A Further Milestone to the Use of Natural Fibres in Concrete – Past Findings, Barriers and Novel Research Avenues

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Abstract. Concrete as a building material is much appraised for its good compressive strength; however, its low tensile strength makes it a quasi-brittle material. Experiments have proven that fibres such as steel and some polymeric fibres can reinforce and enhance the mechanical strength of concrete. The relatively high production cost of these fibres coupled with environmental issues for their end of life disposal and decline in mechanical strength beyond a certain fibre fraction have encouraged the use of natural fibres; particularly due to their renewability, low cost and good tensile strength. This paper reviews published literature in the field of natural fibres, their extraction methods as well as their effect on the mechanical properties of concrete. Alkaline fibre treatment to improve strength, wettability and subsequently, fibre-concrete matrix interfacial adhesion has also been discussed. As part of the research, the current authors have found that by just using untreated (raw) fibres as reinforcement in fact leads to a decline between 75% and 90% in compressive strength tested at 8 days for 2 different fibre lengths and volume fractions, respectively. This decline in strength could be co-related with the phenomenon of fibre agglomeration as seen from microscopic analysis. As such, fibre treatment, to remove different impurities from its surface, constitutes an important step towards the manufacture of natural fibre-reinforced concrete. Furthermore, water adjustment in relation to the total water requirement of the cement, aggregates and water needed to saturate the plant fibres is an important property that requires proper control since water content has a direct impact on the workability of the concrete and can turn into a major constraint. The main challenge of the use of natural fibres in concrete is its degradation with time within the highly alkaline concrete environment. Accelerated ageing experiments for natural fibres in concrete as described in literature have confirmed this deleterious occurrence. Thus, as per findings from the current experimental works and literature, the following recommendations are proposed: natural fibre pre-processing to inhibit agglomeration, adequate water addition to cater for all the constituents of the reinforced concrete and the potential implementation of biomimicry to solve the fibre degradation problem.
1. Introduction

1.1 Concrete as a structural material
The construction industry heavily relies on the use of concrete for structural works ranging from residential dwellings to infrastructural developments owing to its prominent use for foundations’ laying, slab casting, beams, masonry units and load-bearing components whereby concrete mix have been modified in accordance to certain structural needs and specifications. For instance, concrete structures are made to resist cyclonic conditions in tropical regions, mainly Small Developing Islands (SIDS) with the Mauritian context in focus while some countries would require concrete that is able to withstand freeze-thawing weathering conditions. Basically, there are 2 types of concrete: ready-mixed concrete and precast concrete. Ready-mixed concrete accounts for nearly 75% of all concrete types [1] and it can be recognized in trucks with revolving drums. Precast concrete products such as concrete bricks, masonry units and bridge girders are processed in a factory setting following which the concrete products undergo pertinent quality control [2].

Nowadays, it has become much pertinent for engineers to design materials that conform to technical requirements as well as take into account the profitability and sustainability aspects in the foreseeable future. For instance, the engineering requirement for a standard concrete slab, stipulates that a thickness of 4 inches is needed in residential construction with the minimum achievable strength of 3.45 MPa. A thickness of 5 to 6 inches is permissible if the concrete receives occasional heavy loads, such as garbage trucks. Since water in the concrete mix increases the liability of cracking and shrinkage, steel reinforcement may be used that will control crack propagation; ensuring good structural behaviour of the concrete slabs [3]. Furthermore, as per BS EN 772-1:2000, for a masonry unit containing frogs (of a net loaded area of more than 35% of the bed face) without the capping requirement, the expected compressive strength should be no less than 10 MPa at a constant loading rate of 0.05 MPa/s, with the corresponding lowest crushing strength of any individual block not be less than 2.8MPa.

1.2 The use of synthetic fibres in concrete
Despite being a load bearing entity, plain concrete has not befitted all structural engineering purposes. Concrete is termed as a quasi-brittle material as per Słowik [4] since its tensile strength is much lower than its compressive strength. This feature can result in reduced durability and even cause abrupt failures of improperly designed concrete structures due to rapid crack initiation and propagation [5]. To overcome this material behaviour, reinforcement synthetic fibres that are strong in tension are rooted into the concrete. These fibres allow for more distributed cracks with a smaller opening that enhances durability [6]; turning the concrete into a homogeneous and isotropic material [7]. Synthetic fibres for use in concrete are categorised under: (1) Type 1 (monofilament, < 0.3 mm in diameter); and (2) Type 2 (macro synthetic, > 0.3 mm in diameter) [8]. Besides the extensive use of steel fibres as one class of synthetic fibres, polymeric fibres are also commercially used in concrete; mainly classified as polyamides, polyolefins and polyacrylonitrile [9]. These polymeric fibres include but do not restrict to polypropylene, polyethylene, acrylic, nylon, and Aramid [10-11]. As per Talikoti and Kandekar [12], concrete cubes have been prepared with a double wrapping of aramid fibres with impressive compressive strength results that improved by 140%.

1.3 Underlying reasons for the use of natural fibres
At the actual standpoint, our global economy is day by day inclining towards a circular economic pattern. The construction industry is not excluded through the emergence of sustainable housing and circular design in building envelopes. The highly energy and resource intensive production process of synthetic fibres and toxic releases to the atmosphere during their processing and at incineration at the end of their service life [13-14] have majorly impeded their use due to the high carbon footprints of these products. Technical issues with their use in concrete add up to this burden. Zhang et al. [15] investigated aramid microfiber up to 1.5% volume fraction in concrete; revealing that 0.5% fibre fraction was able to
marginally increase the compressive strength and the elastic modulus of the composite. Beyond 0.5% fibre fraction, a decline in these properties were noted. Ward et al. [16] investigated low strength acrylic micro fibres in concrete for compressive, flexural and splitting tensile strengths. The authors found that pre-crack strength factors were all increased, besides compressive strength, which was slightly decreased. In the light of reviewed literature, synthetic fibre processing is found to be detrimental and researchers are pointing out adverse property changes. Thus, there is an urgent need to shift towards sustainable options with the requisite mechanical properties. Among the numerous types of fibres, natural fibres are receiving increased interest for use in concrete owing to traits like availability, cost-effectiveness, satisfactory physical and mechanical properties along with having the potential of extracting the natural fibres from plants that are agricultural wastes.

The idea of using natural fibres in a brittle milieu was first noted with the ancient Egyptians, dating back to 1500 B.C., who used animals’ hair and straw as reinforcement for mud bricks and walls in residential dwellings [17]. Nowadays, natural fibres have crossed boundaries into various sectors such as the non-woven and modern textile industries, pharmaceutical and medical industry [18, 19-26]. Amongst the most widely used natural fibres; banana, coir, pineapple, bamboo, sisal, flax and hemp fibres have found much significance [27-29]. The various fibres have been split into three main class groups arranged according to their morphological structure, namely: (a) bast fibres, (b) leaf fibres, and (c) seed hair fibres [9, 30-32]. Several authors have investigated different fibre extraction methods such as water retting, mechanical decortication, chemical retting, enzyme treatment and steam heat treatment in order to optimize on fibre yield without damaging the extracted fibres. Onuaguluchi and Banthia [33] reported that bast fibres are normally extracted from the retting procedure owing to the long fibre bundles with high tensile strength as the typical attribute of these fibres. Mukhopadhyay and Bhattacharjee [34] proposed that banana fibres, a typical bast fibre be longitudinal sliced from the pseudostems and fed to a fibre extracting machine. With regards to leaf fibres, they are classified as stiff and coarse fibres of relatively high tensile strength. Sarah et al [35] extracted pineapple fibres (leaf fibre) through an optimum semi-mechanical system involving a combination of mechanical decortication system and a chemical retting process. Among the seed fibre, that are typically lightweight and robust fibres, Salit [32] used water retting for a prolonged period and mechanical extraction as the main extraction methods.

With natural fibres, as a class of bio-materials that are competing towards a greener future, it should however, be noted that despite the fibre extraction methods proposed - with every coming technological era, some gaps have not yet been bridged. For instance, most papers have mainly focused on properties such that fibre strength, density and fineness. Nevertheless, an underpinning aspect being the fibre yield has seldom been analysed. Nowadays, a trader will prioritize the use of a plant yielding fibres as a by-product (agro-waste) rather than destroying an ornamental plant for its fibres. The location, ambient temperature, air humidity content of the place of fibre extraction and the method of fibre storage might have significant contributions which is still unclear in literature. The following checklist has been devised as an attempt to provide the reader a comprehensive approach of some treatment methods and few criteria that is a basis towards sustainable stewardship (Table 1).
Table 1. Checklist for fibre extraction [36-39]

| Extraction methods | Mechanical Extraction | Chemical Retting | Water Retting | Enzyme treatment | Steam heat treatment |
|---------------------|-----------------------|------------------|---------------|------------------|---------------------|
| Criteria            |                       |                  |               |                  |                     |
| High fibre yield    | ✓                     |                  |               |                  |                     |
| Least fibre damage/High fibre quality | ✓ | ✓ | ✓ | ✓ | ✓ |
| Minimal chemicals use | ✓ |                  |               |                  |                     |
| Minimal hazardous disposal of waste following extraction | ✓ |                  |               |                  |                     |
| Least labour Intensive |                   |                  |               |                  | ✓                   |

2. Fibres and their use in concrete

2.1 Review of certain mechanical characteristics of natural fibres in concrete:
Natural fibres from all the 3 categories of fibres have been commercially used in concrete. From the bast fibre category, research on banana fibres in concrete has been extensively carried out [34, 40-41]. Among the leaf fibres, sisal is one of the most important and widely used in concrete [42] while among from the seed and fruit fibres, coconut or coir is reported to be the most suitable for concrete [40]. In the same line, some commercial applications of natural fibres within the concrete environment include concrete masonry blocks reinforced with sugarcane bagasse [43], reinforced concrete beam using a natural fibre based composite plate through kenaf and jute rope fibres [44] and concrete slabs reinforced with coconut fibres [45] amongst others. Flax fibres has been on its part used in composite construction materials for reducing brittleness and as reinforcement for building materials to enhance stabilisation [46].

Research has demonstrated that natural fibres in concrete can, under definite conditions, improve its mechanical properties. Bamigboye et al. [47] reported on the use of concrete samples with coconut fibres at 0.5% fibre fraction, whereby the highest compressive strength was achieved from water treated coconut fibres at 28.71 N/mm² while plain concrete had a compressive strength value at around 24 N/mm². Chandel et al. [48] on his part found a rise of 12.71% in compressive strength when plain concrete has been reinforced with 1% by volume of coconut fibres. The difference in compressive strength may be attributed to the difference water content used by both authors as well as the ratio of cement: aggregates established. Chacko and Hema [40] reported an increase in the split tensile strength for both banana and coconut fibres reinforced concrete at 10% fibre content at both 7 and 28 days. Merta et al [49] analysed three types of cementitious composite for flexure containing flax, hemp and sea-grass fibres respectively; for which all fibre dosage was maintained at 1% by volume whereby the sea-grass reinforcement achieved the highest flexural strength. Merta and Tschegg [50] investigated on the use of hemp, wheat straw, and elephant grass at 0.19% fibre by weight and 40 mm length in concrete for determining the fracture energy of each natural fibre reinforced concrete sample. The most distinctive increase in fracture energy was observed by hemp fibre specimens at up to 70% increase while reinforcing concrete with straw and elephant grass fibres resulted in minimal fracture energy rise. The results showed that the presence of such fibres boosts the fracture energy of plain concrete such that cracks cannot extend without stretching and de-bonding the fibres.
2.2 Limitations with the use of natural fibres in concrete
Despite promising results for natural fibre reinforced concrete, few parameters still need in-depth study. The characteristics of any fibre reinforced concrete material is dependent on two material properties: aspect ratio and volume fraction of the fibres. In the same line, Kesavraman [41] tested banana fibre reinforced concrete and observed that both workability and compressive strength of the concrete specimens decreased beyond 0.5% fibre volume fraction. The same deductions were made by Mukhopadhyay and Bhattacharjee [34] who noted maximum compressive strength of banana fibre reinforced concrete at 0.3% fibre volume fraction while at 0.6% volume content, the strength decreased.

Furthermore, preliminary concrete casting performed by the current authors have observed a tendency for fibre agglomeration, as shown in figures 1 and 2, when using fibre beyond a critical length that consequently, inhibits strength development in the concrete. A preliminary test conducted on concrete cubes reinforced with raw (uncleaned) banana fibres showed a decrease in the compressive strength test results. At 0.3 and 0.5% fibre volume fractions and 20 and 40 mm fibre lengths, the compressive strengths were 75.1% and 90.1% lower than the reference plain concrete at 8 days. Through microscope analysis as shown in figures 3 and 4, the authors deduced that the uncleaned banana fibres prevented effective bonding and fibre agglomeration was observed around the aggregates in the concrete matrix. Thus, a basic fibre combing process prior to mixing the fibres into the concrete helps in the removal of the impurities and any residual wax from the fibres, thereby minimising the agglomeration phenomenon.

Water content in the reinforced concrete is a significant aspect that requires close monitoring. Since natural fibres are hydrophilic in nature, they draw water from the concrete. Thus, the correct proportion
of water has to be added to the concrete mix to cater for free water available for cement hydration, binded water in the aggregates to bring them to the saturated surface dry (SSD) conditions and water for the plant fibre absorption. The total water content in a concrete mix is thus, a vital parameter upon which the workability of the concrete is dependent on. A workable concrete is gauged in terms of slump value or Vebe time as the most practiced methods [51] and with natural fibres in the mix, this workability has to be monitored for the amount of water in the mix is varied in relation to the water absorbed by these organic fibres. Moreover, the mechanical behaviour of fibre reinforced concrete is rightly influenced by the size of aggregates, compaction factor and factors related to fibres; being volume of fibre addition, aspect ratio of fibres, fibre orientation and the relative fibre matrix stiffness.

2.3 The importance of fibre treatment in natural fibre reinforced concrete
In fibre reinforced concrete, interfacial bonding between concrete and fibre is vital towards achieving good mechanical properties. Wettability is a key factor that affects bonding. Poor fibre wetting can result into a non-homogenous compatibility of the fibres with their bonding matrix, stress concentration due to interfacial defects and subsequently result in inferior interfaces between the fibres and the matrix. [14, 52]. This results to issues such as poor stress transfer among fibres in a matrix, empty spaces and fibre debonding when loaded [53]. Moreover, almost all ligno-cellulosic natural fibres suffer from their hydrophilic nature and polarity mainly because of their chemical composition and structure due to which their degradation in any host environment is a major issue. Fibre treatment, aimed at refining the adhesion between the fibre surface and the matrix may not only modify the fibre surface but also increase fibre strength. The hydrophobicity of the fibres is enhanced and thus, water absorption of composites is reduced, and their mechanical properties are also enhanced [54]. Chemical treatments including alkali, silane, acetylation, benzoylation, isocyanates, permanganate amongst others are employed in natural fibre-reinforced composites as conventional methods [13-14, 54-56]. However, this review will only consider alkali treatment as the benchmark method since it is one of the most economical and most reported method in literature [57].

2.4 The mechanism of fibre alkaline treatment and relevance in concrete
Cellulose is regarded as the building block of a natural fibre structure and the effect of alkaline treatment on a plant fibre is a swelling reaction which causes a transformation in the natural crystalline structure of the cellulose. The type of alkali (KOH, LiOH, NaOH) and its dosage will impact on the degree of swelling and consequently, influence the degree of lattice transformation from cellulose I into cellulose II [58]. Basically, naturally occurring cellulose is known as cellulose I; existing in parallel strands without inter-sheet hydrogen bonding while cellulose II is a new crystalline structure that is thermodynamically more stable than cellulose I and exists in antiparallel strains with inter-sheet hydrogen bonding. The difference in properties of cellulose I and II occurs due to changes in crystal structure through fibre treatment [59]. NaOH can cause a complete lattice transformation from cellulose I to cellulose II, in contrast to other alkalis that produce only partial lattice transformation [58]. Through alkaline treatment, fibre surface roughness is promoted; enabling effective bonding of the fibre with the matrix. Fibre treatment allows for removal of lignin, hemicellulose, pectin and wax, together with parenchyma cells; up surging the contact area of exposed fibres, and as a result permits plausible adhesion of fibres and the matrix [47]. Chen et al. [60] corroborated the surface roughness phenomenon and further studied the wettability effects to deduce that bamboo fibres treated with low NaOH concentration had enhanced wettability with the reverse also true.

The benchmark for natural fibre treatment for use in polymer composites has typically been the improvement in terms of fibre tensile strength (TS). For instance, Li and Panigrahi [61] investigated on a sisal-polyester matrix composite with NaOH fibre treatments of 0.5%, 1%, 2%, 4% and 10% respectively with 4% treatment yielding the maximum TS. Kabir et al [56] had as basis of their findings that from different fibre treatment options, 8% NaOH treated fibre displayed superior mechanical
strength as compared with other treated and untreated fibre composites. As such, in concrete, compressive strength is one of the preponderant factors.

Zhou et al [62] analysed hemp fibres at 2% Ca(OH)2 treatment in concrete at 2% Ca(OH)2 fibre treatment with the treated fibre reinforced concrete having compressive strength that was 10 % higher than the untreated one at 28 days. As reported earlier, Bamigboye et al [47] carried out compressive strength test on coconut fibre that have undergone water treatment and 1% NaOH treatment. The alkaline treatment sample had compressive strength value at 27.61 N/mm2; merely 3.8% lesser than the water treated one. The reason for this decline might be due to inadequate optimization of the alkaline treatment of the fibre. It should be noted here that treated natural fibres have not been much employed in literature as far as concrete is concerned. Further experimental works should thus, be performed in this field of research to validate the results obtained by some authors.

3. Natural fibre degradation in concrete

3.1 Reported literature for natural fibre degradation in concrete

Natural fibre degradation as a result of environmental interactions or changes in the fibres itself is a major concern with the strong alkaline composition of concrete. [20]. Studies have shown that plant-based natural fibre reinforced cement composites are prone to cause natural fibre disintegration due to absorbed water in the fibres and the highly alkaline cement pore solution in the concrete [33,63-64]. One major deterioration cause of cellulosic fibres in cement composites is the dissolution of lignin and hemicellulose linking individual fibre cells by the alkaline pore solution [65]. Degradation is further intensified by alkaline hydrolysis induced de-polymerization of fibres, whereby linked glucose molecules are disrupted and molecular chain lengths are lessened [66]. Natural fibre disintegration in concrete has been investigated by several authors and the accelerated ageing through wetting and drying cycles has been established as a means to study the degradation mechanism.

Accordingly, backscattered images by Toledo et al. [65] and Savastano et al. [67] confirmed the transport of cement hydration products, mainly Ca(OH)2 within the lumen and void spaces of natural fibres during the accelerated aging test that showed fibre degradation in concrete and hence, progressively caused loss in mechanical strength of the reinforced concrete. Likewise, Kriker et al [68] investigated on the durability of male date palm surface fibres (MDPSF) immersed in three alkaline solutions: Ca(OH)2, NaOH and Lawrence solution. In addition, the durability of MDPSF as reinforcement in small scale concrete beams was also studied. The concrete specimens were cured for six months in two different ways: 28 days in water followed by curing in wet chamber; and 14 days in water followed by a hot dry environment. The results of the investigation have shown that MDPSF are easily attacked by the alkaline solutions under both curing conditions; indicating poor durability of MDPST-reinforced concrete.

3.2 Knowledge gap for natural fibres in the corrosive environments of concrete

The effect of cement pore solution on the degradation of natural fibres in concrete is foreseeable. In this perspective, researchers have worked on two avenues to mitigate this issue – fibre treatment or matrix alteration. There are still some issues to be addressed: how far can the accelerated ageing test/alternate wetting and drying cycles picture the actual degradation of natural fibres in a cementitious matrix or what is the time dependent distribution and correlation of the natural fibres? Thus, fibre durability needs to be well defined and furthermore, the broader picture of cement hydration to concrete carbonation need to be explicitly investigated within a concrete structure to the concrete structure. What might be of substantial help is the concept brought forward by Knill and Kennedy [69]; stipulating that the rate of natural fibre degradation depends on the crystallinity and fibrillar morphology of the cellulose contained in the fibres. Thus, degradation rate is slower with higher crystallinity of cellulose which opens up an avenue of research on fibres with high crystallinity indices. Furthermore, the implementation of biomimicry as a potential attempt to inhibit the degradation might also see light in the coming years.
Self-healing concrete, inspired from nature has already seen dawn with the self-repair of cracks in a concrete structure. The concept of self-healing concrete; inspired from nature has already seen dawn with the self-repair of cracks in a concrete structure. The cracks can be healed by using calcium carbonate precipitating micro-organisms that are embedded in the concrete matrix after immobilization on diatomaceous earth in microcapsules or in superabsorbent polymers (SAP), and will start the precipitation of CaCO$_3$ once a crack occurs [70].

4. Conclusions
With the exhaustive nature of synthetic fibres and plain fibres presenting with a few drawbacks, natural fibres’ use in concrete has shown a positive advancement in the recent years. With regards to fibre extraction, several methods have been designed as per the physical and technical properties of the different categories of fibres. Some promising results have been obtained from literature in terms of compressive strength, split tensile, flexural strength and fracture energy of natural fibre reinforced concrete. In the same vein, findings from the current authors depict fibre agglomeration and its hydrophilicity as a potential setback to obtaining good strength natural fibre reinforced concrete with reported compressive strength values at 75.1% and 90.1% lower than plain concrete cubes at 2 different fibre volume fractions. Thus, an initial fibre preparation phase before use in concrete is deemed important; including fibre combing, optimizing the appropriate fibre length and volume fraction and reviewing the water absorption potential of the natural fibre.

Furthermore, fibre alkaline treatment has been discussed for superior fibre mechanical strength and satisfactory fibre-matrix interfacial adhesion due to improved surface roughness and wettability. As such, one author observed that hemp fibre treated with 2% Ca(OH)$_2$ had improved compressive strength of the fibre reinforced concrete at 10% higher than the untreated one. However, the major concern of natural fibres in concrete remains its degradation in this highly alkaline matrix due to the incompetency of the fibres to resists the hydration products as observed by few authors during accelerated ageing tests. Fibre degradation is an inevitable phenomenon as the concrete ages which has been observed by the poor durability of male date palm surface fibres reinforced concrete subject to a cyclic wetting and drying condition for a period of 6 months. This impediment to scientific progress is quite alarming following which biomimicry has been pointed out as a potential option to combat this issue and bring -the construction industry to the next level of sustainable design.

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