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Secondary Natural Fibre-Reinforced Cementitious Composites: A Comprehensive Review

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ABSTRACT

Construction activities use millions of tonnes of conventional, non-renewable building materials and release 30% of the world's CO2 emissions. Green building materials that are easily accessible, affordable, renewable, recyclable, and thus sustainable should be promoted in order to reduce these issues. The use of waste from secondary natural fibre (SNF) as a biological replacement for synthetic fibre in cementitious composites is reviewed in this research in light of recent trends. The varieties and classification of SNF, as well as its chemical make-up and physical and mechanical characteristics, were highlighted in the article. This study also discussed the mechanical, thermal, and durability characteristics of secondary natural fibre cementitious composites (SNFRC), as well as ways to enhance the durability of SNF in cementitious composites and new trends and applications for SNFRC. The report offered various areas for more research in SNFRC as a conclusion.

1. Introduction

Secondary Natural Fibres (SNF) are fibres derived from plants, animals, and earth surfaces that are predominantly produced for their crops, fruits, meat, milk, and minerals, but also have by-products that create high-quality fibres. These sources include plants, animals, and earth surfaces. They mostly consist of plant, horticultural, and animal fibres as those found in coconuts, oil palms, pineapples, bananas, rice husks, maize cobs, sugarcane bagasse, pig and horse hair, cashmere, wool, basalt fibres, etc. As shown in Figure 1, Primary Natural Fibres PNF are not historically mined or grown for their fibre content, such as cotton, silk, jute, kenaf, sisal, kapok, or asbestos. When crops, fruits, and meat are harvested, secondary plants and animal fibres are typically thrown of as waste. Comparing the PNF, which is primarily grown for the purpose of producing fibre, to the SNF, which is more naturally produced, reveals additional benefits. Researchers have recently become quite interested in the use of secondary and primary natural fibres, also referred to as natural fibres, as a reinforcement of cement-based composites, concrete composites, and even polymeric composites.

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This is due to ongoing global efforts to promote the use of environmentally friendly and sustainable building and engineering materials [1, 2]. Due to this, research has shifted away from synthetic and non-renewable materials and toward natural and renewable ones [3].

The utilisation of secondary and primary fibres on cement-based materials is crucial for improving flexural strength, toughness, ductility, impact resistance, and crack resistance, according to Ardanuy *et al.,* [4]. The post-crack resilience of the concrete matrix is also increased by natural fibres in cement concrete. As the fibres join the matrix cracks and spread the loads, this is particularly advantageous. In order to ensure the durability of the concrete materials as well as an acceptable enough interfacial bond between the fibre and the matrix, natural fibres are therefore advantageous when used as a reinforcement in concrete.

SNF have additional advantages over PNF in comparison to the benefits discussed above the use of secondary and primary natural fibres in cementitious composites. These advantages included, among others: SNF are typically found as agricultural waste, such as coir fibre, rice husk or stalk, sugarcane bagasse, etc. Utilizing waste results in sustainable development because it reduces environmental pollution and overuse of natural fibres like cotton, jute, kenaf, and silk, which have a wide range of applications and uses in textiles, ropes, and bags. Referring to Table 1, secondary natural fibres have the dual benefit of converting trash into a green, sustainable building material in the form of fibre. This review primarily focuses on SNF as reinforcement for cement composites because of these added benefits.

The characteristics of SNF as reinforcement in cementitious composites are the foundation of this review of the literature. Types, classifications, and chemical composition were highlighted in the paper. SNF's mechanical and physical characteristics. A detailed discussion of ways to increase the durability property of secondary natural fibre in cementitious composites was included in the summary of the mechanical, thermal, and durability characteristics of SNFRC. The publication went on to discuss some recent developments in SNF, including the use of nanofibers, which are currently being investigated as reinforcement in cement-based composites [5, 6], as well as recent research on animal fibres such pig hair, wool, and horsehair. The usage of SNF in contemporary construction and engineering materials, including as walls, panels, masonry, and bricks, was also discussed. The paper's conclusion identified a number of knowledge gaps that call for additional research.

1.1 Primary and Secondary Natural Fibres

The two main categories of natural fibres are primary and secondary natural fibres. PNF refers to plant, animal, or mineral fibres that are intentionally grown or produced for the purpose of producing fibres, whereas SNF refers to plant, animal, or mineral fibres that are intentionally grown or produced for other purposes but still produce by-products that yield high-quality fibres. The majority of secondary fibres come from crops, fruits, leaves, grass, animals, and minerals, and their main use in production is to provide food for humans to eat like fruits, vegetables, meat, and milk. They still produce by-products, though, such high-quality fibres. Cocoanut fibre and empty fruit fibre from oil palm trees are two examples of fruit fibres. Banana and pineapple fibres are among the leaf fibres. Animal fibres include cashmere, mohair, goat hair, pig hair, camel hair, horse hair, etc. and grass or reed fibres include sugar cane bagasse, maize cob, etc. The many forms of SNF are further illustrated in Figure 1.

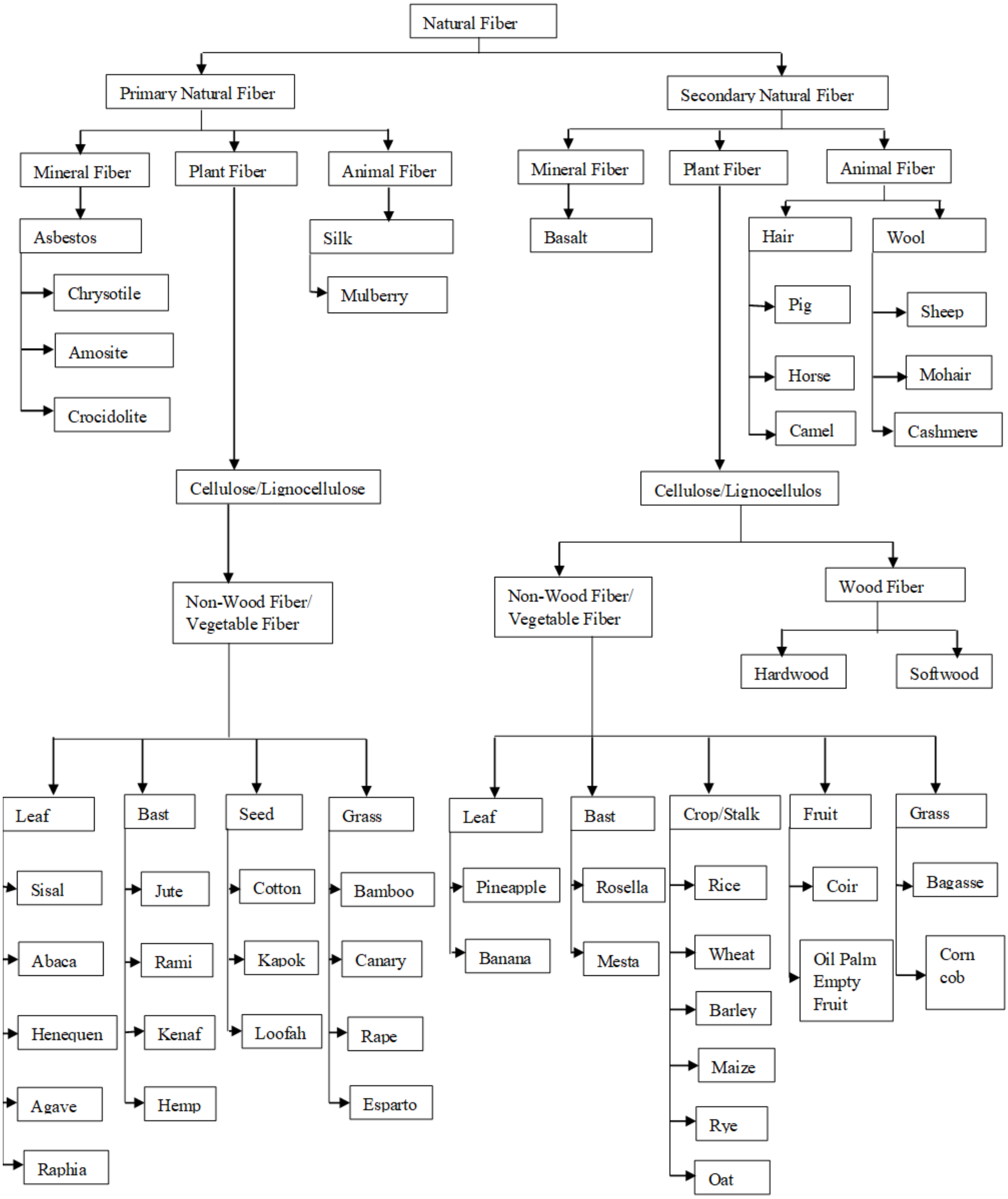

Fig. 1. Types of secondary and primary natural fibre

According to Figure 1, all crop and fruit fibres, such as coir and empty fruit fibre from oil palm trees, are respectively SNF. Likewise, all wood fibres are regarded as secondary fibres. In the opposite direction, basalt fibre is a secondary natural fibre, whereas mineral fibres like asbestos are PNFs. All animal fibers—aside from silk—are secondary fibres since they are intentionally raised for their flesh and milk. The benefits of using secondary natural fibres in construction and civil engineering composite materials over primary natural fibres are listed in Table 1. This study focuses on examining secondary natural fibres in cementitious composites because of the benefits listed in Table 1 of cementitious composites. Coir, oil palm empty fruit, sugarcane bagasse, corn cobs, rice and wheat stalks, maize and barley stalks, rosella bast, mesta bast, banana and pineapple leaves, hard and soft wood, pig and horse hair, and sheep and goat wool are some examples of common SNF in cementitious composites.

Table 1
Advantages of secondary natural fibres over primary natural fibres

S/No.	Secondary Natural Fibre	Primary Natural Fibre
1	Produced for their fruit, milk, meat, and crops, so they can be used twice.	Produced solely for the purpose of processing fibres; therefore, single use.
2	The majority of fibre is derived from plant waste, such as the fibre found in rice husks or stalks, corn cobs, coir, pig and horsehair, sheep wool, etc.	Fibre is obtained from the main crop, seeds, or stems of the plants, such as cotton, kapok, kenaf, ramie, jute, sisal, and other seeds.
3	Pollution is decreased by using waste plant fibre in composites.	Since the plant is primarily used for the manufacture of fibre, waste plant fibre is rarely generated or used.
4	The overuse of primarily natural fibres, which have numerous applications, is reduced by the use of secondary natural fibre in composites.	Primary natural fibres are overburdened when used in polymer and cement composites because they are widely used in the manufacturing of textiles, paper, bags, ropes, and other products.

1.2 Classification Based on Forms of Secondary Natural Fibre

In addition to being categorized based on their origin or sources, SNF can also be categorized depending on the production method or the forms in which they are employed as reinforcement in the composite matrix, according to Ardanuy *et al.,* [7]. Plant-based SNF are divided into three categories based on their forms: strands, staples, and pulp fibres. The pulp fibres are among these kinds that are most frequently utilized in NFRC.

1.2.1 Strand fibre

These are lengthy fibres, ranging in length from 200 to 1000 mm [8]. Strand fibres are made from domesticated or wild plants and animals, usually straight from the source. The majority of long plant fibre is produced via a process called water retting. This type of fibre consists of long animal fibres that have been cut directly from an animal's body as well as bast, leaf, and stalk fibres from plants.

1.2.2 Staple fibre

These are short fibres that can be spun into yarns that range in length from 10 to 200 mm. They are also produced using methods similar to those used to create strand fibres, either directly from plants or animals.

1.2.3 Pulp fibre

To separate these tiny fibres, which range in length from 1 to 10 mm, you should disseminate them in water [9]. Using pulping techniques, pulp fibres are mostly made from wood or vegetable secondary fibres. Thermal, chemical, mechanical, or a combination of these treatments can be used in the pulping process.

1.3 Composition, Mechanical and Physical Properties of Secondary Natural Fibres

The best way to discuss the chemical components of SNF is from two different angles. based on the distinction between animal- and plant-based SNF. Hemicellulose, cellulose, and lignin make up the majority of the plant-based SNF, with very little amounts of water, proteins, peptides, and inorganic substances. The most popular SNF in composites are those derived from plants. Some of the chemical components of the plant-based SNF are highlighted in Table 2. The chemical makeup of the fibres is influenced by factors such as the plant's origin, the environment in which it develops, its age, and the method used to extract the fibre [10-12]. As an illustration, pineapple fibre is soft but contains a lot of cellulose. Coconut fibre and oil palm empty fruit bunch fibre were made of stiff, rigid multicellular fibre with a lacuna in the middle. With a water content of 8–15%, plant-based fibres are hydrophilic in general due to the presence of cellulose and hemicellulose. Additionally, the lignin included in fibres serves as the cement holding all of the hard cells together [13]. The amount of lignin in a fibre affects how tough and robust it is. The morphology, structure, and characteristics of the fibre are impacted by this. As a result, plant fibres could be thought of as naturally occurring composites of cellulose fibrils that are bound together by lignin. These cellulose fibrils are organized along the length of the fibre, regardless of the source, such as the fruit, leaf, or stem [14]. The primary component of secondary natural fibre derived from animals is keratin, a type of protein. The keratin protein has a right-handed -helix-shaped peptide chain, which coils to create protofibrils. Protofibrils are piled to create intermediate filaments (IF), which are surrounded by an amorphous protein matrix. Disulfide bridges and cystines are abundant in matrix proteins. The crystalline phase of the fibre is made up mostly of helical components (25–30%), whereas the amorphous phase is made up of the matrix, nuclear waste, cell membranes, etc. The cuticle, cortical, and medullary cells that make up most of the hair fibre are shielded by a cell membrane complex that binds the hair cells together. Characterizing the fibre is challenging since animal-based secondary natural fibres have variable constituents [15]. The physical and mechanical characteristics of each individual fibre are determined by their chemical compositions, as was previously mentioned [16]. The physical and mechanical characteristics of a few popular secondary natural fibres that have already been the subject of research are summarized in Table 3. The table shows that natural fibres' physical and mechanical characteristics vary depending on aspects like the way they are processed, the environment as a whole, the makeup of the fibres, etc. Natural fibres' physical characteristics, such as length, diameter, and aspect ratio, are valued highly because they can accurately anticipate the fibre’s strength. Consequently, applicable to deciding which kind of fibre could be used for a specific purpose.

Table 2
Chemical Composition of Secondary Natural Fibre

References	Fibre Source	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractive (%)	Ash (%)
Jawaid & Abdul Khalil [9]	Coir Fibre - Fruit	32 - 43	0.15 – 0.25	40 – 45	-	-
Onuaguluchi & Banthia [12]	Coir Fibre - Fruit	21.46	12.36	46.48	8.77	1.05
Onuaguluchi & Banthia [12], Pacheco-Torgal & Jalali [13]	Coconut tissue - Fruit	31.05	19.22	29.7	1.74	8.39
Jawaid & Abdul Khalil [9]	Oil Palm EFB - Fruit	65.0	-	29.0	-	-

Jawaid & Abdul Khalil [9]	Oil Palm EFB - Fruit	65.0	-	19	-	2.0
Jawaid & Abdul Khalil [9]	Oil Palm Frond - Fruit	56.04	27.51	20.48	4.40	2.4
Jawaid & Abdul Khalil [9]	Oil Palm Frond - Fruit	56.01	27.51	20.5	4.5	2.4
Jawaid & Abdul Khalil [9]	Wheat Straw – Crop	38 – 45	15 – 31	12 – 20	-	-
Onuaguluchi & Banthia [12]	Wheat Straw – Crop	33 – 38	26 – 32	17 – 19		6.8
Jiang, Cui, Xu, & Tuo [10]	Wheat Straw – Crop	42.10	20.31	17.53		11.19
Jawaid & Abdul Khalil [9]	Rice Straw – Crop	41 – 57	33	8 – 19	8 – 39	-
Onuaguluchi & Banthia [12]	Rice Straw – Crop	28 – 36	23 – 28	12 – 14	-	14 – 20
Jiang, Cui, Xu, & Tuo [10]	Rice Straw – Crop	39.27	23.14	17.35	14.97	15.35
Jawaid & Abdul Khalil [9]	Rice Husk - Crop	35 – 45	19.25	20	-	14 – 17
Onuaguluchi & Banthia [12]	Barley - Crop	31 – 43	27 – 39	14 – 19	-	2 – 7
Onuaguluchi & Banthia [12]	Corn Stove – Crop	38 – 40	28	7 – 21	-	3.6 – 7
Jawaid & Abdul Khalil [9]	Bagasse – Grass/Reed	55.2	16.8	25.3	-	-
Onuaguluchi & Banthia [12]	Bagasse – Grass/Reed	32 – 48	19 – 24	23 – 32	4.0	3.5
Pacheco-Torgal & Jalali [13]	Bagasse – Grass/Reed	41.7	28.00	21.8	4.0	3.5
Pacheco-Torgal & Jalali [13]	Banana Trunk – Fruit	31.48	14.98	15.07 – 18.6	4.46 – 10.6	8.65
Jawaid & Abdul Khalil [9]	Banana Trunk – Fruit	60 - 65	19	5 – 10	4.6	-
Onuaguluchi & Banthia [12] ; Pacheco-Torgal & Jalali [13]	Banana Leaf – Leaf	25.65	17.04	24.84	9.84	7.02
Abdul Khalil *et.,* [17]	Pineapple Leaf – Leaf	81	-	12.7	5.5	2.0
Mishra *et al.,* [11]	Pineapple Leaf – Leaf	70 - 82	18.0	5 – 12	-	0.7 – 0.9
Jawaid & Abdul Khalil [9] ; Abdul Khalil *et al.* [17]	Hardwood – Wood	31 – 64	25 – 40	14 – 34	0.1 – 7.7	< 1
Jawaid & Abdul Khalil [9]	Softwood – Wood	30 – 60	20 – 30	21 – 37	0.2 – 8.5	< 1
Onuaguluchi & Banthia [12] ; Pacheco-Torgal & Jalali [13]	Eucalyptus – Wood	41.57	32.56	25.4	8.2	0.22

Table 3
Physical and Mechanical Property of Secondary Natural Fibre

References	Fibre Type/Source	Length (mm)	Diameter (mm)	Aspect Ratio (L/Dia)	Density (g/cm^3)	Tensile Strength (MPa)	Young Modulus (GPa)	Elongation at break (%)
Onuaguluchi & Banthia [12] ;	Coir - Fruit	-	-	-	1.17/1.2	95 – 75	4 – 6	30

Pacheco-Torgal & Jalali [13]								
Islam, Hussain, & Morshed [18], Pickering *et al.,* [19], Sanjay *et al.,* [20]	Coir - Fruit	20 – 150	0.15 – 0.44	-	1.2	105 – 252	4 – 6	15 – 40
Sanjay *et al.,* [20]	Oil Palm EFB – Fruit	-	0.15 – 0.50	-	0.7 – 1.55	80 – 248	0.5 – 3.2	17 – 25
Ardanuy *et al.,* [4]	Wheat - Crop	1.238	0.345	4	-	-	-	-
Ardanuy *et al.,* [4]	Bagasse – Grass	1.303	0.348	4	-	-	-	-
Wang *et al.,* [21]	Bagasse – Grass/Reed	-	-	-	1.2	20 – 290	19.7 – 27.1	1.1
Ardanuy *et al.,* [4]; Pacheco-Torgal & Jalali [13]	Banana - Fruit	-	-	-	1.031	384	20 – 51	-
Jawaid & Abdul Khalil [9] ; Wang *et al.,* [21]	Banana - Fruit	-	-	-	1.35	355	33.8	53
Wang *et al.,* [21]	PALF - Leaf	-	-	-	1.5	170 – 1627	82	1 – 3
Onuaguluchi & Banthia [12]	PALF- Leaf	-	-	-	0.8 – 1.6	400 - 627	1.44	14.5
Mishra *et al.,* [11] ; Sanjay *et al.,* [20]	PALF- Leaf	-	20 – 80	-	-	413 – 1627 34.5	34.5 – 82.5	1.6
Nunna *et al.,* [22]	Rosella - Bast	-	-	-	800 – 750	170 – 350	17	-
Pacheco-Torgal & Jalali [13]	Date Palm - Fruit	-	-	-	1300 – 1450	70 – 170	2.5 - 4	-
Nunna *et al.,* [22]	Date Palm - Fruit	-	-	-	463	125 – 200	70	-
Sanjay *et al.,* [20]	Softwood- Wood	-	-	-	1.5	1000	40	4.4
Ardanuy *et al.,* [4]	Eucalyptus- Wood	0.66	0.0109	61	-	-	-	-
Pickering *et al.,* [19] ; Sanjay *et al.,* [20]	Wool - Animal	38 – 153	-	-	1.3	50 – 315	2.3 – 5	25 – 35
Pickering *et al.,* [19]	Feather - Bird	10 – 30	-	-	0.9	100 – 203	3 – 10	-
Jawaid & Abdul Khalil [9]	E -Glass	-	<1.7	-	2.5	2000 – 3500	70.0	2.5 – 3.5
Jawaid & Abdul Khalil [9]	S-Glass	-	<1.7	-	2.5	4570	86	2.8
Sanjay *et al.,* [20]	Carbon (std)	-	0.082	1.4	1.82	2550 - 4000	200	1.3
Pacheco-Torgal & Jalali [13]	Polypropylene	-	-	-	913	250	2.0	-

2. Secondary Natural Fibre Reinforced Cementitious Composites

Hydraulic cement in concrete is used to create fibre reinforced cementitious composites, which have discrete fibres dispersed throughout the matrix [23]. Cement, mortar, and concrete composites with discrete secondary natural fibre scattered throughout the matrix are what is meant by secondary natural fibre reinforced cementitious composites. As a result, the term "SNFRC" refers generally to cement paste, mortar, and concrete composites that contain secondary natural fibre in their matrix.

2.1 Composite's Production/Manufacturing Methods

The manufacture of fibre for use as reinforcement in cementitious matrix involves several distinct types of techniques, which are listed and succinctly described as follows: One Hatschek process is the slurry vacuum de-watering method. (2) Aligned fibres procedures, extrusion technique, cast-in-place mix methodology, dewatering with pressure technology, and aligned fibrous sheets.

2.1.1 Hatschek process

Hatschek was the first to patent this process in 1900. The Hatcheck method is the most common one that researchers use to produce pulp fibre. The procedure consists of a three-phase, continuous process. The three stages are sheet formation, board formation, and curing. Sheet formation is the first of the three. To generate a thin sheet that is about 1 mm thick, it is necessary to use a vacuum system to remove a sizeable amount of the mixing water from the slurry. The thin sheet left over from the previous operation is then used to produce boards. The sheets were rolled up in consecutive layers of the desired thickness using a sizable cylinder. After being sliced, this is placed in a press where it will be crushed and moulded into the desired board shape. The completed board is now being sent for curing. The Hatschek process with air-curing technology can contribute to valorizing the hemp core and corn stalks when they are cooked by an organosolv process without significantly affecting the process or product quality, provided that only a portion of commercial cellulosic fibers are replaced by organosolv pulp.

2.1.2 The extrusion method

A laboratory de-airing ceramic extruder is used in this technique. This machinery permits the production of flat specimens with typical dimensions of 60 mm in width and 8 mm in thickness. The technique improved the extruder's capacity for reinforcing while enabling very good fibre orientation. Diverse and high-performing extruded products are anticipated to offer a solid foundation for the future expansion of wood fibre cement in conventional and emerging markets. As an alternative to the traditional wet and dry techniques of wood fibre cement manufacture, the extrusion method, which is widely used in the ceramic and plastics sectors possesses desirable qualities. Extrusion involves forcing an extremely viscous plastic mixture through a shaped die.

2.1.3 Cast-in-place mix method

Additionally, short strand fibres and pulp/short fibre processing are the main applications for this technique. This process involves mixing the pulp fibre with 50% water and plasticizer to ensure fibre homogeneity before adding cement and any additional aggregates. Then, the mixing continues until the mixture is homogeneous. Typically, a cast-in-place method is used to produce bicontinuous composites with superior mechanical properties and overall performance. However, the fabrication of an interconnected porous skeleton appears tedious and inefficient.

2.1.4 Aligned long strand method

This technique is mostly relevant to the processing of pulp and short fibres as well as short strand fibres. In this procedure, the pulp fibre is first blended with 50% water and plasticizer to ensure fibre consistency, and then cement and any additional aggregates are added to the mixture. Once the mixture is homogeneous, the mixing process is completed. It allows the manufacture of tow or tape type prepregs with highly aligned reinforcements directly from short fibres rather than from pre-existing tows.

2.1.5 Aligned fibrous sheet method

Perforated sheet formed of pulp fibres is used in this technique. With this technique, a mortar mixture made of sand, cement, and water is first created, then placed to the mould and vibrated to the proper consistency. The fibre sheet is then put in place, and it is lightly tamped. The last coat of mortar is then placed, being cautious to keep the fibre sheet straight. Based on the given number of levels, this process may continue up to many layers. Due to the alignment, the process produces composite products with enhanced physical qualities. To produce composites with regulated microstructure and qualities, the fibres might be of varying lengths and a mixture of different types. The composite materials may be nonwoven, discontinuous, fiber-reinforced thermoplastic sheets with controlled fibre orientation distribution.

2.2 Mechanical Properties of Secondary Natural Fibre Cementitious Composites

This technique makes use of perforated paper formed of pulp fibres. In this technique, the mortar mixture is made first from water, cement, and sand before being put to the mould and vibrated to the right amount. The fibre sheet is then positioned and lightly tamped. After that, the final mortar layer is placed, being careful to keep the fibre sheet straight. Depending on how many layers are requested to be used, this process may continue up to many levels.

Table 3
Mechanical Property of Secondary Natural Fibre Reinforced Composites SNFRC

Fibre Type/Concrete type	% Fibre Addition	Method of Processing	Compressive Strength (N/mm^2)	Flexural Strength (MPa)	Elastic Modulus (GPa)	Impact Energy (J)	References
Plain Conc./control	0%	Cast in Place	24.3	1.0	-		Islam *et al.,* [18]
Steel Fibre	1% /Cwt	-	14.4	2.0	-		
Coir Fibre	1%/Cwt	-	18.3	1.6	-		
Plain Conc./control	0%	Cast in Place	34.7	4.34	33.10		Ali *et al.,* [24]
CFRC – 5cm	2%/Cwt	-	43.2	4.01	32.15		
CFRC – 5cm	5%/Cwt	-	36.2	4.46	29.28		

Plain Conc./control	0%	Cast in Place	40.76	-	-		Vajje & Krishna murthy [25]
Basalt Fibre	1%/Cwt	-	42.53	-	-		
Banana Fibre	1%/Cwt	-	40.44	-	-		
Pineapple Fibre	1%/Cwt	-	38.22	-	-		
Plain Conc./control 4PB	0%/Cwt	Cast in Place	-	9.8	-		Yan *et al.,* [26]
CFRC- 4PB	1% /Cwt	-	-	11.2	-		
2LFFRP-PC	0%	-	-	23.2	-		
2LFFRP-CFRC	1%/Cwt	-	-	35.6	-		
4LFFRP-CFRC	1%/Cwt	-	-	47.5	-		
6LFFRP-CFRC	1%/Cwt	-	-	55.8	-		
Plain conc./control	0%	Cast in Place	21.25	4.09	-		Naik *et al.,* [27]
Horse hair	2%/Cwt	-	24.72	4.26	-		
Plain conc./control	0%	Cast in Place	34.07	-	-		Wang & Chouw [28]
Coir-CFRC-25	1.5%/Cwt	-	33.98	-	-		
Coir-CFRC-50	1.5%/Cwt	-	32.18	-	-		
Coir-CFRC-75	1.5%/Cwt	-	32.07	-	-		
Plain Mortar/control	0%	Cast in Place	-	-	-	13.98 J	Ramakrishna & Sundararajan [29]
Sisal-40mm	2% Cwt	-	-	-	-	121.16J	
Coir-40mm	2% Cwt	-	-	-	-	253.5J	
Jute-40mm	2% Cwt	-	-	-	-	68.02J	
Hemp-40mm	2% Cwt	-	-	-	-	64.31J	
Plain mortar/control	0%	Cast in Place	40.3	5.7	-	-	Andiç-Çakir *et al.,* [30]
Untreated CF	0.75%/tw	-	50.0	6.5	-	-	
Treated CF	0.75%/tw	-	50.2	6.8	-	-	
Comp. earth Brick CEB	0%	Cast in Place + CEB mach.	3.84MPa	0.56	-	-	Mostafa & Uddin [31]
Plain Mortar/control	0%	Cast in Place	65	5.2	6.8	-	Hwang *et al.,* [32]
Plain Mortar/control	0%	Cast in Place	78	8.5	-	-	Araya-Letelier *et al.,* [33]

Plain Foam Mortar	0%	Cast in Place	6.5	3.3	0.93	-	Iman *et al.,* [34]
CFRFC	0.1%/tvol	-	7.0	3.5	0.96	-	
CFRFC	0.2%/tvol	-	8.1	3.8	1.01	-	
CFRFC	0.3%/tvol	-	8.1	4.5	1.53	-	
Plain Cement Paste	0%	Vacuum Dewatering	-	11.8	-	-	Savastano *et al.,* [35]
P-Radiata-PR 12	12%/Cwt	-	-	25.0	-	-	
Sisal- S12	12%/Cwt	-	-	20.3	-	-	
Banana- B12	12%/Cwt	-	-	20.1	-	-	
Plain Cement paste	0%	Cast in Place	66	5.9	-	-	Bentchikou *et al.,* [36]
Recycle paper	2%/Cwt	-	43	6.5	-	-	
Recycle paper	4%/Cwt	-	40	6.9	-	-	

The mechanical characteristics of steel fibre and coir fibre were compared in research [18]. There were two types of concrete created (Concrete of normal strength-NSC and concrete of high strength-HSC). The analysis's findings demonstrated that both NSC and HSC coir fibre composites' workability and compressive strength have decreased. The flexural strength, ductility, and toughness of concrete have improved for both NSC and HSC, nevertheless. Ali *et al.,* [24] conducted a similar study on the mechanical and physical characteristics of reinforced concrete with coir fibres. The study's findings show that composites made of coir fibres with higher fibre percentages had higher damping ratios, but lower static and dynamic ratios. It also demonstrates that composites with 5% added fibre and 5 cm coir fibres produce the greatest outcomes [37]. In a different study [25], it was determined how inorganic and organic fibre differed in their qualities. The natural fibres jute, sisal, hemp, banana, and pineapple were compared to basalt fibre. According to the study's findings, the mix's workability decreased as its fibre concentration increased as a result of the fibres' ability to absorb water. Additionally, the results showed that, compared to the control, cube and cylinder fibre reinforced concrete composites with inorganic and other organic fibres outperform it in terms of compressive strength. Additionally, the results imply that as fibre concentration increases, the compressive strength and young modulus of both organic and inorganic fibres decrease. Ayub *et al.,* [38] studied on the mechanical characteristics of concrete reinforced with basalt fibres reported their research findings. Analysis reveals that adding 2% fibre to a mineral admixture improves the compressive strength of the composites while having a minor effect on elastic modulus. The flexural and durability characteristics of coconut fibre reinforced concrete composites (CFRC), which were externally reinforced using flax fibre reinforced poxy polymer, were examined by Yan *et al.,* (FFRP). The study's findings show that the addition of coir fibre significantly boosts the strength, energy, and load of the composites. In proportion to the increase in FFRP layers, the maximum force, deflection, and fracture energy of plain concrete and CFRC composites have all risen. Similar research was conducted by Wang and Chouw [28] to determine the impact load characteristics of Coir Fibre Reinforced Concrete (CFRC). The production and testing of identical 200mm x 100mm cylinders of plain concrete PC and CFRC under varying impact loading. The dynamic impact factor DIF of CFRC is mostly unaffected by the length of the fibre, according to the study's findings for single impact testing. While results from repeated impact tests indicate that the maximum compressive stresses of CFRC-25, CFRC-50, and CFRC-75 in terms of mortar cement composites rise with increasing impact height, several researchers looked into different mechanical properties of SNFRC. Starting with Ramakrishna & Sundararajan's [29] study, which contrasted the impact strength of four (4) natural fibres in composite cement mortars.

The study's findings show that, in terms of the three impact indicators, coir fibre reinforced mortar outperforms sisal, jute, and cannebinus. Studies have also shown that adding fibres to cement mortar increases the mortar's impact resistance by a factor of 4- 18 when compared to a plain mortar mixture. Andiç-akir *et al.,* [30] examined the characteristics of coir reinforced mortar in a related investigation. The study's findings demonstrate that adding untreated fibre to concrete improves the mortar composites' mechanical strength, water absorption, and thermal conductivity when compared to the control. When treated coir fibre is utilized instead of untreated coir fibre, the benefits of enhanced strength, toughness, water absorption, and thermal property improve more. Crushed dune sand was used in place of some of the cement in reinforced mortar made using date palm fibres (CDS). The study's findings show that date palm fibre reinforced composites' mechanical properties decreased when more cement was replaced with CDS. Date palm fibres added to CDS cement boost flexural strength while decreasing compressive strength in tandem [39]. A study on secondary natural fibre reinforced mortar was conducted by Lertwattanaruk and Suntijitto [40]. The SNF used in the study is made up of oil palm fibre and coir fibre that are added at levels of 5%, 10%, and 15% and are chopped into lengths of 5 to 10 mm. The investigation's findings show that adding SNF to composites causes a decrease in both compressive and flexural strengths. However, composites can be used as thermal insulating sheets because their heat conductivity is reduced by 60%. The composites mix with up to 15% fibre addition to cement weight produced the best mechanical and physical properties. Short coir fibre was appropriately washed and boiled before being added to the composites in a recent study by Hwang *et al.,* [32] to assess the impact of short coir fibre on the impact resistance, plastic cracking, and mechanical performance of mortar composites. Three different water to cement ratios (0.3, 0.35, and 0.45) were used, and four different percentages of volume fibre inclusions (0%, 1%, 2.5%, and 4%) were used. To increase the resilience of the composites, fly ash (FA) and ground granulated blast furnace slag (GGBFS) were also added. The study's findings indicate that increasing the amount of fibre used and the W/B ratio causes a reduction in compressive strength and an increase in moisture absorption in mortar composites. As the fibre to mortar ratio increases from 0-4%, the 28-day modulus of rupture and flexural strength both increases, from 5.2 to 7.4 MPa and 6.8 to 8.8 MPa, respectively. The addition of coir fibre to mortar composite enhances the mix's durability, first deflection of fracture resistance, and impact resistance. The characteristics of compressed earthen brick reinforced with banana stem fibre were researched by Mostafa and Uddin [31]. Clay cement, aggregate, sand, and waste fibre from bananas were used to create the compressed earth brick, or CEB. In accordance with ASTM C67-07, a block specimen having nominal dimensions of 120 mm by 120 mm by 90 mm was tested under uniaxial compression. Compressed earth bricks were made using various mixtures with fibre lengths ranging from 0mm to 50mm, 60mm to 70mm to 80mm to 90mm and 100mm. The study's findings demonstrate that B-CEB with 60mm and 70mm fibre provides the best compressive strength. The performance of this fibre reinforced CEB is superior to ordinary CEB. Results of flexural strength and rupture modulus for B-CEB demonstrate a significant improvement over the plain CEB. Recent research was done to evaluate the effectiveness of coir fibre in reinforcing plaster mortar composite [41]. The study's findings show that as the percentage of coir fibre addition increases, post-crack parameters including ductility, residual strength, and toughness improve significantly, but flexural and compressive strength decrease. The mechanical properties of lightweight foam mortar LFM reinforced with coir fibre were examined in a related research project on foam concrete. The study's findings demonstrate that increasing the percentage of fibre content led to an equivalent increase in the elastic modulus, tensile strength, and compressive strength of the LFM composites. Recently, Zanichelli *et al.,* [42] looked into the mortar fracture toughness of LFM reinforced with date palm fibre. The study's findings show that an increase in the amount of date palm fibre added to the composite does not result in a proportional increase in peak load or fracture toughness. With a rise in the fibre content of the date palm fibre reinforced composites, there is a commensurate improvement in the ductility of the composites compared to the control plain samples as well as a delay in the failure of the composites. In a study on high-performance concrete reinforced with coconut fibre, the ductility, young modulus, and ultrasonic pulse velocity were examined [43]. In contrast to the subsequent two mixes, which feature a pozzolanic replacement with PFA and SF replacing 10% of the cement content in the mix, the initial concrete mix was a simple high-performance concrete with no pozzolanas. The study's findings demonstrate that CNFR-PFAC performs better in all three mixtures in terms of youthful modulus and ultrasonic pulse velocity test.

2.3 Thermal Property

On the thermal characteristics of SNFRC for use as insulating materials in buildings, numerous research projects have been undertaken. Onesippe *et al.,* [44].'s investigation looked on the use of natural bagasse fibres as insulators in structures. An organisation that produces sugar cane provided bagasse as a trash. Then, it receives two different types of therapies. The BAGP process involves pyrolyzing fibre at 200°C for two hours. Alkaline therapy known as BAGB contains 5% $Ca(OH)2$. Findings show that composites constructed with alkaline-treated bagasse fibres perform better than composites created with pyrolyzed bagasse fibres in terms of thermal conductivity and specific heat. In a related study, Bentchikou *et al.,* [36] investigated how recycled cellulose fibre affected the characteristics of lightweight cement composites. The study's findings indicate that as fibre addition increases, mechanical characteristics drop. While the thermal characteristics improve with further fibre insertion. As a result, it is advised that the material be used as an insulating partition walling unit, as well as for ceiling and roofing purposes. The physical and mechanical characteristics of coir fibre reinforced mortar were researched by Andiç-Akir *et al.,* [30]. The results show that adding fibre to the mortar mix also enhances its thermal characteristics. A study looked at the properties of cement mortar reinforced with oil palm and coconut fibre for use in walling units. According to the study's findings, fibre cement products with combinations containing up to 15% of both natural fibres and binder by weight have the right mechanical and physical qualities. The heat conductivity of the fibre reinforced sheet is also 60% less than the control. Recent research by Cardinale *et al.,* [45] examined the thermal and mechanical characteristics of masonry reinforced with sheep wool. The study's findings show that as the amount of fibre insertion increases, flexural and compressive strength decreases. However, the value of thermal conductivity also decreases as the amount of fibre inclusion grows, indicating that the thermal performance of composites improves as the amount of fibre addition increases.

2.4 Durability Property

Numerous research projects have been conducted to determine the SNFRC's durability constraint in terms of its durability qualities. The ageing mechanism of cellulose fibre reinforced composites has been studied [46]. The study compared cellulose fibre reinforced composites produced commercially to cellulose pulp fibre studied in a lab under two different accelerated ageing regimes. The experiment's results demonstrate how a combination of accelerated ageing in a CO_2 atmosphere and natural weathering can impair the cement matrix's capacity to absorb water and nitrogen as well as its porosity. While the freeze-thaw simulation is ineffective, the artificial carbonation test is more effective in simulating the artificial ageing of cellulose FRC made of cement. The determination of NFRC fatigue and fracture was the subject of a study [35]. Materials made of cement composites were created in four batches. The study's findings indicate that compared to ordinary unreinforced cement paste, which has a fracture toughness between 0.2 and 0.3MPa, blast furnace slag and OPC paste reinforced with natural fibre have fracture toughness values between 0.6 and 1.9MPa. The eucalyptus, sisal, and banana fibre reinforced composites' intrinsic toughness was estimated to be between 1.2 and 1.4 MPa, which accurately reflects the specimen's actual independent fracture strength. The outcome also shows that composites reinforced with sisal and banana exhibited stable rising R-curve behaviour, which is equivalent to stable fatigue crack growth resistance, as opposed to composites reinforced with waste pulp from eucalyptus grandis, which had only minimal fracture and fatigue resistance to crack growth. The durability and mechanical properties of a mortar reinforced with date palm fibre were investigated by Ozerkan et al. [47]. Date palm fibres had two different treatments with alkali pellets. For two hours, mix NaOH and $Ca(OH)_2$ at 0.175%. According to research findings, 0.175% $Ca(OH)_2$ treatment of bundle date palm fibre outperforms 0.175% NaOH treatment. Additionally, research demonstrates that adding palm fibre to mortar increases flexural strength and sulphate resistance while lowering compressive strength. In a related investigation, the toughness and strength of concrete with coir fibre reinforcement that was exposed to a harsh environment were assessed (Ramli et al., 2013). Fiber inclusion of 0.6%, 1.2%, 1.8%, and 2.4% by binder volume was used to create high strength coir reinforced concrete. According to the study's findings, adding more fibre enhances both compressive and flexural strength. In a similar vein, fibre content increases with an increase in chloride penetration, intrinsic permeability, and carbonation depth. The study's findings imply that adding coir fibre to high strength concrete enhances its mechanical properties. However, the dose of coconut fibre should be kept to a minimum to prevent the detrimental effect of cellulose fibre degradation in the alkaline cement matrix. The durability of synthetic and natural fibre in foam concrete with a density of 1000 kg/m3 was compared in the study (Awang and Ahmad, 2014). The study included a variety of synthetic and natural fibres, such as kenaf (KF), oil palm (OPF), steel (SF), polypropylene (PF), and AR-glass (GF). According to the study's findings, kenaf, AR-glass, and oil palm fibre all displayed more water absorption than the control whereas steel and polypropylene fibre showed very low water absorption in compared to the control. Findings also suggest that, in comparison to the plain control FC, all the fibres contribute to lowering the rate of drying shrinkage. The strength and mechanical properties of flax fibre non-woven reinforced cement composites were investigated in a distinct research project [48]. According to research findings, treated flax non-woven composites perform better than untreated composites in terms of mechanical properties and durability. Pozzolanas are added, which lowers the matrix's $Ca(OH)_2$ content and raises the compressive and flexural strengths of the composites at 28 and 56 days, respectively. The research on the thermal characteristics of secondary natural fibre reinforced composites is described in Table 5.

Table 4
Thermal properties of Secondary Natural Fibre Reinforced Composites SNFRC

Fibre Type/ Composite Type	% of fibre	Curing age (day)	Thermal conductivity (w/mk)	Specific Heat Capacity (J/g.k)	Thermal Diffusivity ($kx10^6xm^2s^{-1}$)	References
Mortar + Silica fume +paper pulp +bentonite + Polymer	0%	365	0.6188	0.27	1.1771	Onésippe *et al.,* [44]
Bagasse B	1.5%/Cwt	365	0.62	0.25	1.5504	
Bagasse P	1.5%/Cwt	365	0.50	0.23	1.5856	
Bagasse B-CBAG B Alkaline treated	3%/Cwt	365	0.47	0.22	1.3114	
Bagasse P-CBAG Pyrolysis treated	3%/Cwt	365	0.46	0.20	1.4228	
Plain cement paste/Control	0%/Cwt	28	1.35	990 (J/kg.oC)	-	Bentchikou *et al.,* [36]
Waste paper cellulose	4%/Cwt	28	1.05	1030 (J/kg.oC)	-	
	8%/Cwt	28	-	1060	-	
	10%/Cwt	28	0.65	1080	-	
	16%/Cwt	28	0.27	1110	-	
Plain Mortar/Control	0%	28	1.800	-	-	Andiç-Çakir *et al.,* [30]
Coir fibre	0.4%/tw	28	1.676	-	-	
Coir fibre	0.6%/tw	28	1.709	-	-	
Coir fibre	0.75%/wt	28	1.767	-	-	
Plain Mortar/control	0%	28	0.68	-	-	Lertwattanaruk & Suntijitto [40]
5% Coir fibre	5%/Cwt	28	0.41	-	-	
5% OPEF fibre	5%/Cwt	28	0.40	-	-	
10% Coir fibre	10%/Cwt	28	0.38	-	-	
10% OPEF fibre	10%/Cwt	28	0.30	-	-	
15% Coir fibre	15%/Cwt	28	0.37	-	-	
15% OPEF fibre	15%/Cwt	28	0.27	-	-	
Plain mortar/control	0%	28	0.381 (W/m^2k)	-	-	Cardinale *et al.,* [45]
Sheep wool fibre	2%/Cwt	28	0.288	-	-	
Sheep wool fibre	5%/Cwt	28	0.138	-	-	
Sheep wool fibre	7%/Cwt	28	0.107	-	-	
Dry wall panel	drywall	28	0.187	-	-	

3. Recent Trends in SNFRC

The research efforts on the most popular SNFRC—primarily secondary plant-based natural fibres (cellulose and lignocellulose fibres) or secondary wood and vegetable natural fibers—have been the focus of this review thus far. The most extensive study has been done on and practical application of these fibre kinds. Scholars have recently been working on a lot of fascinating research projects involving SNF made from animal wastes like hair and wool. Researchers in cementitious composites are advancing their work on nanofibres in addition to animal fibre (nanocrystals and nanofibrils). This section reviews some of the most recent developments in secondary animal fibres and nanofibers.

3.1 Secondary Animal Fibres

As was previously said, research into using animal fibres like hair and wool to enhance the qualities of cementitious materials is unusual. There aren't many recorded research initiatives in this area. This may be explained by the fact that wool has been utilized for garments in most temperate settings despite being a secondary fibre. Although traditionally, it was claimed that horsehair and wool fibre were used in the creation of mud, clay, or bricks to lessen crack in conventional ancient buildings. On the characteristics of these composites, there is little technical or scientific research. Recently, nevertheless, several experts have started looking at the characteristics of wool and hair fibre in building materials.

The ability of wool fibre to fracture and absorb energy in a clay matrix was determined through research [49]. Sardinia, Italy provided the inorganic clay soil that was employed in this study, which is traditionally used in the construction of bricks. The results also show that the composite has a greater post-fracture response at higher deformation regimes the longer the fibre. The performance of horsehair in concrete was examined by Naik *et al.,* [27] in their study on the qualities of horsehair in concrete materials. Three different percentages of fibre were added to cement by weight: 1%, 2%, and 3%. The study's findings show that increasing the proportion of horsehair added to the matrix improves both compressive and flexural strength. Rahman *et al.,* [50] conducted a comparative investigation on the characteristics of cement composites enhanced with horsehair and kenaf fibre as part of a related research project. In comparison to kenaf fibre, the researchers discovered that horsehair recorded greater flexural and compressive strength in the mortar composites. Additionally, kenaf fibre reinforced composite mortar had a higher water absorption rate than horsehair fibre reinforced composite mortar. As compared to the control, the result reveals that as the amount of fibre grows, flexural strength improves while compressive strength decreases as the amount of fibre content increases. On the characteristics of cement mortar with wool fibre reinforcement, recent study has also been described [51]. According to the researchers' final findings, mortar composites reinforced with both treated and untreated fibre exhibit improved flexural and ductility properties when compared to plain mortar. Additionally, the addition of 1% of treated or untreated wool fibre results in a 23% or 18% increase in flexure and a 300% increase in fracture toughness, respectively. Researchers looked at the characteristics of mortar made using sheep wool as a fibre addition in a study that was comparable to the one they conducted on the thermo-mechanical properties of sheep wool fibre reinforced mortar [45]. Sheep wool from unspun waste mattresses was used in this investigation. According to the study's findings, adding more fibre to the wool mortar composite resulted in a corresponding decline in its mechanical performance but improved its ability to insulate heat. Additionally, it has been discovered that 2% of the cement's weight is the ideal percentage for fibre inclusion. In a recent study project, the characteristics of pig hair fibre reinforced mortar were investigated [5]. Pig hair fibre inclusion rates used by the researchers are 0% and 2% by cement weight. The study's findings show that the composites' elastic modulus, porosity, compressive strength, and flexural strength are not significantly different from the control. But compared to controls, pig hair reinforced composites' impact strength significantly increases.

3.2 Secondary Nanocellulose

Recent scientific studies have a tendency to concentrate on nanomaterials and technology. Therefore, it is not surprising that nanocellulose-based composite materials are increasingly using cellulosic natural fibres. The usage of nanofibres in composites is currently receiving a lot of attention from researchers studying composite materials. According to reports, synthetic natural fibres with mechanical and durability capabilities similar to those of cement-based composites, such as polyvinyl alcohol and carbon nanofiber microfibres, are synthetic natural fibres [52].

In light of the aforementioned, processing and research on nanocellulose from natural sources in concrete composites. From cellulose, nano-cellulose is produced. In turn, the majority of commercial cellulose is made from either hardwood or softwood wood fibres. They can also be obtained from plant fibres including banana, hemp, sisal, jute, pineapple, coir, empty fruit bunches from oil palm trees, rice husk, and others. Nanocellulose is the smallest cellulose particle with at least one nanoscale dimension (1-100 nm). They can be divided into two main categories, cellulose nanocrystals (CNCs), also known as cellulose whiskers, and cellulose nanofibrils (CNFs), also known as nano fibrillated cellulose (NFC), or micro fibrillated cellulose (MFC). Researchers working on natural fibre reinforced composites have recently expressed a strong interest in nanocellulose fibres and have published studies on the various techniques used to produce and process cellulose nanofibrils [17].

Using secondary nanocellulose, a small number of research professionals in the field of cement-based fibre reinforced composites conducted study and reported fascinating discoveries. Three distinct extraction techniques for nanocellulose fibres from Eucalyptus kraft pulps were the subject of a study [53]. Refining, sonification, and acid hydrolysis were the techniques used. The study's findings show that the amount of nanofibres produced throughout the refining process was quite little. The cellulose structures of the whiskers were harmed by acid hydrolysis. However, out of the three techniques, sonification was the most successful. When mortar composites reinforced with nanofabrillated cellulose were compared to mortar reinforced with traditional sisal cellulose fibre, Ardanuy *et al.,* [4] looked at the durability property (wet/dry cycle). After five cycles of wet and dry curing and seven days in water, the specimen was evaluated. According to the study's findings, nanocellulose-reinforced composites have greater flexural modulus and strength but less fracture energy than sisal-reinforced composites. The durability of nanocellulose fibre reinforced composite did not significantly improve. The properties of nanofibre reinforced cement composites have been studied and published [12]. The energy absorption and flexural strength of 0.1% nanofibre paste increased by 106% and 184%, respectively, in comparison to the control, according to the researchers.

Therefore, at 0.1% fibre inclusion, the nanofibre paste composites operate at their best. The researchers created a bacterial nanocellulose reinforced fibre cementitious composite as part of a related research project [54]. The paper examines the mechanical effectiveness of Bacteria Nano Cellulose (BNC) used in three different forms on bagasse fibre cement composites: gel, powder, and coating. Results indicate BNC Coated fibre was enhanced with hydration products, which improved the cement contact and stopped the fibre from mineralizing. The impact of raw and sonicated cellulose nanocrystals CNCs on the characteristics of cement paste microstructure was examined by Cao *et al.,* [55]. The bulk of CNCs (94%) are absorbed, according to the findings (aCNC). The number of aCNCs is not decreased by sonification. Recent research efforts compared cement composites reinforced with 9 percent pulp produced by the extrusion process to hybrid composites reinforced with 8 percent pulp and 1 percent Nano fibrillated cellulose [56]. In order to monitor the degradation of the fibres, the cement-based composite was also put through 200 cycles of wetting and drying to accelerate ageing. The researchers came to the conclusion that the mechanical performance of the nano-fibrillated cellulose composite is superior to that of the composites without nanofibre. After accelerated ageing, composites with or without nanofibres showed no degradation in their mechanical characteristics.

4. Conclusion

The goal of green construction and the promotion of sustainability have recently attracted a lot of study interest. Only when more environmentally friendly building materials like SNR are used in place of synthetic fibres will sustainability be attained. Although this is a good endeavour, there are many issues with the durability of these fibres in cementitious composites. Even though many mitigation techniques for treating or changing these fibre surfaces' alkaline matrix in cementitious composites have been researched. There is still much to be done in these areas to promote the use of green SNF instead of synthetic fibre. This is as a result of its wide range of uses in structures as an insulating material for wall cladding, panels, plaster, and masonry. Therefore, the use of SNF, also known as waste natural fibre, to replace synthetic fibres such as steel, carbon, polypropylene, etc. in concrete, mortar, and cement composite has drawn a lot of attention. Waste natural fibre includes items like coir, pineapple, banana, rice husk/stalk, sugar cane bagasse, oil palm empty fruit fibres, basalt fibres, etc. However, despite the wide variety of SNFs accessible, only a few number have been explored by researchers. Among these few fibres studied include coir, oil palm fibre, sugar cane bagasse fibre, wood fibre, flax, pig hair, horsehair, and wool fibre. There is a need or gap for research and documentation on the characteristics of various plant fibres, including wheat, barley, and oat stalks; some stem fibres, including rosella and mesta; and some animal fibres, including camel, rabbit, goat, cow, and human hair.

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