Silicon (2022) 14:135–144
https://doi.org/10.1007/s12633-020-00800-y

REVIEW PAPER

Overview of Workability and Mechanical Performance of Cement-Based Composites Incorporating Nanomaterials

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Received: 12 June 2020 / Accepted: 22 October 2020 / Published online: 28 October 2020

Abstract

The need to enhance the mechanical performance of cement-based composites such as concrete and mortar has led to the development of various innovative ways to meet the current and future performance demand. The recent trend in cement-based composites technology has shown the viability of further enhancement of the mechanical performance of cement-based composites by the incorporation of nanomaterials. As the proportions of components in cement-based composites, it is paramount for the stakeholders in the construction industry to understand how nanomaterials affect the mechanical performance of these composites. Therefore, this overview was undertaken to investigates the effect of nanomaterials on the mechanical properties of cement-based composites. Results from various studies showed that the mechanical properties of cement-based composites can be improved with the incorporation of nanomaterials. The enhancement in the mechanical properties of the cement-based composites with the incorporation of nanomaterials was attributed to the pore filling effect of the nanomaterials coupled with the ability to accelerate hydration reaction which results in the formation of more products. It was also observed that the optimum dosage of nanomaterial varies with types. Therefore, it was recommended to determine the optimum dosage of these materials before its large-scale application.

Keywords Cement-based composites · Nanomaterials · Mechanical properties · Compressive strength

Abbreviations

CNF	carbon nanofibres
CNT	carbon nanotubes
NA	nano alumina
NCC	nano calcium carbonate
NCly	nano clay
NMGt	nano magnetite
NMK	nano metakaolin
NS	nano silica
NT	nano titanium oxide
PC	Portland cement
SCMs	supplementary cementitious materials

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1 Introduction

The need for cement-based composites with higher strength capacity has resulted in the innovative use of various materials such as nanomaterials to enhance the performance of the composites. Traditionally, the use of high content of Portland cement (PC) which is the main binder in cement-based composites can be used to increase the strength capacity. However, PC is relatively expensive and its production has been associated with high carbon dioxide emissions and energy consumption [1–4]. On the other hand, the evolution of cement-based composites and nanotechnology have shown the viability of using nanomaterials at small dosages to replace the high content of PC. In addition to the PC and carbon dioxide reduction with the use of nanomaterials in cement-based composites, these materials also result in enhancement of the mechanical performance of the composites [5–7].

As the name implies, nanomaterials are ultra-fine materials that are capable of modifying the microstructure on a nano-scale in contrast to other materials such as fly ash, slag, etc., which are effective on a micro-scale [8–11]. In addition, their high surface area makes them capable of reacting with the calcium hydroxide in the pore solution to form more calcium silica hydrate which is responsible for strength in concrete [6, 12, 13]. Compared to other materials such as supplementary cementitious materials (SCMs), several studies have shown that the use of nanomaterials in small quantities can result in a significant performance of cementitious composites [5, 14].

The use of various types of nanomaterials such as nano silica (NS), nano alumina (NA), nano titanium oxide (NT) etc., have been explored to improve the mechanical performance of concrete. However, the use of nanomaterials in cement-based composites is still emerging and more understanding of its mechanism and influence on performance is critical to its effective usage. Therefore, the objective of this paper is to explore the effect of different nanomaterials on the mechanical performance of cement-based composites. Cementitious composites considered in this review are mainly concrete, mortar and paste. The mechanical performance of the cement-based composites was discussed in terms of the compressive strength, modulus of elasticity, tensile strength, flexural strength and fracture toughness. Also, the effect of nanomaterials on the workability of the composites was briefly discussed. It is anticipated that the overview will propel more research and applications on the use of nanomaterials in cement-based composites.

2 Overview of Nanomaterials Properties Used in Cement-Based Materials

2.1 Physical Properties

The small size of nanomaterials (i.e. in the range of 1 nm to 100 nm) embodied them with high surface area as shown in Fig. 1 [15]. Due to the smaller size, they are capable of filling the nano and micro voids within the cementitious matrix [16, 17]. Hence, the nanomaterials can fill the voids between cement particles and help in bridging the particles resulting in the accelerated formation of product networks [18, 19].

The higher surface area to volume ratio of nanomaterials also enables them to act as nuclei for the Portland cement phases thereby resulting in the formation of additional hydration products and a corresponding densified interfacial transition zone and microstructure. This is evident in the results observed by Sato and Diallo [20] where the rapid formation of calcium silicate hydrate was observed on the surfaces of tricalcium silicate due to the presence of nano calcium carbonate (NCC) in the matrix. The formation of additional hydration products and the filling effect of the nanomaterials would also improve the interfacial transition zone (ITZ) resulting in a reduction in the permeability of cement-based composites [18]. This mechanism has also been confirmed by Wang et al. [21] and a representative of the ITZ enhancement mechanism when 2D nanomaterials are used is presented in Fig. 2.

On the other hand, the high aspect ratio of nanomaterials such as carbon nanofibres (CNF) and carbon nanotubes (CNT) makes them suitable as an alternative reinforcement in cement-based composites [22, 23]. The ability of these nanomaterials (i.e. CNT and CNF) to reinforce cement-based composites at a nanoscale would result in a more effective bridging effect resulting in enhancement improvement in the mechanical performance and crack mitigation.

2.2 Chemical Properties and Effect on Cement Hydration

Nanomaterials such as NCC increases the rate of formation of the carbonaluminate by accelerating the hydration reaction rate of the tricalcium aluminate [24]. This was confirmed in the study by Sato and Diallo [20] where an increase in the hydration heat and reduction in the induction period was

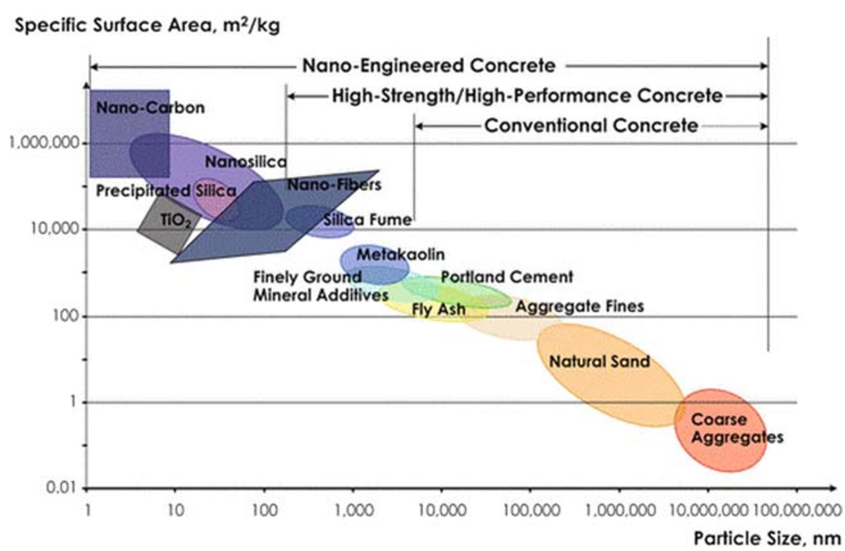

Fig. 1 Size of nano materials relative to other components in cement-based composites [14]

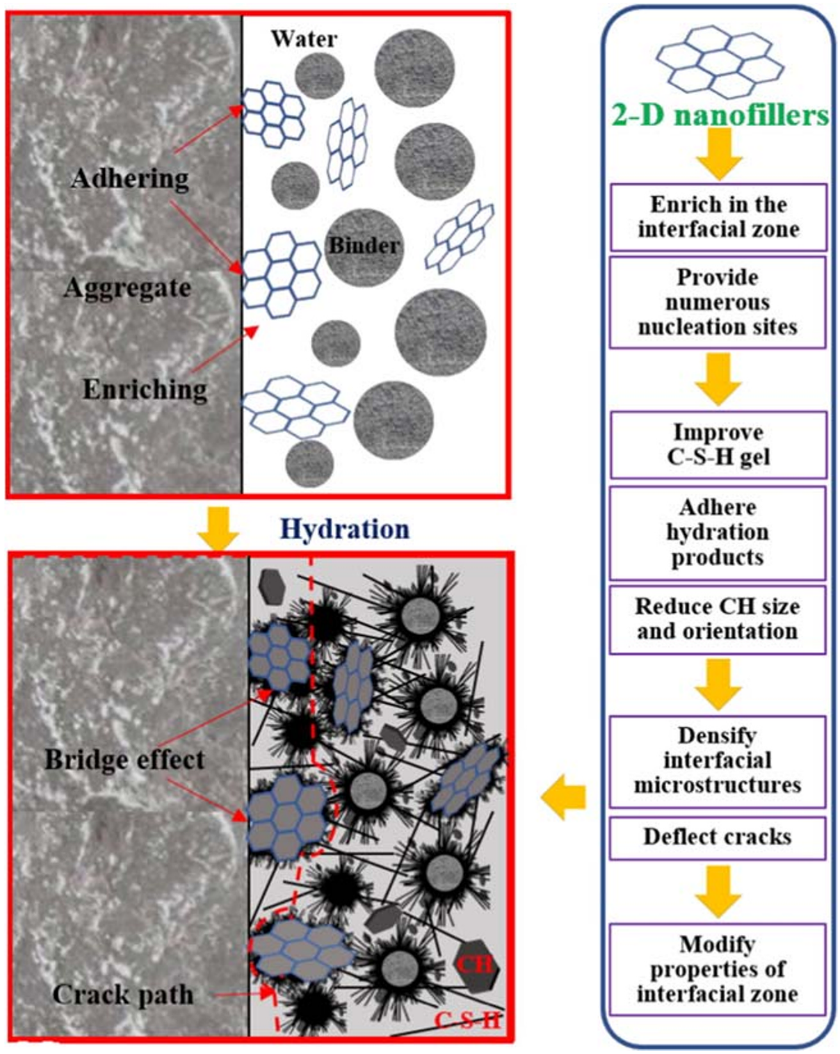

Fig. 2 role of 2D nanomaterials on the interfacial zone [20]

observed. Similarly, the NCC particles can react with the tricalcium silicate to increase the rate of early strength gain and set times [25]. Nanomaterials such as NCly and NS with high pozzolanic reactivity can also react with the calcium hydroxide in the pore solution to yield additional calcium silicate hydrate at ambient temperature resulting in an enhancement of the early strength [14]. However, for nanomaterials such as nano-silica; the enhancement in the mechanical capacity with their introduction has been found to be more dependent on the higher content of silica compounds in the composites which densify the matrix rather than its pozzolanic capabilities [26].

It is worth mentioning that the effectiveness of these nanomaterials to improve the performance of cement-based composites is dependent on the proper dispersion of the nanoparticles within the matrix of the composite. Improper dispersion of nanomaterials will result in agglomeration of the nanomaterials which creates weak areas within the matrix and a corresponding reduction in mechanical performance. The dispersion of nanomaterials can be improved using methods such as ultra sonification, the use of surfactants, chemical admixtures, covalent functionalization, etc.

In addition to the chemical properties of nanomaterials directly related to the cement hydration, some nanomaterials also possess additional properties that contribute to the overall durability of cement-based composites. For example, nano titanium oxide (NT) is embodied with photocatalytic properties which could aid in removing organic impurities from the surface of cement-based composites [27]. Similarly, self-sensing and conductivity properties can be achieved with the incorporation of nanomaterials such as CNT and CNF into cement-based composites [28, 29].

3 Nanomaterials in Cement-Based Composites

The research and development of nanotechnology in recent years have resulted in the viability of incorporating these smaller materials into cementitious composites to enhance the performance of cementitious composites. The viability for nanomaterials to enhance the performance of cementitious composites can be attributed to its high surface area and chemical reactivity which results in the densification of the nanostructure and microstructure of cementitious composites. In addition to the enhancement of the performance of cementitious composites with the incorporation of nanomaterials, nanomaterials are eco-friendly and cheap materials that can be used to reduce the amount of PC used as the binder in the composites. Hence, the significant reduction in the content of PC and the corresponding replacement with a low amount of nanomaterials would result in cost savings. The use of nanomaterials such as NMGt at 0.3% has been found to enhance the mechanical properties of cementitious composites significantly [30–32]. Incorporation of nanomaterials has also been found to increase the hydration and pozzolanic reactivity of the binder components [33]. Several types of nanomaterials can be incorporated into the cementitious composite to enhance its performance. However, NS is the most commonly used.

4 Effect of Nanomaterials on Properties of Cement-Based Composites

Nanomaterials enhance the properties of cement-based composites by acting as a filler and a hydration reaction accelerator. The ability for the nanomaterials to accelerate the hydration reaction can be attributed to their high surface area and their pozzolanic reactivity which reacts with the alkali in the pore structure to form more calcium silicate hydrate. Also, the filler ability of nanomaterials can be associated with their ultra-small size (i.e. about 100 times less than that of cement) which results in more densification of the nanostructure and microstructure of the resulting composite. The nanomaterials are able to act as a filler because of their ability to fill the nano and micro voids within the composite.

The ability for these materials to react with the excess calcium hydroxide which is detrimental to the performance of concrete to produce more calcium silicate hydrate which is the main load-carrying component is responsible for the enhancement of the mechanical properties [7]. There is also a corresponding enhancement of the interfacial transition zone between the aggregate and the binder matrix resulting in enhanced toughness of concrete [34] . Also, several studies have shown that nanomaterials can be used to enhance the bond between short fibres and the cementitious matrix [35, 36]. Studies by Hakamy et al. [37–39] showed that the use of nanomaterials such as nano clay (NCly) can improve the mechanical properties of fibre reinforced concrete with dosage as low as 1%. The optimum dosage of different types of nanomaterials on the mechanical performance of concrete is presented in Table 1.

Table 1 Optimum dosage of nanomaterials on the 28-day strength (%)

Nanomaterial	Compressive	Flexural	Tensile	Reference
NC	4.8	4.8	–	[7]
NS	1	0.5	–	[7]
NS	1.5	–	1.5	[40]
NS	1.5	–	–	[6]
NMK	9	–	–	[6]
NS	2	–	–	[41]
NS	5	–	–	[12]
NA	3	–	–	[12]
NS	1.5	–	–	[42]
NC	2	–	–	[43]
NCC	2	–	–	[44]
NCly	1	1	–	[39]
NS	2	–	2	[5]

4.1 Workability

In contrast to the effect of nanomaterials on the mechanical properties of cement-based composites, the physical properties of the nanomaterials play a significant role in the fresh workability compared to the chemical properties. The workability of cementitious composites is very critical to its proper placing and compaction which is dependent on how workable the fresh mixture is. For most cement-based composites, the slump or flow test is a good way to evaluate the consistency and workability of the fresh mixture.

The incorporation of NS at a dosage up to 1.5% at different water to binder ratio was found to result in a significant decrease in the slump as shown in Fig. 3 [45]. The reduction in the slump of cemental-based composites with the incorporation of NS has been ascribed to the formation of a high water retention structure which results in an increase in the viscosity of the mixture [46]. Similarly, The study by Supit and Shaikh [47] where NCC was incorporated into mortar and concrete showed that the incorporation of the nanomaterial (i.e. NCC)

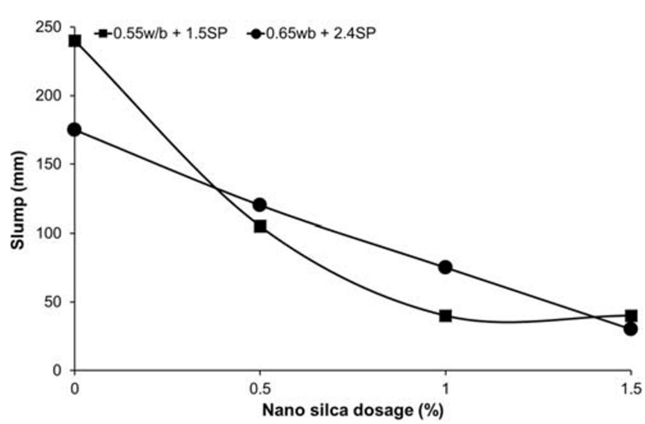

Fig. 3 Effect of nano silica dosage on slump (data from [39])

resulted in a reduction in the workability of the mortar and concrete mixtures compared to the control mixture without NCC. The workability of the mixtures further reduced with a higher content of NCC in the mixtures. The reduction in workability was ascribed to the high surface area of the NCC. Due to the high surface area of the nanomaterials, there would be an increase in the water demand due to higher adsorption of the nanomaterials resulting in lower amount of free water available in the fresh mixture for workability.

In contrast, the use of nanomaterial such as nano magnetite was found to have no effect on the workability of mortars [48]. This phenomenon was attributed to the high hydrophobic characteristics and non-porous morphology of the nano magnetite compared to other types of nanomaterials used in cement-based composites. Hence, it is critical to understand the physical properties of the nanomaterials and their possible influence on the workability before being utilized in cement-based composites.

4.2 Compressive Strength

The incorporation of nanomaterials into cement-based composites has been found to increase both the early and later age compressive strength. Sing et al. [49] reported over 60% increase in the compressive strength after 24 h of curing when NS was incorporated as a partial replacement of 5% of PC. The enhancement in the compressive strength can be attributed to the formation of additional hydration and the pozzolanic reaction of the nanomaterials [49–52]. However, the compressive strength enhancement with nanomaterials such as NT are associated with its pore filling effect only as nano titanium does not posses any pozzolanic reaction when compared to other nanomaterials such as NS [53, 54]. The use of NT at a dosage higher than 3% has also be found to result in a decrease in the compressive strength. The reduction in the compressive strength at higher dosages can be attributed to the possible agglomeration of the NT which results in weak zones within the composite.

Similar observations were reported by Meng et al. [53] where they reported a decrease of approximately 10% in compressive strength of mortars when NT was used to replace cement in the range of 5 to 10%. The study by Behnood and Ziari [55] showed an increase in strength up to 25% when NS was used as a 10% replacement of cement in concrete. The use of 2% NS in higher strength self-compacting concrete also resulted in 43%, 21% and 55% increase in compressive strength at 3, 28 and 90 days respectively [5]. The high increase in the compressive strength was attributed to the accelerated consumption of the calcium hydroxide in the pore solution which results in a corresponding increase in the formation of hydration products. In addition, the NS acts as a pore filler for the nanostructure and microstructure of the concrete which results in a significant reduction in the volume of pores.

Similar study by Givi et al. [42] also showed that the compressive strength of concrete can be enhanced with the incorporation of NS up to a dosage of 2%. However, a dosage of 1.5% was found to be optimum due to the reduction in the compressive strength at a dosage level of 2%. NCLy can also be used as a nanomaterial to enhance the mechanical performance of concrete. An increase in compressive strength up to 56% was achieved when NCLy was used as a 2% replacement of PC [43]. However, when the dosage of the NCLy was increased to 3%, the increase in the compressive strength reduced to 24% when compared to the control. Therefore, for NCLy; 2% can be deemed the optimum for enhanced compressive strength.

The use of nano calcium carbonate (NCC) has also been found to result in a 13% and 18% increase in strength when used as 1 and 2% replacement of cement respectively [44]. This increase in strength can also be associated with the aforementioned reasons for other nanomaterials. In contrast to all other nanomaterials, the use of nano alumina (NA) was found to result in no significant enhancement of the compressive strength when cement was replaced by up to 7% [56]. However, the study by Behfarnia and Salemi [12] showed that the compressive strength of concrete can be increased by 8% when NA is incorporated as a 3% replacement of PC. One of the emerging nanomaterials for enhancing the mechanical performance of cement-based composites are carbon nanotubes (CNT). The addition of CNT into cementitious composites has been reported to increase the compressive strength significantly [57]. The increase in strength with this type of nanomaterials can be attributed to the densification of the microstructure of the composite. Konsta-Gdoustos et al. [58] also reported an increase in the compressive strength when CNTs were used in the range of 0.025 to 0.08% as the replacement of PC.

Similarly, an increase up to 35% has been reported when graphene oxide which has similar properties as that of CNT was used as a 0.5% replacement of cement to reinforce cementitious composites [59]. Nonetheless, most studies have shown that nanomaterials such as NS and NA have a higher effect on improving the early age compressive strength compared to the enhancement at a later age. An enhancement in the compressive strength was also reported when NCC was used to replace PC in high strength concrete [7]. However, the optimum dosage was found to be 4.8% as there was a decrease in the compressive strength at higher dosages. The decrease in the compressive strength at higher dosages of NC was attributed to the insufficient space for the formation of additional reaction products. Study by Khaloo et al. [40] showed that increasing the particle size of NS will result in a reduction in the compressive strength of concrete. The decrease in the compressive strength with increase in the particle size was attributed to the possible accumulation of the NS which results in a weak zone in the matrix.

4.3 Modulus of Elasticity

The addition of nanomaterials such as NS into cement-based composites has been found to enhance the modulus of elasticity (MOE) [60]. Though the use of NA was reported to have no significant effect on the compressive strength, its use as a 5% replacement of PC was found to result in an approximately 145% increase in the MOE at 28 days [56]. This increase in the MOE with the incorporation of nano alumina was attributed to the densification of the interfacial transition zone and reduction in porosity of the composite. This observation is similar to that of Konsta-Gdoustos et al. [58] where they observed an increase in MOE up to 50% when CNTs were incorporated into cementitious composites. Anstari et al. [36] also showed that the MOE of basalt fibre reinforced concrete can also be improved with the use of NA and NS as nanomaterials. Similarly, Sato and Beaudoin [61] reported a significant enhancement in the MOE when NCC was incorporated into cement-based composites with a high content of fly ash and slag. The enhancement of the MOE was associated with the acceleration of the hydration kinetics of tricalcium aluminate and tricalcium silicate.

4.4 Flexural Strength

Similar to other mechanical properties, nanomaterials can be used to improve the flexural strength of cement-based composites [62, 63]. However, the study by Lucas et al. [64] showed that a higher dosage (i.e. greater than 2.5%) of nanomaterials in concrete can result in a decrease in the flexural strength. A decrease of approximately 30% was observed when NA was incorporated in the range of 2.5% to 5% as a replacement of PC. The use of CNT has been found to yield enhanced flexural strength [57]. The enhancement of the flexural strength with the incorporation of the CNT can be attributed to the enhanced bond between the CNTs and the calcium silicate hydrate [57].

Similarly, Konsta-Gdoustos et al. [58] reported an increase up to 25% when CNTs were used as a replacement for cement in the range of 0.025 to 0.8%. The incorporation of graphene oxide into concrete has also been reported to result in an increase of up to 50% in the flexural strength. Ansari et al. [36] reported a significant enhancement in flexural strength of basalt fibre reinforced concrete when NS and NA were incorporated into the composite. The concrete mixtures incorporating NS, however, showed higher improvement in the flexural strength compared to those with NA at the same dosage. An improvement of 18% and 12% in flexural strength was observed for concrete mixtures with NS and NA respectively. This observation is similar to that of Hakamy et al. [39] where it was found out that the flexural strength of cementitious composites can be improved with the use of NCLy at a dosage up to 1%. An improvement of approximately 30% in flexural strength was observed when 1% NCLy was used as a replacement of cement in hemp fabric cementitious composites. The enhancement of the flexural strength with the introduction of NCLy was attributed to the pore filling effect of the NCLy coupled with its pozzolanic characteristics which results in more calcium silicate hydrate formation. However, the optimum amount of NCLy for the flexural strength improvement was found to be 1% as there is a decrease at higher dosages of the NCLy as shown in Fig. 4**.** The decrease in the flexural strength of the composite at higher dosage was attributed to the poor dispersion of the NCly coupled with its corresponding agglomeration in the cementitious matrix.

Studies by Morsy et al. [14] and Li et al. [65] have shown that the agglomeration of nanomaterials in cementitious composites will result in microvoids and consequential weak areas in the composite. Li et al. [66] also concluded that flexural strength of concrete can be enhanced by NS and NA only when it is used at a dosage of 1% maximum as a consequential decrease in the flexural strength was observed at higher dosages (Fig. 5). The study by Wu et al. also showed that the incorporation of 4.8% NC can be used to enhance the flexural strength of high strength concrete. However, higher flexural strength can be achieved with lower dosages of NS (i.e. 0.5%). The varying optimum dosage for different types of nanomaterials shows that an initial evaluation of the optimum dosage of the type of nanomaterial should be carried out before its large-scale application.

4.5 Fracture Toughness

The incorporation of nanomaterials into cement-based composites can be used to improve its fracture toughness. Hakamy et al. [39] reported an increase in the fracture toughness up to approximately 25% of concrete reinforced with hemp fibres and incorporating nano clay at a dosage up to 3%. The enhancement of the toughness of the concrete was attributed to the pozzolanic contribution of the NCly which results in the

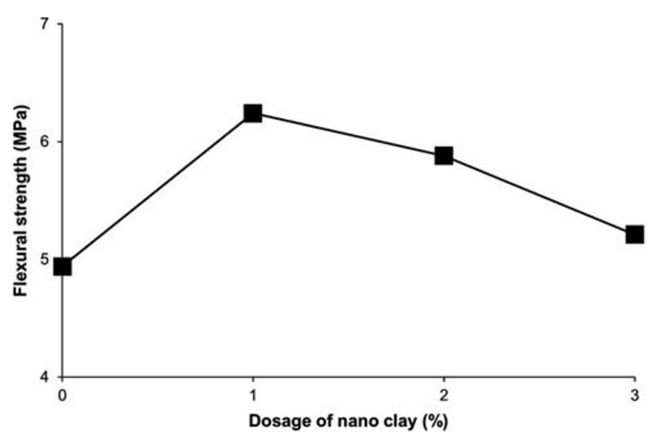

Fig. 4 Effect of nano clay dosage on compressive strength (data from [38])

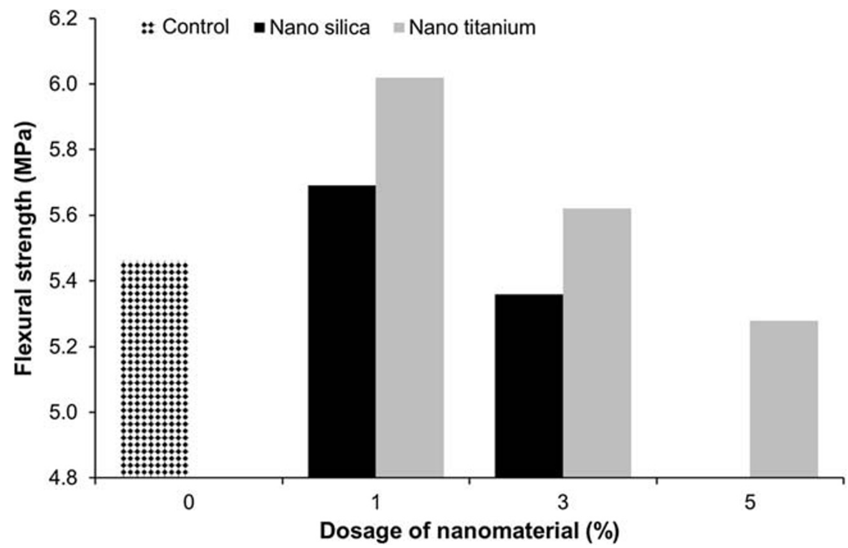

Fig. 5 Effect of nanomaterials dosage on flexural strength (data from [65])

formation of more hydration products and corresponding refinement of the microstructure. This refinement was also found to improve the interfacial bond between the fibres present in the composite and the cementitious matrix. Similar to other mechanical properties evaluated in the study, the use of NCly at a dosage of 1% was deemed to be optimum. This observation correlates with that of Alamri and Low [67] where they found out that the use of 1% CNt can be used to enhance the fracture toughness of concrete up to approximately 40%.

The lower fracture toughness achieved at higher dosages of these materials can be attributed to the accumulation of the nanomaterials due to non-uniform dispersion resulting in higher porosity in the composite. This higher porosity will also lead to a consequential week interfacial bond between fibres and cementitious matrix in fibre reinforced concrete. Nonetheless, Hawreen et al. [23] reported a significant increase in the fracture toughness when carbon CNT were used to reinforce concrete mixtures. The enhanced fracture toughness was attributed to pore filling, nucleation and bridging characteristics of the CNTs. However, the bridging effect of the CNTs was found to confer more to the enhanced fracture toughness. These observations are similar to other studies where carbon CNTs have been incorporated into NSC [68–70].

4.6 Tensile Strength

The study by Jalal et al. [5] showed a significant increase in the split tensile strength of high strength self-compacting concrete mixtures incorporating 2% NS. An increase in tensile strength up to approximately 50% was also achieved when NCly was used as an 8% replacement of the cement [71]. This enhanced tensile strength can be attributed to the filler ability of the nano clay coupled with its high pozzolanic reactivity. The NCLy also serves as an activator in the pore solution which resulted in an increase and accelerated formation of hydration products. An increase in the tensile strength of approximately 50% was observed when graphene oxide was used to reinforce cementitious composite at 1.5% replacement of cement [59]. The enhanced tensile strength with the introduction of graphene oxide can be associated with the high bond between the graphene oxide and the calcium silicate hydrate.

The graphene oxide acting as a nucleation site for the formation of calcium silicate hydrate will also result in the formation of more hydration products on the graphene oxide leading to an improved bond. Ansari et al. [36] also showed that NS and NA can be used to improve the split tensile strength of high strength concrete mixtures reinforced with basalt fibres. However, it was found out that the incorporation of NS resulted in a significantly higher tensile strength compared to the mixtures in which NA were added. The tensile strength of mixtures with NS and NA exhibited approximately 20% and 10% increase respectively. This observation corresponds to that of Khalool et al. [40] where the incorporation of NS up to 1.5% as replacement of PC was found to enhance the split tensile strength of high strength concrete. The increase in the tensile strength of the concrete with the incorporation of NS was attributed to the refinement of the interfacial transition zone.

5 Recommendations and Prospects for Use of Nanomaterials in Cementitious Composites

The use of nanomaterials in cement-based composites is very promising in order to achieve construction composites that would meet future demands. However, some major areas need to be improved in order to ensure the effective and efficient use of these materials in cement-based composites. Some of the areas that require imminent studies are briefly discussed as follows:

a) Dispersion methods: One of the major factors that influence the effectiveness of nanomaterials in cement-based composites is how uniform they are dispersed within the composite's matrix. Due to the presence of Van der Waals attractive forces, nanomaterials tend to agglomerate resulting in a creation of weak areas within the composite and a corresponding reduction in the performance. Hence, it is critical and imminent that more research and development should be carried out in creating more innovative ways to effectively disperse nanomaterials in cement-based composites.
b) High water adsorption: The high surface area of most of the nanomaterials used in cement-based composites coupled with their high surface area which could be hydrophilic have resulted in high adsorption of water during the production of the composites. Hence, there is a need to develop more chemical and mineral admixtures that can be used in addition to the current use of chemical admixtures such as high range water reducers to improve the workability of the mixtures.
c) Potential risks: The majority of the studies on the use of nanomaterials in cement-based composites have only focused on the influence of these materials on the performance of the composites. However, nanomaterials are very small in size and can be inhaled causing possible health problems. Therefore, it is critical to ensure that the use of these materials in cement-based composites and structures made with such composites does not pose any threat to the health and safety of its users. It is suggested that a comprehensive study should be carried out to identify the possible risk associated with the use of nanomaterials in cement-based composites. Categories for the level of toxicity of the nanomaterials should be made and parameters developed to designate how these nanomaterials can be incorporated into cement-based composites. Also, innovative solutions are needed to be provided to find ways in which nanomaterials can be used in a safe manner in cement-based composites.
d) Economic benefits: The use of nanomaterials in cement-based composites is generally deemed to be economical due to the ability to reduce the high content of cement and replace it with a low content of nanomaterials. However, in order to quantify this; there is a need for life cycle assessment of nanomaterials and cement-based composites incorporating nanomaterials to be carried out in order to have a comprehensive understanding of the economical benefits associated with the use of nanomaterials in cement-based composites.

6 Conclusions

This paper presents a short overview of the effects of nanomaterials on the mechanical properties of cement-based composites. Discussion in this paper showed that the mechanical performance of cement-based composites can be enhanced with the incorporation of different types of nanomaterials as partial replacement of cement. However, the optimum dosage of nanomaterial differs with the type of nanomaterials as there can be a consequential reduction in the mechanical performance of concrete when nanomaterials are incorporated at higher dosages.

The increase in the mechanical properties of concrete can be associated with the pore filling effect of the nanomaterials coupled with the formation of additional calcium silicate hydrates as a result of the reaction between the nanomaterials and calcium hydroxide. The decrease in the mechanical properties at a higher use of nanomaterials can be associated with the agglomeration of nanoparticles that occur due to their non-uniform dispersion at early ages resulting in weak areas in the matrix. Nonetheless, the use of NS as nanomaterial in cement-based composites was found to yield more enhancement in the mechanical properties when compared to other nanomaterials used at the same dosage. As the use of nanomaterials is still an emerging and evolving area in high strength concrete, more research is encouraged especially in fully understanding its mechanism when incorporated in concrete made with alternative binders other than PC.

Data Availability Not applicable.

Compliance with Ethical Standards

Conflict of Interest None.

Code Availability Not applicable.

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