

## Review Article

# A Critical Review on Effect of Nanomaterials on Workability and Mechanical Properties of High-Performance Concrete

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Received 12 June 2020; Revised 18 February 2021; Accepted 25 February 2021; Published 8 March 2021

Academic Editor: Chao Wu

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The application of nanomaterials in high-performance concrete (HPC) has been extensively studied worldwide due to their large surface areas, small particle sizes, filling effects, and macroquantum tunneling effects. The addition of nanomaterials in HPC has great contribution to enhancing the pore size of the cementitious matrix, improving the hydration of cement, and making the matrix much denser. In order to present an exhaustive insight into the feasibility of HPC reinforced with nanomaterials, the new development of HPC was summarized and the influence of different nanomaterials on the properties of HPC was reviewed based on more than 100 recent studies in this literature review. Workability, compressive strength, tensile strength, and flexural strength properties of HPC with nanomaterials were discussed in detail. In addition, nanomaterial-modified HPC was compared with the traditional concrete and obtained a lot of valuable results. The results in the present review indicate that the addition of various nanomaterials improves the mechanical properties of HPC, while reducing the workability of HPC. However, there is an optimal dosage of nanomaterial for improving the mechanical properties of HPC. Improving the properties of HPC by adding nanomaterials is expected to become a mainstream technique in the future. This literature review can provide comprehensive and systematic knowledge to researchers and engineers working on HPC and promote the application of this new HPC in modern civil engineering.

## 1. Introduction

Compared with masonry structure and wood structure, the development history of concrete structure is relatively short, but with the advantages of concrete materials such as high strength, high elastic modulus, good plasticity and workability, wide source of raw materials, convenient local materials, and convenient construction, concrete has been widely used in the world since the mid-19th century, and the development speed of concrete structure has also rapidly increased, making it an irreplaceable and widely used material in engineering construction for a long period of time. Concrete material has become one of the most widely used and most consumable building materials in the world. It has made important contributions to the development and progress of the human society [1]. Concrete starts from a low strength grade [2]. With the development of modern civil

engineering projects toward high long-span bridges and large-scale water conservancy projects, the demand for concrete having strength, rigidity, durability, and crack resistance continues to increase. However, traditional concrete cannot meet these requirements. This issue led to the development of a new concrete technology, high-strength concrete (HSC), which can bear a load capacity of up to approximately 90 MPa [3]. Subsequently, high-performance concrete (HPC) and then ultrahigh-performance concrete (UHPC) were produced, and these can meet the strict structural design and durability requirements of modern construction projects. Compared with conventional concrete, HPC is the most comprehensive concrete at present because of its excellent performance in terms of workability, durability, strength, and volume stability. Moreover, it is receiving increasing attention in civil engineering construction and is expected to become the

development direction of concrete technology in the future [4–8]. HPC is composed of more cementing materials, well-graded aggregates, less water, and high-efficiency water-reducing agent to ensure excellent mechanical properties, durability, and stable working performance. Traditional materials and preparation methods of ordinary concrete are not available [9]. Adding admixtures such as fly ash (FA), silica fume, slag powder, metakaolin, and other volcanic ashes to concrete [10, 11] is an effective way to achieve high performance [12–14]. Mixing these mineral powder active materials into HPC can enhance various properties of concrete. Above all, it will replace some cement, which can realize the recycling of waste, reduce carbon dioxide emissions, and achieve environmental protection [15]. Compared with other pozzolans, silica fume has a high specific surface area and a fast pozzolanic reaction speed, which can effectively replace cement and improve concrete strength [16–20]. Fly ash is also a widely used mineral admixture. It mainly contains aluminate glass beads with smooth surfaces and small-size particle. The addition of FA to concrete can play the role of ball bearing, which will reduce the water demand of cement slurry, enhance the workability of fresh concrete, and increase the compactness of hardened concrete [21–24].

Nanomaterials, having been developed in the early 1980s, are a fairly new type of material. Nanomaterials refer to ultra-fine materials with particle sizes in the order of nanometers (1–100 nm). They include a variety of powder materials, such as metal, nonmetal, organic, inorganic, and biological materials [25], and are often located in the transition region between atomic clusters and macroscopic objects. Nanomaterials have small particles and large specific surface areas. When the particle size is as low as 10 nm, the proportion of the surface atoms is 20%, and the number of atoms distributed on the surface of the particles increases sharply with decreasing particle size. When the particle size is 1 nm, almost all atoms are concentrated on the surface of the particles, resulting in the surface effect, volume effect, filling effect, and other special properties of nanomaterials. Therefore, ultrafine powder has a host of unusual mechanical, electrical, magnetic, catalytic, and optical properties compared with traditional granular materials. As a new material, nanomaterials have shown remarkable application prospects in fine ceramics, microelectronics, bioengineering, light industry, and medicine. They are already one of the hotspots in scientific research due to their successful application and regarded as another industrial revolution of the century. Furthermore, they have cross-era significance [1]. The reason why ultrafine particles can be used well in concrete performance is mainly due to the continuous filler of cementitious material composition, as presented in Figure 1 [26]. Silica fume provides UHPC with better strength and durability because of its smaller granularity and high activity [17]. However, its output is low, and its price is high. Generally, silica fume is not considered when the concrete strength is lower than 80 MPa. With the increasing demand for HPC, nanotechnology has produced nanomaterials to replace silica fume. Nanomaterials are widely used in concrete owing to their special nanoeffects.

The results show that the workability, mechanical properties, durability, and microstructure of concrete have been improved with the addition of nanoparticles [27]. Table 1 lists the comparison results for the performances of ordinary concrete, HPC, UHPC, and nanoconcrete. Several nanomaterials are used to reinforce ordinary concrete; examples of such materials include nano-SiO<sub>2</sub> (NS) [32], nano-CaCO<sub>3</sub> [33], nano-Al<sub>2</sub>O<sub>3</sub> (NA) [34], nano-Fe<sub>3</sub>O<sub>4</sub> (NF) [35], nano-TiO<sub>2</sub> (NT) [36], nano-ZnO<sub>2</sub> [37], nano-limestone [38], nano-FA [39], carbon nanotubes (CNTs) [40], and nano-metakaolin (NMK) [41]. Among many nanomaterials, NS has successfully replaced the traditional silica fume with its high pozzolanic activity, making it extensively applicable in HPC. One of the important reasons why NS can considerably improve the mechanical strength of concrete is that the calcium-silicate-hydrate (C-S-H) gel formed by the reaction of calcium hydroxide crystals distributed between the cement-based material matrix and aggregate can heighten the strength of the hardened cement stone matrix due to the high activity of NS [42]. In recent years, with extensive research being conducted on the performance of nano-modified concrete, several studies have found that nanomaterials are very effective as cementing materials in improving the properties of concrete. They can not only considerably reduce the amount of cement but also fill the gaps of materials, thus making a great contribution in enhancing the performance of traditional concrete. Accordingly, the main task of this paper is to summarize and review the latest progress of different nano particles in the research of normal concrete and HPC. The workability, compressive strength, and tensile strength of nanoparticles in HPC under single or mixed conditions are also discussed.

## 2. Workability

Workability is a comprehensive technical property used to ensure the construction operation of each process and obtain the stable performance of fresh concrete. Based on previous experimental research, a slump height of approximately 650 mm is acceptable for fresh concrete and is a sign of sufficient strength for high-quality concrete. In fact, within a certain range, the larger the slump, the better the workability, which indicates that concrete can easily flow without segregation [43, 44]. Moreover, the strength of concrete is related to workability. To ensure maximum strength of fresh concrete, the concrete should have sufficient workability, owing to its self-compacting capability. Therefore, controlling the workability of concrete is meaningful. Slump and slump flow are important parameters for evaluating high-performance concrete.

**2.1. Influence of NS on the Workability of HPC.** A slump is regarded as a suitable indicator of the fluidity of fresh concrete. A lot of studies have shown that NS has an effect on the slump of concrete [45]. Aydin et al. [46] observed the effect of changes in NS and FA on the slump flow of fresh concrete at optimal replacement rates of 2% and 40%, respectively. Their investigation revealed that NS considerably

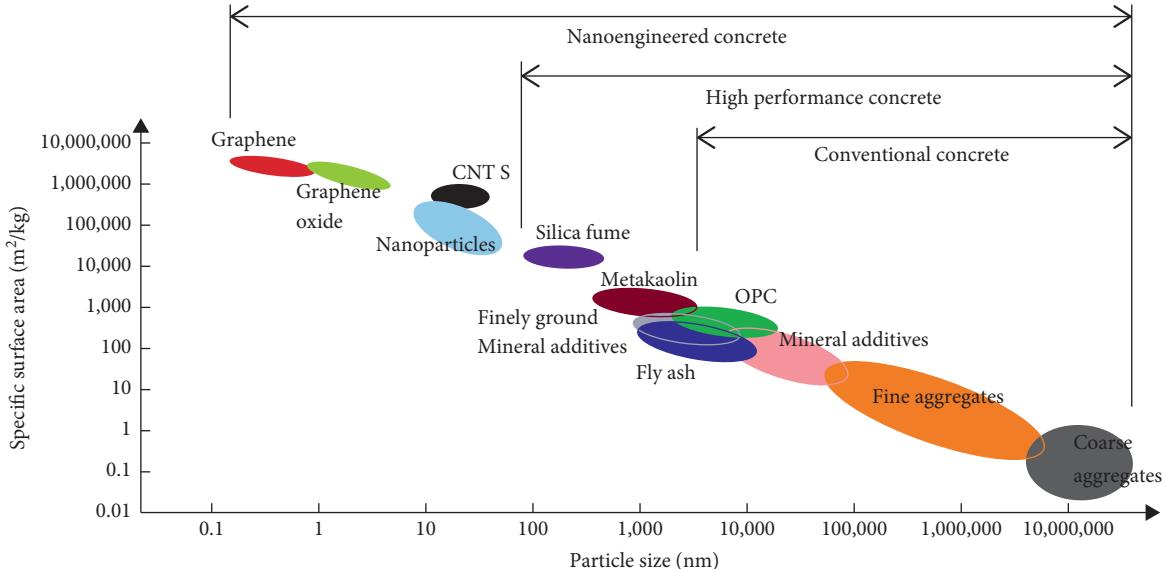


FIGURE 1: Relationship between the particle size and specific surface area of concrete materials [26].

TABLE 1: Summary of the performance of diverse kinds of concrete based on previous studies.

	Compressive strength (MPa)	Flexural strength (MPa)	Water absorption (%)	Reference
Ordinary concrete	10–40	1–10	<30	Mehta and Monteiro [28]
HPC	40–100	11–20	12–25	Hamid et al. [29]
UHPC	100	20–30	<12	Hartmann and B. Graybeal [30]
Nanoconcrete	70	12–20	<12	Aïtcin [31]

improved the performance of fresh concrete and eliminated the segregation of 40% FA when mixing [46]. Hani et al. [47] stated the influence of self-compacting concrete with four contents of NS on a slump under different water-binder ratios. In this investigation, the water-binder ratios of the three series are 0.41, 0.45, and 0.5. In addition, 0%, 0.25%, 0.5%, and 0.75% of cement are planned to be substituted by NS in each series. The most important finding from this study is that the fluidity of all NS mixtures is reduced. Moreover, the addition of 0.75% NS has the greatest influence on the slump of the three water-cement ratios, reducing by 15.2%, 15.5%, and 14.1%, respectively [47]. As shown in Figure 2, NS reduces the slump loss and slump flow loss of concrete mixtures with different water-binder ratios, and these losses increase with the increase in nanoparticle content. This conclusion was supported by Naji Givi et al. [48], who found that low workability may be associated with an increase in the surface area of the mixture upon addition of nanomaterials, which necessitates more cement slurry to wrap the NS. Furthermore, to confirm these results, they obtained through a slump test that the content of NS has a distinct impact on the flowability of fresh concrete. Compared with the control group, the slump of all mixtures containing NS is reduced under a water-binder ratio of 0.4. Moreover, according to ASTM C143 (2015), slump loss is usually used to evaluate the influence of NS on the workability of concrete.

Supit and Shaikh [49] found that adding 2%–4% NS to concrete can observably reduce slump loss, which reaches

60%. Meanwhile, Bahadori and Hosseini [50] observed that the slump loss of concrete containing NS is severe when the ratio of super-plasticizer to cementitious material is unchanged. Zhang et al. [51] also revealed that the slump and slump flow of 15% FA concrete decreased after adding NS. We can observe the influence trend of NS content on the slump and slump flow in Figure 3. In addition, to evaluate the flowability of fresh concrete, Jalal et al. [52] and Güneyisi et al. [53] tested the time and slump diameter of a slump flow test and V-funnel flow test, respectively. They concluded that the fluidity of self-compacting HPC declined after adding NS particles. Nevertheless, the particle size of NS is a contributing factor on the rheological and fresh properties of concrete. Durgun and Atahan [54] studied the influence of colloidal NS (CNS) on the flow performance and rheological parameters of concrete. Self-compacting concrete was modified using CNS with different average particle sizes of 35, 17, and 5 nm. Experiments show that adding CNS increases the  $T_{500}$  time, however, reducing the content of FA decreases the  $T_{500}$  time. These factors show opposite results for the slump flow diameter. When the content of CNS with a particle size of 35 nm exceeds 1.5%, the slump flow time at 500 mm is considerably higher than that of the control group. Senff et al. [55] demonstrated that adding NS can cause a severe slump loss in concrete, which can be attributed to the content of nanoparticles. The main reason for this result is that nano-ultrafine particles contributing to the increasing specific surface area will absorb part of the mixed water. Finally, some scholars pointed out that to avoid a

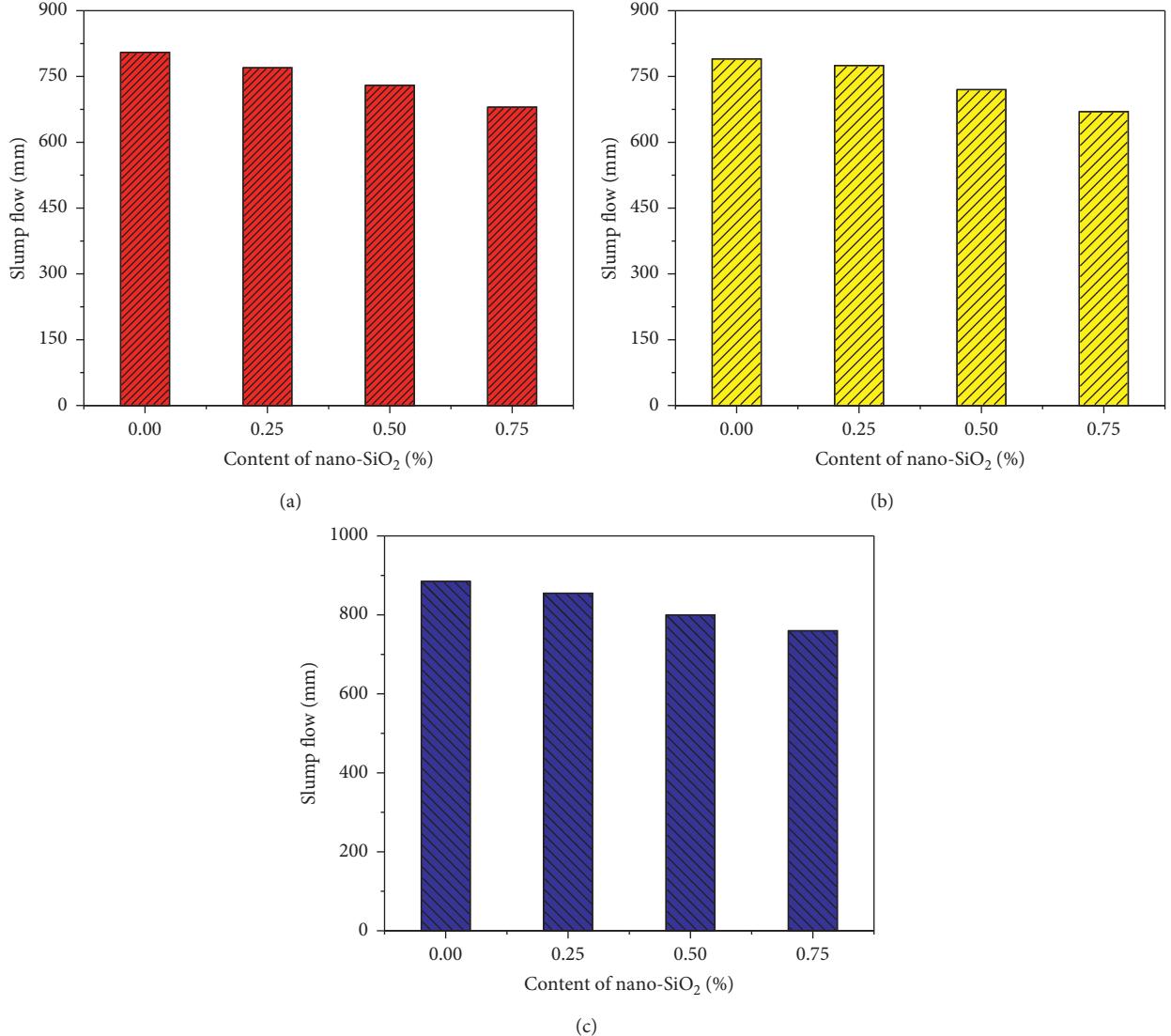


FIGURE 2: Relationship between the slump flow and w/b [47]. (a) w/b = 0.45; (b) w/b = 0.41; (c) w/b = 0.5.

certain degree aggregation of nanoparticles in the dispersion process, the content of NS should be as small as possible (1%–5%) [56, 57].

**2.2. Effect of Nano-CaCO<sub>3</sub> on the Workability of HPC.** Nano-CaCO<sub>3</sub> is a type of nanomaterial with a certain activity, and its cost is only one tenth of that of nanosilicon. As a result, researchers have been interested in applying it to concrete materials. A large number of researchers have demonstrated that the specific surface area of a cement slurry will be sharply increased due to the incorporation of small-sized nano-CaCO<sub>3</sub> particles, which will increase the water demand of the cement slurry. Meng et al. [58] found an association between the water demand of nano-CaCO<sub>3</sub> and cement slurry. They identified that the water demand increases with the increase in the nano-CaCO<sub>3</sub> content. Specifically, when the content of nano-CaCO<sub>3</sub> is 2%, 5%, and 8%, the water demand will rise by 0.4%, 1.8%, and 3.2%,

respectively. However, this effect is suppressed when using a nano-CaCO<sub>3</sub> intermediate slurry. When the content of nano-CaCO<sub>3</sub> is 2% and 5%, the water demand will only decrease by 0.3%. By contrast, when the dosage is 8%, the water demand is essentially the same as the reference water supply. The main reason for this change is that the nano-CaCO<sub>3</sub> intermediate slurry is easier to evenly disperse and can markedly improve the particle size distribution.

The application of nano-CaCO<sub>3</sub> to cement can not only promote the hydration of cement but also cut down the setting time. Wei [59] found that the increase in nano-CaCO<sub>3</sub> content will shorten the initial setting and final setting time of the cement paste. When the content increased from 0.44% to 4.88%, the initial setting time increased from 35 min to 81 min and the final setting time increased from 23 min to 71 min. This effect also occurs for concrete, and a study [60] on UHPC has similar results. Their investigation revealed that 5% nano-CaCO<sub>3</sub> will make UHPC achieve the best workability. Liu [61] explored the workability of steel

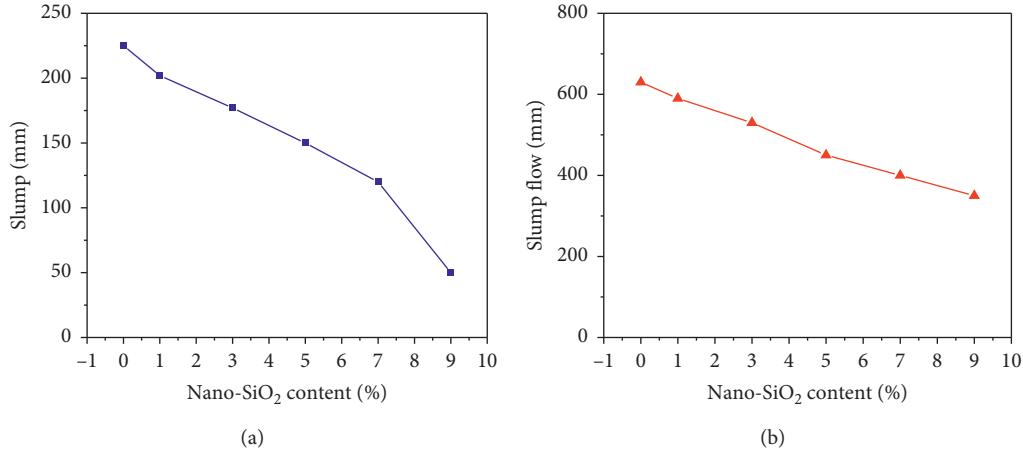


FIGURE 3: Effect of NS content on the (a) slump and (b) slump flow [51].

fiber-reinforced concrete with different amounts of nano-CaCO<sub>3</sub>. It was found that the workability of concrete improved considerably after the addition of nano-CaCO<sub>3</sub>. These data are presented in Figure 4. Clearly, when the content of nano-CaCO<sub>3</sub> varies from 0% to 0.5%, the slump grows slightly. When the added amount of NC increases, the slump increases sharply, and a maximum value of 184 mm is obtained when 1.5% NC is added. However, with the continuous increase in the nano-CaCO<sub>3</sub> content, the slump begins to decline steadily. A number of studies have demonstrated that for ordinary concrete, the optimal content of nano-CaCO<sub>3</sub> is 1.5%, which may be due to the addition of steel fiber that increases the porosity of concrete compared with ordinary concrete, and thus, the optimal content is also increased. This increased content is used to fill the pores in the concrete. However, when the content of nano-CaCO<sub>3</sub> exceeds 2.0%, more free water will be increased and absorbed by the surface area of the mixture, thus causing the slump of concrete to slowly drop. Contrarily, Shaikh and Suptit [62] performed experiments to examine the influence of nano-CaCO<sub>3</sub> content on the workability of an ordinary cement mortar, high-volume fly ash (HVFA) mortar, and concrete. Figure 5 shows that as the proportion of cement replaced by nano-CaCO<sub>3</sub> increases, the workability of the mortar or concrete will decrease.

Shaikh and Suptit [33] explored the effect of the content of nano-CaCO<sub>3</sub> on the workability of cement mortar and HVFA mortar, through a flow meter test, in accordance with ASTM C1437 (2012). Compared with the control group, the workability of mortar containing nano-CaCO<sub>3</sub> is lower. As the content of nano-CaCO<sub>3</sub> used to replace cement increases, the fluidity decreases. Similar to the control mortar, the workability of the HVFA mortar is reduced upon adding 1% nano-CaCO<sub>3</sub>. The decrease in the workability of mortar or concrete is caused by the high-specific surface area of nano-CaCO<sub>3</sub>. However, research by Xu et al. [63] revealed that the application of nano-CaCO<sub>3</sub> in concrete improves the workability of fresh concrete. The slump will gradually rise with the increase in nano-CaCO<sub>3</sub> content. Compared with the concrete without nano-CaCO<sub>3</sub>, the slump of the concrete with 2% nano-CaCO<sub>3</sub> is increased by 8.5%. Nano-CaCO<sub>3</sub> can be well dispersed in concrete, which

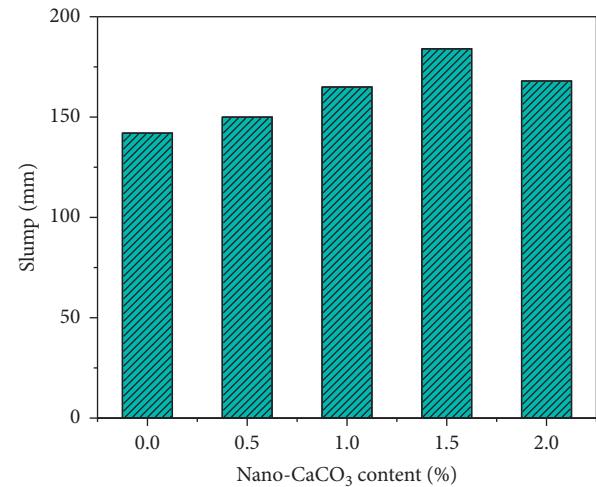


FIGURE 4: Relationship between the slump and NC content [61].

plays a key role in effectively improving the grading of fine particles, reducing accumulation voids, and strengthening the effect of microaggregates, thus improving its water-reducing effect and enhancing the workability of concrete under the same water-binder ratio. Li et al. [38] explored the fluidity curve of a UHPC matrix with different NS and NC contents. Compared with the control mixture, all UHPC substrates containing NS or NC showed lower fluidity. In the mixture containing 1.0% NS and 3.0% NC, the fluidity decreased by 20% and 34%, respectively. Similarly, at a constant NC substitution rate, the fluidity of the UHPC matrix decreases with the increase in NS content. For example, when the content of NS varies from 0.5% to 1.5%, the fluidity of the mixture containing 3.0% NC is reduced by 23% and 35%, respectively. Therefore, the greater the amount of cement replacement, the lower the fluidity.

**2.3. Effect of CNT on the Workability of HPC.** CNT is an allotrope of carbon with a cylindrical nanostructure. Nanotubes are members of the fullerene structural family. It also determines the performance of nanotubes [40]. Wang

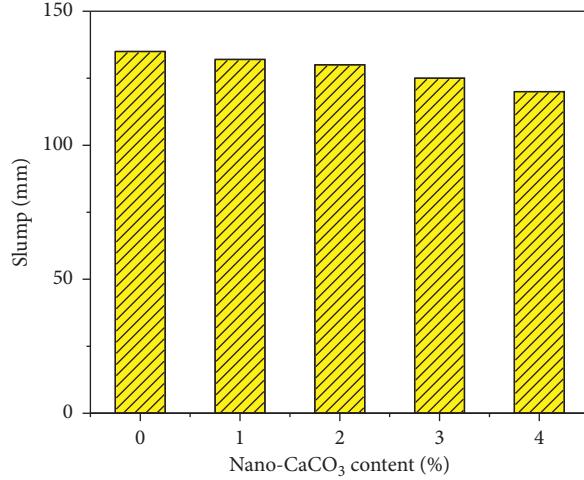


FIGURE 5: Relationship between the slump and NC content [62].

et al. [64] examined the influence of CNT on the workability of concrete through experiments. Figure 6 shows that, when concrete is not mixed with CNT, the slump of the mixture can reach 150 mm. The slump of the concrete mixture gradually decreases, and its fluidity becomes worse, with the increase in CNT contents. When a suitable amount of water-reducing agent (<1.0%) is added to the concrete mixtures with different CNT contents, the slump of the mixture reaches 150–160 mm, meeting the construction requirements. Moreover, CNT has a considerable impact on the adhesion of concrete. In Sun et al.'s study [65], to observe the effect of changes in multiwalled carbon nanotubes (MWCNTs) on the workability of 3D printing polyvinyl alcohol mortar ink, MWCNTs with different volume contents were applied to 3D printing polyvinyl alcohol fiber-reinforced mortar ink. It was found that, compared with the control mixture, the flow value of the new 3D printing mortar modified with MWCNTs can be reduced by a maximum of 3.7%. The addition of MWCNTs will not considerably affect the fluidity of 3D printing mortar, which was also recognized by Sun et al. [66]. Several studies have examined the dispersion of CNTs in polymer composites; however, few studies have investigated the dispersion of CNTs in ordinary Portland cement (OPC) paste. In Figure 7, the slump values of CNT-modified slurry with water-cement ratios of 0.4, 0.5, and 0.6 and a control group (mixed with 0% CNT) are compared. From the figure, we can see that the slump of the control group increases with the increase in water-cement ratio. Moreover, in each mix proportion, the slump is reduced when CNTs are added in small amounts (0.5%, 1%, and 2%) [67].

**2.4. Effect of Titanium Oxide on the Workability of HPC.** Titanium oxide, usually known as titanium dioxide ( $TiO_2$ ), is a natural oxide of titanium. Adding  $TiO_2$  to concrete will change its performance. Joshaghani et al. [68] obtained the dosage of high-range water-reducing admixture (HRWRA) required for each mixture to achieve a slump of  $650 \pm 25$  mm. The solidification delay caused by a high HRWRA dosage is the main

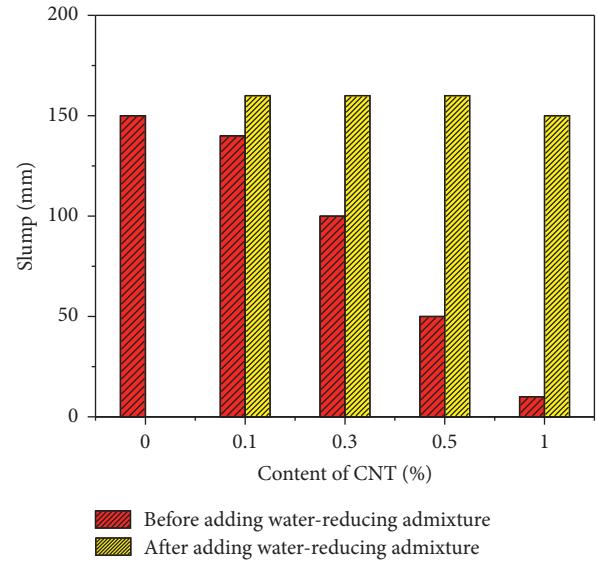


FIGURE 6: Slump of fresh concrete with different amounts of CNTs [64].

reason for the surface subsidence of self-compacting concrete. They observed that the addition of 5%  $TiO_2$  resulted in a high demand for HRWRA under different water-binder ratios. Moreover, adding 5% of nano- $Fe_2O_3$  and nano- $Al_2O_3$  into concrete resulted in a high demand for HRWRA. The water demand of the mixture was increased because the high surface area of the nanoparticles led to more water being absorbed on their surfaces. The data from Figure 8 show the relationship between the content of nano- $TiO_2$  and the slump of the mixture when the water-binder ratio is 0.40. They concluded that compared with the mixture without nano- $TiO_2$ , all the mixtures modified with nano- $TiO_2$  revealed lower slump in a small dosage range [69].

**2.5. Effect of Nano-Kaolin on the Workability of HPC.** NMK is a derivative of industrial mineral kaolin. Kaolin ( $Al_2Si_2O_5(OH)_4$ ) is a layered silicate composed of tetrahedral

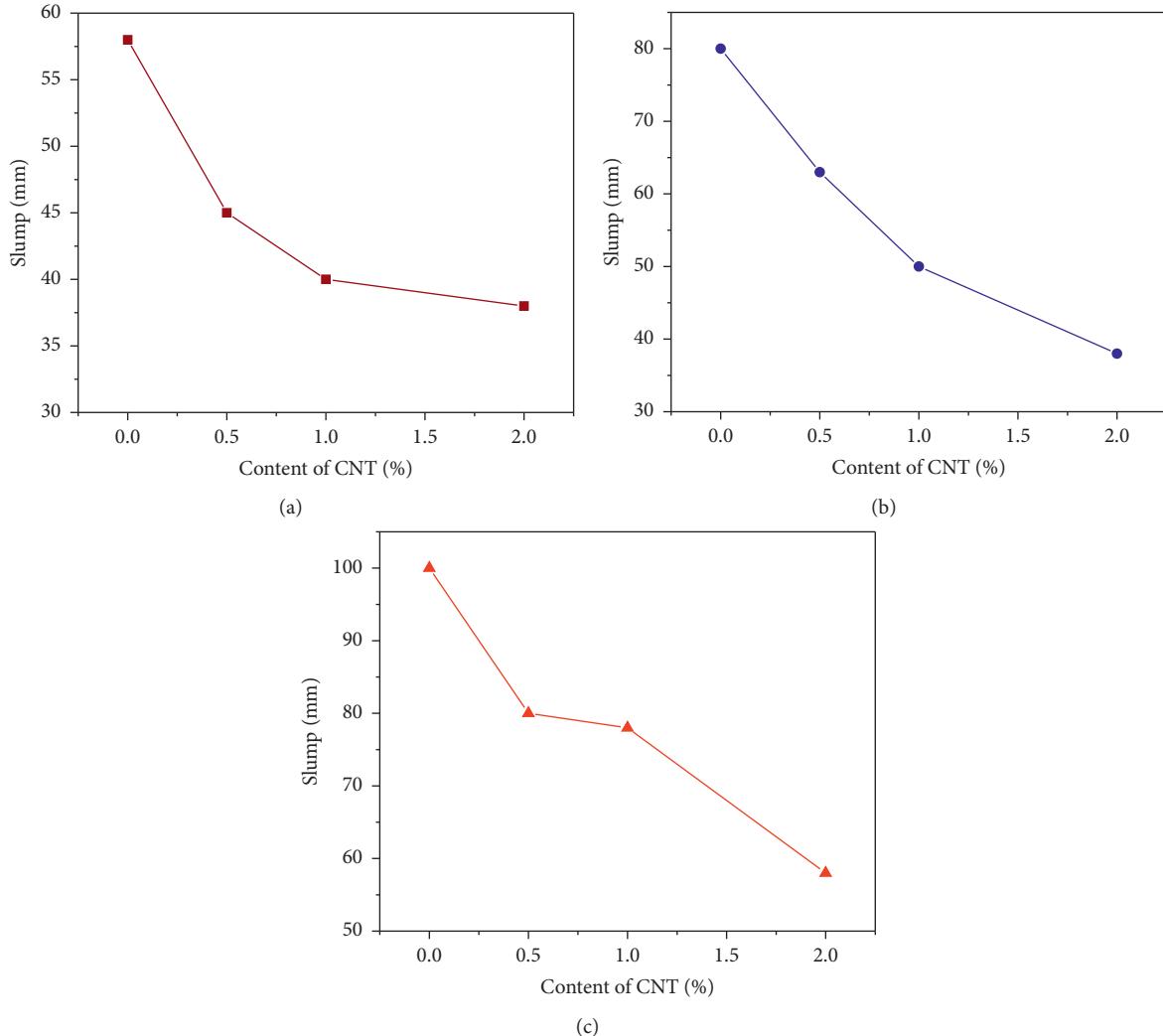


FIGURE 7: Effect of CNT dosage and water/cement on the measured minislump [67]: (a)  $w/b = 0.4$ , (b)  $w/b = 0.5$ , and (c)  $w/b = 0.6$ .

and octahedral coordinated  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . Its main components are hydrated aluminum disilicate, Shi Ying, muscovite, and rutile. NMK is a kind of supplementary material that can be used in concrete to improve its properties. It is based on metakaolin which can considerably modify the performance of various kinds of concrete. The addition of NMK and metakaolin will reduce the workability of UHPC, as presented in Figure 9 [41]. The data reveal that the slump decrease is indeed due to the addition of NMK. Compared with OPC and MK10, the slump decreases with an increase in the NMK content. A number of published papers have reported that the decrease in workability caused by NMK is caused by two factors: namely, high chemical activity and high specific surface area, which can increase the water demand for a hydration reaction. In similar tests, when the NMK content is increased from 0% to 6%, the fluidity of cement mortar decreases by 5.61%–12.47% compared with reference [70]. In addition, the slump of concrete containing 9% NMK decreased by approximately 15.7% [41]. This conclusion was also recognized by Senff et al. [55]. Therefore, controlling the NMK content is

beneficial to obtain the concrete mixture with appropriate workability.

**2.6. Effect of NA on the Workability of HPC.**  $\text{Al}_2\text{O}_3$  is not only the main product in cement hydration but also controls the setting time of cement. NA is actually alumina, and the application of NA to concrete has rarely been studied. Adding NA can better modify some properties of concrete as it can control the setting time of cement. In UHPC, NA is used as a dispersant in cement particles. In addition, because the size of NA is nanoform, NA as a nanofiller can also refine the voids in hydrated gel. Because of the high content of cement in UHPC, the dispersion of cement particles in UHPC must simultaneously occur with the action of silica in the hydration process. However, silica, which is usually used to modify concrete, cannot penetrate the hydration gel; this slows the hydration reaction. However, the addition of NA can accelerate cement hydration by refining cement hydration products. Therefore, adding NA can improve the microstructure of hydrated gel. A research by Gowda et al.

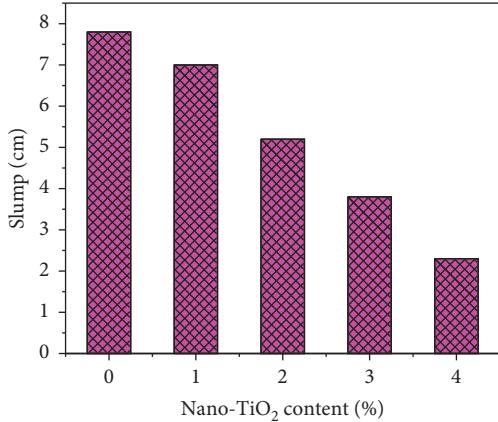


FIGURE 8: Effects of TiO<sub>2</sub> nanoparticles on the workability of concrete [69].

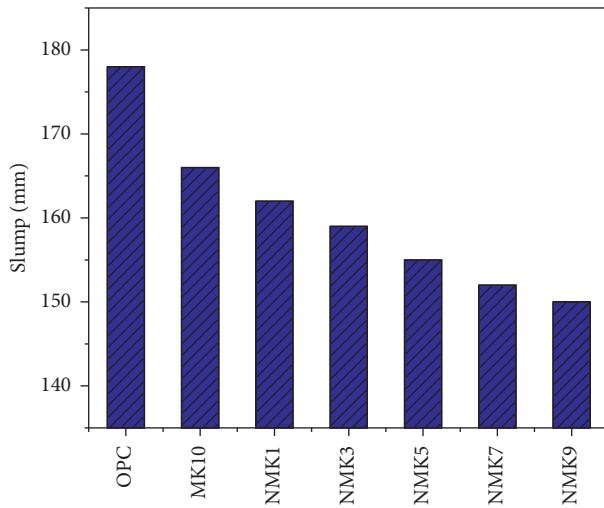


FIGURE 9: Effect of NMK content on the slump of UHPC [41].

[71] stated that adding NA into concrete reduces workability. The workability of the mortar mixture decreases with the increase in NA replacement amount. When the doping amount reaches 5%, the workability considerably decreases. The reason is that the large surface area of NA particles leads to an increased demand for water. The results are shown in Figure 10.

### 3. Mechanical Properties

**3.1. Influence of Nano-SiO<sub>2</sub> on the Mechanical Properties of Concrete.** Adding various nanomaterials to modify the concrete matrix to obtain concrete with excellent mechanical properties is one of the most promising research fields of nanomaterials in concrete application. Several experiments have been performed to examine the mechanical properties, including compressive strength, elastic tensile strength, and flexural strength, of nanoconcrete. NS is a kind of nanomaterial often used to modify HPC. It can be used as a substitute for cement and provides a ball bearing function in cement particles. In addition, NS is used as a superfiller in concrete owing to its particle size, which makes the concrete

structure denser and helps improve the performance of concrete.

**3.1.1. Compressive Strength.** Several studies have identified that the compressive strength of concrete modified by NS is indeed considerably enhanced. The 28-day compressive strengths of the mixtures modified with NS are shown in Table 2. Many experiments have revealed that the compressive strength of cementitious materials can be improved by adding NS within a certain range of dosage. The optimum doping amount has also been considered. The strength will decrease if it exceeds the optimal dosage mainly because a large amount of NS will aggregate and cannot be well dispersed in the mixture [47, 74, 76, 77]. Amin and Abu el-Hassan [81] investigated the influence of the content of NS between 0% and 1.8% and basalt fiber with different contents on the compressive strength and tensile strength. Further research revealed that a large number of C-S-H gels and alumina, ferric oxide, and trisulfate crystals will be produced when the content of NS increases. When the optimal dosage is 1.2%, the amount of the C-S-H gel is the largest, which makes the concrete denser. These results are consistent with those observed in the compressive strength test. The study of Li et al. [38] indicated that 2% is the best dosage to improve concrete performance. Sadr-momtazi et al. [83] found that the optimal content of NS is between 5% and 7%. Compared with the control mixture, the compressive strength will be improved even if the optimum content is exceeded. However, the maximum strength still occurs at the optimum content. An experiment [72] also revealed that a mortar mixed with NS after curing for 7 and 28 days has advantages over a mortar mixed with silica fume in terms of improving strength. In this study, cement was replaced by NS with contents of 5%, 10%, and 15%. The influence of the partial replacement of cement by NS on the compressive strength of HVFA mortar and concrete was also explored [73]. The compressive strength of the mortar was analyzed after curing for 7 and 28 days, and that of concrete was analyzed after curing for 3, 7, 28, 56, and 90 days. The results show that in the range of 1%–6%, the compressive strength of cement mortar in 7 and 28 days reaches the maximum when the content of NS is 2%. Moreover, the compressive strength of the mortar mixed with 40% and 50% FA increases by 5% and 7%, respectively, after 7 days of curing with the addition of 2% slag micropowder. However, when the content of FA in the ordinary mortar exceeds 50%, no evident improvement is observed. By contrast, the 28-day compressive strength of all HVFA mortars is improved by adding 2% NS, and the most significant improvement occurred in mortars with FA contents over 50%. In HVFA concrete, the compressive strength at the early stage (3 days) is also improved owing to the addition of 2% NS. The results are presented in Figures 11 and 12.

**3.1.2. Tensile Strength and Flexural Strength.** The tensile strength of concrete is low, generally 1/10–1/20 of the compressive strength. Amin and Abu el-Hassan [81] found that an HSC composed of 1.2% NS and 3 kg/m<sup>3</sup> basalt fiber

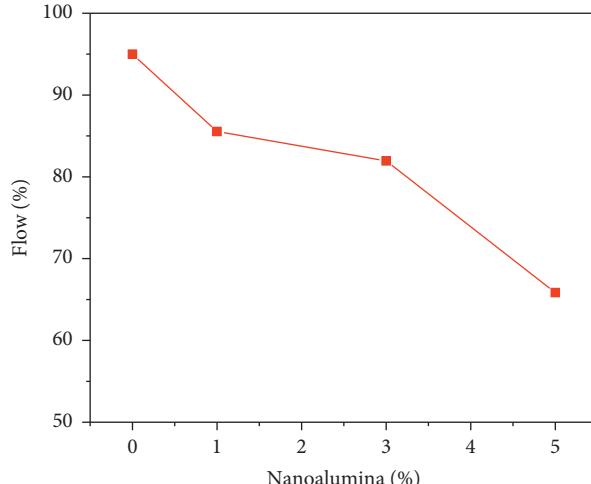


FIGURE 10: Percentage of flow [71].

TABLE 2: Compressive strengths of cementitious materials with NS at 28 days.

Cementitious materials	w/b ratio	Content of NS	Optimum content	Compressive strength increment	Reference
Cement Mortar	0.3–0.5	5%–15%	10%	—	[72]
HVFA cement paste	0.4	1%–6%	2%	5%	[73]
Lightweight aggregate concrete	0.35	1%–3% 0%–7%	3% 5%	3.2%–16.8%	[74] [75]
SCC	0.4	2% NS + 0.08% CNT + 40% FA	2%	20%	[46]
	0.5	0%–0.75%	0.75%	26.9%–48.8%	[47]
	0.4	0.5%–2%	2% + 15 mm 1.5% + 80 mm	—	[76, 77]
	0.5	Basalt fiber + NS	6%	10.4%–19.6%	[78]
Ordinary concrete	0.5	0%–6%	6%	12.45%	[79]
	0.3	5% MS + 1% NS	1%	—	[80]
	0.2	1%–4%	3%	10%	[81]
	0.48	0%–1.8%	1.2%	9.04%	[81]
	0.34	3%–5%	3%	—	[82]
HPC	0.16	0.5%–1.5%	1%	3%	[38]
	0.35	0.75%–1.5%	1.5%	12%	[32]

can achieve the best splitting tensile strength. They revealed that the tensile strength can be increased by 17.42% compared with a control mixture concrete (see Figure 13). Jalal et al. [84] pointed out that the splitting tensile strength of self-compacting concrete can be increased by 25.6%, 30.7%, and 35.9% after curing for 90 days with 10% FA and 2% NS in different cementitious material contents. Fallah and Nematzadeh [85] explored the mechanical strength of HPC mixed with polymer fiber and NS. Tests show that after replacing cement with 1%, 2%, and 3% NS, the tensile strength of cement increased by 12.96%, 7.82%, and 16.10%, respectively. This increase in strength is mainly due to the increased bonding force between the cement base and aggregate. Mohamed's research [86] shows that adding 0.75% NS and 3% nanoclay (NC) to concrete can increase the flexural strength by 4% and 9%, respectively, after curing for 90 days. They also pointed out that adding 3% nanoparticles consisting of 25% NS and 75% NC has great advantages in

improving mechanical properties. Amin and Abu el-Hassan [81] also revealed that, compared with a control group, the flexural strength of concrete after adding NS and NiFe<sub>2</sub>O<sub>4</sub> nanoparticles is increased by approximately 23%.

**3.2. Influence of Nano-CaCO<sub>3</sub> on the Mechanical Properties of Concrete.** According to several studies worldwide, nano-CaCO<sub>3</sub> modified cement-based materials generally have three functions, namely, the chemical, nucleation, and filling functions. Among them, nano-CaCO<sub>3</sub> effects on the hydration process of cement are mainly chemical and nucleation. Detwiler and Tennis provided that calcium carbonate powder particles act as nucleation sites in the process of cement hydration, which increases the precipitation probability of the hydration product C-S-H gel on limestone powder particles and accelerates the hydration of C<sub>3</sub>S. Many hydrated calcium aluminate particles grow on the surfaces of

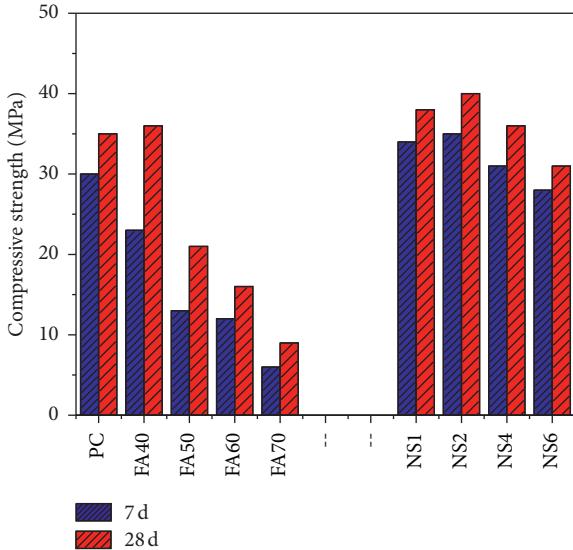


FIGURE 11: Compressive strength of mortars containing NS and FA [73].

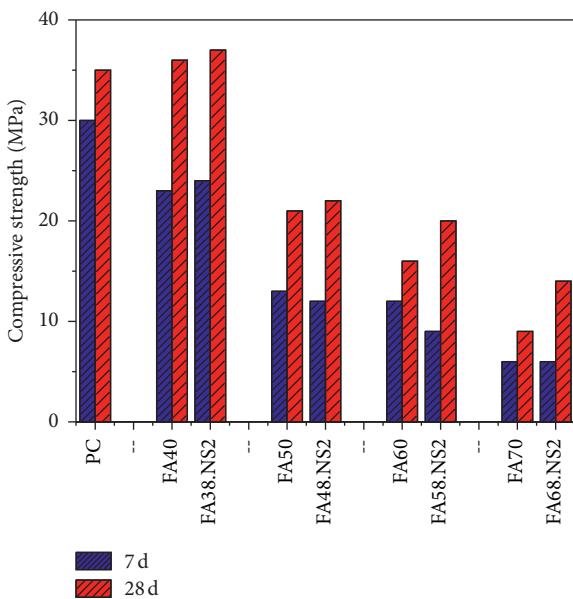


FIGURE 12: Effects of 2% NS on the compressive strength of mortars containing HVFA [73].

major products, such as C-S-H and  $\text{Ca}(\text{OH})_2$ . Calcium aluminate ( $\text{CaO}\cdot 3\text{Al}_2\text{O}_3\cdot \text{CaCO}_3\cdot 11\text{H}_2\text{O}$ ) is produced by the hydration reaction between nano- $\text{CaCO}_3$  and  $\text{C}_3\text{A}$ , and it can improve the early strength of cement-based materials.

The compressive strength of the cementing material modified by a proper amount of nano- $\text{CaCO}_3$  is enhanced, and adding nano- $\text{CaCO}_3$  can exert the combined microaggregate, pinning, and crystal nucleus effects, so as to make the particle gradation more perfect, fill each other, reduce the void ratio, increase the bulk density, and contribute in the enhancement of the flexural and compressive strength. However, this characteristic is related to the content of nano- $\text{CaCO}_3$ , and an optimal

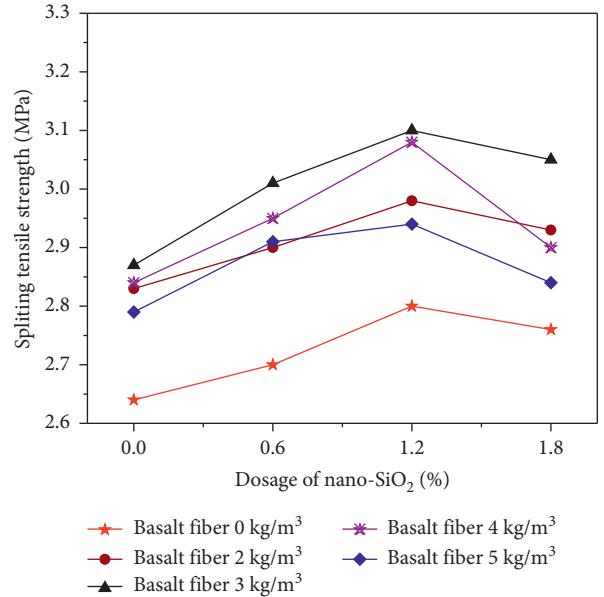


FIGURE 13: Effect of the NS dosage on the splitting tensile strength [81].

content is generally considered. When the content of nano- $\text{CaCO}_3$  exceeds the optimal content, it will not be conducive to improving the performance of the cementitious materials. The main reason is that the van der Waals force of nano- $\text{CaCO}_3$  is higher than that of cement, which easily causes nano- $\text{CaCO}_3$  with fine particles to aggregate in the mixture. According to the literature [59], for a 29.0% FA content, the optimal content of nano- $\text{CaCO}_3$  to enhance the compressive and flexural strength is 2.2%. With this content, the flexural and compressive strengths of cement-based materials are increased by 27.3% and 19%, respectively, compared with the control group. Huang and Zu [60] found that the optimal content of nano- $\text{CaCO}_3$  to improve the UHPC strength (accounting for cement quality) is 3%, and the water-cement ratio should be 0.15, as presented in Figure 14. Meng et al. [58] observed the influence of nano- $\text{CaCO}_3$  content with an average particle size of 60 nm on OPC. The results show that when the content is 2%, the early hydration strength of cement is improved, but when the content exceeds 5%, the strength decreases due to the relative decrease in cement content. Similar findings have been reported in other publications as well [87–91].

When nano- $\text{CaCO}_3$  is mixed into concrete with FA, the early strength hysteresis effect caused by FA can be improved, and the early and late strength of cement-based materials containing FA can be further developed. The composite mineral admixture modified by nano- $\text{CaCO}_3$  prepared in reference [92] can exert the composite function of the early strength of calcium carbonate intermediate and high activity of mineral powder in the later period, so the early and later strengths of concrete are superior. Shaikh and Supit [62] revealed that the optimal content of nano- $\text{CaCO}_3$  modified high-performance FA concrete (e.g., concrete with 40% and 60% FA

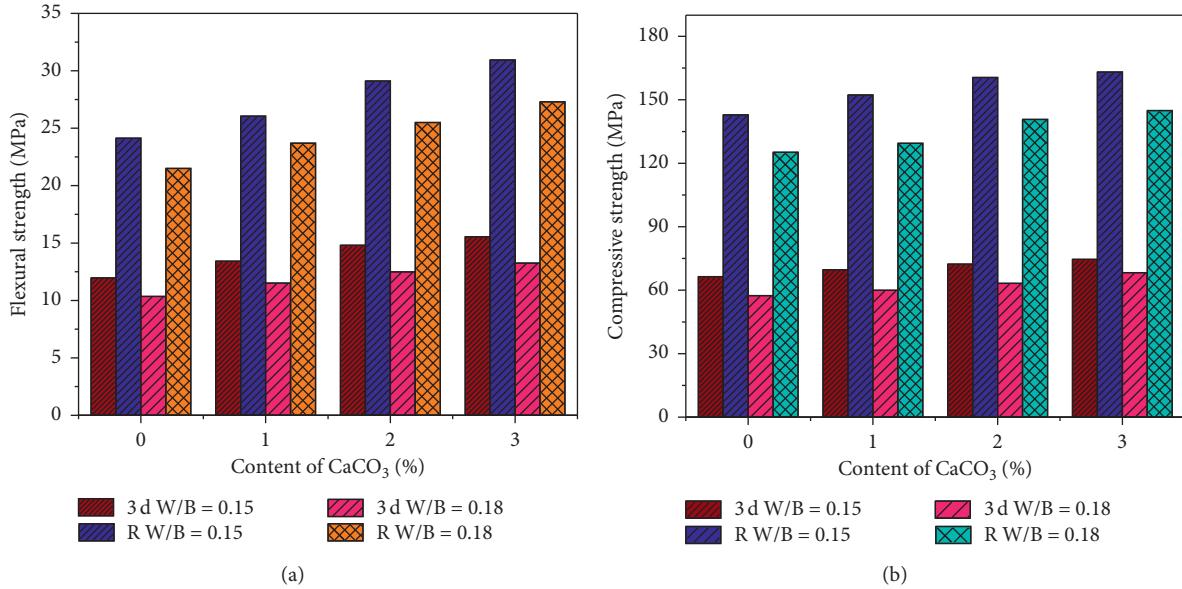


FIGURE 14: Influence of nano-CaCO<sub>3</sub> content on the (a) flexural strength and (b) compressive strength [60].

content, respectively) is 1%. Moreover, the concrete with this content has reasonable compressive strength, low permeable pore volume, and low porosity. Wu et al. [93] found that the addition of 3.2% nano-CaCO<sub>3</sub> considerably improved the bonding performance of the fiber-matrix and the bending performance of UHPC. The main reason is that nano-CaCO<sub>3</sub> improves the densification of the interfacial transition zone from the perspective of microstructure. However, when the content of nano-CaCO<sub>3</sub> exceeds 3.2%, the mechanical properties of UHPC will decrease due to the increase in porosity caused by nano-CaCO<sub>3</sub> agglomeration. Meng et al. [94] also explored the relationship between the mechanical properties of nano-CaCO<sub>3</sub> and concrete with or without FA. They concluded that nano-CaCO<sub>3</sub> has a positive effect on the early mechanical strength of concrete mixed with FA and concrete not mixed with FA. The main reason is that the seed crystal effect of nano-CaCO<sub>3</sub> accelerates the hydration of cement and also produces a filling effect, making the microstructure of cement paste more compact. Shaikh and Supit [62] and Supit and Shaikh [33] investigated the influence of nano-CaCO<sub>3</sub> on the compressive strength of concrete with a large amount of FA. The results show that adding 1% nano-CaCO<sub>3</sub> allows HVFA concrete to have an excellent compressive strength.

In addition, in Xu et al.'s study [63], the changes in the compressive strength of HSC caused by nano-CaCO<sub>3</sub> under a standard curing temperature ( $21 \pm 1^\circ\text{C}$ ) and low-temperature curing ( $6.5 \pm 1^\circ\text{C}$ ) were investigated. It was observed that the compressive strength of concrete modified by adding 1% and 2% nano-CaCO<sub>3</sub> can be increased by 13% and 18% at a standard curing temperature. However, the compressive strength increased by 17% and 14% after curing at low temperature for 3 days. Moreover, the effect of NC on the mechanical

properties of concrete under different curing conditions was investigated by Li et al. [38]. They found that the compressive and flexural strengths increase as the NC content increases. Meanwhile, the optimal content of NC is approximately 2.0%. The influence of nano-CaCO<sub>3</sub> content on the compressive strength and tensile strength of concrete under different curing conditions is presented in Figure 15.

**3.3. Influence of CNT on the Mechanical Properties of Concrete.** The flexibility of CNTs can also be used to modify UHPC. Compared with other nanomaterials, CNTs have great advantages in enhancing the toughness and strength of UHPC [40]. In recent years, CNTs have been widely examined to modify and obtain cement-based composites with excellent properties. However, obtaining uniform CNT dispersions is extremely difficult because they are prone to aggregation. Accordingly, Parveen et al. [95] used Pluronic F-127 as a new dispersant to blend CNT-modified cement composites with excellent performance. In addition, adding 0.1% single-walled nanotube dispersion increases the flexural modulus of mortar by 72%. Moreover, the flexural strength and compressive strength increased by 7% and 19%, respectively, after curing for 28 days. Gillani et al. [96] also addressed this shortcoming. To realize a uniform dispersion of MWCNT, high-energy ultrasonic treatment was performed on the modified acrylic polymers. The amount of MWCNTs added to the cement was 0.05% and 0.1%. They pointed out that the splitting tensile strength, bending strength, and compressive strength of the mixture increased by 20.58%, 26.29%, and 15.60%, respectively, after adding 0.05% MWCNT compared with the control mixture cured for 28 days, as presented in Figure 16. However, the mixing duration is also a factor that affects the strength of CNTs' cementitious composites. The bending strength of materials containing 0.03%, 0.08%,

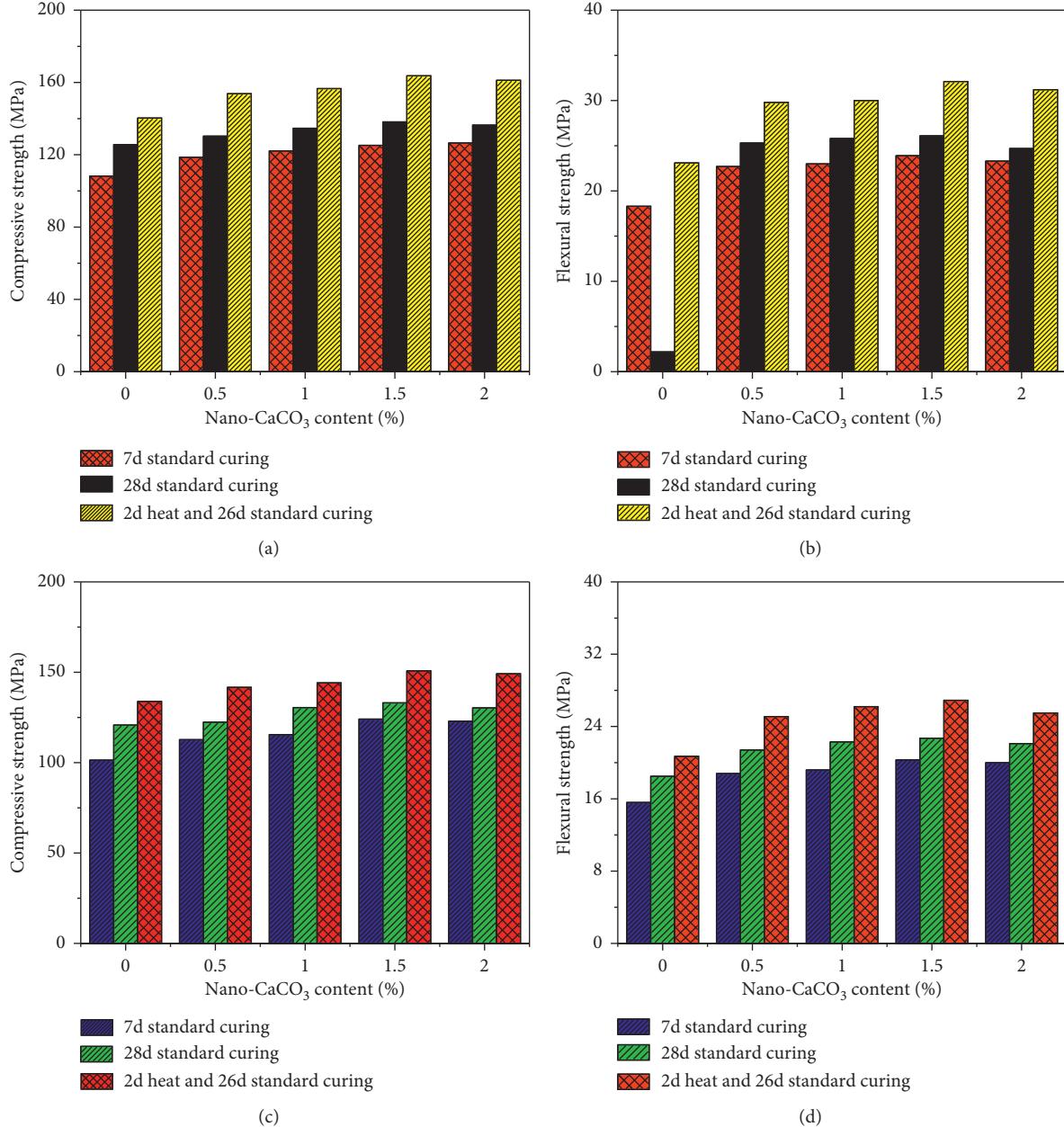


FIGURE 15: Effect of nano-CaCO<sub>3</sub> content on the mechanical strength of UHPC under different water-binder ratios [38]: (a) w/b = 0.16, (b) w/b = 0.16, (c) w/b = 0.17, and (d) w/b = 0.17.

0.15%, or 0.25% MWCNT prepared using stirring times of 1.5, 15, 30, and 60 min, respectively, was studied on the 28th day. These data reveal that the flexural strength of the cement materials added with 0.25% CNTs increased a lot. Compared with the test results of ordinary cement, the flexural strength of the mixture mixed with 0.15% and 0.25% CNTs is considerably increased when the mixing time exceeded 30 min. The mixing effect of CNT cement is presented in Figure 17, and the flexural strength results are shown in Figure 18 [97]. Meanwhile, AI-Rub et al. [98] found the effect of different concentrations of long MWCNTs in cement paste. They showed that nanocomposites modified with low concentrations of long CNTs have the same mechanical properties

as those modified with high concentrations of short CNTs. Many studies have shown that CNTs can be uniformly dispersed in concrete using a certain dispersion method, and the compressive strengths of concrete with CNT can be remarkably enhanced. However, the performance of concrete will deteriorate when the content is excessively high [99–103]. The findings of Jung et al. are shown in Figure 19. The mechanism of influence involves adding a proper amount of CNTs into the concrete and evenly distributing the CNTs in the concrete material, which can better exert its nanonucleation effect, thus enhancing the compressive strength and flexural strength of the concrete. However, when the content of CNTs is too much, it is difficult to

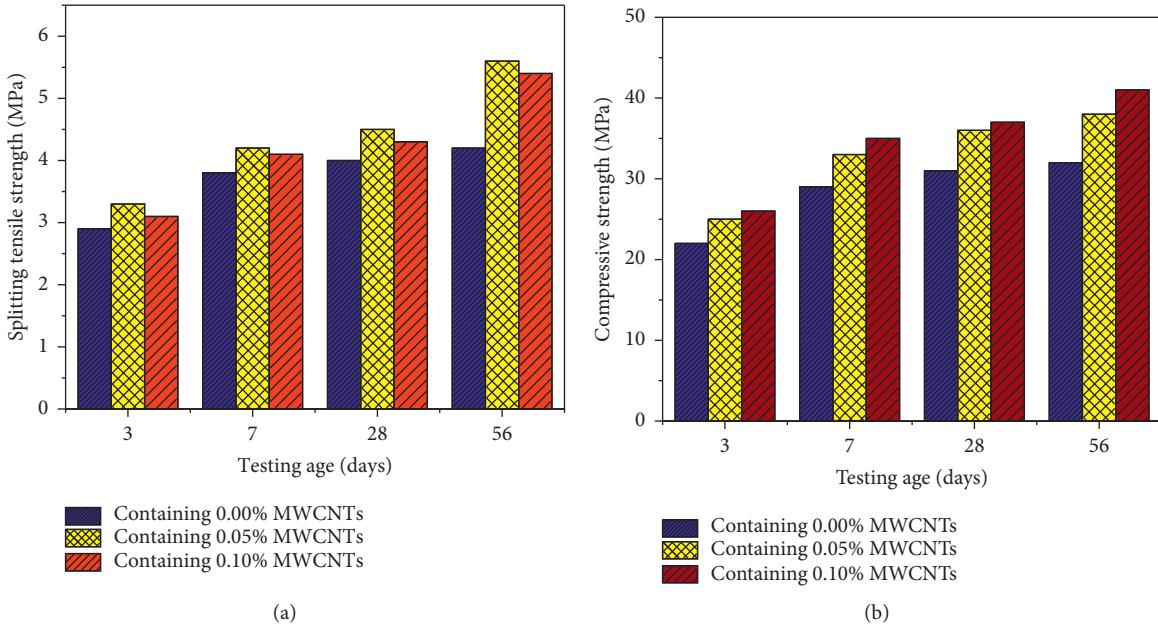


FIGURE 16: . (a) Splitting tensile strength and (b) compressive strength of concrete with different contents of MWCNTs at different ages [96].

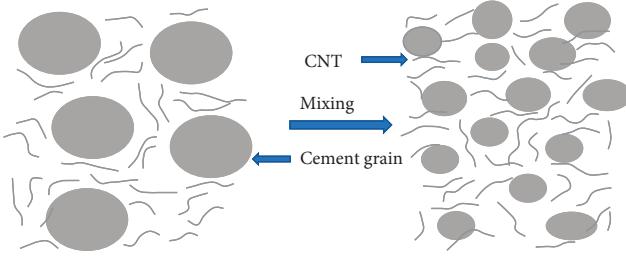


FIGURE 17: Schematic of the mixing effect on the cement grain size [97].

disperse and aggregate inside the concrete, which reduces the bridging effect and leads to the performance degradation of the concrete.

**3.4. Influence of  $TiO_2$  on the Mechanical Properties of Concrete.** The application of  $TiO_2$  in UHPC and ordinary concrete has generally resulted in a strong self-cleaning ability, which enables application of green materials in buildings. Meanwhile, it accelerates the early strength of concrete [36]. However,  $TiO_2$  particles are dusty and small and have a considerable environmental impact during the packaging and production process. Adding a small amount of NT into concrete can effectively improve its compressive strength and flexural strength. The strength of concrete specimens increases first and then decreases with the increase in NT contents. Adding very fine NT will increase the specific surface area of the material and the water demand of the mixture, which will make the matrix material unevenly distributed in the mixture, thus reducing the strength of concrete. The effect of FA and  $TiO_2$  on the flexural strength of self-compacting concrete replacing cement was analyzed by Jalal et al. [104–106]. They found that fly ash will reduce the bending strength at the early curing stage. Therefore,

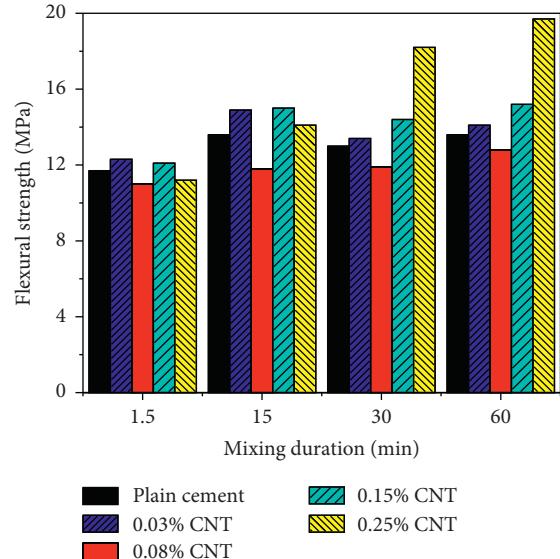


FIGURE 18: Effect of the mixing time on the flexural strength of CNT cement composites [97].

measures to increase curing time can be adopted to improve the bending strength. Replacing cement with 4%  $TiO_2$  nanopowder can increase the content of crystal  $Ca(OH)_2$  at the early stage of hydration and accelerate the formation of the C-S-H gel; this can enhance the strength of concrete. The relevant data are presented in Figure 20. The compressive strength of cement-based materials modified by nano- $TiO_2$  was explored in Meng et al.'s [107] and Zhang et al.'s [108] experiments. When cement was replaced by NT, the compressive strength of the cement mortar increases at early age because NT promotes cement hydration and refines pores. Duan et al. [109] stated that adding a certain amount of

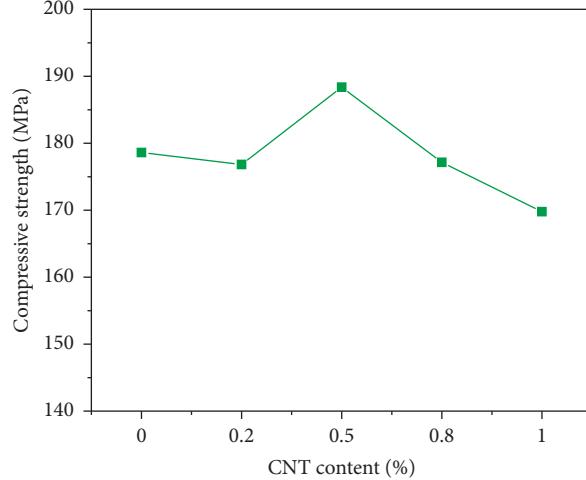


FIGURE 19: Compressive strength of the UHPC-CNT composites [99].

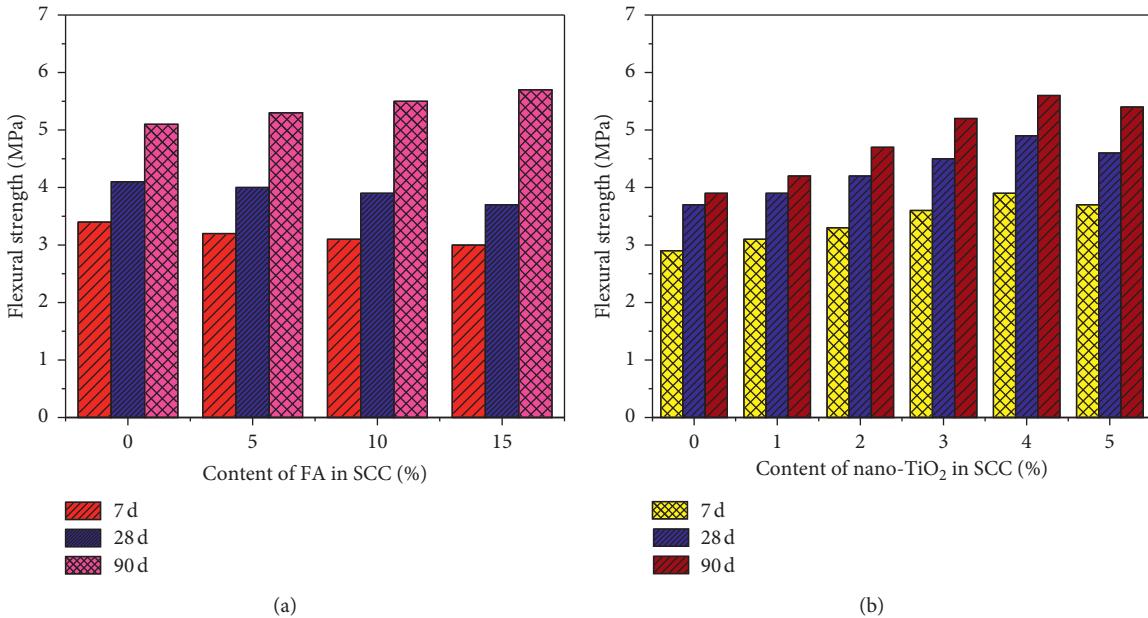


FIGURE 20: Flexural strength results of SCC-FA mixtures (a) and SCC-NT mixtures (b) [104]. (a) Content of FA in SCC, (b) Content of NT in SCC.

nano-TiO<sub>2</sub> can improve the early and late compressive strengths of the mixture. When the optimal content is 5%, NT shows evident effect on the performance of the modified polymer.

### 3.5. Influence of Nano-Kaolin on the Mechanical Properties of Concrete

**3.5.1. Compressive Strength.** Several researchers regard NMK as a suitable mineral admixture precisely because metakaolin can effectively enhance the microstructure of cement-based materials and substantially increase their strength. A number of studies have revealed that the compressive strengths of cement-based composites can be remarkably enhanced with an appropriate amount of NMK

[110, 111], as presented in Table 3. Adding an appropriate amount of NMK can improve the compressive strength of cementitious materials. The results [112, 113] show that the optimum dosage of NMK is 10%. However, the compressive strength and bending strength gradually decrease when the content exceeds optimum value (10%), and the compressive strength of samples containing 12% and 14% NMK is close to the control group. Similar results were obtained by Shoukry and Al-Jabri [114]. By contrast, El-Gamal et al. [115] and Kaur et al. [116] found that the optimal NMK content in cement mortar is 3% and 4%, respectively. Morsy et al. [40] revealed that the compressive strength of a cement mortar modified by 6% NMK and 0.02% CNTs for 28 days increased by 29% and 11%, respectively. These findings show that NMK and CNTs have good synergy.

TABLE 3: Compressive strength of NMK cement-based materials at 28 days.

Cementitious material	w/b ratio	Content of NMK	Compressive strength increment (%)	Reference
Cement paste	0.27	10% NMK	20	[112]
Cement paste	0.3	10% NMK	48	[113]
Cement mortar	0.54	10% NMK	42	[114]
Cement mortar	0.48	3% NMK	54	[115]
Cement mortar	0.3	4% NMK	22.6	[116]
Cement mortar	0.5	6% NMK	18	[40]
Ordinary concrete	0.5	6% NMK + 0.02% CNT	29	[117]
UHPC	0.2	10% NMK	63.1	[41]
		1% NMK	7.88	

Some contrasting findings have also been reported in the literature. Muhd Norhasri et al. [41] examined the mechanical properties of UHPC with NMK content of 1%–9%; the compressive strength of the 1% NMK sample was observed to be the highest. This finding is corroborated by previous studies. However, NMK had no significant effect on the early strength of UHPC, not even a slight decrease. This occurs mainly because the cement and aggregate in the UHPC mixture provide less space, which hinders the filling effect of NMK and reduces the amount  $C_3S$  and  $\beta-C_2S$  phases in the matrix; this results in a slight decrease in the early strength of UHPC.

**3.5.2. Flexural Strength and Splitting Tensile Strength.** NMK is generally used to modify cementing materials; it can remarkably enhance the flexural strength and splitting tensile strength, and its optimal content is approximately 8%–10%. Shoukry et al.'s [118] examined the modification effect of NMK. They found that the bending strength is improved using 2%–14% NMK instead of cement and through surface plastering with 2% fiber content. They also observed that the bending strength increased by approximately 67% compared with the control FRCC when the NMK content was 10%. However, the strength gradually decreases with the increase in the NMK content. As shown in Figure 21, Habeeb et al. [119] provided that the splitting tensile strength was increased by 3.04%–3.41% and 6.95%–7.98%, respectively, with the addition of 2% and 5% NMK into reactive powder concrete (RPC). In Morsy et al.'s [120] study, the influence of 800°C high temperature on the mechanical properties of NMK-modified cement mortar with a cement-sand ratio of 1 : 3 and water-binder ratio of 0.6 was explored. They found that 250°C is the appropriate temperature to maximize the compressive strength (see Figure 22). However, Braganca et al. [35] found that the splitting tensile strength of NMK concrete with 3% content does not improve appreciably when the water-cement ratio is 0.53.

**3.6. Influence of NA on the Mechanical Properties of Concrete.** In the current research, the compressive strength and pore structure of cement can be modified with nanomaterials, such as NS, NA, and CNTs. If nanocement can be economically manufactured and used on a large scale, concrete construction will enter a new era defined by stronger

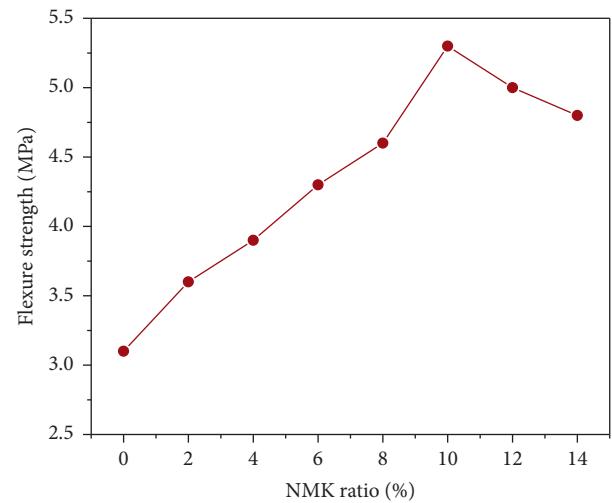


FIGURE 21: Flexural strength of NMK-modified FRCC as a function of the NMK ratio at 28 days of curing [118].

concrete durability. Alumina, as the main chemical substance in the hydration process of cement, can control the setting time of cement. Adding NA into concrete, especially UHPC, substantially influences the performance of concrete. However, research NA concrete is limited.

According to the literature [71], the maximum early strength can be obtained by adding 1% NA instead of cement. The influence of NS, NA, and NT on the mechanical properties of self-compacting mortar containing FA under single and double doping was studied by Mohseni et al. [121]. The content of the three nanoparticles is 1%, 3%, and 5%, respectively. They observed that the compressive strength of the mixture increased with an increase in the curing age, reaching the maximum value at 90 days; this is mainly due to the pozzolanic activities of FA. The results also show that when the contents of NA, NS, and NT are 1%, 3%, and 5%, respectively, the best compressive strength can be achieved. When the mixture is modified with two types of nanoparticles, the combination of NST achieves the highest strength. On the one hand, NT plays an important role in improving the strength. On the other hand, the combined action of FA and NS increases the pozzolanic reaction in mortar. The experimental results under single and double doping are shown in Figures 23(a)–23(c) and 24(a)–24(c). Hamed et al. [122] revealed the effects of adding constant contents of nano-ZrO<sub>2</sub> (NZ), NF, NT, and NA on the

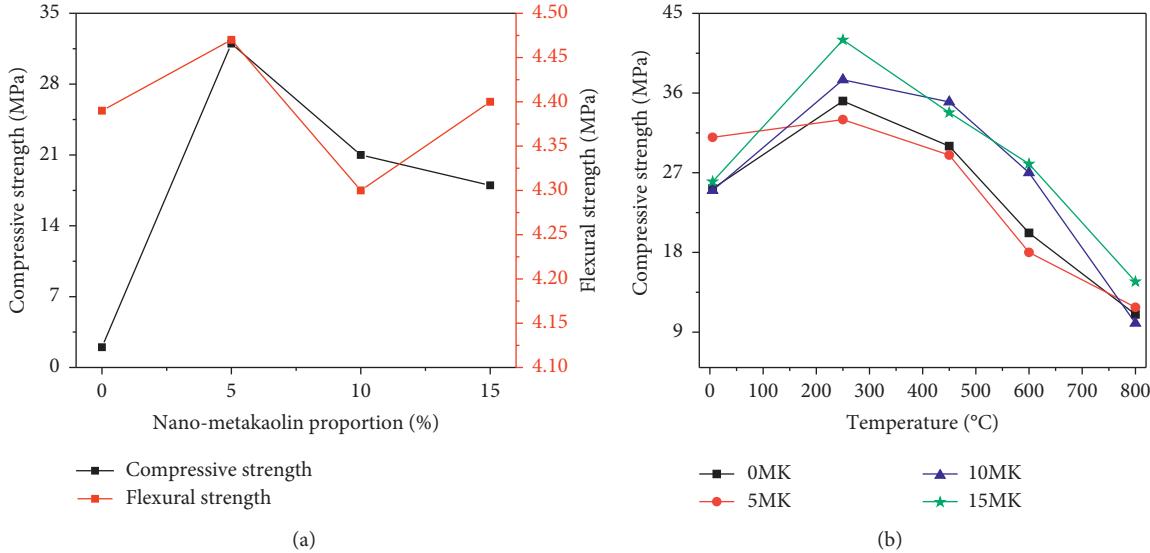


FIGURE 22: Compressive and flexural strength of NMK-cement mortar and NMK proportion and temperature [120]. (a) Different contents of NMK. (b) Different temperatures.

properties of concrete. They proved that NA has unique advantages in improving the mechanical properties of HPC (see Figure 25).

**3.7. Influence of NC on the Mechanical Properties of Concrete.** NC is a type of mineral silicate nanoparticle and is also one of the most economical nanomaterials. It offers several advantages with regard to modifying mixtures. The effects of NC addition on the mechanical performances of the SCC were investigated. Mohammadi and Mirgozar Langaroudi [123] found that compared with the replacement rates of NC at 1% and 2%, the compressive strength is considerably improved when 3% NC is used to replace cement. Moreover, 3% is considered the optimal content of NC for SCC. However, Hamed et al.'s [122] investigated influence of different contents of NC (5%, 7.5%, and 10%) on concrete performance. They found that compared with the as-received NC concrete, the properties of concrete are obviously improved through the sonication of NC particles and the optimum content of NC to replace cement was 7.5%, as shown in Figure 26.

**3.8. Influence of Other Nanomaterials on the Mechanical Properties of Concrete.** Finally, paper [35] indicates that using 1% NF to replace cement can ensure that concrete has better mechanical properties. The reason is that micro-nanomaterial fills the surplus pores and voids of the mixture, which promotes the matrix material to be denser. Joshaghani et al. [68] used the mechanical properties as the starting point and analyzed the influence of different types of nanoparticles (including nano-TiO<sub>2</sub>, NA and nano-Fe<sub>2</sub>O<sub>3</sub>) on the properties of self-compacting concrete through different test methods. Compared with NA and NT, nano-Fe<sub>2</sub>O<sub>3</sub> is considerably better at enhancing compressive strength because hydrated ferric calcium gel is formed in the

microstructure. To handle the large amounts of carbon dioxide emitted and energy consumed during cement production [124], two different proportions of nano palm oil fly ash (NPOFA) were used to replace cement to improve the mechanical properties of concrete. Test data show that the compressive strength of concrete increases gradually when the content of NPOFA is as high as 30%. Ruan et al. [125] and Han et al. [126] found that the mechanical properties of RPC with NZ at a curing age of 28 days improve the compressive strength in comparison with plain RPC.

#### 4. Effect of Different Nanomaterials on Workability and Mechanical Properties of HPC

In summary, a large number of research results show that adding nanomaterials to concrete will reduce its workability. As the content of nanomaterials used to replace cement increases, the workability decreases. Therefore, many scholars believe that in order to maintain a good workability of concrete, the content of nanomaterials should be as small as possible (1%–5%). However, Lui [61] found that the workability of concrete improved considerably after the addition of nano-CaCO<sub>3</sub> when the content of nano-CaCO<sub>3</sub> varies from 0% to 0.5%, the slump grows slightly, and the optimal content of nano-CaCO<sub>3</sub> is 1.5%.

A lot of study results show that adding nanomaterials can exert crystal nucleus effect so as to make the particle gradation more perfect, fill each other, reduce the void ratio, increase the bulk density, and contribute in the enhancement of the flexural and compressive strength. The overall trend is increasing first and then decreasing, and an optimal content is generally considered. There are inconsistent conclusions in the current research on the optimal content. Amin and Abu el-Hassan found that the optimal dosage is 1.2% and the amount of the C-S-H gel is the largest, which

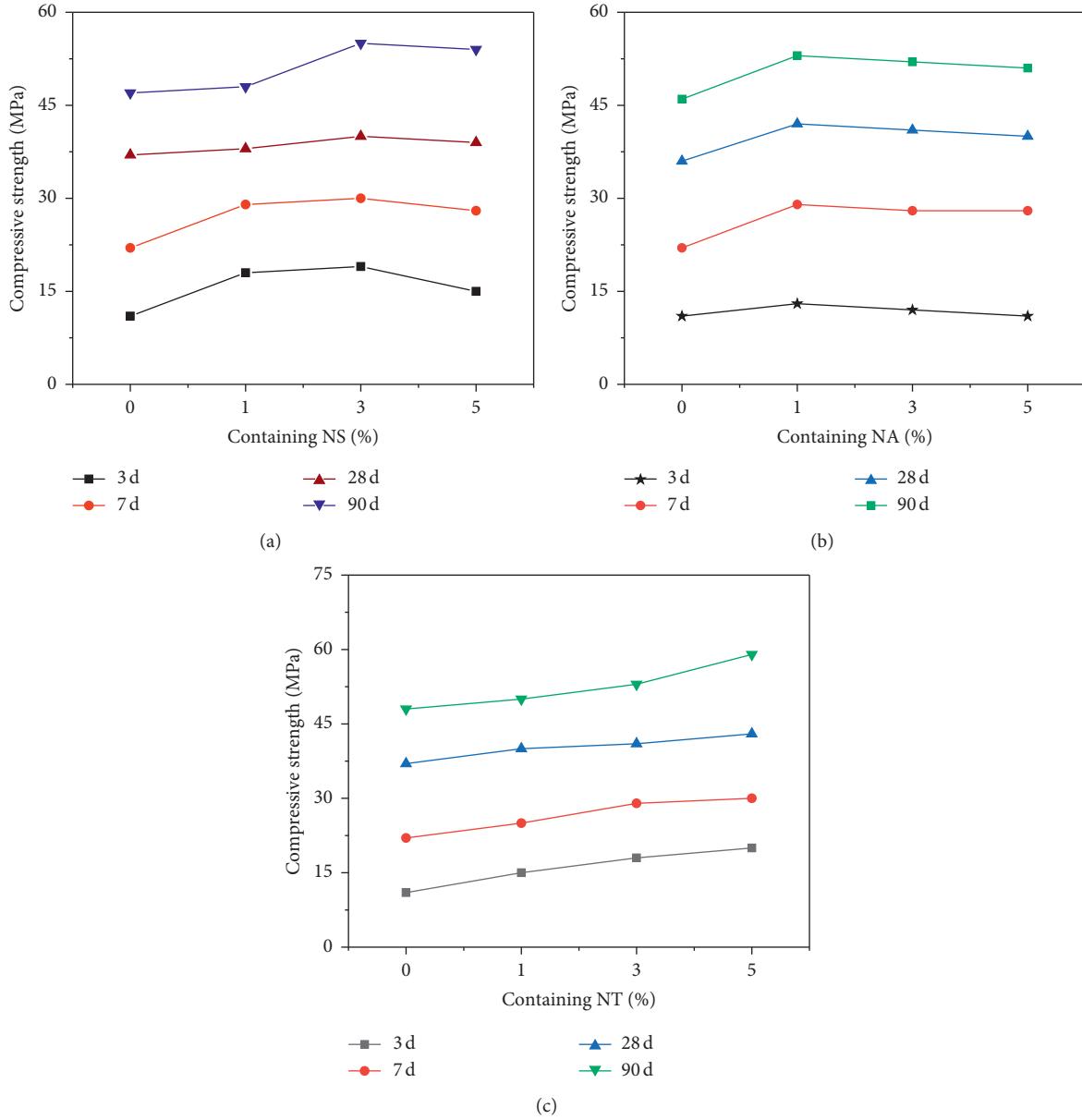


FIGURE 23: Variation of the compressive strengths of self-compacting mortars containing (a) NS, (b) NA, and (c) NT, at different ages [121].

makes the concrete denser [81]. The study of Li et al. indicates that 2% is the best dosage to improve concrete performance [38]. Sadrmomtazi et al. found that the optimal content of NS is between 5% and 7% [83]. It can be concluded that the optimal content of nano-CaCO<sub>3</sub> to enhance the compressive and flexural strength is 2.2% [59]. Huang and Zu found that the optimal content of nano-CaCO<sub>3</sub> to improve the UHPC strength (accounting for cement quality) is 3% [60]. The related results show that when the content is 2%, the early hydration strength of cement is improved [58]. Shaikh and Supit show that adding 1% nano-CaCO<sub>3</sub> allows HVFA concrete to have an excellent compressive strength [62]. Wu et al. found that the addition of 3.2% nano-CaCO<sub>3</sub> considerably improved the bonding performance of the fiber-matrix and the bonding performance of UHPC [93]. Gillani et al. revealed that the flexural strength of the cement

materials added with 0.25% CNTs increased a lot [96]. Duan et al. stated that adding a certain amount of nano-TiO<sub>2</sub> can improve the early and late compressive strengths of the mixture [109]. When the optimal content is 5%, NT shows evident effect on the performance of the modified polymer. The results show that the optimum dosage of NMK is 10% [112, 113], and the similar results were obtained by Shoukry and Al-Jabri [114]. By contrast, El-Gamal et al. [115] and Kaur et al. [116] found that the optimal NMK content in cement mortar is 3% and 4%, respectively. However, Muhd Norhasri et al. found that the compressive strength of the 1% NMK sample was observed to be the highest [41]. Shoukry et al. observed that the bending strength increased by approximately 67% compared with the control FRCC when the NMK content was 10% [118]. Mohseni et al. also showed that when the contents of NA, NS, and NT are 1%, 3%, and

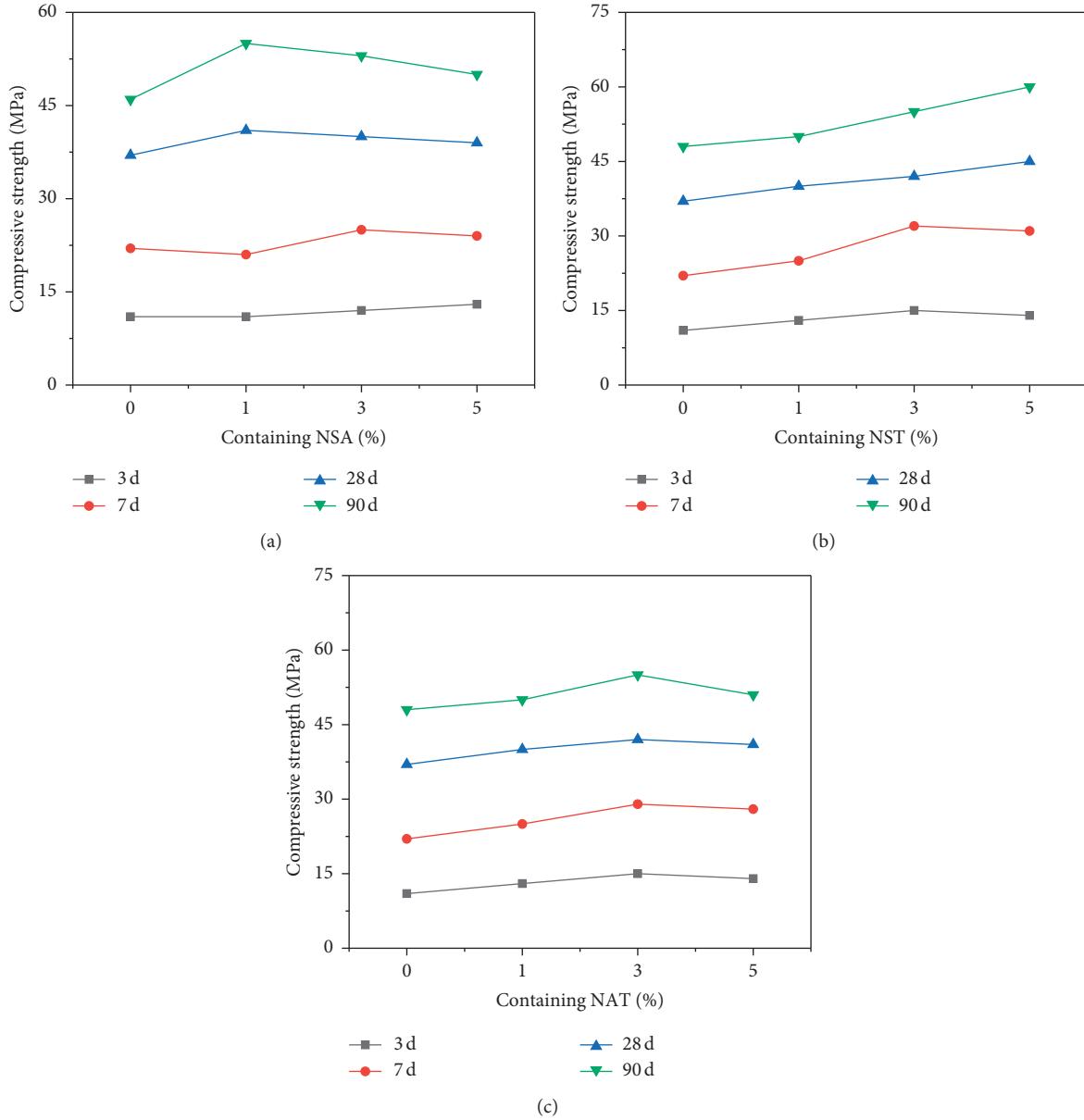


FIGURE 24: Variation of the compressive strengths of self-compacting mortars containing (a) NSA, (b) NST, and (c) NAT at different ages [121].

5%, respectively, the best compressive strength can be achieved [121].

## 5. Effect of Different Nanomaterials on Microstructure of HPC

The microstructure of concrete materials is the most essential factor that determines its mechanical properties and durability. The size of nanoparticle is about 1–100 nm, which is advantageous for the nanoparticle to take part in reactions as a nucleus. The nanoparticles pozzolanic reaction with calcium hydroxide produces more C-S-H gels. Using different electronic microscope techniques (SEM, ESEM, and XRD) to conduct microstructural analyses of concrete showed that the microstructure of concrete with

nano particles is more uniform and dense than concrete without nanoparticles. Therefore, this section will summarize the effects of adding different nanomaterials on the microstructure of concrete.

Khaloo et al. through mercury intrusion porosimetry (MIP) analyzed the pore size distributions of the HPC mixtures with and without 1.5% nano-SiO<sub>2</sub> particles, at the w/b ratio of 0.30 [32]. They show that the pore distributions of the HPC mixtures containing pyrogenic nanosilica with different specific surface areas were finer than those of control HPC mixture. Said et al. through MIP found that the total porosity was significantly lower for mixtures containing nanosilica [42]. More refinement of the pore structure was achieved with increasing the nanosilica dosage up to 6%. Through the BSEM test, they showed notable densification

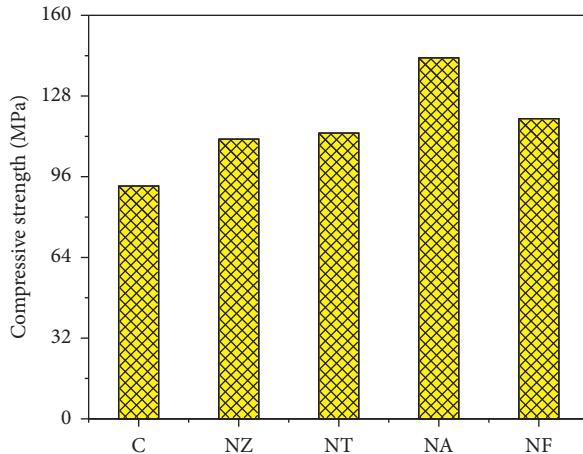


FIGURE 25: Compressive strength of different nanoparticles after 28 days [122].

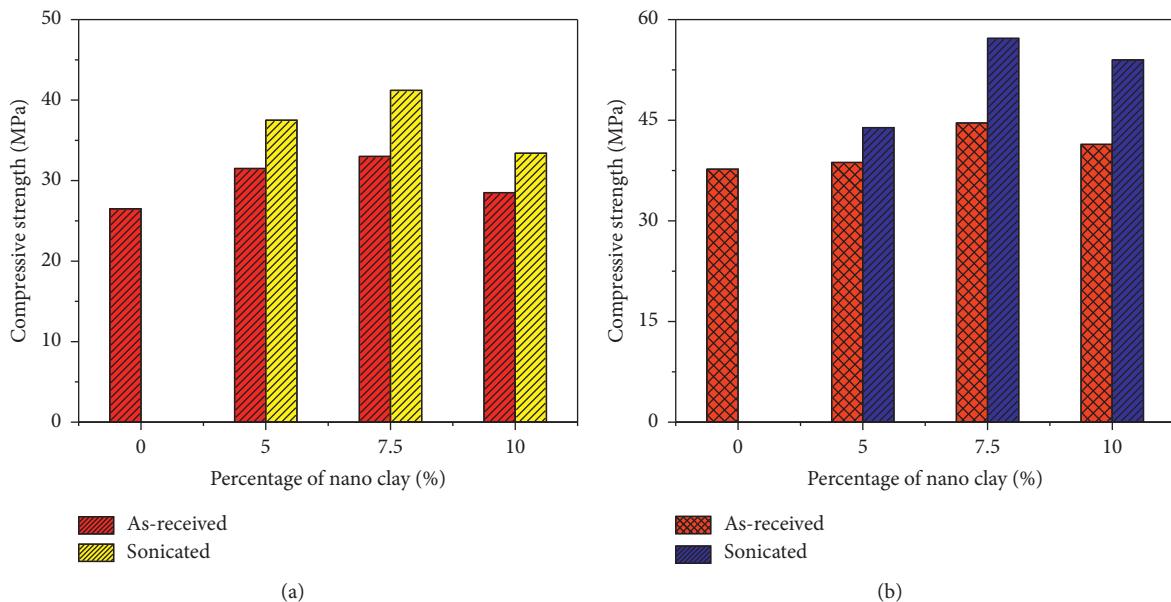


FIGURE 26: Compressive strength of concrete treated with as-received and sonicated NC after (a) 7 days standard curing and (b) 28 days standard curing [122].

in the ITZ for specimens containing nanosilica. Also, for specimens containing Class F fly ash and nanosilica, BSEM showed higher degree of hydration at 28 days relative the control mixture containing only Class F fly ash. Nazerigivi and Najigivi showed that the addition of 80 nm  $\text{SiO}_2$  nanoparticles in ternary blended concrete can fill the cement pores and produce much more C-S-H gel resulting in better mechanical performance of the ternary blended concrete with respect to control concrete [77]. The study of Supit and Shaikh indicated that NS can react more rapidly with the free lime in the course of hydration reaction than fly ash, and more secondary C-S-H gel can be produced to fill into the microvoids due to the fairly tiny particle size and large specific surface area of  $\text{SiO}_2$  nanoparticles in high volume fly ash concrete [73]. Supit and Shaikh [33] showed that calcium carbonate powder particles act as nucleation sites in the process of cement hydration, which increases the

precipitation probability of the hydration product C-S-H gel on limestone powder particles and accelerates the hydration of  $\text{C}_3\text{S}$ . Many hydrated calcium aluminate particles grow on the surfaces of major products, such as C-S-H and  $\text{Ca}(\text{OH})_2$  through (SEM). And the XRD analysis results showed that nano- $\text{CaCO}_3$  is effective in reducing the CH and CS in HVFA and hence the formation of additional CSH gels. Jalal et al. found that replacing cement with 4%  $\text{TiO}_2$  nanopowder can increase the content of crystal  $\text{Ca}(\text{OH})_2$  at the early stage of hydration and accelerate the formation of the C-S-H gel [104]. According to SEM, Parveen et al. indicated that CNTs were well wetted by cement forming a dense reinforcing network, and the presence of CNT all over the fracture surface was identified indicating their homogeneous distribution within the cementitious matrix [95]. It was also observed that CNTs were very tightly inserted between the hydration products of cement (C-S-H phases). This was due

to the fact that CNTs acted as the nucleating agent for C-S-H gel which formed as a coating along the CNT bundles. Al-Jabri and Shoukry indicated that the microstructure of the hardened mortar containing NMK appeared quite dense and compact with relatively less capillary pores as compared with the control mix, causing disappearance of large CH crystals [114]. The NMK modified the interfacial transition zone and increased the bond between the cement paste and aggregate due to its pozzolanic activity. And NMK consumes the CH crystals and results in the creation of supplementary CSH. Therefore, nanomaterials can promote the hydration of concrete, improve the internal structure, and enhance the mechanical strength and durability.

## 6. Conclusions

This review paper reveals the influence of various nanoparticles on the fresh performance and mechanical performance of HPC. NS, nano-CaCO<sub>3</sub>, NA, and TiO<sub>2</sub> are among the nanomaterials currently researched for the development of nanoconcrete. This paper discusses in detail the available information on the workability, compressive strength, and flexural properties of concrete modified with nanoparticles. The analyses of the existing literature provide important insights into the role of nanomaterials in improving the performance of concrete. This paper also intends to compare the performance of concrete modified by nanoparticles with that of control concrete to obtain more valuable results. Therefore, based on a review of more than 100 papers, the conclusions are as follows:

- (1) The slump flow and slump of concrete modified by NS are reduced. The greater the amount of cement replacement, the lower the workability. In this case, an appropriate amount of water-reducing agent should be used to ensure the working performance of HPC containing NS.
- (2) The addition of nano-CaCO<sub>3</sub> reduces the workability of mortar and concrete with high content of FA, and the workability decreases with the increase in cement replacement.
- (3) The slump of HPC is significantly affected by adding CNTs. With the increase in CNT content, the slump drops, and when it reaches 1%, the slump drops below 20 mm. However, the workability of HPC is improved by adding a water-reducing agent.
- (4) The addition of various nanomaterials reduces the workability of HPC, such as NT, Al<sub>2</sub>O<sub>3</sub>, and metakaolin.
- (5) The HPC modified by NS has excellent compressive strength mainly because a large amount of C-S-H gel is generated after NS replaces cement, and the microstructure is more compact. Hence, it is related to the optimal dosage of NS. Researchers have proposed different thresholds to optimize NS replacement. However, the replacement rate of NS cannot be excessively high; a value lower than 5% is generally recommended. The compressive strength will be

reduced owing to the agglomeration of nanoparticles when adding more than the optimal content in the mixture. At the same time, the type, dosage, and size of NS will affect the compressive strength of HPC.

- (6) With the addition of NS, the increasing trends of tensile strength and bending strength are similar to those of compressive strength. NS has an optimal dosage for the influence trend of these strengths.
- (7) Most studies show that adding nanomaterials (e.g., nano-CaCO<sub>3</sub>, CNTs, TiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub>) to HPC not only reduces the amount of cement but also promotes the hydration of C<sub>3</sub>S and increases the mechanical properties of concrete. The change in performance depends on the dosage, and exceeding the optimal dosage will reduce the strength.

## Conflicts of Interest

The authors declare that they have no conflicts of interest in this paper.

## Acknowledgments

The authors acknowledge the financial support received from the National Natural Science Foundation of China (grant nos. 51979251 and U2040224), Natural Science Foundation of Henan (grant no. 212300410018), Program for Innovative Research Team (in Science and Technology) in University of Henan Province of China (grant no. 20IRTSTHN009), and Program for Science & Technology Innovation Talents in Universities of Henan Province, China (grant no. 21HASTIT013).

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