Review Article

Mahdi Hosseini*, Milan Gaff*, David Hui, Petr Konvalinka, Hynek Maňák, Haitao Li*, Ahmad Hosseini, and Pritam Ghosh

Studying the effect of nanofillers in civil applications: A review

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Abstract: The incorporation of nanofillers into structures has revolutionised the field of civil engineering. By enhancing mechanical, thermal, and functional properties, nanofiller-reinforced cemented structures offer solutions to challenges in durability, strength, and sustainability for modern construction. This article reviews the advances in nanofiller-reinforced fibre-reinforced polymer laminates, emphasising their role in civil applications, such as structural reinforcement, seismic retrofitting, and long-term durability improvements. The study also explores challenges in manufacturing, scalability, and environmental impact, providing directions for future research and large-scale adoption.

Keywords: FRP, nanoparticles, nanofillers and their properties, durability, strength

*** Corresponding author: Mahdi Hosseini,** College of Civil Engineering, Nanjing Forestry University, Nanjing, 210037, China; Jiangsu Highway Intelligent Detection and Low Carbon Maintenance Engineering Technology Research Center, Nanjing, 210037, China, e-mail: civil.mahdi.hosseini@gmail.com

*** Corresponding author: Milan Gaff,** Department of Furniture, Design and Habitat Brno, Mendel University in Brno, Brno, 61300, Czech Republic; Faculty of Civil Engineering, Experimental Centre, Czech Technical University in Prague, Thakurova 7, 166 29, Prague 6, Czech Republic, e-mail: gaffmilan@gmail.com

*** Corresponding author: Haitao Li,** College of Civil Engineering, Nanjing Forestry University, Nanjing, 210037, China; Jiangsu Highway Intelligent Detection and Low Carbon Maintenance Engineering Technology Research Center, Nanjing, 210037, China, e-mail: lhaitao1982@126.com

David Hui: Department of Mechanical Engineering, University of New Orleans, New Orleans, LA, 70148, United States of America

Petr Konvalinka: Faculty of Civil Engineering, Experimental Centre, Czech Technical University in Prague, Thakurova 7, 166 29, Prague 6, Czech Republic

Hynek Maňák: Department of Furniture, Design and Habitat Brno, Mendel University in Brno, Brno, 61300, Czech Republic

Ahmad Hosseini, Pritam Ghosh: Fiber Composite Laboratory, Hindustan Institute of Technology and Science, Chennai, 603103, India

1 Introduction

Composites are a class of materials that have gathered significant interest across multiple domains, including electronics, sports, biomedical applications, aircraft, and automotive sectors [1–3]. They consist of two or more components, each exhibiting unique characteristics such as elevated stiffness, strength, reduced thermal expansion, and resilience to environmental deterioration [4–6]. The necessity for composites emerges from the observation that a singular material frequently lacks all the requisite qualities. However, this can be accomplished by judiciously integrating various materials to attain the intended result. The essential elements of composites are the matrix and the reinforcement. The composite type also varies based on the selected matrix and reinforcement. The need for innovative materials in civil engineering has driven significant advancements in composite technology. Fibre-reinforced polymers (FRPs) have gained attention due to their high strength-to-weight ratio, corrosion resistance, and design flexibility. The integration of nanofillers, such as carbon nanotubes (CNTs), graphene, nano-silica (NS), and nanoclays, into FRP laminates has further enhanced the mechanical properties, enabling their use in more demanding applications. This article explores the potential of nanofillers in addressing key challenges in civil engineering, including improving the performance of structures under mechanical, thermal, and environmental stresses.

FRPs have become increasingly significant in civil engineering applications due to their advantageous properties, such as high strength-to-weight ratio, corrosion resistance, and ease of application. These materials are particularly valuable in the reinforcement and rehabilitation of concrete structures, offering a sustainable alternative to traditional materials. The use of FRPs in civil applications is diverse, encompassing various structural components and methods of installation.

Severe load conditions may result in damage to structures, and their replacement is an expensive undertaking. Consequently, structures are designed to endure significant loads in adverse environmental conditions and transient dynamic stresses. Due to this concern, numerous techniques have been employed across diverse contexts, including fibre-reinforced plastics. Carbon fibre-reinforced polymer (CFRP) composites serve as an exceptional alternative to numerous materials due to their compelling combination of properties and evident advantages. Bounjoum *et al.* [7] demonstrated that CFRP reinforcement enhanced the flexural strength of concrete beams by 45% and substantially improved the crack resistance. The load-bearing capability of the beams was augmented by 40% relative to unreinforced specimens.

The superior physical and mechanical properties of nanofillers may improve different aspects of concrete that exhibits quasi-brittle behaviour. But, to the authors' best knowledge, there is no consensus yet on the contribution of nanofillers to mechanical properties. Some researchers have reported significant improvements in mechanical properties [8–10], while others have reported negligible improvement or even degradation in mechanical properties [11,12].

The incorporation of nanofillers in civil engineering materials has garnered significant attention due to their potential to enhance the mechanical, thermal, and durability properties of construction materials. Nanomaterials such as CNTs, graphene oxide (GO), silica nanoparticles, and nanoclays have been widely studied for their reinforcing capabilities in cementitious materials, asphalt mixtures, and polymer composites. While studies have demonstrated improvements in material properties with the addition of nanofillers, the optimal content to maximise benefits while maintaining cost-effectiveness and processability remains unclear. Excessive nanofiller content can lead to agglomeration and uneven dispersion, adversely affecting material performance. Limited research has explored the long-term behaviour of nanofiller-modified materials under environmental conditions such as freeze–thaw cycles, UV exposure, and chemical attack. Understanding these effects is crucial for ensuring the reliability and sustainability of nanofiller-enhanced materials. Achieving a uniform dispersion of nanofillers in construction materials is a critical challenge. The environmental footprint and cost implications of producing and incorporating nanofillers in civil materials need to be thoroughly assessed. This includes the energy-intensive production of nanofillers and their lifecycle analysis compared to conventional materials. The presented article addresses these gaps, which will pave the way for efficient and sustainable application of nanofillers in civil engineering, ensuring enhanced material performance while meeting economic and environmental criteria.

2 FRP-reinforced concrete beams strengthened in shear

Reinforced concrete beams strengthened in shear using FRPs exhibit enhanced load-carrying capacity and reduced risk of brittle shear failures [13]. Proper estimation of shear force contribution and appropriate FRP application methods are crucial for effective strengthening. The use of FRP sheets, including configurations like two-sided or fully wrapped systems, has been shown to effectively enhance shear strength by increasing the load-carrying capacity of beams [14]. Research has shown that reinforced concrete components with externally bonded FRP plates are prone to ageing and may experience FRP debonding under comparatively modest loads. Near-surface mounted (NSM) is an innovative reinforcement technique that employs FRPs placed into slots created in the concrete overlay of reinforced concrete structures. Numerous studies have looked at the application of NSM in the shear strengthening of reinforced concrete structures [15–18]. Fayed *et al.* [19] worked on reinforcement of shear-critical RC beams by the integration of prestressing and NSM rod techniques. They studied structural performance for cracking load, ultimate load, load-deflection response, ultimate deflection, and stiffness. The study revealed that combining prestressed NSM rods with internal prestressing has resulted in shear capacity increases of up to 70.4%, showcasing the effectiveness of hybrid strengthening methods. Huang *et al.* [20] found that concrete beams reinforced with CFRP grids improved shear capacity, with grid dimension and stirrup ratio significantly influencing performance. Horizontal fibres provided anchoring effects, enhancing stress distribution and overall shear behaviour of the beams. The shear strength improvement is influenced by the load levels during strengthening, with a noted reduction in effectiveness as the applied load increases.

The integration of polyphenylene benzobisoxazole (PBO or Zylon) fibres in a cementitious matrix has been found to improve shear strength by up to 25%, although effectiveness diminishes under higher load conditions [21]. Figure 1 presents the shear failure of beams consisting of different beam configurations. Table 1 presents the use of different nanoparticles.

The incorporation of nanoparticles in FRP strengthened reinforced concrete beams significantly enhances shear strength and structural performance due to several synergistic effects [33–37]. Nanofillers such as NS, CNTs, and GO improve the tensile strength and ductility of the concrete matrix by refining the microstructure and strengthening the interfacial transition zone (ITZ) between the cement paste and aggregates. This enhancement delays crack initiation and

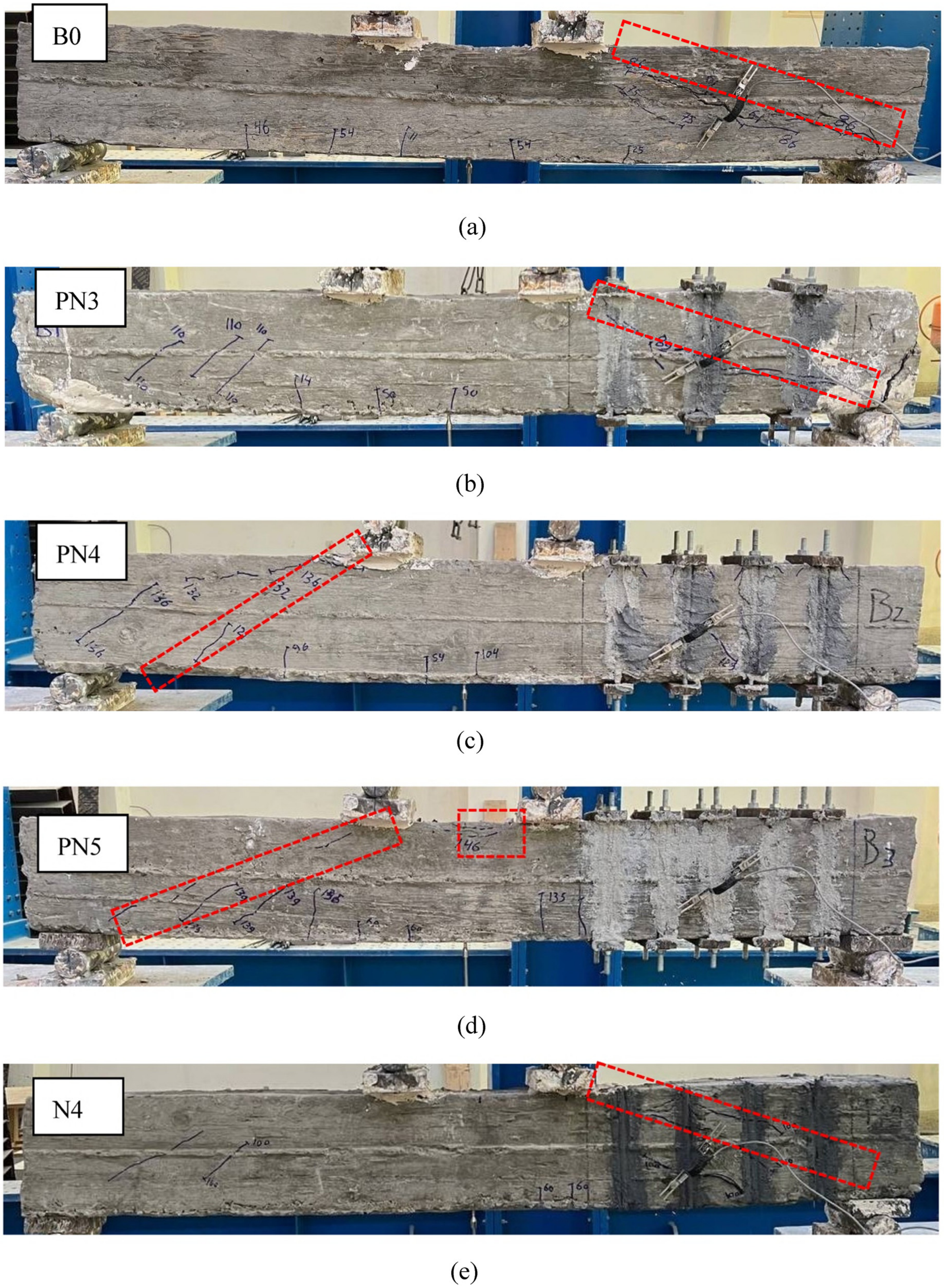

Figure 1: Shear failure of beam under different conditions [19]. (a) Unstrengthened beam (B0). (b) Externally strengthened beam with three prestressing pair tendons (PN3). (c) Externally strengthened beam with four prestressing pair tendons (PN4). (d) Externally strengthened beam with five prestressing pair tendons (PN5). (e) NSM rods without prestressing.

Table 1: Use of different nanoparticles

Sample no.	Ref.	Nanoparticles	Property enhancement
1	Mohajerani *et al.* [22]	NS	Rapid hydration mechanical strength
	Liu *et al.* [23]		Durability
2	Jenima *et al.* [24]	Nano-TiO_2	Increased degree of hydration
	Chen *et al.* [25]		Mechanical strength
			Durability
3	Atiq Orakzai [26]	Nano-Al_2O_3	Enhanced mechanical properties
			Enhanced compactness of ITZ
4	Kim *et al.* [27]	CNTs	Mechanical strength and self-healing
5	Li *et al.* [28]	Graphene nanoparticles	Mechanical, self-sensing, and self-healing
6	Najafi Kani *et al.* [29]	Nano-Fe_2O_3	Abrasion resistance and compressive strength
7	Hosseini *et al.*, [30]	Nanoclays	Increase surface roughness and compressive strength
8	Amin and Abu el-Hassan [31]	(Ni ferrite)	Compressive strength
		(Cu–Zn ferrite)	
		NS	
9	Ren *et al.* [32]	Nano-titanium dioxide	Compressive strength
		NS	

reduces crack propagation under shear loads. Additionally, nanofillers contribute to crack-bridging and energy dissipation mechanisms, which increase the beam's ability to resist diagonal tension failures typically associated with shear. These combined effects result in higher ultimate shear capacity and improved performance under both monotonic and cyclic loading conditions.

This advancement is attributed to the improved ITZ and the mechanical properties of the concrete matrix, which are bolstered by the addition of nanomaterials. The use of multi-walled carbon nanotubes (MWCNTs) and NS has been shown to improve the tensile and shear strength of concrete, addressing its inherent weaknesses [38,39]. Studies indicate that beams with NS exhibited a notable increase in ultimate load capacity, with improvements of up to 39% depending on the NS ratio and shear span-to-depth ratio [39]. Research demonstrates that beams containing nanoparticles, such as nano-titanium (NT) and nano-aluminium, perform better under both monotonic and cyclic loading conditions, showing enhanced load-deflection characteristics and reduced cracking [40]. The inclusion of nanoparticles in the adhesive layers of FRP systems has been linked to improved interlaminar shear strength and fatigue resistance, which are crucial for maintaining structural integrity under load [41].

3 Nanofillers and their properties

In general, nanomaterials have been utilised in enhancing the performance of concrete due to their compact microstructure influence and hastening the reaction of cement hydration [42,43]. The incorporation of nanofillers in shear-critical RC beams significantly enhances their structural performance, particularly in terms of shear strength and crack resistance. Various studies have demonstrated that nanomaterials, such as NS, CNTs, nano-titanium and graphene nanoparticles, improve the mechanical properties of concrete, leading to better load-bearing capabilities and reduced crack propagation. The following sections detail the effects of these nanofillers on concrete structures.

The incorporation of nanomaterials into cement-based composites fundamentally alters key concrete parameters. Nanomaterials such as NS, CNTs, and GO increase the rate of hydration and refine the microstructure, leading to higher compressive and tensile strength. They reduce the total porosity and pore size distribution, improving the density and permeability resistance of concrete. NS, in particular, reacts pozzolanically with calcium hydroxide to form an additional calcium silicate hydrate (C–S–H) gel, which enhances the bonding matrix. CNTs contribute to higher flexural strength and modulus of elasticity by bridging microcracks and delaying their propagation. Additionally, nanomaterials improve the resistance to freeze–thaw cycles, sulphate attack, and chloride ion penetration, thereby extending the durability and service life of concrete. The resulting nanomodified concrete exhibits superior mechanical and durability characteristics compared to conventional mixes, even at low nanomaterial dosages (typically ≤3 wt%).

3.1 NS

The use of NS, a highly reactive pozzolanic material composed of ultrafine silicon dioxide particles, has garnered significant attention in civil applications due to its ability to enhance the mechanical and durability properties of concrete. NS, when incorporated into concrete, reacts with calcium hydroxide to form additional calcium silicate hydrate, which improves the concrete's strength and durability. This makes it a promising material for various civil engineering applications, including ultra-high-performance concrete (UHPC) and recycled aggregate concrete (RAC).

The use of NS in civil applications, particularly in UHPC, enhances mechanical properties and microstructural characteristics [44,45]. UHPC is a pioneering construction material noted for its exceptional strength, durability, and versatility. It is composed of carefully selected components, including fine particles, fibres, and specialised admixtures, achieving compressive strengths exceeding 120 MPa, markedly surpassing conventional concrete [46,47]. It improves compressive, split tensile, and flexural strength, with optimal results observed at 2% addition by cement weight. The nucleation effect of NS promotes the formation of a calcium silicate hydrate gel, resulting in a denser concrete matrix with lower porosity. This leads to stronger, more durable concrete, making it suitable for various civil engineering applications [48]. Vandhiyan *et al.* [49] experimentally investigated the effects of corrosion on reinforced concrete beams with NS, emphasising the bond strength characteristics. The compressive strength of concrete, assessed at 28 days, varied from 15.88 to 31.77%, corresponding to the incorporation of 1.5% NS by weight of binder, which was identified as the optimum dosage. Compressive strengths varied from 5.50 to 15.67% when assessed at 60 days. Incorporating 1.5% NS into the binder weight produced an optimum mixture with improved strength characteristics. The flexural strength, assessed at 28 days, varied from 16.53 to 42.99% for different amounts of NS. The tensile strengths at 28 days varied from 7.90 to 15.79% with differing amounts of NS. Rezaifar *et al.* [8] examined the compressive strength of concrete with NS and steel fibres. It was determined that incorporating up to 10% NS as a cement substitute and 1% steel fibres enhanced the compressive strength by 88.79 and 59.69% for 7-day and 28-day specimens, respectively. Furthermore, compressive strength improved by 152.26 and 114.03% for specimens containing 10% NS and 1% steel fibres at 7 and 28 days, respectively. Additionally, the rate of compressive strength increase in the 7-day specimens exceeded that of the 28-day specimens. Figure 2 presents the effect on compressive strength for NS content.

NS promotes the hydration process and induces a nucleation effect, which leads to the formation of more amount of calcium silicate hydrate gel, resulting in a denser concrete matrix with lower porosity. In RAC, NS enhances compressive strength and reduces porosity, leading to a denser ITZ and increased resistance to chloride penetration. The pozzolanic reaction of NS at later stages further densifies the microstructure and reduces the pore size, enhancing the durability of the concrete. While NS offers numerous advantages, it is important to consider its impact on the workability of concrete. The addition of NS can decrease the workability, which may require adjustments in mix design or the use of superplasticisers to maintain desired consistency [51–53]. The use of NS in concrete not only improves performance but also offers environmental and economic benefits. It allows for the use of recycled materials, such as rice husk ash, to produce NS, which can be cost-effective and sustainable [54]. The incorporation of NS in UHPC demonstrates significant potential for advancing concrete technology by augmenting strength, durability, and sustainability in forthcoming infrastructure initiatives. Table 2 presents the effect of NS nanofiller on compressive strength.

3.2 NT

NT nanoparticles are produced, yielding particles that range in size from 1 to 100 nm. Their nanometre scale offers a significant specific surface area, greatly enhancing their reactivity [63]. Three different phases of TiO_2 exist: rutile, anatase, and brookite. These stages possess certain attributes that render them appropriate for diverse potential applications [64]. The use of NT nanofillers in civil

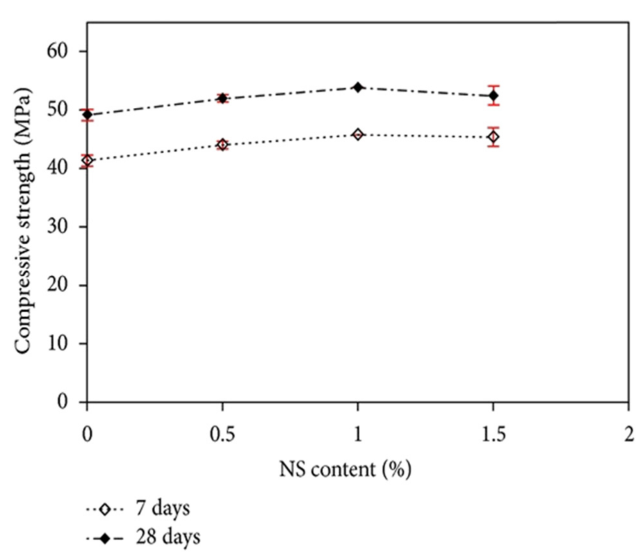

Figure 2: Effect on compressive strength of NS content (%) [50].

applications has garnered significant attention due to their ability to enhance the mechanical properties of construction materials and their environmental benefits. These nanoparticles are primarily utilised for their photocatalytic properties, which contribute to self-cleaning surfaces and pollution reduction. These applications are particularly relevant in urban environments where air pollution is a major concern. The integration of NT into construction materials like concrete and mortar not only improves their strength and durability but also offers innovative solutions for environmental challenges. NT improves the strength and durability of concrete and mortar. Studies have shown that incorporating NT in proportions ranging from 0.5% to 12% can significantly enhance the mechanical properties of these materials [65]. The nanostructure of TiO_2 contributes to the formation of a denser cementitious matrix, which results in improved elastic properties and resistance to environmental degradation [66].

NT photocatalytic properties enable it to degrade air pollutants such as nitrogen oxides and sulfur oxides into non-harmful substances. This makes it an effective material for reducing pollution in urban areas with high-rise buildings [67,68]. The application of TiO_2 as a coating on building exteriors can significantly lower the concentration of air pollutants, contributing to cleaner urban environments. The photocatalytic action of TiO_2 also imparts self-cleaning properties to surfaces, reducing maintenance costs and enhancing the aesthetic longevity of buildings. This is particularly beneficial for structures exposed to environmental pollutants [65]. While TiO_2 nanofillers offer numerous benefits, challenges such as determining the optimal dosage and understanding the synergistic effects with other materials remain. Additionally, the economic and environmental implications of large-scale TiO_2 use in construction need further exploration to ensure sustainable application [66]. Various enhancements in compression properties due to the infusion of NT are presented in Table 3.

Table 2: Effect of NS nanofiller on compressive strength

Ref.	Nanofiller (wt%)	Days	Enhancement (%)
El-Baky *et al.* [55]	7	28	55.7
Rezaifar *et al.* [8]	10	7, 28	88.8, 59.7
Alvee *et al.* [56]	5	28	33.63
Ren *et al.* [32]	3	28	16
Althoey *et al.* [57]	0.4, 0.8	28	10, 13
Torabian Isfahani *et al.* [50]	1.5	7, 28	30.3, 41.2
Kong *et al.* [58]	1	208	12
Tobón *et al.* [59]	5, 10	28	11, 87
Behzadian and Shahrajabian [60]	3	28	30
Li *et al.* [61]	0.5, 1	28	11.4, 23
Wang *et al.* [62]	1, 2, 3	3	14.2, 18, 23.5
Wang *et al.* [11]	1, 2, 3	28	3.2, 13.3, 16.8

3.3 CNTs

The incorporation of CNTs into cement-based materials significantly enhances their mechanical properties, making them highly beneficial for civil engineering applications. CNTs improve the compressive and flexural strength, modulus of elasticity, and durability of cementitious composites. These enhancements are attributed to the unique properties of CNTs, such as their high aspect ratio and excellent mechanical strength, which contribute to the improved performance of the composites. The addition of CNTs to cement mortar has been shown to improve both compressive and flexural strength. For instance, mortar samples with treated CNTs exhibited superior strength compared to untreated samples and control specimens [82,83]. Mousavi and Bahari [84] found that the addition of 0.05 wt% functionalised MWCNTs significantly improved the mechanical properties of cement paste. Compressive strength increased by approximately 14, 8.7, and

Table 3: Effect of NT nanofiller on compressive strength in 28-day testing

Sample no.	Ref.	Nanofiller (wt%)	Enhancement (%)
1	Huang *et al.* [69]	1	64.65
2	Meng *et al.* [70]	2	17
3	Noorvand *et al.* [71]	1.5	19.06
4	Mohseni *et al.* [9]	1	85
5	Rahim and Nair [72]	1.5	33
6	Martins *et al.* [73]	2	15.8
7	Han *et al.* [74]	5	11.7
8	Wang *et al.* [62]	2	4
9	Staub de Melo and Trichês [75]	2	22.71
10	Reches *et al.* [76]	1	18.03
11	Kang *et al.* [77]	5	21
12	Joshaghani *et al.* [78]	3	11.2
13	Janczarek *et al.* [79]	3	36
14	Rawat *et al.* [80]	4	29.05
15	Zhang *et al.* [81]	1	10

26.6% at 3, 7, and 28 days, respectively. Similarly, flexural strength was enhanced by factors of approximately 3.214 compared to control specimens, as reported by Mousavi and Bahari [84]. These high values are attributed to the use of functionalised MWCNTs, which significantly improved the dispersion, interfacial bonding, and crack-bridging ability within the cement matrix. Additionally, the control specimens exhibited relatively low baseline strength, which amplified the relative increase. This indicates that MWCNTs can effectively enhance mechanical properties in civil applications.

CNTs contribute to increased durability by reducing porosity and water absorption, thus enhancing resistance to environmental attacks such as sulphate exposure [82]. Liu *et al.* [85] discussed the application of CNT–cement-based composites in the optimisation design of civil building structures. The study highlights the advancements in one-dimensional nanomaterials and their impact on construction materials. The presented research findings demonstrate significant improvements in various structural properties. When using CNT-reinforced composites, there were a 7.26% enhancement in seismic resistance, an 11.17% increase in stability, a 10% improvement in material quality, and an 11.21% boost in resistance to external factors, thereby enhancing the overall safety and performance of building structures. Chiadighikaobi *et al.* [86] reviewed the reinforcing cementitious concrete with CNTs, addressing the concerns related to the quasi-brittle behaviour of conventional concrete that leads to cracking and reduced durability in structural applications. It highlights the potential of CNTs to enhance the macromechanical properties of concrete, making it a more effective structural material. The study discusses the development and characterisation of cement-based materials reinforced with CNTs, comparing their effects to other reinforcing fibres. It also examines the environmental impact and sustainability of using CNTs in concrete production, emphasising their significant potential to improve the performance and durability of cement-based materials.

Kim *et al.* [27] investigated the use of CNTs in concrete, focusing on mechanical properties and the challenges associated with their dispersibility when mixed with cement paste. It highlights the tendency of CNTs to form bundles or aggregates due to their high aspect ratio and van der Waals forces, which complicates their effective integration into concrete. The study specifically examines the effectiveness of aqueous dispersions of CNTs prepared with poly-carboxylic-based surfactants, comparing their properties to those of PVP-based dispersions. It aims to demonstrate the enhancement of mechanical properties, such as compressive and flexural strength, through the use of these CNT dispersions in cementitious composites. The obtained enhancement in compression and flexural properties is depicted in Figures 3 and 4.

3.4 Graphene nanoparticles

GO is attracting attention primarily due to the close packing effect [87] and nucleation effect [88]. GO also exhibits remarkable mechanical properties, with an elastic modulus reaching 300 GPa and an intrinsic strength of 112 GPa [28]. The hydration degree of cementitious composites can be enhanced following the incorporation of GO, resulting in a more compact structure with improved mechanical and durability properties. The GO nanoparticles can modulate the morphology of

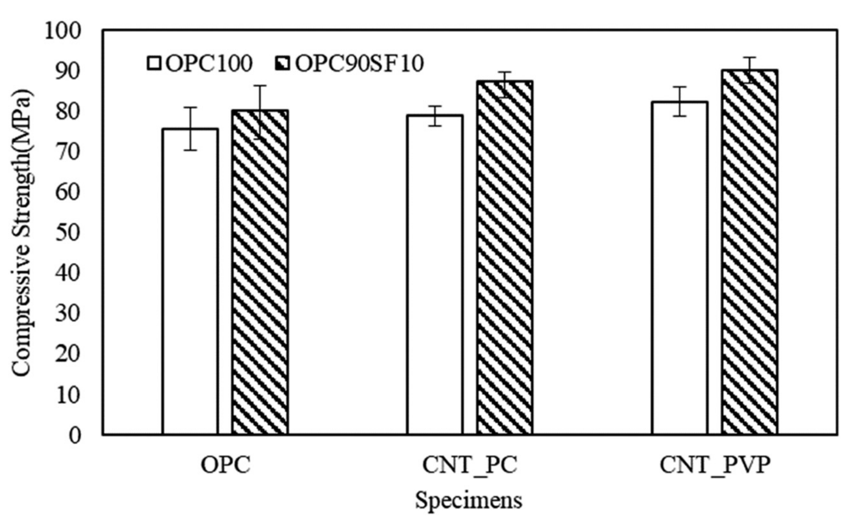

Figure 3: Effect of compressive strength on CNT-reinforced cement composite [27].

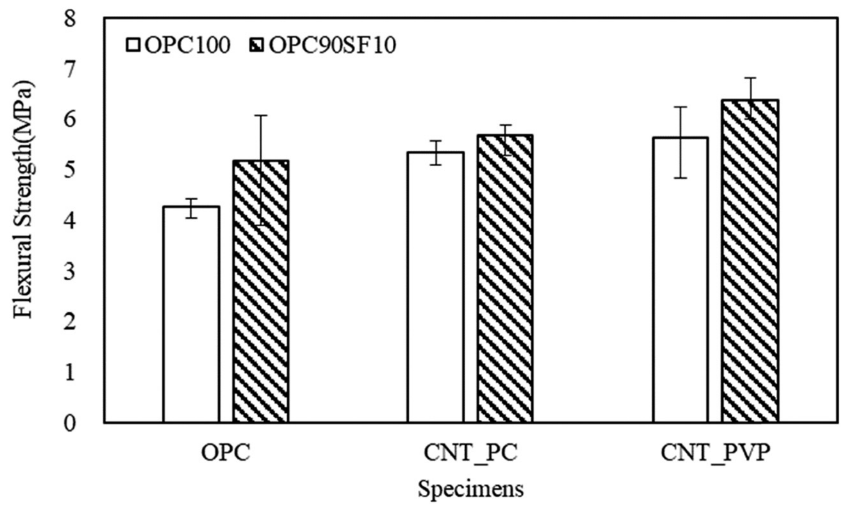

Figure 4: Effect of flexural strength on CNT-reinforced cement composite [27].

cement hydration products [89], thereby enhancing the mechanical and transport properties of concrete. Furthermore, prior studies have demonstrated that the beneficial effects of GO are evident when a minimal mix fraction of GO is utilised [90], and advancements in nanotechnology have significantly decreased the costs associated with industrial-scale GO manufacturing. Nonetheless, previous research has primarily concentrated on the influence of GO on the mechanical and durability properties of underwater concretes; moreover, nearly all prior studies were conducted in laboratory settings, neglecting the impact of water on GO-infused cementitious composites, which may render the identified degradation mechanisms unsuitable for actual underwater conditions.

Graphene nanoparticles, particularly GO and graphene nanoplatelets (GNPs), have shown significant potential in enhancing the mechanical properties of cementitious materials in civil engineering applications. These enhancements are primarily due to the nanoparticles' ability to improve the microstructure of the composites, leading to increased strength and durability. Incorporation of GO and GNPs has been shown to significantly enhance the compressive strength of concrete and mortar. For instance, GO incorporation improved compressive strength by 4.37–9.82% in mortar specimens immersed in a river for 3 years [91]. Similarly, GNPs increased the compressive strength of 3D-printed mortar from 70.7 to 133.3 MPa [92]. In another study, GNPs enhanced the compressive strength of concrete by 16.58% at a concentration of 0.1% [93]. Figure 5 presents the effect of GO on the compressive strength of UHPC. Similarly, GO and GNPs also improve flexural and tensile strengths. GO incorporation resulted in flexural strength improvements of 7.78–22.33% and tensile strength enhancements of 8.14–28.73% [91]. GNPs in 3D-printed mortar increased flexural and tensile strengths to 20.66 and 14.67 MPa, respectively. Figures 6 and 7 present the effect of GO on flexural and tensile strength of UHPC. GO enhances the durability by reducing the porosity and improving the resistance to leaching and cracking, which is crucial for marine infrastructure. Additionally, GO improved abrasion resistance by 23% at 28 days in concrete mixes [94].

4 Advantages of nanofiller reinforcement

Nanofiller reinforcement refers to the integration of nano-scale additives (typically <100 nm in size) into construction materials such as concrete or FRPs to enhance their

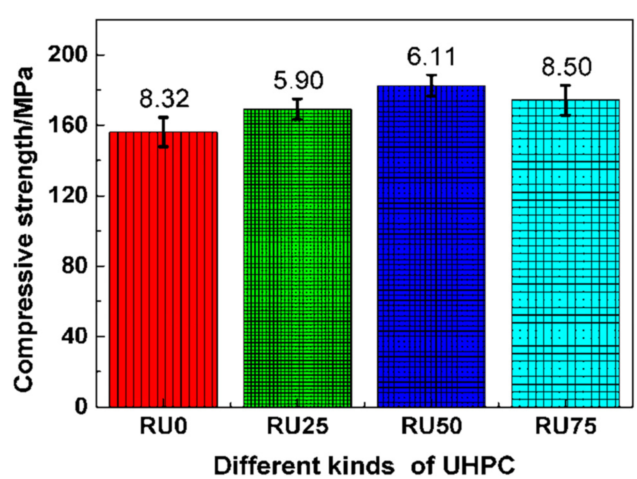

Figure 5: Compressive performance of recycled-sand-based UHPC at different GO contents and recycled sand replacement ratios: RU0 (0%), RU25 (25%), RU50 (50%), and RU75 (75%) [90].

performance. These nanofillers act as secondary reinforcements, improving mechanical strength, stiffness, durability, and crack resistance by modifying the microstructure and interfacial bonding characteristics of the matrix. Nanofiller reinforcement has revolutionised the construction industry by significantly enhancing the performance and durability of materials used in civil structures. These nanofillers, often composed of nano-sized particles such as CNTs, graphene, nanoclays, or NS, are incorporated into traditional construction materials to improve their mechanical, thermal, and chemical properties. One of the primary advantages is the remarkable increase in mechanical strength and stiffness, enabling materials like concrete and polymer composites to withstand greater loads. Additionally, the inclusion of nanofillers enhances impact resistance and fracture toughness, making structures more resilient to mechanical stresses and environmental challenges.

Durability is another critical benefit of nanofiller reinforcement. Nanoparticles help arrest micro-cracks in materials, preventing their growth and thereby extending the lifespan of structures. Furthermore, nanofiller-reinforced materials exhibit improved resistance to environmental degradation, including moisture, UV radiation, and temperature variations, ensuring long-term stability and reduced maintenance requirements. Nanofillers also contribute to superior thermal and fire resistance, particularly with materials like nanoclays and graphene, which enhance a structure's ability to endure high-temperature conditions.

Another significant advantage is the potential for creating lightweight yet robust structures. By enhancing the strength of materials without adding large quantities of materials, nanofillers enable the construction of lighter buildings and infrastructure, reducing the overall structural weight while maintaining or even improving the load-bearing capacity. They also improve the ductility, allowing structures to absorb and dissipate energy during dynamic events like seismic activity, thus increasing their resistance to damage from such loads [95].

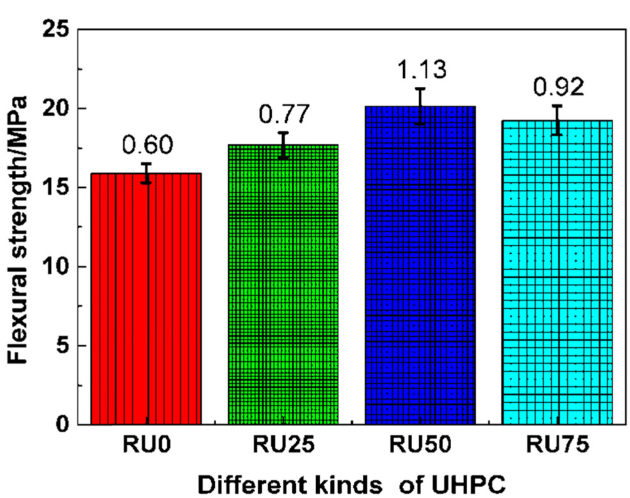

Figure 6: Flexural performance of recycled-sand-based UHPC at different GO contents and recycled sand replacement ratios: RU0 (0%), RU25 (25%), RU50 (50%), and RU75 (75%), where natural sand is replaced with recycled sand [90].

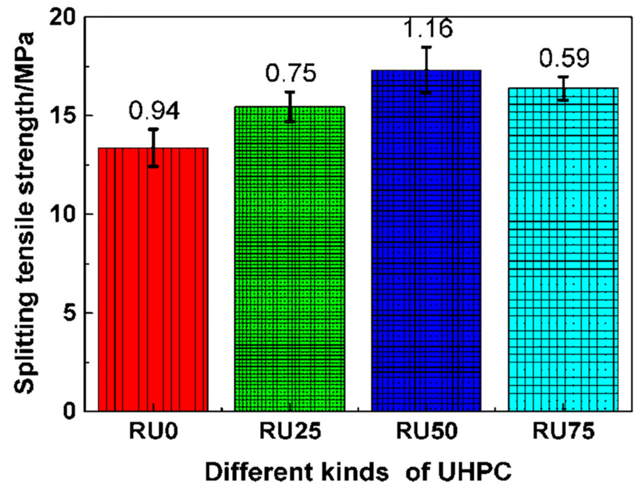

Figure 7: Tensile performance of recycled-sand-based UHPC at different GO contents and recycled sand replacement ratios: RU0 (0%), RU25 (25%), RU50 (50%), and RU75 (75%), where natural sand is replaced with recycled sand [90].

Nanofillers also introduce advanced functionalities, such as self-healing properties in construction materials. Certain nanofillers can react with external agents, like moisture, to autonomously repair micro-cracks, enhancing the durability and reducing the need for frequent repairs. From a sustainability perspective, the improved efficiency and extended lifespan of nanofiller-reinforced materials reduce the consumption of resources, making construction practices eco-friendly. While the initial costs of incorporating nanofillers may be higher, the reduced maintenance and replacement expenses over time contribute to long-term cost-effectiveness.

Among various nanofillers, NS is one of the most widely studied and cost-effective options, offering consistent improvements in compressive strength, microstructure refinement, and durability. CNTs exhibit the highest mechanical performance due to their excellent tensile strength and crack-bridging capabilities, but they require advanced dispersion techniques and are costlier. Therefore, NS offers the best balance between performance, cost, and ease of use, especially for large-scale civil applications.

5 Applications in civil engineering

Applications of nanofillers in civil engineering are diverse, ranging from high-performance concrete and asphalt to reinforced composite beams and columns. They are also widely used in protective coatings and sealants for corrosion resistance, as well as in the construction and repair of bridges and lightweight prefabricated panels. By integrating nanofillers into civil structures, engineers can achieve stronger, smarter, and more sustainable infrastructure that meets the demands of modern construction.

Nanofillers significantly enhance the mechanical properties of materials, making them more resilient to extreme loads and environmental conditions [96,97]. The use of nanofillers can reduce the environmental impact of construction materials by improving their longevity and reducing the need for frequent repairs [98]. The application of nanofillers as structural reinforcement in civil structures has gained significant attention due to their ability to enhance the mechanical properties and durability of construction materials. Nanofillers, such as CNTs, graphene, and nanoclays, are integrated into traditional materials like concrete and polymers to improve their performance under various conditions. This integration not only strengthens the materials but also promotes sustainability in construction practices. CNTs are known for their exceptional strength-to-weight ratio. CNTs enhance the tensile strength and ductility of concrete [51]. Graphene nanomaterials improve the electrical conductivity and mechanical properties of composites, making them suitable for advanced structural applications [99]. Nanoclays improve the compressive strength and durability of concrete by enhancing the bonding between cement particles [98].

5.1 Beam and column reinforcement

The incorporation of nanofillers in beam and column strengthening presents a transformative approach in civil engineering, enhancing the mechanical properties and durability of concrete structures. Nanomaterials, such as NS and nanoclays, have been shown to significantly improve the compressive strength and overall performance of concrete, making them valuable in structural applications. The incorporation of nano-fillers in beam and column strengthening primarily enhances the properties of the concrete matrix surrounding the existing steel reinforcement. Nanomaterials such as NS or nanoclays refine the ITZ, reduce microcracks, and improve bond strength between steel and concrete. This leads to improved load transfer, increased confinement efficiency, and better synergy between the reinforcement and the surrounding material. Importantly, nano-fillers do not physically interfere with the placement or geometry of existing reinforcement but serve to enhance its effectiveness by strengthening the surrounding matrix [8,82]. NS acts as a partial replacement for cement, filling voids and enhancing the microstructure of concrete, leading to increased strength and durability [100]. Research indicates that while NS can enhance strength, improper combinations with other materials, like dolomite powder, may lead to reduced strength. While nanoclays improve the bonding between cement particles, resulting in enhanced mechanical properties and sustainability of concrete structures [98]. Despite the promising advancements in nanotechnology for concrete applications, the balance between performance enhancement and economic feasibility remains a critical consideration for future developments in civil engineering.

5.2 Seismic retrofitting

The use of nanofillers in seismic retrofitting presents a transformative approach in civil engineering, enhancing the resilience and performance of structures against seismic events. Nanomaterials, such as CNTs and silica nanoparticles, improve the mechanical properties of traditional materials, leading to more effective retrofitting solutions. Nanofillers significantly increase the compressive and tensile strength of concrete and other building materials, making them more resistant to seismic forces. Incorporating nanomaterials like nano-Al_2O_3 and CNTs into cement composites enhances their energy-absorbing capabilities by refining the microstructure, improving the ductility, and increasing the crack resistance and post-yield energy dissipation. These improvements are beneficial for seismic retrofitting applications, particularly when combined with other reinforcement strategies. While nanofillers can improve local material behaviour, they are not intended to replace conventional seismic retrofitting methods such as FRP wrapping, shear walls, or base isolation systems. Additionally, the dosage of nanofillers is typically low (≤3% by weight of binder), contributing negligibly to structural weight and seismic mass [95].

5.3 Smart structures

The integration of nanofillers in civil applications has led to the development of smart structures that enhance the safety and functionality of construction materials. These advancements leverage the unique properties of nanomaterials to create self-sensing and self-healing capabilities, significantly improving structural health monitoring (SHM) and the overall performance. Nanofillers, such as CNTs and carbon black, are incorporated into cement-based composites to create materials that can detect stress and strain through changes in electrical resistance [101,102]. An example application of smart bricks was demonstrated by Ubertini *et al.* [103], where piezoresistive clay bricks were developed using carbon-based nanomaterials to monitor structural strain in masonry walls. These bricks were embedded in prototype wall sections and were able to detect crack initiation and progressive deformation under applied loads. Such systems can support post-earthquake assessments, long-term degradation monitoring, and automated alerts in heritage or critical infrastructure. Nanotechnology enables the development of materials that can autonomously repair damage. Nanobots can be deployed to mend cracks in structures, enhancing longevity and safety. This self-healing capability is crucial for maintaining the structural integrity of buildings, especially in high-stress environments. The addition of nanofillers improves the mechanical performance of construction materials, making them more resilient to environmental stresses [104]. Research indicates that composites with specific nanofillers exhibit superior performance at high temperatures, maintaining their sensing abilities even after exposure to extreme conditions.

6 Challenges and considerations

The incorporation of nanoparticles in civil engineering applications holds significant potential for improving the mechanical, thermal, and durability properties of construction materials. However, several challenges must be addressed to ensure their effective and safe utilisation. One of the primary challenges is achieving uniform dispersion of nanoparticles within matrices such as concrete, polymers, or composites. Due to their high surface energy, nanoparticles tend to agglomerate, resulting in uneven distribution and reduced material performance. Advanced dispersion techniques are often required, increasing the complexity of material preparation.

Health and environmental concerns also play a critical role in the adoption of nanoparticles. Their minuscule size allows them to penetrate biological systems, posing potential risks to human health during manufacturing, handling, and application. Additionally, the environmental impact of nanoparticle waste remains an area of active research, necessitating the development of safe handling protocols and recycling methods.

Economic factors are another consideration. The production of nanoparticles often requires sophisticated technologies, leading to high costs. Scaling up laboratory-based methods to industrial-scale production poses additional financial and technical challenges. Moreover, the long-term performance of nanoparticles in construction materials is not yet fully understood. Factors such as weathering, chemical interactions, and potential degradation over time need thorough investigation to ensure the reliability of these materials under real-world conditions.

The lack of standardisation and regulatory frameworks further complicates the widespread adoption of nanoparticles in civil applications. Engineers and manufacturers face uncertainty due to the absence of clear guidelines, making it difficult to ensure compliance and performance consistency. Compatibility with traditional construction materials is another critical issue. Nanoparticles can sometimes react chemically with conventional materials, affecting the stability and performance of the composite structure.

Addressing these challenges requires a multi-disciplinary approach involving materials scientists, civil engineers, and policymakers. Research into cost-effective production methods, health and safety protocols, long-term performance studies, and the development of standardised codes will be crucial for unlocking the potential of nanoparticles in civil engineering while ensuring safety, sustainability, and economic feasibility.

7 Future directions for the use of nanoparticles in the civil industry

To unlock the full potential of nanoparticles in civil engineering, future research and innovation must strategically address the challenges of dispersion, safety, cost, long-term performance, standardisation, and material compatibility. One crucial area for advancement is the development of advanced dispersion techniques. Uniform distribution of nanoparticles is essential for achieving consistent material properties. Research into ultrasonication, electrostatic dispersion, and chemical treatments tailored to specific matrices can significantly improve the dispersion process. Additionally, emerging technologies such as machine learning and computational simulations can optimise formulations, ensuring precise and efficient integration of nanoparticles into construction materials.

Health and environmental concerns associated with nanoparticles necessitate the establishment of enhanced safety protocols. This includes the development of biodegradable and less toxic nanoparticles to mitigate risks during production, application, and disposal. Closed-loop manufacturing systems, which recycle nanoparticle waste and reduce emissions, can play a pivotal role in minimising environmental impact. Comprehensive safety guidelines must also be developed, focusing on proper handling, storage, and disposal practices to protect workers and the environment.

The cost of nanoparticle production is another barrier to widespread adoption in civil engineering. Future efforts should focus on creating cost-effective synthesis methods that utilise abundant or waste materials as precursors. Innovations in manufacturing processes, such as scaling up laboratory techniques while maintaining efficiency and quality, will help reduce costs. Collaborations between academic institutions, industries, and governments can drive research into affordable solutions and accelerate the commercialisation of nanoparticle technologies.

Long-term performance studies are essential to ensure the durability and reliability of nanoparticle-enhanced materials under real-world conditions. Accelerated ageing tests, field trials, and predictive models can provide insights into how nanoparticles interact with environmental factors such as moisture, temperature fluctuations, and chemical exposure over time. These studies will help engineers design materials that maintain their enhanced properties throughout their lifecycle, reducing maintenance costs and extending the lifespan of infrastructure.

The establishment of standardisation and regulatory frameworks is critical for building trust and confidence in the use of nanoparticles in civil applications. Clear guidelines and codes of practice will provide a foundation for engineers and manufacturers to design and produce materials that meet safety, quality, and performance standards. International collaboration between researchers, policymakers, and industry stakeholders can streamline the development and implementation of these frameworks.

Material compatibility research is another vital area for future exploration. Understanding the chemical interactions between nanoparticles and traditional construction materials will help prevent adverse reactions that could compromise the stability or effectiveness of composites. Advanced characterisation techniques, such as spectroscopy and microscopy, will enable researchers to optimise nanoparticle formulations and achieve seamless integration with existing materials.

Finally, the focus should extend to smart and sustainable applications of nanoparticles in civil engineering. Innovations such as self-healing concrete, energy-efficient coatings, and pollution-absorbing materials can address pressing global challenges like urbanisation, climate change, and resource scarcity. By aligning nanoparticle research with sustainability goals, the civil industry can develop solutions that are not only technologically advanced but also environmentally responsible.

By addressing these future directions, the civil engineering industry can fully leverage the transformative potential of nanoparticles, creating safer, more durable, and sustainable infrastructure for the future.

8 Conclusion

The integration of nanoparticles in the civil industry represents a significant leap forward in advancing the performance and functionality of construction materials. These microscopic materials offer unparalleled opportunities to enhance strength, durability, and sustainability while enabling innovative applications such as self-healing concrete, energy-efficient coatings, and pollution mitigation systems. However, their widespread adoption requires addressing critical challenges, including achieving uniform dispersion, ensuring health and environmental safety, reducing costs, understanding long-term performance, and establishing standardised regulations.

Through interdisciplinary collaboration and sustained research efforts, the potential drawbacks of nanoparticles can be mitigated, paving the way for transformative innovations in infrastructure development. As the civil industry embraces these advancements, nanoparticles will undoubtedly play a pivotal role in building resilient, efficient, and sustainable structures, contributing to a smarter and greener future.

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