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REVIEW

Review of recent developments in cement composites reinforced with fibers and nanomaterials

Jianzhuang XIAO[a], Nv HAN[a], Yan LI[b*], Zhongsen ZHANG[b], Surendra P. SHAH[c]

[a] *College of Civil Engineering, Tongji University, Shanghai 200092, China*

[b] *School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China*

[c] *Center for Advanced Cement-Based Materials, Northwestern University, Evanston, IL 60208, USA*

[*] *Corresponding author. E-mail: liyan@tongji.edu.cn*

ABSTRACT The quest for high-performance construction materials is led by the development and application of new reinforcement materials for cement composites. Concrete reinforcement with fibers has a long history. Nowadays, many new fibers associated with high performance and possessing eco-environmental characteristics, such as basalt fibers and plant fibers, have received much attention from researchers. In addition, nanomaterials are considered as a core material in the modification of cement composites, specifically in the enhancement of the strength and durability of composites. This paper provides an overview of the recent research progress on cement composites reinforced with fibers and nanomaterials. The influences of fibers and nanomaterials on the fresh and hardened properties of cement composites are summarized. Moreover, future trends in the application of these fibers or of nanomaterial-reinforced cement composites are proposed.

KEYWORDS cement composites, fiber, nanomaterial, mechanical property, durability

1 Introduction

The increasing application of cement composites in the construction industry has benefited from its abundant resources, low cost, and simple operating processes. With the expansion of industry requirements for the performance of construction materials, concretes with new characteristics, such as high mechanical properties, self-cleaning performance, fire resistance, and 3D printability, are being developed for application in particular circumstances. The addition of reinforcing fibers and nanomaterials has broad prospects for the performance enhancement of cement composites. In fact, nanomodification and fiber reinforcement of cement-based materials have together been identified as one of the top 10 engineering research fronts, based on the top 10% highly cited papers determined using the co-citation clustering method [1].

In recent decades, various types of fibers have been applied to cement reinforcement. The mechanical properties of cement composites, such as strength, toughness, and impact resistance, can be distinctly enhanced via the addition of these reinforcing materials [2]. The related reinforcing mechanism is mainly the bridge effect of fibers on inhibiting crack propagation, which has been comprehensively investigated by Barluenga [3]. Moreover, researchers are conducting efforts to reinforce cement with environmentally friendly materials, such as plant fibers and mineral fibers, which have also resulted in significant mechanical enhancements for cement composites [4].

The market for nanomaterials reveals a booming development in the world's annual revenue growth rate, which increased from 25% in 2000–2010, to 44% in 2010–2013, and is estimated to be 30 billion dollars in 2020 [5]. The development of nanotechnology has provided opportunities to enhance the performance of cement composites through the addition of nanomaterials [6]. During the last decade, research on the reinforcement of cement composites with nanomaterials has been very active and scientifically lively. The sizes of nanomaterials commonly used in cement composites are less than 100 nm, which lead to unique physical and chemical properties, notably

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their superior mechanical properties and large specific surface areas. These nanomaterials can be divided into 0D (nanoparticles), 1D (nanofibers), and 2D (nanosheet) materials according to their geometrical morphologies [7]. In 2016, Shah et al. [8] reviewed the modification of cement-based materials by nanomaterials, including nano-SiO_2 (NS), nano-clay (NC), nano-Al_2O_3 (NA), and carbon nanomaterials. These nanomaterials are applied either as admixtures or additives for cement modification, which can improve the performance of cement composites in terms of workability, mechanical strength, shrinkage, durability, and fire resistance.

Figure 1 compares the annual numbers of Science Citation Index (SCI) papers on fiber reinforcement and nanomodification of cement composites, showing that the annual number of SCI papers has increased at accelerating levels each year from 2015. In this paper, recent developments in cement composites reinforced with fibers and nanomaterials are thoroughly reviewed. Indices of performance of reinforced cement composites, including fresh properties, mechanical properties, durability, and thermal resistance, are also extensively discussed. Based on this review, some future research trends in the field of cement composites are proposed.

2 Types of fibers and nanomaterials in cement composites

2.1 Fibers

2.1.1 Steel fiber

Steel fibers are the most widely applied type of commercial fiber as reinforcement in cement composites and can be classified, based on their production processes, as cold-drawn wire fibers, shaved cold-drawn fibers, mill cut fibers, melt-extracted fibers, and cut sheet fibers. In addition, according to the compositions of its raw materials, steel fiber can be further categorized into cold-drawn carbon steel and stainless-steel fiber. As shown in Fig. 2, steel fibers in cement composite reinforcements exhibit a great variety of shapes, such as straight, hooked-end, and corrugated. Table 1 summarizes the different shapes of steel fibers used as reinforcement in cement composites. Meanwhile, micro steel fiber has been used to increase the interface area of fiber and matrix, and to enhance the mechanical properties of reinforced cement composites, and has been shown to improve the mechanical properties of cement composites compared to those of other microfibers such as polyethylene (PE) and polyvinyl alcohol (PVA) fibers [9,10]. However, the mass production of steel fibers is environmentally problematic because of its significant carbon footprint. Recycled steel fibers have therefore started to attract more attention for possible application and have been observed to produce comparative results in terms of flexural strength compared to their industrial-steel-fiber counterparts [11].

2.1.2 Synthetic fiber

Carbon fiber (CF) is one of the most common synthetic fibers used in cementitious composites to enhance their properties because CF has an extremely high strength and modulus, good corrosion resistance, low density, excellent thermal stability, and high conductivity. The tensile strength of CF can be as high as 7 GP with a modulus as high as 900 GPa, which makes it attractive for the reinforcement of concrete [25]. However, because of the high-temperature carbonization/graphitization step during its manufacturing process, the surface of CF exhibits lipophobicity, excessive smoothness, and less adsorption, which are detrimental for bonding between CF and matrices. Therefore, surface treatments are applied onto CF, via wet chemical modification, dry modification, and multi-scale modification [26].

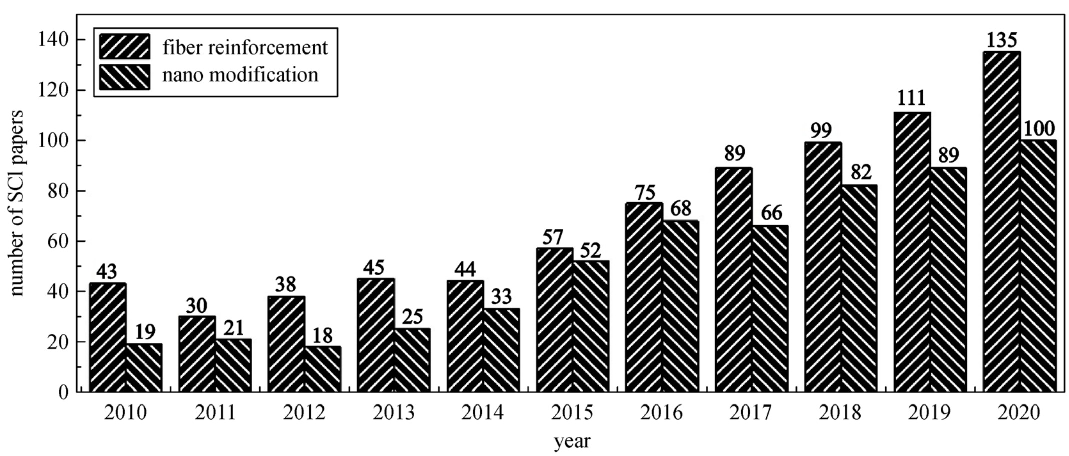

Fig. 1 Annual number of SCI papers on fiber reinforcement and nanomodification of cement composites.

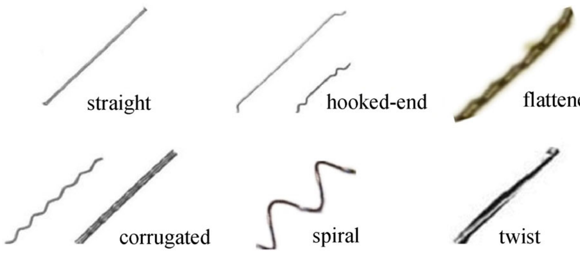

Fig. 2 Different types of steel fibers [12,13]. (Reprinted from Materials & Design, 31(5), Holschemacher K, Mueller T, Ribakov Y, Effect of steel fibres on mechanical properties of high-strength concrete, 2604–2615, Copyright 2010, with permission from Elsevier.) (Reprinted from Materials & Design, 33, Xu Z, Hao H, Li H N, Experimental study of dynamic compressive properties of fibre reinforced concrete material with different fibres, 42–55, Copyright 2012, with permission from Elsevier.)

Glass fiber, on other hand, is a widely available and versatile industrial material for general and electrical applications. The raw material of glass fiber is silica, which is abundant and inexpensive. Some other ingredients, such as calcium, aluminum, and sodium, are added to glass-fiber products to improve their properties. Glass fiber is divided into several types according to their application. E-glass fiber is the most common type of glass fiber, which accounts for more than 90% of the market. Other glass fibers are usually much more expensive and have special requirements [27]. Alkali-resistant glass fibers are fabricated with 15%–20% zirconium, which endows them with a good alkali resistance due to the stability of zirconia in alkaline solutions, making these fibers more suitable for application in a cement environment [28].

Polymeric fibers are applied as concrete reinforcements because of their cost effectiveness and excellent mechanical properties, as shown in Table 2. Polymeric fibers have high strength, elasticity, excellent wear resistance, and chemical resistance; therefore, they are widely used as reinforcement for cement composites, especially high-strength concrete. In addition, the melting temperature of polymeric fiber is usually no more than 200°C [29]. Because of the low melting temperature of polymeric fibers, the application of polymeric fibers is able to reduce the spalling of cement composites at elevated temperatures. Commonly used polymeric fibers include polypropylene (PP), PE, polyethylene terephthalate (PET), and PVA fibers. PP and PVA fibers are the two most frequently adopted polymeric fibers for concrete reinforcement, whereas PE fiber is the emerging reinforcing fiber type, characterized by an ultra-high strength and elastic modulus of up to 2–3 GPa and 100 GPa, respectively.

2.1.3 Mineral fiber

Mineral fibers are also widely applied in the reinforcement of cement composites. The mineral fibers are obtained via a multi-step electrothermal method instead of a one-step process. Its natural raw materials and industrial waste materials are melted in an electrothermal melting unit and then formed via centrifugal blowing. Commonly used mineral fibers include basalt fiber, slag fiber, and asbestos

Table 1 Different types of steel fibers

shape	diameter (mm)	length (mm)	tensile strength (MPa)	elastic modulus (GPa)	density ($kg \cdot m^{-3}$)	elongation at break (%)	reference
straight	0.5–0.9	25–60	500–2000	200	7840	0.5–3.5	[13,14]
hooked-end	0.37–0.9	25–62	1050–2311	200–210	7700–8000	–	[15–19]
flattened-end	0.5–1	30–50	900–1150	200–212	7700–7850	–	[13,20,21]
corrugated	0.75–1	30–60	1100	200	7900	–	[22,23]
spiral	0.9	15–30	1300	–	7700	–	[13]
twist	0.3	30	2428	200	7900	–	[24]

Table 2 Physical and mechanical properties of selected polymeric fibers

fiber type	diameter (μm)	length (mm)	tensile strength (MPa)	elastic modulus (GPa)	density ($kg \cdot m^{-3}$)	elongation at break (%)	reference
PP	15–81	4–19	240–700	1.5–9	910	7–9	[30–33]
PE	20–24	18	2400–3000	100	970	2–3	[34,35]
PET	300	35	101	0.19	1100–1390	–	[36,37]
PVA	12–39	9–12	800–1600	20–42.8	1290–1300	6–10	[14,38–40]
PL[a)]	45	12–54	1340	9.5	875	–	[17,41]
PAN[b)]	5–25	12	400	3–8	1180	10.1	[33]

Notes: a) PL: polyester; b) PAN: polyacrylonitrile.

fiber; among these materials, basalt fibers possess excellent characteristics and are considered to be promising new mineral fibers.

Basalt is a natural volcanic igneous rock with a density of 2.7–2.8 $g \cdot cm^{-3}$ and a Mohs hardness of 5–9 [42]. The tensile strength of basalt fiber is approximately 2650 MPa, and its elastic modulus is 75–115 GPa. In addition, basalt fibers have excellent high-temperature resistance, enabling these materials to withstand 1100°C–1200°C for hours [43]. The main chemical components of basalt fibers are Si, O, Fe, and Ca, among others. However, the ≡Si–O–Si≡ in basalt fibers can react with OH^- in an alkali environment, which destroys the silicate ion skeleton network. Thus, various approaches have been employed to protect basalt fibers, including surface modification of basalt fibers using chemical coatings with amino silanes, and alkalinity adjustment of the cement matrix using silica-containing additives [44].

2.1.4 Plant fiber

Plant fibers are also being considered for use in cement reinforcement because of their environmental protection features. Plant fibers are derived from natural and renewable sources, such as bast, leaf, seed, stalk, wood, grass, and other crop residue fibers. Individual plant fibers are obtained via a retting and pulping procedure. The pulping method may either be a mechanical pulping or chemical pulping process [45]. Cellulose, the main chemical constituent of plant fibers, contains many hydroxyl groups, and therefore a number of treatment methods, such as alkali treatment [46] and CNT coating [47,48], have been used to modify the interfacial adhesions between plant fibers and cement matrix. Thus far, sisal, jute, and hemp are the most widely used plant fibers. Oil palm and coconut fibers are also capturing the interest of researchers because of their significantly high toughness [49].

2.2 Nanomaterials

Nanomodification is a mainstream trend in the reinforcement of cement composites, which is expected to result in a more efficient use of this binder. Figure 3 shows the microstructures and morphologies of different types of nanomaterials.

2.2.1 Oxide nanoparticles

Recently, many oxide nanoparticles, such as NS, NA, nano-Fe_2O_3 (NF), and nano-TiO_2 (NT) have been adopted for the enhancement of cement performance. NS, which has a higher pozzolanic activity than normal silica fume, is the most common nanomaterial used in the modification of cement composites [58]. Raw materials for the preparation of NS are mainly silicon halide, water glass, and silicate. The preparation process generally utilizes mechanical pulverization to crush the silica particles into nano-scale sizes with the aid of a super-jet mill or high-energy ball mill. NF, on the other hand, is another typical nanoparticle applied for the enhancement of the mechanical properties of cement composites. Industrial green alum, green iron, or iron nitrate are usually used as raw materials for the preparation of NF. Meanwhile, NT is known as a self-cleaning addition to cement composites because of its photocatalytic action, which is an ideal auto-clean feature needed for nanoengineered building materials [59].

2.2.2 Nano-clay

NC is a general term for layered mineral silicates, including bentonite, kaolinite, montmorillonite, hectorite, and halloysite [54]. It is a group of processed clays for the nanomodification of cement composites. The most commonly used method for preparing NC is intercalation, which forms thin flakes of clay by utilizing the ion exchange characteristics of clay minerals and the scalability of the interlayer distance. The addition of NC to cement can reduce the pore size and porosity of the cement and enhance its mechanical properties.

2.2.3 Carbon nanomaterial (carbon nanotubes, nanocarbon fibers, and graphene oxide)

Carbon nanotubes (CNTs) and carbon nanofibers (CNFs) are typical 1D nanomaterials with cylindrical nanostructures and high aspect ratios greater than 1000, whereas graphene oxide (GO) is a 2D carbon sheet, which exhibits extraordinary mechanical and thermal performance. The tensile strength of 1D carbon nanomaterials is as high as 65–93 GPa, whereas the elastic modulus approaches 1 TPa [60]. In addition, the thermal decomposition temperatures of CNTs range from 600°C to 750°C [50]. The standard methods for preparing CNTs include the graphite arc method, chemical vapor deposition method, and laser evaporation method. GO, on the other hand, is commonly made chemically with concentrated acids and oxidizing agents [55].

3 Mechanical enhancement of cement composites with fibers and nanomaterials

3.1 Mechanical properties

3.1.1 Effect of fibers

The addition of fibers can affect the mechanical properties of cement composites, including ductility, fracture tough-

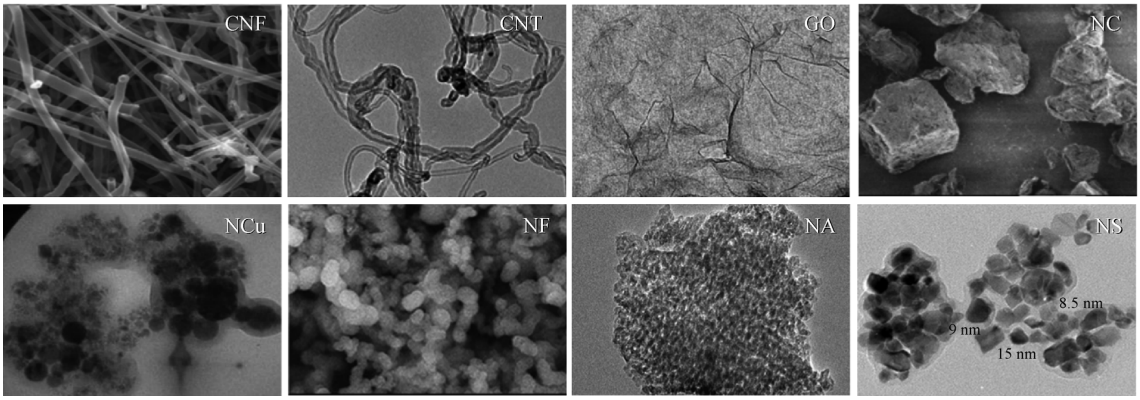

Fig. 3 Microstructures and morphologies of nanomaterials [50–57]. (Reprinted from Construction & Building Materials, 98, Amin M S, El-Gamal S M A, Hashem F S, Fire resistance and mechanical properties of carbon nanotubes–clay bricks wastes (Homra) composites cement, 237–249, Copyright 2015, with permission from Elsevier.) (Reprinted from Construction & Building Materials, 91, Heikal M, Ismail M N, Ibrahim N S, Physico-mechanical, microstructure characteristics and fire resistance of cement pastes containing Al_2O_3 nano-particles, 232–242, Copyright 2015, with permission from Elsevier.) (Reprinted from Construction & Building Materials, 94, Khotbehsara M M, Mohseni E, Yazdi M A, Sarker P, Ranjbar M M, Effect of nano-CuO and fly ash on the properties of self-compacting mortar, 758–766, Copyright 2015, with permission from Elsevier.) (Reprinted from Construction & Building Materials, 164, Sharkawi A M, Abd-Elaty M A, Khalifa O H, Synergistic influence of micro-nano silica mixture on durability performance of cementious materials, 579–588, Copyright 2018, with permission from Elsevier.) (Reprinted from Composites. Part B, Engineering, 165, Panda B, Ruan S, Unluer C, Tan M J, Improving the 3D printability of high volume fly ash mixtures via the use of nano attapulgite clay, 75–83, Copyright 2019, with permission from Elsevier.) (Reprinted from Cement and Concrete Composites, 70, Murugan M, Santhanam M, Sen Gupta S, Pradeep T, Shah S P, Influence of 2D rGO nanosheets on the properties of OPC paste, 48–59, Copyright 2016, with permission from Elsevier.) (Reprinted from Construction & Building Materials, 134, Wang H, Gao X, Wang R, The influence of rheological parameters of cement paste on the dispersion of carbon nanofibers and self-sensing performance, 673–683, Copyright 2017, with permission from Elsevier.) (Reprinted from Materials & Design, 32(7), Nazari A, Riahi S, Computer-aided design of the effects of Fe_2O_3 nanoparticles on split tensile strength and water permeability of high strength concrete, 3966–3979, Copyright 2011, with permission from Elsevier.)

ness, and energy absorption capacity. Fiber reinforcement has been investigated widely in terms of type, content, shape, distribution, and orientation of fibers.

Steel fibers have long been considered as the best reinforcement for the improvement of the mechanical properties of cement. In a study by Alavi et al. [61], the addition of steel fibers (1%) to cement composites enhanced the compressive and tensile strength by 30%–62% and 8%–10%, respectively. The application of steel fibers can also strengthen the punching shear performance of the cement composite. According to Xiao et al. [62], the addition of steel fibers improves the ductility, deformation, and energy consumption of both natural aggregate concrete and recycled aggregate concrete. In that particular research, the punching shear capacity of concrete was increased by 7%–15% when 0.5%–1.0% volumetric ratios of steel fibers were used. In a study by Kakooei et al. [63], the addition of PP fiber improved the compressive strength by more than double and decreased the permeability and shrinkage of the concrete. Meanwhile, a study was conducted by Kazmi et al. [64] to investigate the effect of PP fibers on the axial stress–strain behavior of recycled concrete. The stress–strain curves of PP fiber-modified concrete exhibited higher ductility, peak stress, and energy dissipation capacity compared to those of the unmodified concrete. Some investigations were also performed to compare the influence of PP fibers and steel fibers on the impact strength of concrete. The addition of steel fiber was determined to be more efficient for increasing the impact strength of concrete because of its higher tensile strength and better cohesion, especially when the fiber is in a hooked-end shape.

Aside from these two types of traditionally used fibers, plant fibers and mineral fibers are also being explored for the purpose of concrete reinforcement. Ali et al. [65], for example, investigated the impact of coconut fiber on the mechanical and dynamic performance of concrete because coconut fiber had the highest toughness among the tested plant fibers. In that study, the compressive strength and splitting tensile strength increased by 24% and 11%, respectively. Nanosized plant fibers, such as CNF, have also been used as filler to reinforce concrete, which can improve the flexural strength by 2.7 times, according to research by Cengiz et al. [66]. Basalt fiber is another important fiber for concrete reinforcement. It can strengthen mechanical properties, especially flexural strength and tensile strength, because of the good interfacial bond between basalt fibers and cement matrix. The splitting tensile and flexural strength of basalt-fiber concrete has been demonstrated to generally increase by

24.34% and 9.58%, respectively. However, in the research reported by Jiang et al. [32], the compressive strength did not improve significantly.

Much research has focused on the effect of the shape and content of fibers on the mechanical properties of cement composites. Table 3 summarizes the effect of steel fibers on the flexural strength of cement composites. In a number of studies on steel fibers, many kinds of fiber shapes, such as straight, hooked-end, spiral, twisted, and corrugated shapes, have been investigated. The shape of the fiber can directly affect the mechanical behaviors of the reinforced concrete. According to a comparison of straight, corrugated, and hooked-end fibers, the bond properties of hooked-end fibers are the best, those of straight fibers are the weakest, and those of corrugated fibers are intermediate. In a relevant study, the bond properties of hooked-end fibers were improved by 3–7 times relative to those of straight fibers. In terms of flexural strength, the hooked-end was also demonstrated to be the most effective shape, with a 17%–50% increment for the cement composite [67]. On the other hand, in a research study on tensile behavior by Park et al. [24], twisted fiber exhibited considerably greater enhancement than those by hooked-end and straight fibers. Meanwhile, spiral steel fiber is believed to strengthen the dynamic properties of cement composites more significantly than other fiber shapes are able to do. The influence of fiber length was also investigated. The flexural properties increased with fiber length, for lengths up to 19.5 mm. However, when the fibers were longer than 19.5 mm, the dispersion of the fibers became difficult. Yoo et al. [68], on the other hand, conducted experiments to determine the optimum content of straight steel fibers to improve the compressive and pullout properties of concrete. The compressive strength and elastic modulus were enhanced as the content increased up to 3%, whereas concrete containing 4% fibers exhibited the weakest compressive properties because of the poor dispersion of the fibers.

The distribution and orientation of fibers also significantly influence the mechanical properties of reinforced cement composites. The placement method of fresh cement composites has been demonstrated to affect the distribution and orientation of the fibers, wherein the fibers tend to align perpendicular to the flowing direction. In Barnett et al.'s research [71], ultra-high-performance fiber-reinforced concrete was prepared in a horizontal pan mixer, and round panel specimens were produced for a flexural test. Different fiber orientations were achieved when the specimens were poured in different ways. The highest flexural strength was observed for specimens with fibers flowing outwards from the center during their preparation process, which led to the lining up of the fibers perpendicular to the radius of the panel and an increase in the bridging effect between the radial cracks during the tests. Meanwhile, Kang et al. [15,72,73] conducted a series of studies on the effect of the distribution characteristics of fibers on the mechanical properties of concrete. In these studies, two placement procedures were implemented to create two different fiber orientations in the manufacture of the specimens (Fig. 4). The flexural strength of the specimen with fibers placed in parallel was 61% higher than that of the specimen with fibers placed transversely. The fiber direction also influenced the concrete split tensile strength. In a study by Li et al. [74], directionally distributed steel-fiber-reinforced concrete was prepared via a layer-by-layer casting method. The strength of the specimens subjected to loading perpendicular to the fiber direction was almost twice that of the specimens subjected to loading in a parallel direction.

3.1.2 Effect of nanomaterials

The addition of nanoparticles to cement composites enhances the mechanical properties, especially the compressive strengths, of the composites. On the other hand, compared to the addition of nanoparticles, the addition of

Table 3 Enhancement by steel fiber of flexural strengths of cement composites

shape	cement matrix	diameter (mm)	length (mm)	volume fraction (%)	flexural strength (MPa)	enhanced extent (%)	reference
straight	mortar	300	30	0.5	14.68	–8.93	[69]
		200	12	2.0	15.64	6.54	
		200	25	2.0	19.45	45.15	[70]
hooked-end	mortar	375	30	0.5	17.35	4.08	[69]
		775	62	1.5	16.79	14.76	
		550	35	2.0	6.3	200.00	[16]
corrugated	concrete	750	30	2.0	8.86	112.47	[22]
		750	45	1.5	6.84	64.03	
		750	60	1.5	8.44	102.40	
twisted	mortar	300	30	1.5	14.59	10.70	[69]

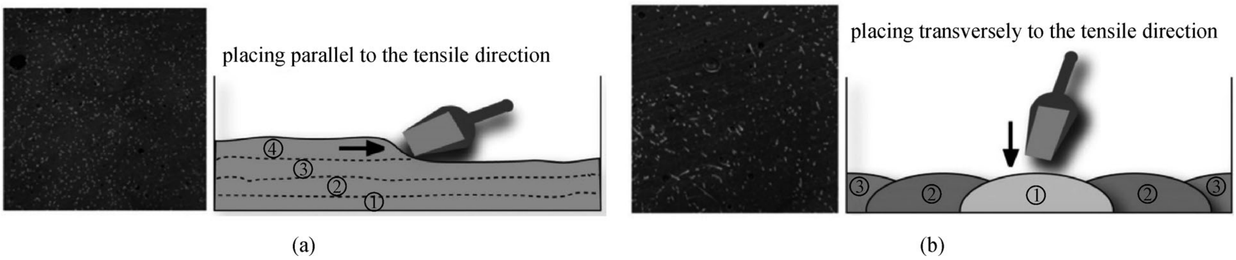

Fig. 4 Fiber distributions for different fiber placements [15]: (a) placement parallel to tensile direction; (b) placement transverse to tensile direction. (Reprinted from Cement and Concrete Research, 41(10), Kang ST, Kim JK, The relation between fiber orientation and tensile behavior in an Ultra High Performance Fiber Reinforced Cementitious Composites (UHPFRCC), 1001–1014, Copyright 2011, with permission from Elsevier.)

NFs is more efficient at enhancing flexural strength and toughness because of its relatively high aspect ratio. Aydın et al. [75] demonstrated that the addition of CNTs generates a higher energy-absorbing capacity and ductility for concrete and that the flexural toughness of concrete increased by 21% with 0.08% CNT. However, although the addition of CNTs and CNFs is proven to enhance flexural strength, the improvement in compressive strength is negligible, according to Konsta-Gdoutos et al. [76]. Only 5% and 2% increases in compressive strength were observed in concretes with CNTs and CNFs, respectively, and such increases depended on the CNT and CTF content.

The influence of different nanomaterials on the compressive strengths of cement composites is summarized in Table 4. NS is one of the most favored nanofillers for enhancing the compressive strengths of cement composites. According to Stefanidou and Papayianni [77], the application of NS increased the compressive strengths of cement composites by 30%–50% because of the existence of NS as nuclei. In a research study by Zapata et al. [78], on the other hand, the compressive strength of NS cement composite was observed to increase by 15%. By comparison, that of a cement composite containing micro-silica (MS) was increased by only 1%. According to their observation of the microstructures, NS led to the densification of hydration and acted as a filler, whereas MS served only as a filler. However, NS enhanced only the early-age (3 d) strength but had no significant effect on standard-age (28 d) and long-age (56 d) strengths, according to Shaikh et al. [79]. NA is another nanomaterial that is commonly used in concrete modification. In a study by Heikal et al. [80], the compressive strength of concrete with 1% NA content increased by 27.22%. However, super-abundant NA negatively influences the hydration of cement because of a coating effect. According to Madandoust et al. [81], the compressive strength of mortar containing NS, NF, and NC was enhanced as the content of nanomaterials increased to 4% for NS, 2% for NF, and 3% for NC.

Among these nanomaterials, 1D carbon nanomaterials (CNTs and CNFs) are known to be more effective for the enhancement of cement composites. Mohsen et al. [82] reported that the flexural strength of cement paste with 0.25% CNTs increased by 60% compared to that of plain paste; however, a greater amount of CNTs would decrease the strength because of poor dispersion. According to Cui et al. [83], the optimum content of CNT for cement reinforcement is 0.5%, resulting in increases in compressive and flexural strengths by 79% and 64.4%, respectively. In a research study by Gdoutos et al. [84], the flexural strength of concrete with CNT and NCF increased by 87% and 106%, respectively. A micro-scale investigation of the pore structure revealed that cement paste with additional CNTs had a lower porosity and more uniform pore-size distribution. Furthermore, the CNT-containing cement paste had a higher fracture energy and flexural toughness due to the bridge effect of the CNTs. Meanwhile, in a study by Wang et al., the fracture energy of cement paste containing treated CNT was up to 312.16 $N \cdot m^{-1}$, whereas the flexural toughness index was up to 57.5% [85].

3.2 Strengthening mechanism

The effect of fibers on the mechanical properties of cement composite is mainly due to the bridging effect on crack initiation and propagation. The main factors affecting the effectiveness of the enhancement include the shape, length, content, and type of fibers. The major bonding mechanism in a fiber–cement system is the physiochemical adhesion and friction of the reinforcement [99]. This type of bond is determined by the fiber surface roughness and properties of the interfacial transition zone in the cement matrix. Because most fibers are not completely inert, including glass fibers and basalt fibers, which are commonly believed to be inert, the strong alkali condition in the cement matrix could result in chemical reactions at the fiber–cement interface, leading to a negative effect on the fiber reinforcement [100]. For straight fibers, the physiochemical bond is the dominant form for the interface. To

Table 4 Enhancement by nanomaterial of compressive strengths of cement composites

type	cement matrix	weight fraction (%)	diameter (nm)	specific surface area ($m^2 \cdot g^{-1}$)	compressive strength (MPa)	enhanced extent (%)	reference
CNT	paste	0.1	10–40	93.81	76.88	4.0	[50]
		0.05	10–20	40-300	72.44	13.0	[86]
NA	paste	1	15 ± 3	165 ± 12	80 ± 0.5	29.0	[80]
	mortar	3	8	200	45.48	3.8	[87]
		1	15 ± 3	200	43.5	17.6	[52]
		1.25	13	100 ± 15	68.4	20.2	[88]
NC	mortar	3	1–2	265	58.1	18.1	[89]
		5	3	–	31.4	11.0	[54]
NCu[a)]	mortar	21	15 ± 3	200	42 ± 0.5	5.0	[52]
		3	15	200	43.53	16.4	[81]
NF	mortar	3	30	–	36.4	26.0	[90]
		2	60	60	41.76	11.7	[81]
		0.5	20–60	60	70.8	24.4	[88]
NS	paste	5	15	95	40.5 ± 0.5	55.8	[91]
		3	15 ± 5	160 ± 20	144	8.0	[92]
		4	15	–	70.5 ± 0.5	15.6	[80]
	mortar	5	20	220	54.80	30.1	[87]
		9	12–40	300	39.15	66.5	[93]
		3	30–70	–	72.25	16.1	[94]
		1	5–20	–	97.0	7.4	[95]
		4	15	200	43.03	15.1	[81]
		3	15 ± 3	200	40.0	8.1	[96]
		1.25	12	200	63.6	11.8	[88]
		1.3	15	200	50.9	8.3	[97]
		4	25	160	40	14.3	[79]
		2	8–20	–	40	14.3	[53]
		0.5	14	200	50	25.0	[77]
NT	mortar	5	15 ± 3	200	43.5	17.6	[96]
		3	15 ± 3	155 ± 12	59.6	36.4	[97,98]
		5.2	21	50	49.5	5.3	[97]

Notes: a) NCu: Nano CuO.

further improve the stress transfer efficiency of the interface, fibers are deformed into different shapes, such as hooked-end and wave-shaped steel fibers. For these types of fibers, the anchorages between the fiber and cement matrix are improved [101], and an additional type of bond, attributed to the interlocks between the deformed fibers, is generated. The bond strength is determined mainly by the geometric features of these fibers [102].

Nanomaterials can efficiently influence the properties of cement composites because of their nano-scale sizes, large specific surface areas, and correspondingly enhanced reactivities. Therefore, much research has been conducted on the mechanisms of nanomodification in cement composites. According to Refs. [103–106], the role of nanomaterials in the modification of cement composites can be summarized as follows.

Nanomaterials act as fillers in an open system of cement mortars, decreasing the porosity and strengthening the structure of the transition zone. Most nanomaterials act as the nucleus for hydration products, accelerate the peak times, and drop the heat release rate value. The sizes of solid particles of C–S–H will grow, with the nanomaterials as crystallization centers. In addition, nanomaterials decrease the sizes of $Ca(OH)_2$ (abbreviated here as CH) crystals, which also modify the microstructures of cementitious composites. The improvement of microstructures accounts for the strength enhancement of the cement composites.

CNTs and CNFs could be impeded within the hydration products and act as reinforcement for bridging cracks at the micro-scale, which enhances the mechanical properties of cement composites. However, the effect of CNT and CNF on the hydration of cement composites remains a debatable point. Some studies [104] have reported that CNTs and CNF have no chemical affinity with the reactions of cement hydration, and thus no additional hydration products are generated in cement composites with CNTs. Nonetheless, carbon-based materials are considered to have an electrostatic interaction with the ionic compounds of the cement paste, which is positive for the growth of hydration products. Therefore, CNTs can act as nucleation agents that modify the kinetics of the reactions and promote the growth of hydration products, especially during the early age of the composite. Although the addition of CNTs has no significant effect on the types of hydration products, the degree of polymerization of C–S–H is increased, the orientation index of calcium hydroxide crystals is reduced, and the microstructures of the cement composites are modified. However, other research studies present opposite conclusions [105]. Tafesse and Kim [106] observed an opposite phenomenon and argued that pure CNTs act only as micro fillers without being capable of accelerating the hydration of cement composites.

4 Properties and performance of cement composites

4.1 Workability

The fresh properties of cement composites are also affected by many characteristics of natural or artificial fibers, such as the shapes, content, and types. The influence of the shapes and content is relatively clear: the flowability of cement composites decreases with increasing fiber content and length–diameter ratios.

Different types of fibers produce various effects on the fresh properties of cement composites. According to Nadiger and Madhavan [107], the impact of steel or glass fiber on the workability of cement composites could be negligible. However, contrary conclusions were inferred by other researchers. In a research study by Yu et al. [101], for example, the slump flow of concrete linearly decreased as the content of steel fiber increased from 0.5% to 2.5%. In a study by Cao et al. [19], the filling ability, passability, and viscosity of fresh concrete exhibited significant changes with increasing content of steel fiber, resulting in a poorer fresh property. Polymeric fibers are considered to cause problems on workability, which damages the mechanical properties of the resulting reinforced concrete. Li et al. [108] studied the influence of PP fibers on the fresh properties of concrete and determined that both the content and length of PP fibers influenced the packing density, flowability, cohesiveness, and adhesiveness of the concrete. When the volume content of PP fibers was less than 0.05%, the packing density increased, and then decreased gradually with increases in the fiber content. On the other hand, for the same content, long PP fibers also decreased the packing density. The flowability and adhesiveness of the concrete exhibited a similar trend to that of the PP fibers, whereas the cohesiveness of the concrete increased. In that research, a new model was developed to estimate the workability of fiber-reinforced concrete. Meanwhile, in a study by Bhogayata and Arora [109], PET and PVA fibers also caused a reduction in workability due to the increased viscosity and reduced consistency of the fresh mixture. Because of their high absorption, plant fibers can cause more damage to the fresh properties of cement composites, and thus pre-treatment and pre-wetting methods should be conducted to reduce the water absorption of plant fibers.

Nanoparticles have large specific surface areas, which significantly influence the rheological behaviors of their modified concretes. Senff et al. [97] observed an apparent variation in the rheological behavior of cement mortars that contain NS and NT additives. The addition of NS and NT at high content led to a significant reduction in open time and flow table values due to the acceleration of the hydration process. Measurement of the temperature of hydration revealed the main exothermic peak of curing appearing in 4–7 h, which is 4 h earlier than that for unmodified mortar. In a research study by Zabihi and Hulusi Ozkul [110], on the other hand, flowability, hydration heat properties, and surface adsorption were tested to investigate the effect of NS on the fresh properties of polymer-modified concrete. The addition of NS was observed to decrease the flowability of concrete, especially when the NS was smaller. NS was also inferred to be an accelerator in the hydration process, which significantly affected the hydration peak time. Abd El Aleem et al. [91] observed a similar acceleration for their NS-modified cement composite, which was attributed to the additional formed bonds of C–S–H due to the presence of $H_2SiO_4^{2-}$. These C–S–H particles could act as a nucleus, facilitating the formation of more compacted C–S–H phases, which restrict the growth of CH crystals. The workability of nanomodified cement composites can be modified by superplasticizers (SPs) [98]. The results of a Marsh cone test suggested that the flowability of cement composites could be maintained at acceptable levels through the addition of higher SP dosages. A variety of SPs, such as lignosulfonate-based, melamine-based, naphthalene-based, and polycarboxylate-based SPs, can be used in cement composites. In a study by Shaikh and Supit [111], five different SPs were added to cement composites containing NS and nanocalcium carbonate. The SPs used in that study included polymers based on polyether in water, solutions based on inorganic salts and modified organic compounds, aqueous solutions based on surfactants, polycarboxylate ether in water, and modified naphthalene sulfonate. The test results on workability and compressive strength showed that the addition of NS had a more negative effect on the workability than that of the addition of nanocalcium carbonate. The compressive strength of the cement composite with the polycarboxylate ether-based superplasticizer was the highest for all five SPs. Meanwhile, increasing the NS content significantly reduced plastic shrinkage. Likewise, Zapata et al. [78] showed that NS could improve the rheology of superplasticized cement composites with low water/binder ratios and achieved a better fluidity for a high NS content. The different types of nanofillers exerted various effects on the rheology of concrete because of their different hydrophilic characteristics and specific surface areas. The yield stresses of concrete with CNTs and CNFs have been measured to be 3–4 times higher than those of concrete with NS, but the plastic viscosities of concrete with CNTs and CNFs were observed to be lower than that of NS-modified concrete [112].

4.2 Durability

Durability is another critical characteristic of reinforced or modified cement composites, enabling the material to resist weathering conditions, chemical attacks, and abrasion, and to maintain its expected properties. Although steel fibers are believed to be able to significantly strengthen the mechanical properties of cement composites, their influence on durability is more complicated. According to Mo et al. [113], the water absorption and sorptivity of concrete increases with increasing steel-fiber content, which harms the durability of the concrete. Moreover, the chloride diffusivity of concrete was observed to markedly improved when steel fibers were added [114]. Zhang et al. [115], on the other hand, studied the impact of steel fibers on the carbonation resistance, permeability resistance, freeze–thaw resistance, and cracking resistance of cement composites. Their results showed that these properties could be enhanced by steel fibers of appropriate content. When the fiber content was excessive, the carbonation resistance and cracking resistance decreased accordingly.

Compared to steel fibers, polymeric fibers have a stronger ability to enhance the durability of concrete by preventing shrinkage cracks and reducing the conductivity of pores. Liu et al. [31] compared the effects of glass fiber and PP fiber on chloride-ion permeability resistance. Both fibers were able to improve chloride-ion permeability resistance; however, the use of PP fibers resulted in considerably greater improvement. When the content of glass fiber and PP fiber was 1.5%, the migration depth of chloride ions in the concrete decreased by 10.9% and 21.7%, respectively. Furthermore, according to Algin and Gerginci [116], the addition of PP fibers limits the weight loss and deterioration of the mechanical properties of concrete, such as dynamic elastic modulus and strength, under freeze–thaw conditions. A half-cell test by Bolooki Poorsaheli et al. [41] suggested that PP fiber is beneficial for increasing the life service of concrete structures. On the other hand, according to Zhang et al. [117], the addition of PVA fibers can improve permeability resistance, cracking resistance, carbonation resistance, and freezing–thawing resistance. When the volume fraction of fiber is less than 1.2%, the durability indices of permeability resistance and cracking resistance increase with fiber content. However, the durability indices of carbonation resistance and freeze–thaw resistance were observed to begin to decrease as the fiber content increased from 0.9% to 1.2%. Meanwhile, according to Cui et al. [33], the addition of polyacrylonitrile (PAN) fiber could significantly increase the wheel-impact indexes of concrete under freeze–thaw cycles. It can also enhance the compactness of concrete by reducing microcracks in the transition zone. Other synthetic fibers, such as carbon, glass, and basalt fibers, have also exhibited effectiveness at enhancing the resistance of their reinforced concrete to corrosion and durability [27,118]. Ma's [119] study demonstrated that carbon-fiber-reinforced technology remarkably improves the corrosion resistance of concrete members for sea-crossing bridges. On the other hand, compared to CFs, glass fibers are prone to corrosion during cement hydration, which directly affects their long-term performance and strength stability. Qin et al. [27] therefore determined that a 30% addition of fly ash or 10% addition of silica fume to cement matrix could effectively improve the corrosion resistance of alkali-resistant glass fibers. The optimal volume fraction of glass fiber is 2%–4%, and the length is between 6 and 40 mm. Liu et al. [31] also investigated the effect of glass fiber and PE fiber on the durability of concrete via chloride penetration tests. The migration depth of concrete with 1.5% in volume glass fiber, PE fiber, and hybrid fiber decreased by 10.9%, 21.7%, and 23.3%, respectively.

In response to environmental concerns, pioneering researchers are attempting to replace traditional reinforcing materials with natural resources. However, plant fiber is usually considered to be harmful to the permeability of cement composites, which should otherwise be usable in marine environments. Zhao et al. [120], for example, suggested that the application of pineapple leaf fiber and ramie fiber caused significantly larger coefficients of capillary absorption and chloride diffusion of reinforced concrete than those of the plain concrete. However, according to Sekar and Kandasamy [121], coconut-fiber-reinforced concrete has a moderate chloride-ion penetrability and sorptivity value, indicating that these composite concretes could be used for practical application. In addition, plant-fiber-reinforced cement composites are inferred to be susceptible to deterioration in cement matrices because of the alkaline pore solution, which weakens the link between individual fiber cells by dissolving the lignin and hemicellulose existing in the middle lamellae of the fibers [39]. An additional deterioration mechanism is the alkaline hydrolysis of cellulose molecules, which causes de-polymerization of fibers, thereby leading to a lower tensile strength [122]. Research by Roma et al. [123] revealed that exposure to tropical climate causes a severe reduction in the mechanical performance of sisal- and eucalyptus-fiber-reinforced cement-based roofing tiles, which can be attributed to alkaline attacks and petrifaction of the natural fibers and progressive microcracking of the cement matrix. Meanwhile, Mohr et al. [124] investigated the durability of kraft-pulp-fiber–cement composites for wet/dry cycling. These composites exhibited significant losses in first crack strength, peak strength, and post-cracking toughness after exposure to 25 wet/dry cycles. Thus, necessary approaches for improving the durability of plant fibers in cement-based materials should be further explored.

Nanomaterials can refine the pore structure of concrete and improve its permeability resistance, which is a crucial factor contributing to the durability. Behfarnia and Salemi [87] studied the effects of NS and NA on improving the freeze–thaw cycle resistance of cement composites. After 300 freeze–thaw cycles, the water absorption of NS-containing concrete specimens was determined to be higher than that of NA-containing concrete. This improvement was attributed to the restricted growth of CH, leading to a more homogeneous matrix and pozzolanic reaction. NS and NT were also used to enhance the chloride diffusivity of recycled aggregate concrete via refinement of the pore structure, which revealed that NT had a better enhancing effect. Meanwhile, Lee et al. [58] observed that a combination of NS and CNT could improve the permeability and corrosion resistance of cement composites. The optimum dosages for both NT and NA were determined to be 3% for cement concrete, whereas nanoparticle content above 3% resulted in a drop in strength and durability properties [125,126]. The application of NS led to the consumption of CH and greater C–S–H gel formation, and the CNTs also accelerated the crystalline growth. These results demonstrated that the synergistic effect of NS and CNT enhanced the durability of cement composites. On the other hand, according to Fan et al., the addition of NC reduces the porosity of cement mortar, which improves its acid resistance. In that study, the optimum content of NC was determined to be 3% [127]. Meanwhile, Mirgozar Langaroudi and Mohammadi [89] used NC in self-consolidating concrete containing mineral admixtures. The addition of NC improved segregation and bleeding, decreased both water absorption and penetration depth, and enhanced electrical resistance.

4.3 Thermal resistance

The deterioration of concrete under thermal treatment and fire is the result of the interaction of chemical, physical, and mechanical processes. The elevated temperature generates a severe deterioration in the mechanical properties of both the fiber and cement matrix.

Abdallah et al. [18] conducted research on the bond–slip behaviors of straight and hooked fibers in concretes exposed to high temperatures. The strength of the concretes decayed with increasing temperature because of the damage to the bonds between the steel fiber and cement matrix. The bond between the hooked-end fiber and cement matrix exhibited better thermal stability in the temperature range 20°C–400°C because of the mechanical interlocking of the interface. In another study, polymeric fibers were added to prevent the thermal spalling of concrete via the generation of empty tunnels to release trapped vapor [127]. The geometry of the PP fiber generally influences its spalling suppression property. The effects of the cross section, length, type, and content of the fibers were studied by Maluk et al. [129], who determined that the addition of PP fibers with small cross sections, longer lengths, and greater content are more effective in the suppression of spalling. However, a different conclusion was proposed by Rudnik and Drzymała [130]. According to their research, the type (monofilament, fibrillated, and bundled), length (12 and 19 mm), and content (1.8 and 3.0 kg/m^3) of PP fibers have no significant influence on the thermal behavior and stability of concrete. Thus, further studies involving a more extensive range of parameters will have to be conducted.

Plant fiber is a good thermal insulation material because of its high porosity and water absorption. The thermal insulation capacity of fiber-reinforced cement composites therefore increases with an increase in plant-fiber content, and thus plant fiber has been applied to control the heat loss of fiber-reinforced cement composites. On the other hand, CF provides a different approach to enhancing the thermal properties of cement composites. CF has high thermal conductivity, which can limit sudden bursts and reduce the burst temperature.

NS, NF, NT, and CNT are commonly used as admixtures or additions for improving the thermal resistance of concrete. These nanoparticles result in high pozzolanic reactions, which increase the combined water content in cement composites and decrease the limits of their thermal expansion. These nanoparticles are more effective than microparticles, such as silica fume and fly ash, for improving the thermal resistance of cement composites. In a study by Mijowska et al. [131], NS and NF exhibited no apparent effects on the flexural strength of mortar at high temperatures and enhanced the compressive strength at temperatures less than 450 °C. Compared to NS, NF was observed to be more effective at improving thermal resistance. Farzadnia et al. [132], on the other hand, studied the influence of NT on the thermal resistance of cement composites at 1000 °C. The residual compressive strength of mortar containing 2% NT was improved at elevated temperatures, whereas the permeability resistance of the mortar was slightly damaged when the temperature reached 300°C. Similarly, Amin et al. [50] researched the influence of CNTs on the thermal resistance of cement bricks. The residual compressive strength of CNT-modified cement exhibited a 41% increase at 300°C compared to that of plain cement, which could be due to the improved stability of its microstructure at elevated temperatures.

5 Recent developments and future trends

5.1 Synergistic effects of fibers and nanomaterials

Many achievements at enhancing the performance of cement composites with a single type of fiber or nanomaterial have thus far been attained. Some studies have been conducted on combinations of two or more types of fibers and nanomaterials in cement composites. Hybrid effects of fibers were achieved via combinations of fibers of different types or scales. Hybrids of steel fibers and PP fibers have been widely used for enhancing the properties of cement composites [70]. An excellent synergistic effect of steel and PP fibers on the dynamic performance of cement composites was observed by Guo et al. [133] in their research. Meanwhile, a combination of three kinds of fibers, namely steel fibers, PP fibers, and polyester (PL) fibers, for cement composites was investigated by Koniki and Prasad [17]. In that study, the tensile and flexural strengths were improved because of the inhibition of crack growth. However, the application of polymeric fibers reduced its workability, leading to improper compaction. Therefore, the content of polymeric fiber should be limited to no more than 0.1%. The synergistic effects of the particle materials and fibers, on the other hand, were investigated in previous research. Ali et al. [134] conducted tests on the mechanical and durability performance of concrete that contains a high-performance mineral admixture silica fume and glass-fiber reinforcement. The results showed that combined incorporation of 0.5% fiber and 10% silica fume produced a better mechanical and durability performance, which exhibited a synergistic enhancing effect. Similarly, the synergistic effect of macrosteel fiber and microcellulose fiber was discovered and demonstrated by Banthia et al. [20]. With regard to hybrids of nanomaterials, on the other hand, CNF and CNTs were combined to enhance the flexural and compressive properties of cement composites, which affected the microstructure of hydration because of the multi-scaled crack bridging effect of the CNTs [70].

In a study by Mohseni et al. [96], a combination of NT and NS in cement mortar improved the chloride permeability, electrical resistivity, and compressive strength. The compressive strength of the mortar that contains both NT and NS was higher than that of mortar containing only either NT or NS at the same content. Meanwhile, according to Lee et al. [58], a combination of NS and CNT could also enhance the mechanical properties, permeability, and corrosion resistance of cement mortar. The NS and CNT modified the pore structures, filled the pores, and confined the crystalline growth of the matrix. The microstructure of the mortar was also denser because of the consumption of CH and the addition of C–S–H.

However, some challenges accompany the combination of micro- and nano-scale materials, including high price, difficulty in dispersion, and high SP demand of nanomaterials. According to Li et al. [95], the workability of mortar decreases in the presence of MS and NS, but could be compensated by SP. The synergistic effect of MS and NS on the mechanical properties and microstructure is significant because of the enhanced filling of the matrix. In a research study by Aydın et al. [75], a combination of fly ash and NS improved the fresh properties of concrete and limited segregation and bleeding. When CNT was then introduced to concrete that contains both fly ash and NS, the fresh and mechanical properties were further enhanced because of the higher energy-absorbing capacity of the CNTs.

5.2 Surface treatment on fibers

Good interfacial adhesion is vital to the performance of fiber-reinforced cement-based composites. Surface coating on steel fibers was often applied to provide efficient reinforcement and to obtain synergy between the fibers and cement matrix due to improved interfacial bonds [135]. One of the most commonly used types of coating for steel fibers is copper, which effectively prevents corrosion during transportation and storage. With regard to the influence of copper coating on interfacial properties, copper coating was observed to positively contribute to the interfacial bond between steel fibers and cement paste with the addition of a CaO-based expansive agent [136,137]. However, Li and Stang [137] determined that the interface strength for copper-coated steel fiber remains at a similar level as that for steel fibers and proposed that the dissolution of brass coating leads to weak adhesive strength at the interface. In addition to copper coating, several other coatings for steel fibers have been adopted to improve the interfacial properties or prevent corrosion of the fibers. He et al. [138] presented an approach for increasing interfacial strength by growing an NF coating on steel fibers using the electrodeposition method. Pi et al. [139] proposed a surface modification method for coating steel fibers with an NS multilayer film, achieving increased bond strength and pullout energy due to the chemical reaction between NS and the CH formed from cement hydration.

With regard to plant fibers, fiber pre-treatments are commonly implemented to improve the indices of performance, such as dimensional instability, durability, mechanical strength, of the resulting cement composites. Various processes, including silane treatment, acetylation, acrylation, alkali treatment, pulping, and hornification, have been investigated by researchers for the modification of plant fibers [39]. Alkali treatment has been suggested to be able to remove natural and artificial impurities and fibrillate fiber bundles into smaller fibers, thereby increasing the specific surface area. The obtained rough surface can offer higher resistance to pullouts of the fiber from the matrix due to the greater number of mechanical interlocks formed between them [122]. Li et al. [140] reported that a higher immediate and long-term toughness was achieved in alkali-treated coir-fiber-reinforced cement mortar because of the improved fiber–cement bond and toughness. Hornification, whereby fibers are alternately dried and re-wetted to irreversibly decrease the water retention value, has also been shown to enhance the fiber–cement interfacial bond [141] and durability of cement mortar composites [142]. A study by Ferreira et al. [141] showed that the adhesion stress and frictional stress of hornificated fibers in a cement mortar matrix increased by 40% and 50%, respectively. Claramunt et al. [142] also demonstrated that hornificated fibers can effectively improve the mechanical strength and durability of cement mortar composites.

5.3 3D printing of cement composites

3D printing of cement composites is a promising method for promoting the industrialization of construction. The cement composites are deposited through a nozzle to fabricate structural components layer by layer without formworks. Because plain concrete has a high compressive strength, whereas its flexural strength, tensile strength, and crack resistance are quite low, it is necessary to apply reinforcement to 3D printed cement. Existing fiber-reinforced systems can then be combined with 3D printing technology to produce enhanced 3D concrete structures in accordance with standard structural design specifications. Concrete incorporated with fibers has already been demonstrated to be compatible with current 3D concrete printing devices and technologies [29,85]. An effective solution for applying reinforcement to 3D printed cement is to add short fibers to 3D-printed cementitious composites. Weng et al. [143] experimentally studied the printability and mechanical properties of PVA-fiber-containing 3D-printed mortar. In that study, a novel 3D printed concrete with dimensions of 78 cm × 60 cm × 90 cm ($L\times W\times H$) was successfully fabricated. Meanwhile, in a study by Mechtcherine et al. [144], a new kind of reinforcement, namely mineral-impregnated CF, was added to 3D-printed concrete. The mineral-impregnated CF resulted in a more significant enhancement in the mechanical properties of concrete compared to those by polymeric fibers. The mechanical and anisotropic properties of PE-fiber-containing 3D-printed concrete were carefully examined in Ding et al.'s [145] study. Their results showed that ultimate strength and post-peak performance are related to the content, length, uniform, and aligned orientation of the fibers. Although PE-fiber-reinforced 3D-printed concrete still demonstrated anisotropic behavior, the flexural strengths in the directions parallel and perpendicular to the printing plane were enhanced, whereas the failure form was no longer dominated by a weak interface.

Printability and buildability are the two main processing factors for 3D-printed cement composites; therefore, highly thixotropic materials are more suitable for 3D concrete printing. Agitation prompts the mixed material to flow in the printer, which increases the printability during the 3D printing process. Meanwhile, semi-stiff materials extruded from the printer exhibit favorable buildability. Some nanomaterials are observed to have an immense effect on the thixotropy of cement composites, which is favorable for cement printing. In a research study by Shah et al. [8], a designed cement composite was modified with NC to achieve high flowability during casting and high green strength after placement. In addition, NC was determined to be able to effectively improve the thixotropy of concrete mixtures for 3D printing because of their charged edges and small particle sizes [54]. Meanwhile, Kruger et al. [146] studied the effect of NS on the thixotropic performance of 3D-printed concrete. The initial static yield shear stress and green strength of the 3D-printed concrete increased with increasing NS content. Moreover, the application of NS reduced the 3D printing construction time.

5.4 Multifunctional cementitious composites

The addition of fiber and nanomaterials not only enhances the mechanical properties of cementitious materials, but also modifies a number of functionalities, such as thermal, electrical, and electromagnetic properties [147,148]. The thermal conductivities of cementitious materials are closely related to their densities, especially for high-porosity concrete. If the dry density of fiber-reinforced foamed concrete, which can be in the range 300–1850 $kg\cdot m^{-3}$, is decreased from 800 to 600 $kg\cdot m^{-3}$, a 35% reduction in thermal conductivity may occur [149]. Natural fiber-reinforced foamed concrete also has excellent acoustical and thermal insulation characteristics due to its unique chemical composition and natural hollow structure [150]. Furthermore, the addition of natural fibers can modify the mechanical performance of reinforced foamed concrete, especially its toughness. According to Othuman Mydin et al. [49], the addition of coconut coir fiber can improve the compressive strength, flexural strength, and splitting tensile strength of concrete. The strength of foamed concrete increases as the volume percentage of coconut coir fiber increases from 0% to 0.4%. On the other hand, in a study by Mahzabin et al. [151], surface treatment was conducted on kenaf fiber to modify the surface morphology, enhance the surface roughness, and improve the surface adhesion between the fiber and cement matrix.

Nanocarbon materials (CNTs, CNFs, and GO) have unique electrical and thermal properties, which are widely used in multifunctional cementitious composites [152]. The electrical conductivity of CNT-modified composites has been revealed to increase when the composites are exposed to a smoking environment, and thus the material can be used as a smoke detector [153]. Cementitious materials with CNTs or CNFs also exhibit higher electrical conductivities, which are up to approximately eight times higher than that of plain cement [154]. Li et al. [155] determined that a small amount of NF can significantly affect the electrical resistances of cementitious composites, which decrease by 45% with 5% NF content. Furthermore, according to Luo et al. [156], the addition of CNTs increases the frequency response function amplitude (i.e., damping ratio) of composites. More interestingly, NT-containing cementitious composites can decompose organic pollutants and acid oxides by utilizing the photocatalytic effect of nanomaterials [157], which endows cement composites with air purification capabilities.

6 Concluding remarks

Because of the increasing demand for high-performance cement composites, the properties of cement composites, such as architectural versatility, excellent mechanical properties, and durability, have been undergoing continuous improvements. This paper reviewed the recent research trends in the improved performance of cement composites reinforced by fibers and nanomaterials. To pursue the overarching objective, three parts have been identified for this review: (i) types of fibers and nanomaterials used in the reinforcement of cement composites; (ii) enhancement of cement composites reinforced with fibers and nanomaterials; and (iii) application prospect of reinforced cement composites.

The first part includes the application status and basic properties of fibers and nanomaterials commonly used in cement composites. Steel and polymeric fibers occupy the main market for cement composite reinforcement because of their excellent mechanical properties and high commercialization. Synthetic fibers (including CF, glass fiber, and polymeric fiber), mineral fibers, and plant fibers are becoming a new alternative for reinforcement because of their unique characteristics, such as high specific strength, low cost, low energy consumption, and local availability. NS is the most popular nanoparticle used in current research on nanomodified cement composites because of its mature technology and cost. CNTs and CNF also attract much attention as 1D nanomaterials, which have the advantages of both nanomaterials and fibers.

The second part of the research concerns the mechanical properties, fresh properties, durability, and thermal properties of cement composites reinforced with fibers and nanomaterials. The literature reviewed in this section highlights both the internal and external causes influencing these properties. As an internal cause, the enhancement of cement composite with a certain fiber or nanomaterial is effective but limited. Steel fiber leads to better performance in the enhancement of mechanical properties, whereas polymeric fibers have more advantages in terms of durability and thermal property improvement. The supporting role of nanomaterials is concentrated on the compressive strength and permeability resistance; only CNTs and CNF can combine fiber reinforcement and nanomodification. As an external cause, the surface treatment and dispersion method of fibers, and the application of SP also affect the enhancement. Because of the alkali environment in cement composites, both mineral fiber and plant fiber require surface treatment to prevent interaction between the fiber and cement matrix and to strengthen the interfacial adhesions. The dispersion method mainly affects the orientation and distribution of the fibers, which can cause variations in flexural strengths greater than 50%. Furthermore, the addition of fiber and nanomaterials usually negatively affects the flowability of cement composites, and thus additional SP is recommended to maintain the flowability at acceptable levels.

The third part of the research concerns hybrids of multiple reinforcements and reinforced cement composites applied in the 3D printing area. Hybrids of fibers and nanomaterials are a promising way of producing high-performance cement composites because of the synergistic effects of nanomaterials or fibers. Detailed studies on the mechanisms of these synergistic effects are required to provide a mix-proportion design method for cement composites reinforced with hybrid fibers and nanomaterials. Furthermore, the addition of fibers and nanomaterials can affect the fresh properties of cement composites, which provide a basis for the modification of its printability and buildability. Further research on the application of fibers and nanomaterials in 3D-printed cement composites should be conducted, to pursue its practical applicability in 3D printing construction.

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