental friendly [30]. Their properties such as low cost, good specific mechanical properties, and their requirements of low energy during production [33] will result in 10% decrease in weight, 80% decrease in energy required for production, and 5% reduction in cost of constituent utilized in contrast to their synthetic counterpart [25]. Though their moderate mechanical properties prevent them from being used in extreme loading conditions, nevertheless, for numerous reasons, they can compete with their synthetic counterpart.

vi. Their tensile performance can compare fairly with synthetic ones [30]. Attentions have been drawn to resilient non-conventional materials with comparable qualities as those presented by construction materials habitually used in civil engineering [32]. According to Da [12], vegetable fibres offer durability and resilience, even in excessive loading situations thereby contributing to infrastructure sustainability through reduced repair events and consecutively extending infrastructure service life.

vii. They have low density, less abrasiveness, and lower cost [28]. Vegetable fibres have mechanical properties which can contribute to sustainable construction materials relevant in construction sector. According to [5], the low density of vegetable fibres help in achieving better efficiency while their low abrasiveness makes their processing easier and more recyclable.

viii. They can be fashioned on site into complicated shapes and can also be easily cut to length on site. For complex shapes construction, vegetable fibres are usually suitable as their in-plane shear ability allows the membrane to seize the complex geometries required [10].

3 Types of Vegetable Fibres Used in Cement Composites

Different types of vegetable fibres exist; as seen in Table 1, these vegetable fibres with varied physical, mechanical, and chemical characteristics have been used in cement composites. The classifications include as seed-fibres, bast-fibres, and leave-fibres, stalk fibre, grass and other fibre crop residue, and wood and specialty fibres [4, 20]. The fibres under these categories which have been found suitable for cement composites are shown in Figs. 1 and 2:

i. Seed fibres:seed fibres are obtained from the seeds and seed cases of various plants. Popular fibres under this category include coir, cotton, kapok and milk-weed. The most studied fibre in this group is the coir fibre and it is the extracted husk of coconut. This fibre has been extensively utilized as composite materials in civil engineering; worthy of note is their utilization in cementitious matrices as a very suitable construction material for resisting earthquakes [22]; which meant that their composites have higher impact strength [38].

ii. Bast-fibres: jute, flax, abaca, kenaf, ramie, hemp can be grouped and defined as bast fibres. These fibres are gotten from the exterior of various plants. A common mechanical property possessed by fibres under this category is their

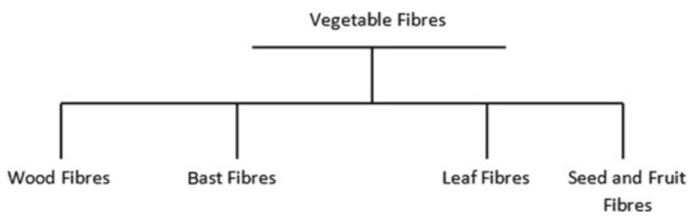

Fig. 1 Classification of vegetable fibres [35]

Fig. 2 Samples of fibre under different classification [6]

high tensile strength and ability to be a good thermal insulator [44]; therefore, they hold a high prospective, especially where there is a demand for considerable strength.

iii. Stalk fibres: Fibres such as baggasse, rice straw, wheat straw, barley etc. are obtained from the stem/stalks of plants. These fibres are usually bigger in diameter and showed significant differences in potassium and galacturonic acid content, strength, and rigidity [26]; there is no doubt that they will play a crucial role in the improvement of cement composites.

iv. Grass and other fibre crop residue: Grass fibers such as bamboo, elephant grass, peanut shell, corn husk, millet stover, hazelnut husk etc. are those fibres that originated from tall grasses. They have also been studied as component in cement composites [1].

v. Wood and specialty fibres: Wood fibres are sourced from a wide variety of trees while specialty fibres are industrially processed vegetable fibres with unique attributes such as bond enhancement and alkali resistance features. The fibres under this group have shown great potential in improvement of cement composites; for example, in a study conducted by [15] in which cement content was replaced with wood fibres using 1% by weight of cement, it was reported that significant improvement in the compressive strength by more than 40% with 1% by weight of the wood fibers was obtained.

Leaf fibres: the fibres in this group are gotten from the leaf of plants and they include sisal fibres, banana fibres, pineapple fibres, caroa fibres and henequen fibres. They are usually obtained by mechanically scrapping them away from the leaf of plants. Several experimental studies have recognized the positive effects of the inclusion of these types of vegetable fibres on the properties of cement composites. However, the most studied fibre in this group is sisal because of its strength, durability, ability to stretch, affinity and resistance to deterioration in salt water [2, 29] (Table 2).

Table 2 Vegetable fibre Types and Properties [14]

Fibre	Density (g/cm^3)	Diamater (um)	Length (mm)	Elongation (%)	Tensile modulus (GPa)	Tensile strength (Mpa)	Specific modulus	Cellulose (wt%)	Hemi-cellulose (wt%)	Lignin (wt%)	Pectin (wt%)
Alfa	0.89	–	–	5.8	22	35	25	45.4	38.5	14.9	–
Abaca	1.5	–	–	1.0–10	6.2–20	400–980	9	56–63	20–25	7–13	1
Bamboo	0.6–1.1	25–40	1.5–4	2.5–3.7	11–32	140–800	25	26–65	30	5–31	–
Bagasse	1.25	10–34	10–300	1.1	17–27.1	222–290	18	32–55.2	16.8	19–25.3	–
Banana	1.35	12–30	300–900	1.5–9	12	500	9	63–67.6	10–19	5	–
Coir	1.15–1.46	10–400	20–150	15–51.4	2.8–6	95–230	4	32–43.8	0.15–20	40–45	3–4
Cotton	1.5–1.6	10–45	10–60	3–10	5.5–12.6	287–800	6	82.7–90	5.7	<2	0–1
Curaua	1.4	7–10	35	1.3–4.9	11.8–96	87–1150	39	70.7–73.6	9.9	7.5–11.1	–
Flax	1.4–1.5	12–600	5–900	1.2–3.3	27.6–103	343–2000	45	62–72	18.6–20.6	2–5	2.3
Hemp	1.4–1.5	25–500	5–55	1–3.5	23.5–90	270–900	40	68–74.4	15–22.4	3.7–10	0.9
Henequen	1.2	–	–	3.7–5.9	10.1–16.3	430–570	11	60–77.6	4–28	8–13.1	–
Jute	1.3–1.49	20–200	1.5–120	1–1.8	8–78	320–800	30	59–71.5	13.6–20.4	11.8–13	0.2–0.4
Kenaf	1.4	–	–	1.5–2.7	14.5–53	223–930	24	31–72	20.3–21.5	8–19	3–5
Oil palm	0.7–1.55	150–500	–	17–25	0.5–3.2	80–248	2	60–65	–	11–29	–
Palf	0.8–1.6	20–80	900–1500	1.6–14.5	1.44–82.5	180–1627	35	70–83	–	5–12.7	–
Ramie	1.0–1.55	20–80	900–1200	1.2–40	24.5–128	400–1000	60	68.6–85	13–16.7	0.5–0.7	1.9
Sisal	1.33–1.5	8–200	900	2–7	9–38	363–700	17	60–78	10–14.2	8–14	10

4 Improvement of Durability of Vegetable Fibre-Cement Mortar Composites

Alkaline pore solution within the cement matrix has been reported to be the major cause of degradation of vegetable fibres leading to a reduction in their durability, subsequently resulting into untimely failure of the cement composite [43]. It is therefore imperative that the durability issues surrounding vegetable fibers as reinforcement in cement composites be urgently addressed so that they could be widely accepted for use in various applications.

Three methods have been identified:

(1) Fibre impregnation with blocking agents and water-repellent agents
(2) Fibre treatment with alkaline and acidic chemicals, coating agents and hornification process
(3) Cement matrix modification.

(1) **Fibre impregnation with blocking agents and water-repellent agents**

The findings of [16] on the treatment of a vegetable fibre with sodium sulphite, sodium silicate, barium, sulfite salts, magnesium sulfate, iron and copper compounds showed that noticeable effect on the durability of the fibre reinforced cement composite was achieved with the blocking agents used. In the same study also, the adoption of water repellent additives which include PVA, rubber latex, formine and stearic acid, amide wax, tar, asphalt, silicon and oil were used to impregnate the vegetable fibre. The results indicated that only reactions from the interactions of formine and stearic acid with the vegetable fibres resulted into significant reduction in fibre embrittlement of the cement composites.

(2) **Fibre treatment with acidic, alkaline chemicals and coating agents**

The most widely accepted and used acid for vegetable fibre treatment is the sulphuric acid because of its economic and environmental advantages. However, other acids that could be used include fluoridric and chloridric acids [7].

The report of durability studies performed on some vegetable fibers such as sugar and coir fibres used as reinforcement in concrete samples by subjecting them to sulphuric acids revealed that, mass and compressive strength losses are determined by the type of vegetable fibre used as reinforcement. Coir fibre reinforced cement composite recorded 14, 22 and 28% losses in mass after 30 days, 1 and 2 years immersion in the acid while sugarcane fibre concrete suffered losses of 14.5, 23.5 and 30.8% after similar duration of immersion in the same medium [37].

Some common alkaline chemicals used are sodium hydroxide, lithium hydroxide, calcium hydroxide, hydrogen peroxide, potassium hydroxide and ammonia. Of all these chemicals, sodium hydroxide is commonly used to treat vegetable fibers. As seen in Fig. 3, sodium hydroxide alters the orientation of highly packed crystalline cellulose order and forming an amorphous region thereby providing more access

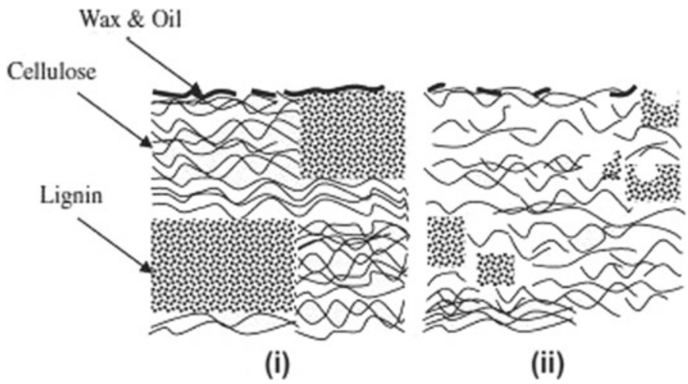

Fig. 3 Arrangement of (i) raw and (ii) treated fibre [18]

for penetration of the chemicals [18]. The investigations conducted by [41] on the assessment of durability of coir and sisal fibre reinforced cement composites revealed that more loss of durability was obtained from immersion in the calcium hydroxide compared with that from sodium hydroxide solution. For sodium hydroxide's effect on durability of the vegetable fibre cement composites, 70% of the original strength was retained after immersion in the solution for 420 days while after 300 days immersion in calcium hydroxide, a significant loss in strength was reported by the authors.

Coating involves the process of improving the surface of the vegetable fibre either by dipping, brushing or immersion in agents capable of forming thin layers of water-resistant films on the fibre surface. Some of the methods that have been used include silane coating and polymer coating of vegetable fibre reinforced cement composites. The coating method also assists in enhancing the interface between the matrix and the fibre thereby creating a stability and improved adhesion of the vegetable fibers to the cement-mortar matrix [9]. In a study by [9] it was concluded that 6% weight of silane is capable of reducing water absorption potential of vegetable fibers, hence improving the durability.

Hornification is also known as wetting and drying cycles which is recommended to be done prior to inclusion of vegetable fibre in cement composites. This process helps to improve the dimensional stability while reducing the possibility of fibre mineralization from $Ca(OH)_2$ on the fibre surface [17]. Claramunt et al. [11] reported that 20 and 13% higher enhanced compressive and flexural strength after 4 wet and dry cycles were obtained from previously hornified kraft pulp fibres on comparison with untreated fibre reinforced cement composites

(3) **Matrix modification**

For matrix modification, polymer based materials and pozzolanic materials have been suggested by some authors to improve the cement mortar in the composite prior to vegetable fibre inclusion.

The use of polymer chemical admixtures help to improve the bonding between the vegetable fibers and it is usually accompanied by a decrease of permeability due to low porosity [36]. The low porosity is caused by the development of thin films within the polymers which is capable of effectively blocking the pores developed during cement hydration. Hence, movement of moisture and heat which are elements majorly responsible for degradation through the pores are significantly reduced. A study by [3] on the durability of vegetable fibers with polymer modified cement matrix showed enhanced dimensional stability after 50 numbers of wet and dry cycles. As reported by the authors, this improvement was caused by the limitations imposed on the pores/voids during the cycles which resulted into enhanced microstructural network of the cement composite. The polymer admixtures also facilitated the reduction of interfacial debonding at the transition zone which ultimately improved the compactness of the vegetable fibre-cement matrix.

Modification with pozzolanic materials such as fly ash, blast furnace slag and silica fume etc. have been reported to improve the durability of the composite as well by reducing the calcium hydroxide which is responsible for the formation of alkaline environment that degrades the vegetable fibers [13]. Due to the high pozzolanic activities attached to their reaction in the matrix, they are capable of effectively consuming the formed calcium hydroxide within the cement matrix thereby enhancing the durability of the vegetable fibre cement composites [24, 39].

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