

Study on the effect of nanosilica suspension on the properties of cement-based grouts

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The agglomeration trend of nanosilica particles was found to significantly affect the properties of cement-based materials. The influence of nanosilica suspension on the fluidity, setting time, and compressive strength of cement-based grouts were studied. The hardened pastes were characterized by thermogravimetric (TG) analysis and scanning electron microscopy (SEM). The results showed that the fluidity of cement-based grouts with nanosilica suspension had obviously improved. The setting time was obviously decreased, compared with the reference sample. The compressive strengths for 1 day, 3 days, and 28 days were 12.8%, 14.3%, and 10.1% higher than that of the reference group, respectively. This paper may provide a novel route to improve the mechanical properties of cement-based materials without affecting their workability.

Keywords: *cement, nanosilica, scanning electron microscope, compressive strength*

1. Introduction

As a kind of widely used civil engineering material, the production of Portland cement may lead to global warming impacts owing to the CO₂ emission [1]. Many mineral admixtures, such as fly ash, ground granulated blast furnace slag, silica fume, nano-clay [2], and nano-metakaolin [3], have been used to prepare cementitious materials for the purpose of reducing the Portland cement clinker consumption and then decreasing the CO₂ emission [1].

In recent years, nanosilica has been introduced into cement-based materials as a supplementary cementitious material and/or admixture [4]. Owing to the nanoscale size of the particles, nanosilica is more effective than other mineral admixtures for the modification of cement-based materials [5], resulting in improvement in the plastic and hardened materials [6]. On the one hand, nanosilica particles can fill the voids between the cement grains [7], acting as a nano-filler [8], and then forming higher packing and dense composites, which result in a lower demand for slurry water and contributing to an enhancement of the mechanical properties [9] because of reduced capillary porosity [10].

On the other hand, the incorporation of nanosilica may enhance the density of the matrix owing to its pozzolanic reactivity [11]. When nanosilica particles were incorporated into cement-based materials, nanosilica could react with H₂O and form H₂SiO₄²⁻, which may react with Ca²⁺ owing to the pozzolanic activity, forming additional C-S-H [7]. The above reaction may contribute to the consumption of calcium hydroxide [3] and then accelerate the hydration of cement. So, silica plays a vital part in strengthening the mechanical properties and durability of cement-based materials [12].

However, the introduction of nanosilica particles may result in deterioration of the properties of cement-based materials [13]. For example, Tayeh et al. [14] suggested that the incorporation of nano agriculture waste decreased the workability of ultrahigh-performance concrete. The workability of slurry may be reduced due to the high specific surface areas [15] and agglomeration trend of nanosilica particles, which contribute to adsorb a great amount of water [4]. The above phenomena may affect the rheological behavior of the fresh mixture [13] and ultimate hardened properties [16]. Senff et al. [17] presented that the addition of nanosilica in cement mortar may reduce the flow table spread from 230 mm down to 207 mm,

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Table 1. Chemical composition of Portland cement, fly ash, and slag powder (wt%)

Constituent	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	SO ₃	Loss
Cement	63.71	20.35	5.0	3.3	1.37	0.39	2.48	2.6
Fly ash	2.4	61.9	28.8	2.5	0.8	0.3	0.6	1.7
Slag powder	38.1	30.0	13.6	0.6	7.6	0.3	0.3	4.6

Table 2. Performance indices of Portland cement

Indices	Density (g/cm ³)	Consistence (%)	Stability > 80 μm	Specific surface area (m ² /kg)	Setting time (min)	Compressive strength (MPa)		
						1 day	3 days	28 days
Cement	3.08	21.35	Qualified	1.8	340	160	195	22.1 37.4 62.6

owing to the obvious increase of the viscosity of paste. Hence, some researchers suggested that the appropriate amount of nanosilica particles added in cement-based materials should be in the range of 1–5 wt% [18]. Additionally, the property had been strongly dependent on the dispersion state of nanosilica particles. Cement-based materials with well-dispersed nanosilica particles exhibit a dense microstructure even if nanosilica content is small [19]. In contrast, cement-based materials with poor dispersed state present an unsatisfactory property owing to voids and weak zones formation [20].

The experimental investigation reported herein is to improve the properties of cement-based grouts with a novel nanosilica suspension. Accordingly, nanosilica suspensions with different components were prepared. The effect of nanosilica suspension on the fluidity, setting time, and compressive strength of cement-based grouts were investigated. The results obtained allow comparisons to be made among reference samples, samples with unmodified nanosilica, and nanosilica suspension. According to the standard practice, the documentation and optimization of cement-based grouts properties are based on measured fluidity, setting times, and compressive strength development. The presence of nanosilica suspension may improve the compressive strength and solve the problem of significant decrease in fluidity, which result from the addition of unmodified nanosilica particles.

2. Experiments

2.1. Materials

The cement used in this test is Grade 52.5 II Portland cement, which was provided by Taizhou Yangwan Conch Cement Co., Ltd (Taizhou, P. R. China). Its chemical constituents and main performance indices are shown in Tables 1 and 2.

The granulated blast furnace slag powder is Grade S95, which was purchased from Yangzhou Hengrun Marine Heavy Industry Co., Ltd (Yangzhou, P. R. China). Fly ash is Grade F II, which was obtained from Jiangsu Huadian Energy Co., Ltd, (Yangzhou, P. R. China). The chemical compositions of these two mineral admixtures are also shown in Table 1.

The sand used in the test is natural river sand with a fine modulus of 2.75, a stacking density of 1,425 kg/m³, and an apparent density of 2,580 kg/m³. Equal amounts of grit (diameter of 0.6–1.18 mm), medium sand (diameter of 0.30–0.60 mm), and fine sand (diameter of 0.15–0.30 mm) were mixed uniformly.

Nanosilica with specific surface area of 140 m²/g and average particle sizes of 10 nm were purchased from Shanghai Yuanjiang Chemical Co., Ltd (Shanghai, P. R. China).

Polycarboxylate superplasticizer (PCE, P540) was purchased from Shanghai Chenqi Chemical Technology Company (Shanghai, P. R. China). De-foaming agent (P80) was obtained from MÜNZING Chemie Corporation (Münzingstraße, Germany). The expanding agent (YH-S) was supplied

by Tianjin Weihe Technology Admixture Company (Tianjin, P. R. China). Methacryloxy propyl trimethoxyl silane (KH570) was purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, P. R. China).

2.2. Preparation of nanosilica suspension

The preparation process of nanosilica suspension was shown as follows: 0–1.5 g of KH570 was added into a 50-mL glass beaker with 25 mL of distilled water and homogenized by mechanical stirring to form solution A. Then, 5 g of nanosilica particles was added into solution A under stirring at 300 rpm for 2 h and then sonicated for 30 min; 0–1.5 g of P540 was added into a 50-mL glass beaker with 25 mL of distilled water and stirred at 300 rpm for 30 min to form solution B. Solution B was dropwise added into solution A under stirring at 300 rpm to form solution C and sonicated for 30 min to obtain nanosilica suspension. The suspension showed excellent stability and uniformity for at least 60 days, which is presented in Figure 1.

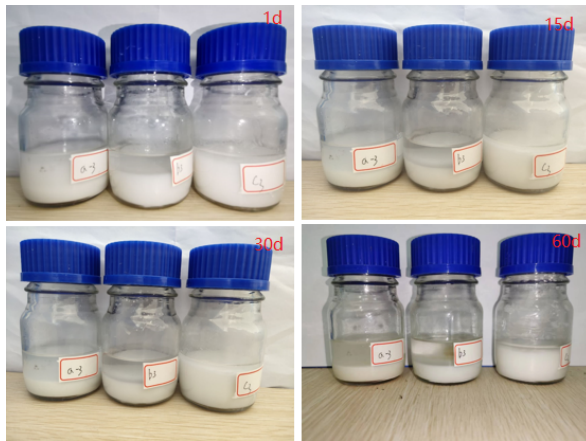


Fig. 1. Picture of suspension for different days. a3—unmodified nanosilica particle solution; b3—nanosilica suspension (γ -(2,3-epoxypropoxy)propyltrimethoxysilane was used as a silane coupler); c3—nanosilica suspension (methacryloxy propyl trimethoxyl silane was used as a silane coupler)

2.3. Paste

Fresh paste was prepared with water–binder ratio (W/C) at 0.22 and binder/aggregate weight ratio at 1.0. The ratios of fly ash and slag powder in the mixture were 20 wt% and 10 wt%, respectively. The PCE, P80, and YH-S to cement ratios were 0.5 wt%, 0.1 wt%, and 0.05 wt%, respectively. Portland cement, slag powder, fly ash, sand, PCE, P80, and YH-S were blended at 60 rpm for 5 min using a cement mortar mixer. Nanosilica suspension was added into a mixer with the appropriate amount of water. Then, solid components were poured into the mixer and mechanically mixed at 60 rpm for 3.5 min.

2.4. Tests and characteristics

The chemical compositions of Portland cement, slag powder, and fly ash were determined by ARL Quant’X X-ray fluorescence (ThermoScientific, Waltham, USA).

The fluidity, setting time, and compressive strength tests were based on the People’s Republic of China Building Industry Standards–Cementitious grout for coupler of rebar splicing (JG/T 408-2013).

A Pyris 1 TG simultaneous measuring instrument (PerkinElmer, Waltham, USA) was used to investigate the content of calcium hydroxide up to 800°C at a scanning rate of 10°C min^{−1}. The CH content was calculated using Eq. (1) [21] as

$$m_{CH} = m_{H_2O} \times \frac{74}{18} + m_{CO_2} \times \frac{74}{44} \quad (1)$$

where m_{CH} was the total CH content; and m_{H_2O} and m_{CO_2} were mass loss ratios due to the decomposition of CH and CaCO₃, respectively.

Scanning electron microscopy (SEM) images were recorded using an S-4800 scanning electron microscope (Hitachi, Tokyo, Japan), and the fracture surface was sputter-coated with gold before observation. SEM micrographs were obtained under conventional secondary electron imaging conditions with an accelerating voltage of 10 kV.

Table 3. The effects of unmodified nanosilica, nanosilica suspension, silane coupler, and PCE content on the fluidity of grouting pastes

Composition	Content (wt%)	Fluidity (mm)	
		Initial	30 min
Reference	0	350 ± 4	325 ± 3
Unmodified nanosilica (nanosilica/binder)	0.2	355 ± 3	325 ± 5
	0.5	335 ± 6	200 ± 2
	0.8	280 ± 2	180 ± 3
	1.0	250 ± 3	150 ± 4
	1.5	200 ± 2	130 ± 4
	2.0	150 ± 3	120 ± 2
Nanosilica suspension (nanosilica/binder)	0.2	350 ± 6	345 ± 3
	0.5	345 ± 5	335 ± 4
	0.8	335 ± 5	320 ± 5
	1.0	330 ± 4	300 ± 3
	1.5	310 ± 3	200 ± 2
	2.0	295 ± 3	165 ± 2
Silane coupler (silane/nanosilica)	0	320 ± 4	230 ± 3
	4	330 ± 4	320 ± 2
	10	350 ± 3	345 ± 5
	20	355 ± 4	355 ± 4
	30	355 ± 5	355 ± 3
PCE (PCE/nanosilica)	0	340 ± 3	315 ± 4
	4	350 ± 5	325 ± 3
	10	355 ± 3	330 ± 2
	20	350 ± 4	330 ± 4
	30	345 ± 2	330 ± 3

3. Results and discussion

3.1. Workability and setting time

The effects of unmodified nanosilica, nanosilica suspension, silane coupler, and PCE content on the fluidity of grouting pastes are listed in Table 3. For cement-based grout mixture, the fluidity greatly decreased with unmodified nanosilica content, with neither initial nor 30 min fluidity. The greater the content of unmodified nanosilica, the greater was the reduction in fluidity. Actually, the grouting pastes presented poor workability when the unmodified nanosilica content was higher than 0.5 wt%. This phenomenon may be attributed to the high specific surface areas and adsorbing a great amount of water [4], which resulted in a decrease in the available amount of lubricating water in the grouting pastes. In contrast, almost all pastes with nanosilica suspension showed well workability except the 2 wt% nanosilica one. However, the flu-

idity for 30 min was obviously decreased when nanosilica content was higher than 1 wt%. This result indicated that the introduction of nanosilica suspension could help to increase the fluidity of grouting pastes. The mechanism may be attributed to the presence of silane coupler and PCE in suspension, which could modify the hydrophilia nature and increase the steric hindrance of nanosilica particles. The effect of silane coupler and PCE on the fluidity of grouting pastes will be discussed in the following section.

As shown in Table 3, the fluidity of grouting pastes was greatly improved by the presence of silane coupler. This may be attributed to the hydrophobic nature of nanosilica particles, which may be reinforced by the cover of silane molecules [22]. The introduction of silane in suspension could greatly enhance the fluidity of grouts with nanosilica particles in an indirect way. Furthermore, the silane molecules, which were distributed in the sur-

Table 4. The influences of unmodified nanosilica, nanosilica suspension, silane coupler, and PCE content on the setting times of grouting pastes

Composition	Content (wt%)	Setting time (min)	
		Initial	Final
Reference	0	660 ± 15	750 ± 20
Unmodified nanosilica (nanosilica/binder)	0.2	580 ± 20	660 ± 25
	0.5	500 ± 15	570 ± 20
	0.8	460 ± 10	540 ± 20
	1	410 ± 20	470 ± 15
	1.5	340 ± 15	420 ± 20
	2	270 ± 10	350 ± 15
Nanosilica suspension (nanosilica/binder)	0.2	640 ± 30	710 ± 25
	0.5	590 ± 25	660 ± 20
	0.8	560 ± 25	630 ± 15
	1	650 ± 30	720 ± 20
	1.5	940 ± 40	1,010 ± 35
	2	1,590 ± 50	1,660 ± 40
Silane coupler (silane/nanosilica)	0	500 ± 20	580 ± 20
	4	540 ± 15	620 ± 15
	10	590 ± 20	670 ± 25
	20	910 ± 30	990 ± 30
	30	1,810 ± 45	1,880 ± 35
	0	540 ± 10	620 ± 15
PCE (PCE/nanosilica)	4	560 ± 15	640 ± 20
	10	580 ± 20	650 ± 15
	20	600 ± 15	670 ± 10
	30	620 ± 10	700 ± 20

face of fine aggregates, may serve as a lubricating agent at mixing stage [22]. Moreover, the increase in fluidity may be due to the improved wettability of nanosilica particles after the introduction of silane in suspension [23]. As also listed in Table 3, it is interesting that the pastes which contained more than 10 wt% PCE presented no decrease in fluidity for 30 min. As is well known, the fluidizing effect of PCE is mainly dependent on the adsorption behavior on the surface of cement grains [24]. It has been widely accepted that the adsorption of PCE into cement particle surfaces is mainly driven by the electrostatic interaction between two related particles [25]. Therefore, it is easy to understand that the higher charge density of anionic polymers will lead to a larger adsorption amount on cement mineral surfaces. Moreover, the presence of silane coupler and PCE may modify the hydrophilia surface and increase the steric hindrance of nanosilica particles, which may contribute to the reduction

of absorbing water and improve the dispersity of nanosilica particles, respectively.

The influences of unmodified nanosilica, nanosilica suspension, silane coupler, and PCE content on the setting times of grouting pastes are listed in Table 4. Both the initial and final setting times of pastes were significantly decreased by the introduction of unmodified nanosilica. Similarly, the higher the content of unmodified nanosilica, the higher was the reduction in the setting times. Generally, a short final setting time may damage equipment, while a long time will decrease the grouting effectiveness [26]. For grouts with nanosilica suspension, the setting times decreased with increasing nanosilica contents. However, the setting times increased significantly when the nanosilica content is higher than a threshold value, that is, 0.8 wt%. This trend was different to the grouts with unmodified nanosilica. At the initial period of hydration, the addition of well-dispersed

nanosilica may assist to accelerate the hydration of pastes and faster formation of calcium hydroxide crystal [27]. The accelerating rate depends upon the specific surface areas of nanosilica particles, which act as nucleation sites for the hydration [7]. Furthermore, the incorporation of nanosilica may contribute to accelerate C_3S dissolution [28]. The faster formation of calcium hydroxide crystal and accelerated C_3S dissolution may result in the decrease in setting times. Moreover, the large specific surface areas and high surface energy of nanosilica particles yield better absorption of water in pastes and reduce the fluidity, thus shortening the setting times [29].

The introduction of silane coupler may greatly increase both the initial and final setting times. At the dissolution stage, the hydrolysis of silane may consume free water, which, in turn, reduced the water to cement ratio in the pastes. Moreover, the dissolution speed of cement particles was slowed down by the addition of silane coupler [30]. Portland cement particles may be covered with a gel-like film formed by the hydrolysis of silane and caused a decrease in the ion diffusion rate in the first few hours [31]. At the dynamic balance stage, silane had a high degree of hydrolysis and was polymerized, which may generate multiple types of intermediates. The C-S-H gel and C-H crystal may be bonded by these intermediates due to the attraction of hydrogen bonding. Furthermore, the surface of C-H crystal may be tangled by a layer of silane, which may prevent cement particles to contact with free water and put off the growth of crystal [30].

It can be seen in Table 4 that both the initial and final setting times slightly increased with increasing PCE content. The cement hydration kinetics may be significantly influenced by the charge density and side chain length of PCE [25]. The induction period could be prolonged with increasing charge density. Furthermore, the hydration of C_3A and C_3S may be restrained by the presence of PCE. Moreover, the diffusion of free water and calcium ions may be reduced and hindered owing to the presence of PCE at the cement surface. Additionally, the incorporation of PCE and presence of calcium ions may contribute to the formation of a complex in the pore solution [32]. All the

above may contribute to prolong the hydration process and then increase the setting times of grouting pastes.

3.2. Compressive strength

The influence of unmodified nanosilica on the compressive strength of hardened grouts is shown in Figure 2. As shown in Figure 2, although unmodified nanosilica could present a filling effect and pozzolanic activity, the incorporation of unmodified nanosilica had no positive effect on the compressive strength for all ages. This result may be attributed to the significant decrease of fluidity by the introduction of unmodified nanosilica, which presented a high specific surface area and adsorbed a great amount of water [4].

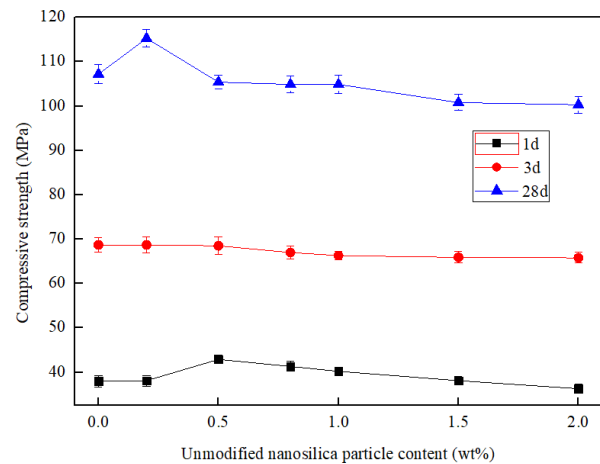


Fig. 2. The influence of unmodified nanosilica particles on compressive strength of hardened grouts

Figure 3 illustrates the influence of nanosilica suspension on the compressive strength of hardened grouts. The compressive strength of specimens with 0.2 wt%, 0.5 wt%, 0.8 wt%, and 1.0 wt% nanosilica particles were higher than those of the reference specimen for ages up to 28 days of curing, showing that the introduction of nanosilica in the form of suspension could improve the compressive strength of cement-based grouts. On the one hand, the filling effect may attribute to form a higher packing and dense matrix. On the other hand, the pozzolanic reaction could also result in a higher densification of the grouting matrix. However, the compressive strength decreased when

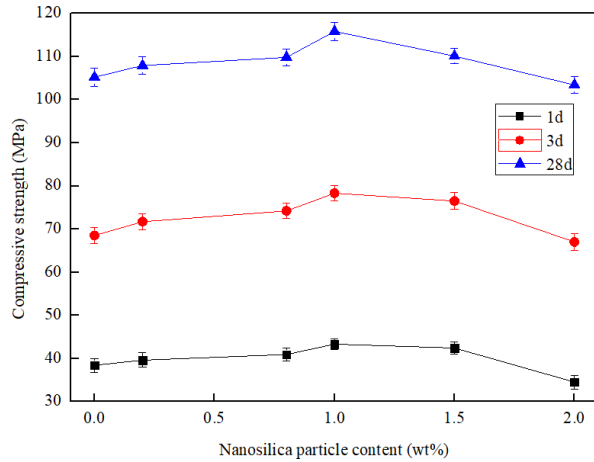


Fig. 3. The influence of nanosilica particles content on the compressive strength of hardened grouts

nanosilica content was higher than 1.0 wt%, which may be owing to excessive introduction of silane in suspension.

The influence of silane ratio in suspension on the compressive strength of hardened grouts is shown in Figure 4. The compressive strength for ages up to 28 days of curing increased with increasing silane ratio and then decreased. However, the compressive strength of specimens with 20 wt% and 30 wt% silane in suspension was lower than that of the reference specimen. As discussed above, a high silane ratio had a significant negative effect on both the initial and final setting times. The extension of initial setting time could greatly reduce the hydration rate of grouts and decrease the early-age compressive strength of hardened grouts.

The effect of PCE ratio in suspension on the compressive strength of hardened grouts is shown in Figure 5. The compressive strength for all ages of grouts increased with increase in the PCE ratio. Moreover, compressive strength for ages of up to 28 days were all higher than that of the reference specimen. The introduction of PCE could reduce mixing water and decrease the voids, forming a dense matrix, resulting in an increase in the compressive strength. Furthermore, the adsorption of PCE on the surface could reduce the agglomeration of nanosilica particles and then improve their dispersity state, which was attributed to a high influence on the hardened paste properties.

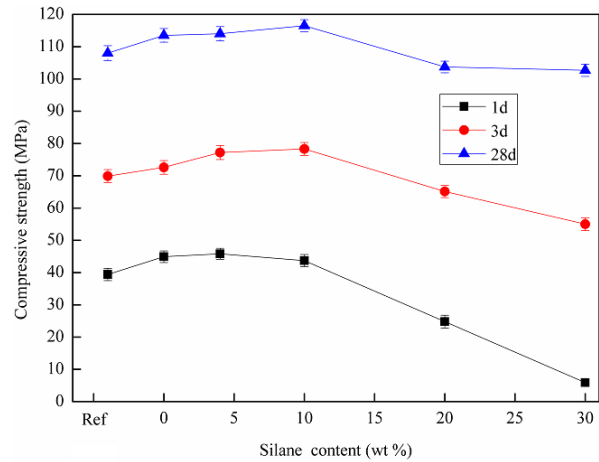


Fig. 4. The influences of silane ratio in suspension on compressive strength of hardened grouts

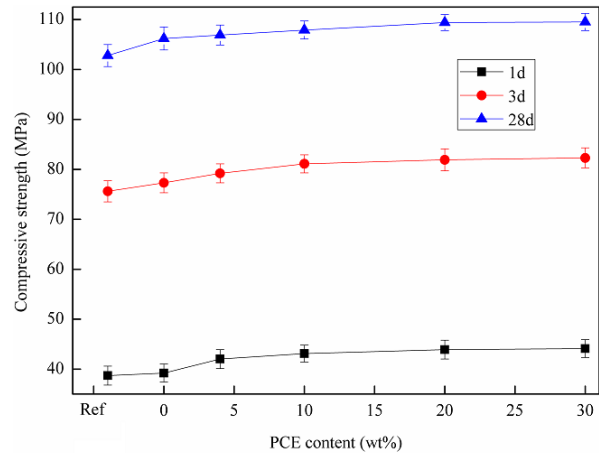


Fig. 5. The influences of PCE ratio in suspension on compressive strength of hardened grouts

3.3. Thermogravimetric (TG) analysis

The TG-DTA curves of specimens with 0 wt% and 0.5 wt% nanosilica particles in the form of suspension for 1 day of curing are shown in Figure 6. The peak around 425°C was attributed to CH dehydration, and the peaks around 630°C and 690°C were the most associated with CaCO₃ decomposition possible. In the reference, the CH content was 11.65%, calculated according to Eq. (1) (Figure 6A), and the CH content of 0.5 wt% nanosilica group was 10.78 wt%, which was smaller than that of the reference specimen (Figure 6B). Obviously, cement-based grouts with nanosilica suspen-

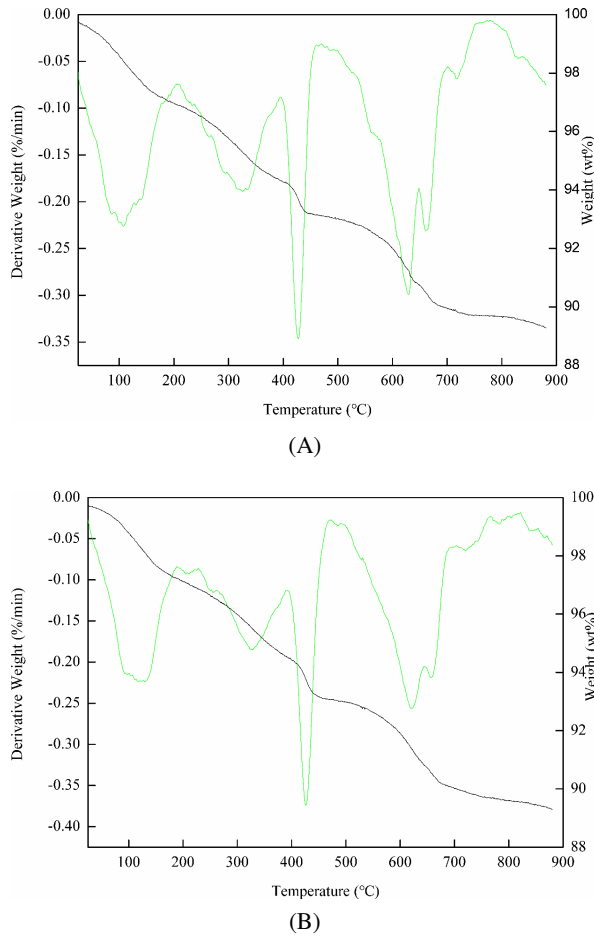


Fig. 6. **(A)** The TG and differential thermal analysis (DTA) curves of specimens with 0 wt% nanosilica particles for 1 day of curing. **(B)** The TG and DTA curves of specimens with 0.5 wt% nanosilica particles for 1 day of curing. TG, thermogravimetric

sion presented less formation of calcium hydroxide, while there was more formation of C-S-H gel at early-age hydration. These results indicated that the beneficial role of nanosilica suspension may contribute to a crystal nucleus and accelerate the hydration of Portland cement. Nanosilica in suspension may contribute to highly efficient nucleation sites for monomeric silica units released from the Portland cement clinker phase during hydration [28]. Moreover, the pozzolanic effect of nanosilica particles consumed a large amount of CH, resulting in the undersaturation of Ca^{2+} in the slurry, and thus accelerating the hydration rate of cement,

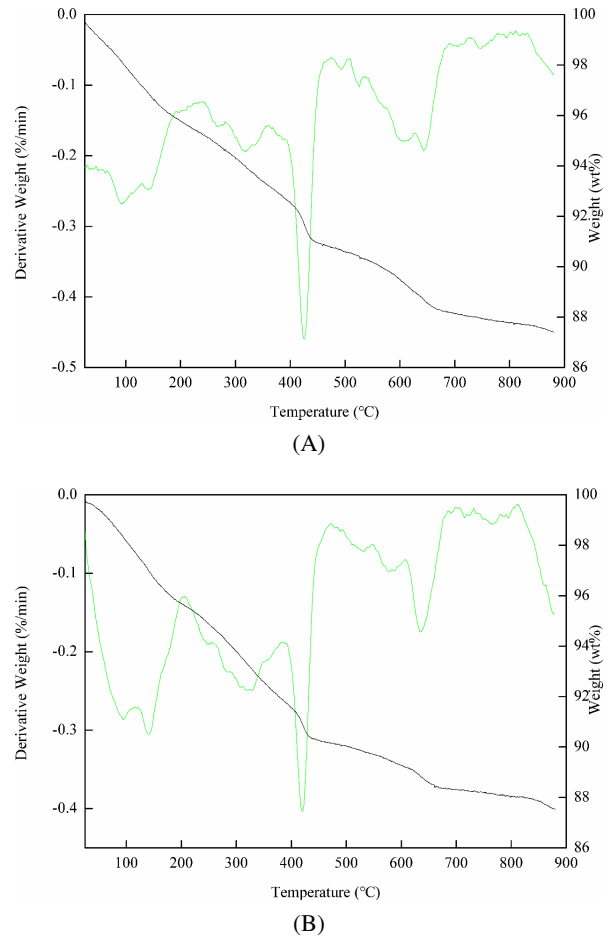


Fig. 7. **(A)** The TG and DTA curves of specimens with 0 wt% nanosilica particles for 28 days of curing. **(B)** The TG and DTA curves of specimens with 0.5 wt% nanosilica particles for 28 days of curing. TG, thermogravimetric

which may contribute to increase the consumption of C_3S and the formation rate of C-S-H gel [33].

The TG–DTA curves of specimens with 0 wt% and 0.5 wt% nanosilica particles in the form of suspension for 28 days of curing are shown in Figure 7. According to Eq. (1), the CH content in the reference curve was 12.77 wt% (Figure 7A) and the CH content in the TG–DTA curve with 0.5 wt% nanosilica (Figure 7B) was 9.59 wt%. The mass loss of dehydration of calcium hydroxide for reference specimen was higher than that of specimen with 0.5 wt% nanosilica. Along with the hydration, the concentration of Ca^{2+} and OH^- gradually increased. Nanosilica particles present

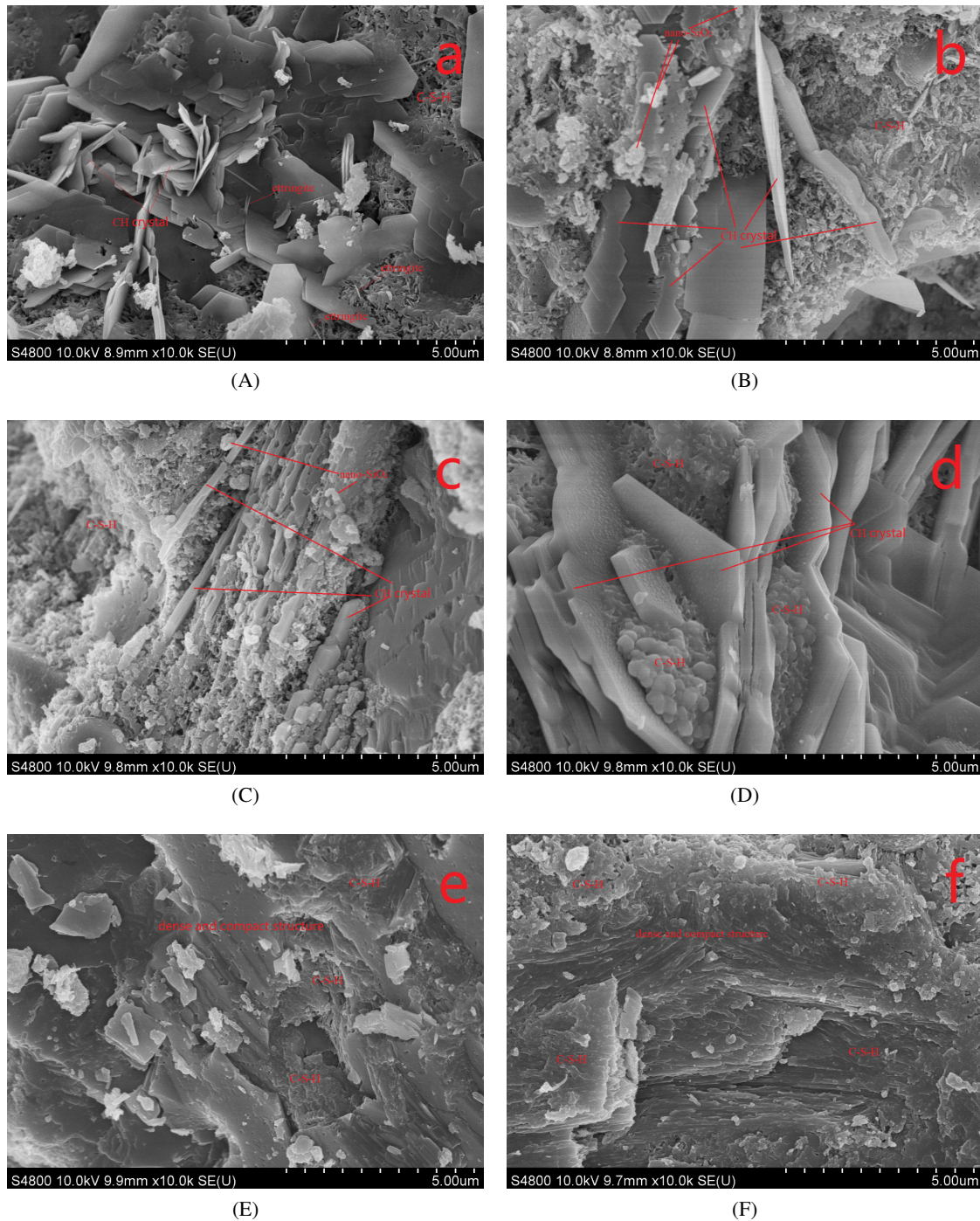


Fig. 8. (A) The SEM micrographs of cement grouts with 0 wt% nanoparticles for 1 day of curing. (B) The SEM micrographs of cement grouts with 0.5 wt% unmodified nanoparticles for 1 day of curing. (C) The SEM micrographs of cement grouts with 0.5 wt% nanoparticles for 1 day of curing. (D) The SEM micrographs of cement grouts with 0 wt% nanoparticles for 28 days of curing. (E) The SEM micrographs of cement grouts with 0.5 wt% unmodified nanoparticles for 28 days of curing. (F) The SEM micrographs of cement grouts with 0.5 wt% nanoparticles for 28 days of curing

a pozzolanic activity and may act as nucleation sites. Then nanosilica could react with water, form $\text{H}_2\text{SiO}_4^{2-}$ in an alkali environment, and then react with calcium hydroxide to form an additional C-S-H gel [7], resulting in an extra consumption of calcium hydroxide crystals. So, the incorporation of nanosilica particles in cement-based grouts could enhance the cement hydration kinetics and result in higher densification of the matrix, which improves the strength and durability of the cement-based grouts [34].

3.4. SEM micrograph

The SEM micrographs of cement-based grouts with various content of nanosilica particles for 1 day and 28 days of curing are shown in Figure 8. There were a large number of needle bar ettringite and thin sheets of CH crystal encased in CSH gel in the hydration products of reference specimen for 1 day (Figure 8A). However, the structure of CSH gel was relatively loose and the microstructure was shaggy. After mixing with unmodified and modified nanosilica particles, the microstructure of cement-based grouts for 1 day became denser and more compact (Figures 8B and 8C). Because there were fewer CH crystals in the two images, the crystals were surrounded by more and denser CSH gel. Furthermore, specimens with nanosilica particles had lower capillary pores compared with the reference specimen, in particular in the surface area and lower depth [35].

A great amount of sheet-like calcium hydroxide crystals could be observed in the SEM image of reference specimen for 28 days (Figure 8D). In contrast, a denser and more compact C-S-H gel in addition to the lesser formation of calcium hydroxide crystals [36] could be evident observed in SEM micrographs of specimens with 0.5 wt% unmodified and modified nanosilica particles for 28 days (Figures 8E and 8F). Moreover, a great amount of rock-like C-S-H was formed due to the pozzolanic reaction between nanosilica and calcium hydroxide [26]. The existence of C-S-H could bridge cement particles and produce a rigid system, resulting in the improvement of the early strength of cement-based grouts [27].

4. Conclusions

In our study, we showed that it is possible to control the conflict between workability and compressive strength of cement-based grouts by the introduction of a suspension containing nanosilica particles, silane coupler, PCE, and water. The efficiency depended on the ratio of silane/PCE to nanosilica in suspension on the one hand and the incorporation content of nanosilica particles in the grouting mixture. The specific findings could be highlighted as follows:

1. The optimal dosage of modified nanoparticles was 0.8%, and the initial fluidity and 30 min fluidity of grouting materials were 335 mm and 320 mm, respectively. The compressive strength for age up to 28 days increased by 10.1% over that of the reference group.
2. Both the initial and final setting times of grouting pastes were significantly decreased by the introduction of unmodified nanosilica particles, while the introduction of silane in suspension may greatly increase both the initial and final setting times.
3. Nanosilica suspension could promote the hydration process of grouts and conduct secondary hydration with CH crystal generated by Portland cement hydration. In addition, the sample at the age of 28 days consumed 3.18% more CH crystal than the reference.
4. The hydration products of reference specimen were isolated and the microstructure was shaggy. In contrast, the micrograph of specimens with nanosilica particles presented a lesser formation of CH crystals in addition to a dense and compact microstructure, which resulted in an improvement of compressive strength.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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