Mechanical properties of fly ash concrete composite reinforced with nano-SiO_2 and steel fibre

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A parametric experimental study has been conducted to study the effect of nano-SiO_2 particles and steel fibres on the mechanical properties of the concrete composite containing fly ash. Five different nano-SiO_2 contents (1%, 3%, 5%, 7% and 9%) and five different steel fibre contents (0.5%, 1%, 1.5%, 2% and 2.5%) were used. The results indicate that addition of nano-SiO_2 and steel fibres decreases the slump and slump flow of the fresh concrete composite containing fly ash, and both the slump and slump flow decrease gradually with the increase in nano-SiO_2 and steel fibre content. The addition of nano-SiO_2 improves the mechanical properties of concrete composites containing fly ash. There is an increase in the compressive strength and compressive modulus of elasticity with increase of nano-SiO_2 content when it is below 5%, while they begin to decrease after the nano-SiO_2 content is beyond 5%. Steel fibres help improve the mechanical properties of concrete composite containing fly ash and nano-particles. With the appropriate fibre content, the reinforcement of steel fibres on the compressive strength and compressive modulus of elasticity of the concrete composite becomes more obvious as the fibre content increases.

Keywords: Fly ash, concrete composite, mechanical property, nano-SiO_2, steel fibre.

CONCRETE composite is one of the main construction materials in civil engineering, with large quantities of it being consumed all over the world each year. Cement is an important raw material in the production of concrete composite. During the course of manufacturing of cement, large amounts of carbon dioxide (CO_2) get into the atmosphere. Global warming can be attributable to anthropogenic greenhouse gases (GHGs), which have gone up to an alarming rate. However, approximately 77% of the anthropogenic GHGs is comprised of CO_2 and the current atmospheric concentration of CO_2 has reached 390 ppm, which is the highest ever recorded[1]. It is generally estimated that the amount of CO_2 emitted from the worldwide production of Ordinary Portland Cement (OPC) corresponds to approximately 7% of the total emissions into the Earth's atmosphere[2]. The emissions of CO_2 in cement and concrete industry can be controlled by the incorporation of recycled industrial waste in the mix design, without reducing the quality of the final product[3]. One of the solutions for this global concern is the use of supplementary cementitious materials as a replacement for cement, for example, the most readily available fly ash, a by-product of coal-buring thermal power stations[4,5]. The usage rate of fly ash in China is currently low. The disposal of fly ash has become a considerable environmental problem, because it as a waste material may cause substantial environmental hazards. To increase the usage rate, large quantities of fly ash are proposed to be incorporated in the structural and paving concrete mixes. The main effect of fly ash in concrete covers three aspects, often called morphologic effect, pozzolanic effect and microaggregate effect[6]. Morphologic effect indicates there are many microbeads in fly ash working as 'lubricating balls' when incorporated in fresh concrete; hence it benefits the fluidity. The microaggregate effect indicates that the microbeads in fly ash can disperse well in concrete and combine firmly with gel produced in cement hydration, and thus promote concrete density. The pozzolanic effect indicates that the unfixed SiO_2 and Al_2O_3 in fly ash can be activated by $Ca(OH)_2$ product of cement hydration to produce more hydrated gel. Numerous studies have been focused on the development of concrete composites containing large amounts of fly ash[7–12]. However, fly ash concrete composite has lower strength at early age than normal concrete because pozzolan reaction of fly ash activates at mature age. For proper use of fly ash in various concrete structures, other materials should be used simultaneously to overcome this shortage of fly ash in concrete composites.

Nowadays, nanoparticles have been gaining growing attention and have been applied in many fields to fabricate new construction materials with novel functions owing to their unique physical and chemical properties[13]. Nanomaterials have been considered as the most promising materials of the 21st century by scientists. In recent years, much attention has been paid to the application of nanomaterials in civil engineering, because nanoparticles possess many special properties such as large specific

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surface area and high activity due to their small size[14]. If nano-particles are integrated with cement-based building materials, the new materials might possess some outstanding properties. The pozzolanic activity of nano-SiO_2 is more obvious than that of silica fume, and nano-SiO_2 can react with calcium hydroxide ($Ca(OH)_2$) crystals, which are arrayed in the interfacial transition zone between hardened cement paste and aggregates and produce C–S–H gel[15]. Previously, the effects of nano-SiO_2 particles on different properties of concrete composites have been studied. It has been shown that utilizing nanoparticles in concrete improves the mechanical properties of the specimens besides improvement in microstructure and pore structure of the concrete specimens[16–20]. Nanoparticles can act as heterogeneous nuclei for cement paste, further accelerating cement hydration because of their high reactivity, as nano-reinforcement, and as nano-filler, densifying the microstructure, thereby leading to reduced porosity[21].

Concrete composite is known to easily crack under low-level tensile stress, for its inherent weakness in resisting tensile forces. A variety of researches have been conducted to investigate the characteristics and advantages of fibre reinforced concrete in the last few decades. Fibres suitable for reinforcing concrete can be made of steel[22], glass[23], polyethylene[24], polypropylene[25], polyvinyl alcohol[26], polyester[27] and natural plants[28]. Among these, steel fibre is the most popular and widely used in both research and practice. Steel fibre reinforced concrete has been successfully used in several types of construction due to the fact that addition of steel fibres improves the durability and mechanical properties of hardened concrete, namely the flexural strength, toughness, impact strength, resistance to fatigue, vulnerability to cracking and spalling[29–32]. In particular, the steel fibre reinforced concrete possesses many excellent dynamic performances such as high resistance to explosion and penetration, compared to plain concrete and even the traditionally reinforced concrete in civil and defence engineering[33]. Findings also indicate that the steel fibre reinforced concrete is a better energy-absorbing and impact-resisting material. For example, the steel fibrous concrete is six times better in receiving impact loads than the non-fibrous concrete[34]. At present, owing to high strength and toughness and high stress resistance, steel fibre reinforced concrete is increasingly being used in structures such as flooring, housing, precast, tunnelling, heavy-duty pavement and mining.

The mechanical properties of concrete composites are so important in the mix design and application of concrete composites. However, so far, there is little information available on the combined effect of nano-SiO_2 particles and steel fibres on mechanical properties of concrete composite containing fly ash. Studying these aspects is necessary and helpful to promote the application of this new concrete composite. This article reports the mechanical properties of fly ash concrete composites reinforced with nano-SiO_2 and steel fibre.

Experimental programme

Raw materials

The cement used was OPC (Class 42.5R; Tianrui Cement Co, China) for which the chemical and physical properties are presented in Table 1. Grade I fly ash was used to make the high performance concrete for which the chemical properties are also presented in Table 1. Because the amount of fly ash in concrete for structural use is generally limited to 15–25% of the total cementitious materials, the content of fly ash in the present study was selected as 15% (ref. 35). In this experimental study, amorphous nano-SiO_2 (Wanjing New Material Co. Ltd, China) with a solid content of more than 99% was used. According to the information of the supplier, the average particle size of nano-SiO_2 is 30 nm. Physical properties of the nanoparticles are presented in Table 2. The steel fibres used in this study were mill-cut (Yujian Steel Fibre Co, Ltd, China) for which the physical properties are presented in Table 3. A photograph of the fibres is shown in Figure 1. Coarse aggregate with a maximum size of 20 mm and fine aggregate with a 2.76 fineness modulus were used. A high-range water-reducing agent, commercial name polycarboxylate HJSX-A, was used to adjust the workability of the concrete mixture. The performance indices of the high-range water-reducing agent are presented in Table 4. This water-reducing agent was made of many kinds of polymer organic compounds, most of which belong to poly carboxylic acid salt. It has great reducing properties with only a small dosage.

Table 1. Properties of cement and fly ash

Composition (%)	Cement	Fly ash
Chemical composition		
SiO_2	20.85	51.50
Al_2O_3	5.32	18.46
Fe_2O_3	2.69	6.71
CaO	62.97	8.58
MgO	3.66	3.93
Na_2O	0.15	2.52
K_2O	0.62	1.85
SO_3	2.48	0.21
Physical properties		
Specific gravity	3.11	2.16
Specific surface (cm^2/g)	3287	2470

Table 2. Physical properties of nano-SiO_2

Average particle size (nm)	SiO_2 content (%)	Specific surface area (m^2/g)	Apparent density (g/cm^3)	pH value
30	99.5	200 ± 10	0.055	5–7

Table 3. Properties of steel fibres

Length (mm)	Equivalent diameter (mm)	Length diameter ratio	Tensile strength (MPa)
32	0.56	52.0	800

Table 4. Properties of high-range water-reducing agent

Solid content (%)	Total alkali content (%)	Fluidity of cement paste (mm)	Density (g/cm^3)	Content of Cl^- (%)	pH value
30	1.2	260	1.052	0.078	4.32

Figure 1. Photograph of the steel fibres used.

Besides, the concrete mixture mixed with this reducing agent has little slump loss.

Mix proportions

In all 11 mixture proportions were made, and the first one was control mix containing only 15% fly ash (without nano-SiO_2 and steel fibre). The cement was replaced by the same quantity of fly ash by mass, and the fly ash content (by mass) is 74.1 kg/m^3. Five proportions were arranged with nano-SiO_2 replacing the same quantity of cement by mass (1%, 3%, 5%, 7% and 9%), and 15% cement replaced by fly ash, and the contents (by mass) of nano-SiO_2 were calculated as 4.94, 14.82, 24.7, 34.58 and 44.46 kg/m^3 respectively. The remaining five proportions were arranged with steel fibre mixed in concrete by volume ranging from 0.5% to 2.5% (0.5%, 1.0%, 1.5%, 2.0% and 2.5%) with the dosage of cementitious materials unchanged, and 15% cement (74.1 kg) replaced by fly ash and 5% cement (24.7 kg) replaced by nano-SiO_2. Then, the volumes of steel fibres in 1 m^3 concrete of the remaining five proportions are 0.005, 0.01, 0.015, 0.02 and 0.025 m^3 respectively. With the specific gravity of steel fibre (7.85 g/cm^3), the contents (by mass) of steel fibre were calculated as 39.25, 78.5, 117.75, 157 and 196.25 kg/m^3 respectively. Mix proportions are given in Table 5.

Preparation of specimens

The 150-mm concrete cubes were cast for cube compressive strength, 150 × 300 mm quadruple prisms for axial compressive strength and compressive modulus of elasticity. All the materials were mixed in the mixing plant. In order to distribute nano-SiO_2 and steel fibres uniformly, a forced mixing machine was adopted. This machine has an axis with several vanes, which is different from the self-loading concrete mixer. When the axis is turning, it drives the vanes to turn and the mixture can be well-mixed. With the application of the forced mixing machine, nano-SiO_2 can be broken down well. The mixing procedure, which was designed by trial and error, was chosen as follows: the coarse aggregate and fine aggregate were mixed initially for 1 min, and then the steel fibres were mixed for 1 min (if required), and the cement, fly ash and nano-SiO_2 were mixed for 2 min. Finally, the high-range water-reducing agent and water were added and mixed for 3 min. The distribution of nano-SiO_2 and steel fibres has great effect on the working performance of the mixture and the flexural properties of concrete composite. If nano-SiO_2 and steel fibres are not distributed well, they will be assembled altogether. From the working performance of the mixture, and the fracture section of the specimen of the concrete composite, it can be seen that nano-SiO_2 and steel fibres in the present study are well distributed. After casting, all the specimens were levelled with a steel towel. Immediately after finishing, the specimens were covered with plastic sheets to minimize moisture loss from them. The specimens were then stored at 23°C in casting room. They were demoulded after 24 h, and then cured at 100% relative humidity and controlled temperature (21° ± 2°C) for 28 days before testing. According to the curing standards for concrete in China, the temperature range of the standard curing room for concrete should be controlled within 21° ± 2°C.

Slump and slump flow test

The workability of the fresh concrete composites can be evaluated by the parameters of slump and slump flow. The tests of slump and slump flow were carried out according to the Chinese Standard[36]. The slump flow can be expressed as the spreading diameter of the fresh

Table 5. Mix proportions of the concrete composites

Mix no.	Cement (kg/m^3)	Fly ash (kg/m^3)	Nano-SiO_2 (kg/m^3)	Steel fibre (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Water-reducing agent (kg/m^3)
1	419.9	74.4	0	0	647	1151	158	4.94
2	414.96	74.4	4.94	0	647	1151	158	4.94
3	405.08	74.4	14.82	0	647	1151	158	4.94
4	395.2	74.4	24.7	0	647	1151	158	4.94
5	385.32	74.4	34.58	0	647	1151	158	4.94
6	375.44	74.4	44.46	0	647	1151	158	4.94
7	395.2	74.4	24.7	39.25	647	1151	158	4.94
8	395.2	74.4	24.7	78.5	647	1151	158	4.94
9	395.2	74.4	24.7	117.75	647	1151	158	4.94
10	395.2	74.4	24.7	157	647	1151	158	4.94
11	395.2	74.4	24.7	196.25	647	1151	158	4.94

Figure 2. Testing apparatus of compressive modulus of elasticity.

concrete composite in the slump test. The slump can reflect the fluidity of the fresh concrete composite, and slump flow can reflect the cohesive properties of the fresh concrete composite. If the difference of the maximum and minimum diameters is less than 50 mm, the average of the two diameters can be taken as the value of slump flow. The larger values of slump and slump flow indicate that the fresh concrete composite has better workability.

Cube compressive strength and axial compressive strength test

The tests of cube and axial compressive strengths were carried out by hydraulic pressure universal testing machine according to the Chinese Standard[37]. Before testing, the specimen placed on the pad of the elevating platform of the test machine. The loading rate of cube compressive strength test was controlled between 0.5 and 0.8 MPa/s. The loading rate of axial compressive strength test was controlled between 0.2 and 1 MPa/s. The cube and axial compressive strengths can be computed as follows

$$f_{cu} = \frac{F_1}{A}, \quad (1)$$

$$f_{cp} = \frac{F_2}{A}, \quad (2)$$

where f_{cu} is the cube compressive strength (MPa); f_{cp} the axial compressive strength (MPa); F_1 the maximum pressure at failure in cube compressive strength test (N); F_2 the maximum pressure at failure in axial compressive strength test (N); and A is the area of the cross-section of the specimen (mm^2). Each set includes three specimens, and the average value was computed as the final result.

Compressive modulus of elasticity test

Compressive modulus of elasticity test was also carried out by hydraulic pressure universal testing machine according to the Chinese Standard[37]. During the course of loading and unloading, the deformation of the specimen was measured using two micrometers with dial indicators, which were supported by dial holders on the two symmetrical sides of the specimen. In order to make the top loading board touch the upper surface of the specimen closely, preloading twice of 'loading–unloading' was carried out, and the preload was one-third of the maximum pressure at failure. The testing apparatus of compressive modulus of elasticity test is shown in Figure 2. To keep the deformation changing equably, the loading rate of compressive modulus of elasticity test was controlled between 0.2 and 1 MPa/s. The elastic deformation of each grade of pressure can be computed as the difference of the numerical readings of the micrometer with dial indicator when the specimen was being loaded and after the specimen was unloaded. Compressive modulus of elasticity can be computed as follows

$$E_c = \frac{F_a - F_0}{A} \times \frac{L}{\Delta n}, \quad (3)$$

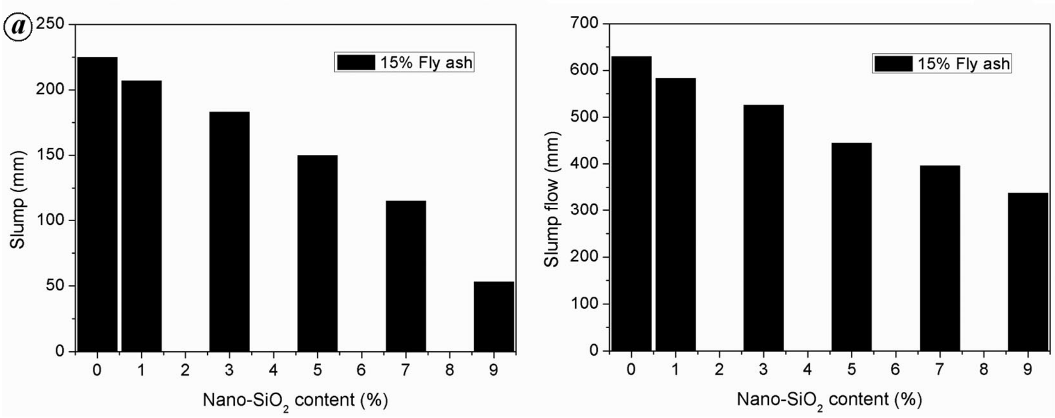

Figure 3. Effect of nano-SiO_2 content on (***a***) slump and (***b***) slump flow.

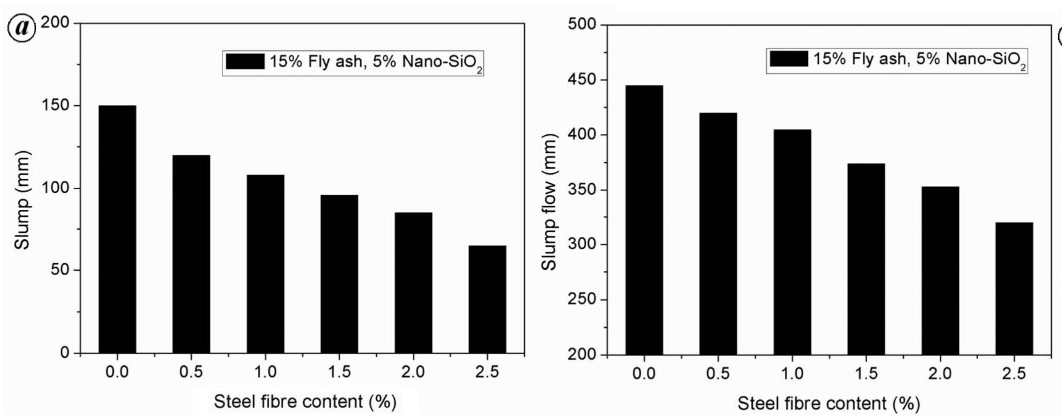

Figure 4. Effect of steel fibre content on (***a***) slump and (***b***) slump flow.

where E_c is the compressive modulus of elasticity (MPa); F_a is the final pressure (one third of the maximum pressure at failure; N); F_0 the initial pressure (the pressure of 0.5 MPa; N); L the scale distance for deformation measurement (mm); A the load-carrying area of the specimen (mm^2) and Δn is the average value of the deformation difference of both sides under the pressure of F_a and F_0 when the specimen was loaded for the last time (mm). Each set includes three specimens, and the average value was computed as the final result.

Results and discussion

Slump and slump flow

Figure 3 *a* and *b* illustrates the variations of the slump and slump flow respectively of the concrete composite with 15% fly ash with the increase of nano-SiO_2 content. It can be seen from the figure that the addition of nano-SiO_2 decreases the slump and slump flow of the concrete composite with 15% fly ash. With the increase of nano-SiO_2 content, both of the slump and slump flow decrease gradually. Compared with the concrete composite without nano-SiO_2, the decrease of the slump and slump flow was determined as 76.4% and 46.3% respectively, for the concrete composite with 9% nano-SiO_2 content. For the slump, there is a sharp decrease when the nano-SiO_2 content increases from 7% to 9%. The mixing water exists in the form of free-layer water, adsorbted-layer water and filling water, and the different forms play different roles in contribution to workability[38]. The free-layer water makes the solid particles separate each other and thus contributes to workability. The adsorpted-layer water is close to the surface of the solid. Because the solid surface will adsorb water molecules, the free-layer water will be restrained by this adsorption effect. As a result, this water makes no contribution to workability. The filling water only fills into space among solid particles and makes no contribution to the workability as well[39]. For concrete composites containing nano-SiO_2, the amount of adsorpted-layer water is dependent on the surface area of the nanoparticles. As nano-SiO_2 exhibits significantly higher specific surface area than cement, nano-SiO_2 particles need high amount of adsorpted-layer water. The excess amount of fine particles which cannot fill in porosities will absorb water on their surface when the nano-SiO_2 content increases. Therefore, the addition of nano-SiO_2 decreases the workability of concrete composite.

Figure 4 *a* and *b* presents the variation the slump and slump flow respectively, of concrete composite with 15% fly ash and 5% nano-SiO_2 with the increase of steel fibre content. From the figure, it can be seen that the addition of steel fibres decreases the slump and slump flow of the concrete composite with 15% fly ash and 5% nano-SiO_2. This indicates that the addition of steel fibres has adverse effect on the workability of concrete composite containing fly ash and nano-SiO_2. Compared with the concrete composite without steel fibres, the decrease of the slump and slump flow was determined as 56.7% and 28.1% respectively, for the concrete composite with 2.5% steel fibre content. With the increase of steel fibre content, both the slump and slump flow decrease gradually. Inside the steel fibre reinforced concrete composite, there must be enough cement paste to be filled into the interspace among the aggregates. In addition, cement paste is needed to wrap the surface of the aggregates and steel fibres to form a layer of lubricant, which can reduce the friction force between the aggregate and steel fibre to ensure that the concrete composite has enough flowability. The more cement paste the concrete composite needs, the more water is needed. Therefore, the addition of steel fibres decreases the flowability of fresh concrete composite containing fly ash and nanoparticles. The same conclusion on concrete composite without fly ash and nanoparticles can be drawn based on the existing research results[40].

Effect of nano-SiO_2 on mechanical properties of concrete composites

Cube compressive strengths of concrete composites were determined at 3, 7, 28 and 60 days of curing, and axial compressive strengths and compressive modulus of elasticity of concrete composites were determined at 28 days. The test results of the effect of nano-SiO_2 on the mechanical properties of concrete composites containing fly ash are given in Figure 5 *a–c*. The relationship curves between the cube compressive strength of four curing periods of concrete composite and the content of nano-SiO_2, with the fly ash content of 15% are given in Figure 5 *a*. From the curves, it can be seen that the cube compressive strength of concrete containing nano-SiO_2 and fly ash increases gradually with the increase in curing period under standard maintenance condition. For all the curing periods, the cube compressive strength of concrete composites containing fly ash increases gradually with the increase of nano-SiO_2 content when it is below 5%, while there is a decrease in the cube compressive strength when the nano-SiO_2 content is beyond 5%. Because the pozzolanic reaction of nano-SiO_2 produces additional C–S–H gel, which grows into the capillary spaces that remain after the hydration of the cement in mortar mixes at the early curing stage, all the concrete mixes containing nano-SiO_2 were found to have higher cube compressive strengths than the control mix at 3 days. The cube compressive strength of concrete mix at 3 days with 1%, 3%, 5%, 7% and 9% cement replacement with nano-SiO_2, was higher than the control mix (37.1 MPa), and the mix with 5% nano-SiO_2 content attained the maximum compressive strength (45.1 MPa), which increased by 21.6% than the control mix. At 7 and 28 days, compared to 3 days, the increase in the cube compressive strength of concrete composites with increase in nano-SiO_2 content is less obvious when the nano-SiO_2 content is below 5%. At 60 days, the decreasing trend of the cube compressive strength is more obvious with the increase of nano-SiO_2 content than the other curing periods when the nano-SiO_2 content is beyond 5%. The variations of axial compressive strength of fly ash concrete composites with 1%, 3%, 5%, 7% and 9% cement replacement with nano-SiO_2 at 28 days curing are illustrated in Figure 5 *b*. As can be seen from the figure, the variation regularity of the axial compressive strength of concrete composites containing nano-SiO_2 and fly ash with the increase of nano-SiO_2 content at 28 days is the same as the cube compressive strength.

Figure 5 *c* shows the variation of compressive modulus of elasticity of concrete composites containing 15% fly ash with the increase of nano-SiO_2 content at the curing period of 28 days. From the test results, it can be seen that the compressive modulus of elasticity of fly ash concrete with different percentages of cement replacement by nano-SiO_2 was higher than the control mix. When the content of nano-SiO_2 is below 5%, there is a considerable increase in flexural modulus of elasticity with increase in the nano-SiO_2 content. In particular, when the nano-SiO_2 content increases from 1% to 3%, there is a sharp increase in the compressive modulus of elasticity of the concrete composites, which increases from 47.1 to 49.8 GPa. When the nano-SiO_2 content is 5%, which is 50.6 GPa, the compressive modulus of elasticity reaches a maximum. However, just like compressive strength, when the nano-SiO_2 content is beyond 5%, there is a decreasing trend in the compressive modulus of elasticity.

The reason why the addition of nano-SiO_2 can increase the compressive strength and compressive modulus of elasticity of concrete composites containing fly ash may be closely related to the specific nanometre effect of nano-SiO_2 particles. Above all, nano-SiO_2 particles, possessing high specific surface area, can react with $Ca(OH)_2$ and produce C–S–H condensed gel. Hence, during the course of the pozzolanic reaction, the amounts and dimensions of crystals of $Ca(OH)_2$ are reduced and C–S–H gel, produced by pozzolanic reaction, forms a denser transition zone[20]. Besides, extremely fine particle size of nano-SiO_2 may have accelerated cement and fly

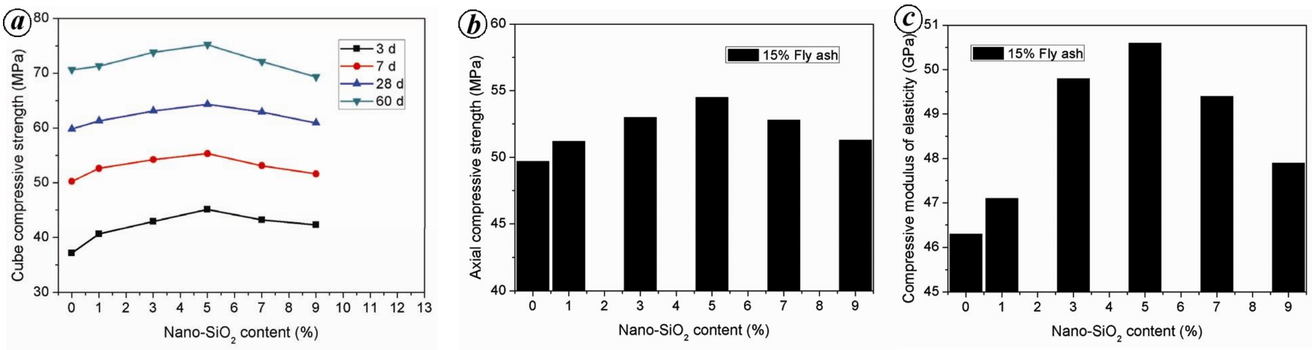

Figure 5. Effect of nano-SiO_2 content on (***a***) cube compressive strength, (***b***) axial compressive strength and (***c***) compressive modulus of elasticity.

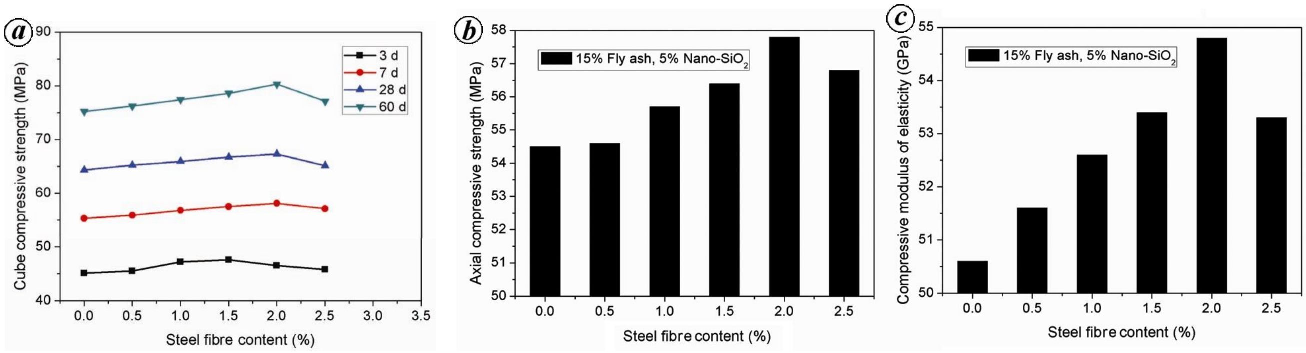

Figure 6. Effect of steel fibre content on (***a***) cube compressive strength, (***b***) axial compressive strength and (***c***) compressive modulus of elasticity.

ash hydration by providing high number of nucleation sites for precipitation of cement hydration products in the fly ash concrete composites. In addition to the nucleation effect, nano-SiO_2 may have acted as a reactive filler which reduces bleeding and increases packing density of solid materials by occupying the space between cement and fly ash particles[41]. Nanoparticles can fill a notable part of voids existing in the matrix of cement paste even in agglomerated manner, due to their ultra-fine dimension. Furthermore, when small amounts of nanoparticles are uniformly dispersed in the cement paste, they act as a nucleus to tightly bond with cement hydrate and also to promote hydration of cement due to their high activity, which is favourable for the strength of cement mortar[20]. Therefore, the addition of nano-SiO_2 can increase the flexural strength and flexural modulus of elasticity of concrete composites containing fly ash with the appropriate nano-SiO_2 content.

Effect of steel fibre on mechanical properties of concrete composites

Cube compressive strengths of steel fibre reinforced concrete composites containing 15% fly ash and 5% nano-SiO_2 were determined at 3, 7, 28 and 60 days of curing, and the axial compressive strengths and compressive modulus of elasticity were determined at 28 days. The test results are given in Figure 6 *a–c*. The variations of cube compressive strength with steel fibre content at different curing periods are shown in Figure 6 *a*. A considerable increase in the cube compressive strength was observed by increasing the curing period. For each curing period, there is an increasing trend in cube compressive strength with the increase of steel fibre content not beyond 2%. The bonding strength between the fibre and the concrete matrix has a major effect on the compressive strength of steel fibre reinforced concrete composites. At 3 days, the hydration reaction degree of the cementing material is very low in the early phases, and the bonding strength between the fibre and the concrete matrix is relatively low. As a result, with the increase of steel fibre content, there is no obvious variation on cube compressive strength at 3 days curing. Similarly, at 60 days, the hydration reaction degree of the cementing material is much higher, and the reinforcement of steel fibres on the cube compressive strength of the concrete composite is more obvious. At 60 days, as the fibre fraction of steel fibre is increased from 0% to 2%, the cube compressive strength increases (6.8%) from 75.2 to 80.3 MPa. However, the cube compressive strength begins to decrease after steel fibre content is increased continuously with the fibre dosage beyond 2%. The variations of axial compressive strength of concrete composites containing 15% fly ash and 5% nano-SiO_2 with the increase of steel fibre content at 28 days curing are shown in Figure 6 *b*. From the figure, it can be seen that the variation of the axial compressive strength of concrete composites containing nano-SiO_2 and fly ash with the increase of steel fibre content at 28 days is the same as that of the cube compressive strength.

Figure 6 *c* indicates the contrast relationship between compressive modulus of elasticity of nonfibrous concrete composites (15% fly ash and 5% nano-SiO_2) and steel fibre reinforced concrete composites (15% fly ash and 5% nano-SiO_2) with different fibre dosage. From the figure, it can be seen that the addition of steel fibres can increase the compressive modulus of elasticity effectively. Also, the variation of compressive modulus of elasticity of concrete composites containing fly ash and nanoparticles with the increase of steel fibre content is similar to that of compressive strength. That is, the compressive modulus of elasticity increases gradually with increase in steel fibre content and the compressive modulus of elasticity reaches a maximum when the steel fibre content is 2%, while it decreases when steel fibre content is beyond 2%.

With the existence of steel fibres, the external load can be transferred to them through the interfacial bonding between the fibres and concrete matrix. Steel fibres can restrain the crack propagation and traverse across the cracks to transfer internal force, and the steel fibres and the concrete matrix will bear the load as a whole[42]. As a result, the bearing capacity of the concrete composite is improved. With the addition of nano-SiO_2 and fly ash, the particle size of nano-SiO_2 and fly ash is smaller than cement, which can effectively improve the interfacial structure properties. Nano-SiO_2 can react with $Ca(OH)_2$ to form $CaSiO_3$, which has filling action and improves the weak part inside the composites. Consequently, the bonding force between the steel fibres and the concrete matrix is strengthened[43]. The larger content of steel fibres has greater positive effect to restrict crack propagation and transfer the internal force. Therefore, with the appropriate fibre content, the reinforcement of steel fibres on the mechanical properties of the concrete composite becomes more obvious as the fibre content increases. However, the large amount of fibres may increase the number of microcracks and cause some defects inside the concrete composites if the steel fibre content is too high. Therefore, steel fibre content more than 2% will decrease the flexural strength and flexural modulus of elasticity of concrete composites containing fly ash and nano-SiO_2.

Conclusion

The following conclusions can be drawn from the results presented in this article:

- Both the slump and slump flow of fresh concrete composite containing fly ash decrease with the addition of nano-SiO_2 and steel fibres. With the increase of nano-SiO_2 and steel fibre content, the workability of the fresh concrete composite declines gradually.
- Effect of nano-SiO_2 on the mechanical properties of concrete composite containing fly ash is significant. The addition of nano-SiO_2 increases the compressive strength and compressive modulus of elasticity of concrete composites containing fly ash. There is an increasing tendency in the compressive strength and compressive modulus of elasticity with increase in nano-SiO_2 content when it is below 5%; they begin to decrease when the nano-SiO_2 content is beyond 5%.
- Steel fibres help improve the mechanical properties of concrete composite containing fly ash and nanoparticles. The compressive strength and compressive modulus of elasticity of concrete composite containing fly ash and nano-SiO_2 are more than that of the concrete composite without steel fibre. The reinforcement of steel fibres on the cube compressive strength of the concrete composite of long-age curing is obvious. With the appropriate fibre content, the reinforcement of steel fibres on the mechanical properties of the concrete composite becomes more obvious as the fibre content increases.

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