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Recent Advances in the Use of Cellulosic Polymers for Enhancing Concrete Performance: A Comprehensive Review

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Abstract

Cellulose, the most prevalent biopolymer on Earth, has proven to be an effective multifunctional material for enhancing the performance of concrete and other cement-based products. The current review analyzes recent developments in the application of cellulosic polymers in concrete and cement composites, including microcrystalline cellulose (MCC), cellulose nanofibrils (CNF/NFC), cellulose nanocrystals (CNC), carboxymethyl cellulose (CMC), and hydroxypropyl methylcellulose (HPMC). Special attention is paid to their interfacial interactions with cement hydration products, modes of incorporation, and impact on the properties of fresh concrete and performance of hardened materials (mechanical performance, transport properties, durability, etc.). According to published data, the addition of CNF in an amount of approximately 0.1 wt. % results in a 106% enhancement of flexural strength and a 184% increase in energy absorption capacity. Meanwhile, the flexural strength was enhanced by CNC (approximately 0.2 vol. %) by approximately 30%. Ultra-high-performance concrete containing nanocellulose experienced a 45-75% reduction in autogenous shrinkage in the initial 24 h. Nevertheless, the effects and signs of these improvements are strongly determined by the cellulose structure, dosage, surface chemistry, dispersion quality, consumption of water, cement formulation, and other parameters, which must be controlled because excessive amounts of cellulose and its improper dispersion could negatively influence the workability, hydration process, and strength development. In addition, potential drawbacks such as agglomeration, requirement for high energy input for dispersion, incompatibility with certain chemical admixtures, durability under aggressive environments, and other factors are considered in this review.

Keywords: Cellulosic Polymers; Nanocellulose; Mechanical Strength; Sustainable Construction.

1. Introduction

The use of cellulosic polymers in concrete technology is a breakthrough approach in the field of material science. There is an increasing research focus on utilizing cellulose, which is one of the largest natural polymers available in the world, for improving concrete properties. Owing to its ability to reinforce concrete and its sustainability in nature because of its availability in plant cell walls, cellulose helps in making the structure durable and sustainable at the same time. This unique property makes this compound useful in an era where engineering needs to be conducted in eco-friendly ways; hence, this thorough analysis [1, 2].

The use of concrete as the material of choice in today's construction industry persists because of its robustness, strength, and flexibility of application. Being the fundamental component of construction on a global scale, concrete supports buildings and their structures [3, 4]. Nevertheless, concrete is a porous material that is prone to permeation, frost damage, and corrosion owing to its vulnerability to various climatic factors. These problems have become an object of discussion recently, as concrete has become more popular, and researchers now tend to look at the effects of polymer additives on its properties and economy [2, 5, 6]. Moreover, with the development of energy-efficient and sustainable structures as well as novel construction materials, this topic has gained importance [7, 8, 9].

Cellulosic polymers belong to a group of biopolymer materials based on cellulose, which is an unbranched polymer composed of β-D-glucose subunits located within the cell walls of plants.

Their sustainable origin and good mechanical properties render cellulosic polymers suitable construction materials. Cellulosic polymers include microcrystalline cellulose, nanocellulose, and derivatives soluble in water, such as carboxymethyl cellulose (CMC), whose broad range of applicability testifies to their versatile nature [10, 11]. Within the scope of concrete, cellulosic materials serve as fillers and reinforcement agents that increase the durability of the material while fostering sustainable development through the use of a sustainable source of cellulose, such as agricultural residues [1]. Cement-based materials also have great potential in terms of the utilization of cellulose-based additives, as their morphology and surface chemistry can be manipulated in such a way that they affect reinforcement, water retention, hydration, and rheology upon dispersion in the matrix [12].

The reasons behind the incorporation of cellulose polymers in concrete are sustainable and functional. Cellulose, a polymer present in abundance in nature, is a sustainable option, as synthetic polymers usually cause environmental pollution. Cellulose, being a strong polymer, makes it possible to enhance the strength of composite materials, whereas bottom-up and top-down approaches make micro- and nanocellulose suitable for use in cement matrices [1, 2].

This review provides a critical analysis of new developments in the utilization of cellulosic polymers to improve concrete behavior. The topics covered include the chemical and physical attributes of cellulose that can affect cement-based materials, means of introducing the material, impact of addition on concrete in its fresh and hardened states, and recent innovations in this field. What is unique about this study is that all the quantitative data are arranged into tables that allow comparisons across studies.

This study was divided into six parts. The second part describes the chemical and physical aspects of cellulosic polymers in relation to concrete. The third part discusses various techniques for incorporating cellulosic polymers and their effects on the workability and microstructure. The fourth part highlights the effect of cellulosic polymers on the mechanical strength, durability, and transport properties. The fifth part discusses the latest developments in this field of technology and application.

The literature used for this review was selected from Scopus, Web of Science, ScienceDirect, and Google Scholar databases using various keywords such as “cellulose concrete,” “cellulosic polymers cement,” “cellulose nanofibrils cement,” “cellulose nanocrystals cement,” “nanocellulose cementitious materials,” “cellulose fiber concrete,” “carboxymethyl cellulose concrete,” and “hydroxypropyl methylcellulose concrete.” The search mostly involved peer-reviewed articles published between 2010 and 2026, especially those written after 2020. Articles that directly addressed cement paste, mortar, concrete, ultra-high-performance concrete, pervious concrete, or other cement-based composites made with cellulose material and reported quantitative data on dosing, workability, strength, durability, or sustainability were selected for inclusion. Articles devoted exclusively to non-cement applications of cellulose, including food packaging, agriculture, batteries, furniture, and polymer composites, but not cementitious composites, were rejected. Review papers were used to track research trends and select key references, while quantitative data for comparison tables were obtained primarily from primary experimental papers. Owing to the huge heterogeneity in cellulose form, dosing basis, mixing method, cement mixture, curing, and testing procedures, the evidence was analyzed qualitatively but not quantitatively with meta-analysis.

Earlier reviews have offered informative assessments of nanocellulose in cement materials and cellulosic fiber-reinforced cement composites. Nevertheless, these reviews tend to focus only on one type of material: cellulose nanofibrils or cellulose nanocrystals, or simply consider cellulose among other natural fibers or bio-based composites. This review presents an application-oriented approach that considers microcrystalline cellulose (MCC), cellulose nanofibrils/nanofibrillated cellulose (CNF/NFC), cellulose nanocrystals (CNC), carboxymethyl cellulose (CMC), and hydroxypropyl methylcellulose (HPMC) in cementitious materials.

The core point of this review is the systematic comparison of the above cellulose-based materials in terms of their role, usage range, method of preparation and dispersion, impact on the state under fresh conditions, hydration process, mechanical performance, transport characteristics, and durability. Unlike other reviews, which mostly highlight the beneficial effects of these additives, this study examines not only the advantages, but also the disadvantages, namely agglomeration, increased water requirement, changes in rheological properties, change in setting time, admixture incompatibility, uncertainty of long-term durability, and scaling up problems. Finally, the performance of the additives is evaluated from environmental and economic perspectives through life cycle analysis and costs per unit of mechanical performance.

Table 1. Principal cellulosic polymers used in concrete: Role, dosage, and best reported effect.

Polymer	Primary role in concrete	Optimal dosage	Best reported effect	Practical limitations and implementation challenges	Source
MCC	Rigid filler; rheology modifier	1% wt.	Yield stress +190%	May substantially increase the yield stress and reduce workability at higher dosages. Its relatively low aspect ratio limits its reinforcing efficiency compared to CNF and CNC. A uniform distribution is required to avoid local stiffening of the mixture.	[13]
CNF / NFC	High-aspect-ratio reinforcement	0.1% wt.	Flexural +106%	Highly hydrophilic and prone to agglomeration. May increase water demand and viscosity and require controlled dispersion, often through high-shear mixing, sonication, or compatible superplasticizers. An excessive dosage can adversely affect workability and strength.	[14]
CNC	Stiff nano-reinforcement; nucleation	0.2% vol.	Flexural +30%	Relatively high production costs and sensitivity to particle surface chemistry, cement composition, and admixture compatibility. The effect on hydration and strength can vary when the dispersion is inadequate or the dosage exceeds the optimum level.	[13, 15]
CMC	Water-retention agent; set retarder	0.1–1% wt.	Viscosity up to 2520 cP	It can markedly delay setting and may reduce early age strength at high dosages. Excessive viscosity may hinder mixing and placement, whereas entrapped air or poor compatibility with other admixtures can reduce the performance.	[11]
HPMC	Viscosity modifier; anti-bleeding	0.3–0.4% wt.	Bleeding <1%	May prolong the setting time and reduce the early strength when overdosed. Increased viscosity can reduce flowability and may require adjustment of the superplasticizer dosage and mixing sequence.	[16]

On the other hand, Table 1 focuses on the functionality and well-known effects of each polymer, whereas the physical properties of the polymers in terms of size, crystallization, modulus, and strength are shown in Table 2. For example, the mechanical benefit is associated with a dosage of 0.1% NFC, which resulted in 106% and 184% enhancement of flexural strength and energy absorption in cement paste [14], respectively, and with a dosage of 0.2% volume CNC, in which the flexural strength increased by approximately 30% [15]. As mentioned before, water-soluble polymers affect the water and rheological performance much more than reinforcement; for instance, the viscosity of carboxymethyl cellulose can reach up to approximately 2520 cP, and it significantly increases setting times from 160/320 min (initial/final) to 706/783 min at 4% dosage [11].

2. Chemical and Physical Properties of Cellulosic Polymers Relevant to Concrete

The chemical and physical attributes of lignocellulosic polymers play a significant role in their interaction with cement systems. Cellulose is a very distinctive substance that can undergo many modifications because of its distinctive structure, and the high crystallization degree of cellulose nanofibrils makes them very strong; thus, when properly introduced, tensile strength can be imparted into the concrete matrix [19]. There are a large number of hydroxyl groups in cellulose that allow the formation of hydrogen bonds with the cement matrix [1].

Cellulose is a linear polymer of β-D-glucose repeating units joined via β-1,4-glycosidic bonds, whose extensive hydrogen bonding leads to a highly crystalline organization that lends cellulose high stability and mechanical performance. The derivatives, particularly cellulose nanofibrils and nanocrystals, have nanometric sizes and exceptional mechanical performance, attributed to their crystallinity. The hydroxyl groups on the surfaces of these materials make them excellent candidates for functional modification, such as surface/interface engineering, with respect to specific applications [19, 20, 21]. Functionalization allows the development of specific composites capable of enhancing the physical and mechanical performance of concrete [5]. The hydroxyl groups on the surface of cellulose can play a role in interface engineering and affect the dispersion, hydration, and interactions of cellulose nanomaterials with hydrated cement products [25–27].

Cellulosic polymers establish good interactions with water molecules, which can be utilized to improve hydration. The addition of these polymers results in enhanced water retention capacity and therefore reduces the risk of failure due to rapid drying by ensuring adequate moisture content in the mixture, thus extending its life span. Water-soluble cellulose polymers, including hydroxypropyl methylcellulose, exhibit effectiveness in the adsorption of water molecules from mixtures to retain mixed water. They are useful in improving water retention and reducing bleeding, cracking, and workability; however, a high dosage may result in a reduced hydration process [16]. Cellulosic hydrogels are perfect examples of such polymers [24].

Environmental concerns regarding petrochemical synthetic materials have prompted the search for alternative biodegradable solutions. Cellulose, which is sourced from readily available lignocellulosic biomass, represents a sustainable approach for boosting concrete performance in an environmentally friendly manner. Regarding the utilization of cellulose in cementitious systems, the environmental significance of cellulose must be judged not only in terms of biodegradation but also in relation to the origin of cellulose, the production process, and the influence of such processes on the properties of the concrete mix [55, 56].

The strength and modulus of cellulose provide several benefits, despite the main issue being the incorporation of such properties into composites. With the help of “bottom-up” and “top-down” approaches, scientists create cellulose-containing materials that have excellent mechanical properties. The strengthening effect of cellulose microfibers and nanofibers enhances the structure while making an environmental contribution through plastic replacement [1, 2].

The compatibility of CNF with cementitious materials is essential. Because of the high aspect ratio and reactivity of CNFs, they can enhance the mechanical properties of OPC pastes. PCNF, SCNF, and LCNF affect the workability and strength differently. For instance, the addition of SCNF leads to dispersion stability improvement, thus increasing workability and causing fast hydration owing to the nucleation effect; 0.1% addition of SCNF resulted in a 13% increase in the compressive strength after 90 days compared to the control sample, whereas 0.1% PCNF caused a 70% improvement in the flexural strength [25]. CNCs also have a similar behavior because even low concentrations (~0.2% by volume) of CNCs lead to a better hydration rate and higher flexural strength with an approximately 30% increase in flexural strength obtained by Cao et al. [15]; in addition, Fu et al. [48] reported increases of up to 20% in flexural strength for nine types of CNC and two chemistries of cement. The exact mechanism of hydration acceleration includes steric stabilization and short-circuit diffusion according to kinetic studies of C_3S with CNC [26], whereas the effects of CNC include microstructure refinement, lower porosity, and an improved interfacial transition zone, as reported in the corresponding reviews [27]. The following table contains the quantitative physical properties of the key solid cellulose forms.

Table 2. Quantitative physical properties of cellulose forms relevant to cement systems.

Property	MCC	CNF	CNC	Source
Crystallinity (%)	55–80	50–70	49–95	[13]
Diameter	1–10 µm	5–50 nm	3–21 nm	[17]
Aspect ratio	~10	>100	10–70	[13]
Elastic modulus (GPa)	—	up to 150	110–220	[17]
Tensile strength (GPa)	—	up to 3	2–6	[18]
Density (g/cm³)	~1.5	~1.6	~1.6	[13]

3. Methods of Incorporating Cellulosic Polymers into Concrete

The incorporation of cellulosic materials into concrete has proven to be a groundbreaking method for improving efficiency and sustainability. This involves incorporating cellulose microfibrils and nanostructures into concrete to increase its mechanical strength. Cellulose modification makes it compatible with the matrix, which helps deal with problems associated with porosity and fragility, whereas obtaining cellulose from renewable sources such as agricultural waste promotes sustainability [1, 5].

3.1 Polymer Modification Techniques for Enhanced Performance

Polymers can modify the performance of a substance by improving its resilience and toughness. The incorporation of both inorganic and organic polymers can aid in increasing the adhesion property, providing water-resistant capabilities, while retaining rheological properties to make the substance less brittle and increase its lifespan. Cellulose polymers extracted from plants can serve the dual purpose of limiting the use of nonbiodegradable materials while strengthening cement mixtures [1, 5].

3.2 Dosage Forms and Mixing Procedures

The selection of additives and mixing techniques can affect the characteristics of both fresh and hard concretes. The ability to mix fibers along with certain binders and their quantities can impact the workability and mechanical characteristics, while mixing and curing of the material is vital for UHPC owing to its unique features [28, 29].

3.3 Effects on Workability and Setting Time

Cellulose-based polymers influence rheological behavior and increase adhesion, resulting in cohesive and flowing material when mixing and placement occur—a desirable characteristic for big jobs, where workability impacts the efficiency and stability of formworks. As nanocellulose has a high-water absorption capacity, it allows modification of the rheological properties of the fresh matrix, improving viscosity and yield stress, but retaining water better [30]. Cellulose-based products may help regulate setting time, which can be achieved by adapting setting time to weather conditions [2, 5].

3.4 Influence on Concrete Microstructure Development

The interaction between the cellulose fiber and nanocellulose with the cement matrix leads to an improved microstructure that becomes denser and homogeneous. The use of micro- and nanocellulose enhances internal cohesion and reduces brittleness, whereas improved aggregate distribution and lower permeability assist in controlling performance, ultimately resulting in sustainable construction practices [1, 19].

3.5 Challenges in Uniform Dispersion of Polymers

Dispersion uniformity is key to success. Additives can form aggregates depending on their physical and chemical nature, leading to inconsistencies in behavior. Depending upon the nature, concentration, and dispersion of nanocellulose, and even the composition of the cementitious binder, there could be a difference in outcomes; thus, dispersion is critical in determining efficacy [30]. Sonication, homogenization, and TEMPO oxidation, combined with surface modification, have been used as pretreatments to achieve better dispersion and rheological control. These are validated by comparisons between mechanical and ultrasonic dispersions, which highlight their significant impact on the strength and ductility of UHPC [31]. Shrinkage reducers and superabsorbent polymers have helped address concerns in UHPC [5, 29].

3.6 Critical Interpretation of Reported Results

However, the performance of cellulosic polymers on cement composites is not always entirely positive and varies significantly from one research study to another. This variability has been attributed to the different cellulose sources; morphological, structural, and chemical properties; particle size and aspect ratio; lignin content; and dispersion method used. CNF and CNC have been found to enhance cement hydration and mechanical properties at low and properly dispersed doses; however, excessive dosing and improper dispersion have been shown to increase viscosity, decrease fluidity, entrain air, retard hydration, and hence lower strength [15, 25, 30, 31, 48]. Variations in cement composition, W/B ratio, compatibility with superplasticizers, secondary cementitious materials, curing conditions, and test age make it difficult to compare results in the literature. Thus, the reported performance improvements should be viewed as case-specific rather than generalizable, and future research needs to adopt a standardized definition of dosage, mixing procedure, and statistics [27, 30, 31].

4. Impact of Cellulosic Polymers on Concrete Performance

Polymers made from cellulose have the advantage of being produced from renewable sources. They help in increasing the mechanical qualities by offering adhesion and cohesion, thereby improving the strength and durability of products while also tackling issues associated with permeability, such as frost damage and corrosion. Another reason for the success of these polymers is their rheology modification capabilities [1, 5].

4.1 Improvement in Mechanical Strength and Durability

The combination of excellent tensile strength and high modulus makes cellulose an efficient reinforcing material. It has been shown that the incorporation of nanofibrillated cellulose into Portland cement results in an increase in compressive strength exceeding 50% at 0.3% by weight concentration of nanocellulose, while enhancing the porosity and hydration products of the cement [33]. Different ways of obtaining cellulose-based materials highlight the ability of cellulose to act as a reinforcing agent and reduce its environmental footprint while improving material performance and structure lifetime [1, 2]. Studies on the influence of natural and artificial fibers, such as jute, sisal, carbon, and geopolymer high-strength materials, also show that fiber reinforcement improves strength [34, 35, 36, 37, 38].

4.2 Resistance to Cracking and Shrinkage Control

Recent developments have shown promising results regarding cracking and shrinkage reduction. Nanocellulose is especially efficient in preventing autogenous shrinkage because, in UHPC, cellulose filaments and nanofibrils decrease early age autogenous shrinkage by 45–75% at 24 h and by 22–53% after 7 days without reducing the flexural strength, and even allowing lower amounts of silica fume with similar shrinkage characteristics [39, 40]. The use of polyvinyl alcohol (PVA) fibers works in tandem with the above effects by increasing the tensile strength, bonding with cement-based structures, preventing cracking, and enhancing ductility, despite PVA fibers losing their compressive strength at high temperatures [41, 42].

4.3 Enhancement of Freeze–Thaw and Chemical Resistance

Cellulosic polymers can help reduce freeze-thaw and chemical damage through their ability to alter the microstructure and increase permeability. Studies have suggested that cellulose nanofibers can decrease sulfate ion penetration, along with increased resistance to sulfate ions and alkali silica reactions in OPC-based composites. The improvements reported were about halving the post-exposure loss of strength from 50% to below 20%, and ASR expansion was also reduced considerably, with differences observed between lignin-based and delignified CNF at doses of 0.05 to 0.3% [43, 44]. Earlier, 0.15% CNF proved ideal for increasing the compressive and flexural strengths of concrete by 26.5% and 25.8%, respectively, while offering resistance against frost and salts [18]. Improved formulations have been proven to lower water permeability and improve sulfate and chloride resistance [45, 46].

4.4 Effects on Concrete Porosity and Permeability

Porosity and permeability significantly affect the durability. The inclusion of polymers increases density but decreases porosity, which lowers permeability and makes the material more resistant to environmental conditions, while increasing its strength properties. Moreover, cellulose-based materials improve sustainability by substituting non-degradable fillers used in biocomposites [1, 5].

4.5 Long-Term Performance and Aging Behavior

The passage of time affects durability through environmental conditions and the natural porous nature of concrete. The use of polymer-based admixtures, such as cellulose-based admixtures, increases cohesiveness and helps prevent the ingress of fluids, thereby increasing lifespan. Another alternative for improving the mechanical properties is fiber-reinforced polymer (FRP), which helps decrease the impact of concrete on the environment during its entire lifetime [5, 47]. Table 3 summarizes the values obtained for the mechanical and durability characteristics of the principal cellulose and polymer admixtures.

4.6 Long-Term Durability under Aggressive Environmental Exposure

Cellulose-based polymers may optimize porosity characteristics and inhibit water permeability; however, the question of stability under aggressive actions is yet to be studied in depth because of the lack of studies concerning this issue at advanced ages. CNF-containing materials have exhibited increased frost resistance and less sulfate attack [18, 43, 44], while lignin-based and delignified CNF-based materials have been found to decrease strength reduction and expansion due to the alkali-silica reaction under sulfate attack [18, 37, 44]. Nonetheless, the effect of durability improvement depends significantly on cellulose type, dosage, dispersion efficiency, binder composition, and curing conditions. Cellulose hydrophilicity might also affect moisture distribution in wetting-drying and freeze-thawing processes; however, carbonation, chloride action, and high humidity and temperature have not been fully studied. Thus, further research should study the effect of cellulose-containing binders under extended exposure periods, that is, 90, 180, and 365 d [30, 39, 43, 45, 46].

5. Recent Technological Advances and Applications

Recent developments signify the trend towards the use of environmentally friendly materials in building structures. The use of micro- and nanocellulose as additives for improving the mechanical characteristics but decreasing its environmental impact has become possible owing to the development of new technologies for extraction and treatment, which allows the use of cellulose as a reinforcing material [1, 19].

5.1 Development of Nanocellulose-Reinforced Concrete

The properties of nanocellulose, including its high strength and light weight, make it a useful additive. The tensile strength and durability of the material increase owing to the fact that the crystalline structure of the material allows it to form strong hydrogen bonds with the matrix, while the functionalizing property of nanocellulose with different additives makes it even more versatile [1, 19]. CNC obtained from agricultural waste products, such as sugarcane bagasse, could be used as an additional cementitious material, with a 10% substitution reaching up to 42.4 MPa, which was 13.9% higher than the control mixture [49]. Combined nanocellulose systems integrating CNC, CNF, and bacterial nanocellulose are emerging as a route to superior multifunctional reinforcement [27].

Table 3. Reported mechanical and durability outcomes for selected cellulose/polymer additives.

Additive	Dosage	Property Affected	Reported Change	Source
CNF (cement paste)	0.1% wt.	Flexural / energy absorption	+106% / +184%	[14]
NFC + 40% slag	0.1% wt.	Flexural strength	6.5 vs 3.1 MPa (+110%)	[14]
NFC (sisal)	3.3% mass	Flexural / elastic modulus	+26.4% / +41.5%	[32]
MCC	1% wt.	Plastic viscosity / yield stress	+21% / +190%	[32]
Silica-coated CNF (SCNF)	0.1% wt.	Compressive strength (90 d)	+13% vs control	[25]
Pure CNF (PCNF)	0.1% wt.	Flexural strength	+70%	[25]
CNC	0.2% vol.	Flexural strength	+~30%	[15]
CNC (9 types)	~0.2% vol.	Flexural strength	Up to +20%	[48]
CNC from bagasse (SCM)	10%	Compressive strength	42.4 MPa (+13.9%)	[49]
Nanocellulose filaments	0.15–0.30%	Autogenous shrinkage (UHPC)	−45–75% (24 h)	[39]
LCNF / DCNF	0.05–0.3% wt.	Sulfate / ASR resistance	Strength loss ~50%→<20%	[43]
Nanofibrillated cellulose	0.3% wt.	Compressive strength	>+50%	[33]
CNF (pervious concrete)	0.15% wt.	Compressive / flexural (28 d)	+26.5% / +25.8%	[18]
Cellulose fiber + bacteria	0.45% vol.	Compressive & split-tensile; healing	+25%; heals 2.5 mm cracks	[50]
PVA fibers	Variable	Ductility / crack control	Improved; fewer micro-cracks	[41]
HPMC	0.3–0.4%	Workability / crack resistance	Improved; bleeding <1%	[16]
Micro-/nanocellulose	0.05–2%	Durability / permeability	Reduced permeability	[1]
Polymer additives (general)	Variable	Adhesion & waterproofing	Improved durability	[5]
Sisal fiber (geopolymer)	Disperse	Strength & durability	Markedly enhanced	[38]

5.2 Innovations in Sustainable and Eco-Friendly Concrete Mixes

The use of modified cellulose derived from readily available biomass is an environmentally friendly solution to replace chemical admixtures for enhanced workability and durability. Simultaneously, cellulose acts as an effective filler in the solution to the problem of plastic pollution, thus reducing its harmful effects on the environment [1, 12]. The sustainability of cellulose-enhanced concrete depends on both the performance benefit and processing burden associated with cellulose production, including biomass source, drying, chemical treatment, fibrillation energy, transportation, and mixing requirements [55, 56].

5.3 Case Studies of Infrastructure Applications

Applicational studies have revealed that the addition of cellulose-based materials will enhance the physical and mechanical features, resolve issues such as porosity and corrosion as well as resistance to frost, and satisfy environmental demands [5, 47].

5.4 Integration with Other Additives and Hybrid Systems

The combination of cellulosic polymeric material with mineral additions or artificial resins may significantly increase the strength and adhesion capabilities of the resulting composite, as well as its durability and decrease permeability. One of the most promising hybrid systems is the use of cellulose fibers as a carrier material for crack-healing bacteria since the ability of fibers to retain moisture and the biocompatibility of the substance ensure calcite formation by bacteria, and with 0.45% of fibers being added to the composition, it has been shown that these composites have achieved an increased strength and resistance by 25% while closing up cracks up to 2.5 mm wide [50]. Cellulose-based materials, along with supplemental cementitious material or biological self-healing agent-based hybrid systems, might be able to offer multiple functionalities, but their efficacy is dependent on the compatibility and stability of the cellulose-cement interphase [27, 30, 50].

5.5 Future Trends and Potential Industrial Applications

The use of cellulose aids in the formation of lightweight yet strong biocomposites, offering mechanical performance and longevity while minimizing dependence on non-biodegradable components. The process of modifying cellulose to produce nanofibrils and nanocrystals creates the potential for developing new material designs, suggesting a move towards a bioeconomy based on sustainable renewable materials [1, 19]. The future directions for this area of study include cellulose functionalization, which has better dispersion capabilities, compatibility with superplasticizers, anti-agglomerating properties, and increased stability in alkaline cementitious systems. Proper mixing techniques and experimental validation through mortar/concrete mixtures and not solely cement pastes are also required prior to practical applications [25, 27, 30, 31].

Table 4. Quantitative environmental and cost indicators for cellulose-reinforced concrete.

Indicator	CNF concrete	Conventional	Δ	Source
GWP, mass (kg CO_2-eq/m³)	509.88	506.88	+0.59%	[55]
GWP per strength (/m³/MPa)	8.57	10.02	−14.5%	[55]
Price (US$/m³)	150	145	+3.33%	[55]
Price per strength (/m³/MPa)	2.52	2.87	−12%	[55]
Nanocellulose (kg CO_2-eq/kg)	1.8–1100	n/a	—	[56]
Cement share of global CO_2	5–10%	5–10%	—	[55]

The environmental and economic performance of reinforced concrete needs to be assessed based on volumetric indicators as well as indicators that have been adjusted for performance. While the CNF mixture, described in Table 4, was found to have a marginally larger global warming potential and cost per unit volume, their values normalized on a compressive strength basis were lower owing to the increased compressive strength [55]. This cannot be generalized because the environmental burden associated with nanocellulose depends heavily on the raw material used, drying needs, chemical treatment required, energy consumed to fibrillate, power source, transport distance, and scale of production [56]. In addition, estimations in laboratory settings might not reflect the production in the ready-mix industry or the precast industry, where dispersion energy, admixture compatibility, process losses, etc., could influence both cost and environmental impact. Thus, future research needs to provide environmental and economic indicators for both per unit volume and performance, as well as industrial production scenarios.

As a raw mass metric, the CNF-enhanced concrete's global warming potential slightly exceeds that of the control (509.88 vs. 506.88 kg CO_2-eq/m³), but when normalized according to compressive strength, it becomes 14.5% smaller (8.57 vs. 10.02 kg CO_2-eq/m³/MPa) and 12% less expensive per MPa because of the increased strength [55]. The carbon footprint of nanocellulose fabrication depends greatly on the technology used, ranging from 1.8 to 1100 kg CO_2-eq/kg, which means that only mechanical or enzymatic processing technologies can produce environmentally sustainable materials [56]. This information is important because cement production accounts for approximately 5-10% of all CO_2 emissions in the world [49]. (The +3.33% increase in cost according to the mass metric is reproduced literally from the source; the ratio 150/145 corresponds to +3.45%). To demonstrate the importance of the above facts in perspective, Table 5 provides a comparison of the results obtained by other researchers.

Table 5. Study-by-study comparison: best quantified result per study

Source	Focus	Best quantified result
[1]	Micro-/nanocellulose in polymer composites	Micro- and nanocellulose enhance mechanical performance of biocomposites.
[19]	Assembly of nanocelluloses	Nanocelluloses provide sustainable, high-potential advanced materials.
[2]	"Bottom-up" / "top-down" cellulose materials	Both strategies yield strong cellulose-based materials.
[25]	CNF in OPC-based materials	SCNF +13% compressive strength; PCNF up to +70% flexural strength.
[15]	CNC additions in cement paste	~30% flexural gain at 0.2% vol.; raises hydration.
[14]	NFC in cement paste	0.1% NFC: +106% flexural and +184% energy absorption.
[32]	Cellulosic fiber cement composites (review)	Sisal NFC: +26.4% flexural modulus and +41.5% modulus.
[48]	CNC across 9 types and 2 cements	Flexural strength up to +20%, higher hydration.
[26]	C3S hydration kinetics with CNC	explains the CNC acceleration via short-circuit diffusion.
[27]	CNC in cement composites (review)	CNC refines the microstructure; ~20% compressive gain.
[49]	CNC from bagasse as SCM	10% CNC reaches 42.4 MPa (+13.9% vs control).
[39]	Nanocellulose in UHPC	Autogenous shrinkage of −45–75% at 24 h.
[40]	CNF/CNC physical properties	1% CNF: flexural +34.5%, compressive +23.3%.
[43]	LCNF/DCNF durability	Strength loss ~50%→<20%; ASR expansion-97%.
[16]	HPMC in concrete (iron tailings)	HPMC improves workability and crack resistance.
[30]	Nanocellulose in cementitious materials (review)	The type, dosage, and dispersion of nanocellulose govern its effects.
[31]	Two cellulose nanomaterials on cement paste	Contrasting effects on setting, rheology, and strength.
[33]	Nano fibrillated cellulose in Portland cement	>50% compressive strength at 0.3%; refined microstructure.
[18]	CNF in pervious concrete	+26.5% compressive, +25.8% flexural; better frost resistance.
[44]	CNF for sulphate resistance	CNF lowers sulfate-induced damage in cement.
[50]	Cellulose-fiber bacteria carriers	+25% compressive & split-tensile; heals 2.5 mm cracks.
[55]	LCA & cost of CNF concrete	−14.5% CO_2 and −12% cost per MPa.
[56]	Harmonized LCA of nanocellulose	Production: 1.8–1100 kg CO_2-eq/kg by process.
[5]	Polymer additives in concrete	Additives improve strength, adhesion, waterproofing, and durability.
[38]	Sisal-fiber geopolymer concrete	Sisal fibers markedly enhance strength and durability.
[37]	High-strength geopolymer concrete	HS-GPC enhances the mechanical strength while maintaining sustainability.
[41]	PVA fiber in reinforced concrete	Improves ductility and crack control; fewer microcracks.
[42]	Synthetic/macro fibers, thermal behavior	Review of fiber effects on the thermal response of FRC.
[35]	Jute fiber in concrete	Jute fiber improves properties while lowering the environmental impact.
[57]	Jute laminate column wrapping	Jute laminates enhance the mechanical properties of columns.
[36]	Carbon fiber + silica fume	Combined use significantly improves concrete strength.
[34]	Natural & synthetic fibers review	Fibers improve workability, strength, and durability.
[12]	Modification of cellulose	Sustainable processing broadens the applications of cellulose.
[11]	Carboxymethyl cellulose (CMC)	CMC is versatile across industries owing to its unique properties.
[22]	Cellulose in 3D/4D printing	Cellulose enables the fabrication of sustainable bio-composites for printing.
[23]	Cellulose functionalization (FDM)	Functionalization boosts compatibility and printability.
[20, 21]	Nanocellulose surface engineering	Interface engineering has expanded the use of advanced nanocellulose.
[47]	Fiber-reinforced polymers in concrete	FRP improves the performance with a lower lifecycle impact.
[58]	Geopolymers vs. cement + nanofiller	Nanofillers support sustainable smart construction mixes.
[51, 52]	Biochar-concrete	Biochar aids in the properties and carbon-neutral construction.
[53]	Biomaterials in concrete (bibliometric)	Maps growing research on biomaterials in concrete.
[54]	Cork-modified polymer concrete	Cork lowers brittleness and increases ductility/energy absorption.

6. Critical Discussion and Research Gaps

The advantages found in studies of cellulosic polymers in cementitious matrices must be approached with caution because the performance depends heavily on the specific system. When added in small amounts and uniformly dispersed, CNF and CNC could aid in hydration, refine the microstructure, and enhance the mechanical properties. However, an excessively high dosage or poor dispersion increases viscosity, reduces workability, entraps air, delays hydration, and decreases strength [15, 25, 30, 31, 48].

Differences in the results from literature sources do not arise only from the different celluloses used. Properties such as morphology, crystallinity, aspect ratio, surface chemistry, and lignin content depend on the cellulose type and origin and determine the water absorption capacity, dispersibility, and interaction with cement hydration products. In addition, the basis of the dosage, mixing energy, sonication technique, W/B ratio, superplasticizer compatibility, cement mineral composition, SCM, curing regime, and test age can make great differences as well [15, 25, 26, 27, 30, 31, 48]. The increased strengths found in some cases might also arise owing to changes in the effective water availability, bleeding, and acceleration of the hydration and nucleation processes.

Some crucial problems in this field are yet to be solved. Standardized procedures for dispersion, mixing sequence, and dosages need to be created to allow better comparability between research results. Comparisons of MCC, CNF/NFC, and CNC using identical mixes are currently rare, while most of the conducted studies are limited to cement paste and short testing times. The effects of long-term exposure to sulfate attack, chloride ions, carbonation, wet/dry cycling, and freezing/thawing require more studies. Future research will need to confirm the performance of cellulose-reinforced systems in mortars and concretes in ready-mix and precast production processes [27, 30, 43, 55, 56].

7. Conclusions

The integration of cellulosic polymers within concrete provides a highly promising route towards increased efficiency and sustainability. Exploiting cellulose, nature’s most common polymer, entails overcoming difficulties in the areas of synthesis, derivatization, and dispersion; however, it is evident that there are considerable mechanical and durability advantages, along with decreased environmental load. In all the analyzed literature, the inclusion of cellulosic polymers into the matrix improves various mechanical, functional, and durability characteristics of the product. It helps to achieve better adhesion and waterproofing, as well as increases resistance to the negative effects of freeze–thaw cycles, corrosion, and other factors affecting the durability and overall condition of concrete, helping to solve certain problems that occur within this material. Using cellulosic polymers allows the creation of constructions that are stronger, more durable, less prone to porosity and environment-related damage, provide better adhesion and waterproofing, and are resistant to freezing-thawing processes and corrosion. Cellulosic polymers can be extracted from agricultural waste, avoiding the use of artificial additives and greener products. However, some questions require further analysis. First, there are limited data on the use of various types and quantities of cellulose to determine its effect on the mechanical performance, functionality, and durability of the resulting material. In addition, the natural porosity of concrete requires more durable composites to increase durability. There is also a need for standard procedures, including testing the quality of cellulosic polymers. Future research should focus on exploring new methods of extracting and modifying cellulosic polymers, as well as systematically analyzing of "bottom-up" and "top-down" methods. It is also important to consider cellulose as a sustainable composite material. Such work will require interdisciplinary efforts. Owing to the mechanical properties of cellulose, it will be possible to create innovative, high-quality constructions that are strong, durable, and eco-friendly. Moreover, there are a significant number of modern applications of fiber-reinforced polymers, where the same criteria are considered important. Thus, the study of cellulosic polymers may have a crucial role in redefining sustainable construction practices.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

AI Declaration Statement

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Author Contribution Statement

A.S. Noori and S.R. Kasim: proposed the review problem. A.S. Noori and S.R. Kasim: developed the theory and performed the computations. A.S. Noori and M.K. Al-Kamal: verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

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