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Analysis of Mechanical Properties and Microstructure of Nano- and Micro-SiO_2 Materials as Cementitious Composite Binder

Won-Woo Kim[1*] and Jae-Heum Moon[1]

Abstract

This study evaluated the setting time, mechanical properties and microstructure of Portland cement (OPC) by adding SiO_2 nano- and micro-particles. The setting time was reduced due to the pozzolanic reaction of the nano- and micro-SiO_2, and the compressive strength was increased through a reduction in the porosity of the microstructure. When nano- and micro-SiO_2 were used alone, micro-silica was the most effective in reduced the initial and final setting times and developing compressive strength. When two or more nano- and micro-SiO_2 were used, a micro-sized binder and a small amount of nano-silica effectively improved performance as the setting time was reduced to 50–52% of that of ordinary Portland cement (OPC). It appears that a small amount of nano-silica could reduce the setting time and increase compressive strength because it caused the pozzolanic reaction and because the nanoparticles filled the pores between the silica fume and cement, which were composed of relatively large particles. This result could also be derived from compressive strength and microstructure analysis. Cement paste containing to nano- and micro-silica increased the strength by approximately 112% compared to OPC. Because nano-binders may cause a reduction in flow due to their large specific surface area, adding chemical admixture needs to be considered during mix design. In addition, the particle size distribution must be considered when nano- and micro-materials are used because an imbalance in particle size distribution can increase the pore size in the microstructure.

Keywords Nano particle, Nano-SiO_2, Micro-SiO_2, Pozzolanic reaction, Nano-silica, Micro-silica

1 Introduction

With the development of various materials and new technologies, construction materials have been developed using nano- and micro-materials on cement binders. Representative micro-sized particles include pozzolanic binders and fillers used in ultra-high performance concrete (UHPC), such as micro-silica and silica sand (Kang et al., 2019; Richard & cheyrezy, 1995; Van et al., 2014; Zanni et al., 1996). Reactive SiO_2 materials are expected to enhance strength as binder through the pozzolanic reaction as they are relatively small particles compared to cement and fill the pores in cementitious composites (Goldman & Bentur, 1993; Van et al., 2014).

UHPC is a material developed by optimizing the reactivity and particle size distribution of such materials. For UHPC, however, studies have mainly been conducted on the application of micro-sized materials and carbon-based nanomaterials (Dong et al., 2020; Lee et al., 2018; Smarzewski & Barnat-Hunek, 2013; Terence, 2005; Yu et al., 2022), and only a few studies have examined the application of nanoparticles as binder. Several attempts have been made to provide various functions to concrete using nanomaterials. For instance, photocatalysts have been used for research

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*Correspondence:
Won-Woo Kim
kimwonwoo@kict.re.kr
[1] KICT (Korea Institute of Civil Engineering and Building Technology), 283, Goyang-Daero, Ilsanseo-Gu, Goyang-Si, Gyeonggi-Do 10223, Republic of Korea

on self-purifying concrete because they can remove nitrogen oxides and cause antibacterial and sterilization effects in the presence of water and ultraviolet rays (Jimenez-Relinque et al., 2015; Karapati et al., 2014). Research has also been conducted on shielding concrete (Micheli et al., 2014) using the electrical conductivity of carbon nanotubes (CNTs) and graphene (Janjaroen et al., 2022; Karapati et al., 2014). In addition, CNTs research for use as a construction material to improve the mechanical properties of cementitious composites is continuously being conducted (Chan & Andrawes, 2010; kim et al., 2020). However, studies on hydration characteristics between nano- and micro-construction materials and cement are still insufficient. Studies of nano-SiO_2 are also mostly structural performance and mechanical properties studies on mortar and concrete without examining reactivity in cement pastes (Du et al., 2014; Masoud et al., 2019; Meysam & Mahmood, 2018). Therefore, this study examined the applicability of nano- and micro-SiO_2 particles as binder for construction materials.

Because SiO_2 nanoparticles have a large surface area when used alone, their contents are significantly restricted. Reactivity, microstructure and compression characteristics were evaluated when they were used alone in small quantities or as a binder with micro-SiO_2 particles. Mixing parameters were determined considering the particle size and specific surface area of materials that can be used as binder among the nano- and micro-SiO_2 that cause the pozzolanic.

2 Experimental Design

2.1 Materials

The OPC cement used in this study was sourced from company Asia cement in Korea. Nano- and micro-SiO_2 consisted of nano-silica 15 nm obtained from company Sinopro, micro-silica and silica fume from company Elkem, and fumed silica from company OCI (Fig. 1). Tables 1 and 2 show the chemical composition of OPC and the physical properties of the nano- and micro-SiO_2, respectively. The main components of the cement were CaO (61.6%) and SiO_2 (20.7%). The nano- and micro-SiO_2 consisted of 96.08 to 99.78% SiO_2, and the particle size was approximately 0.75 to 0.07% of that of the cement. As the particle size was smaller, the specific surface area was approximately 47 to 612 times larger than that of cement. Table 3 lists the mix proportions of cementitious composites. The water-to-binder (*W/B*) ratio was fixed at 0.3, and the nano- and micro-SiO_2 binder type and content were determined as variables. Since nanoparticles are expensive compared to cement, they are highly likely to be applied to high-strength concrete. Chemical admixtures, such as superplasticizers, were not used in the mixes because they can affect the setting time of the cementitious composites.

To examine the applicability of the nano- and micro-SiO_2 binder, their reactivity was examined. Because nanomaterials have a small particle size and a large specific surface area compared to the unit weight, it is difficult to use them at the same content as typical binder. Therefore, reactivity was analyzed using *K*-value to select nanomaterials that are suitable construction materials. The material performance improvement was examined

Table 1 Chemical composition of OPC

	Chemical composition (%)							
	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
OPC	3.2	20.7	5.2	3.4	61.6	2.1	2.6	0.9

LOI loss on ignition

Table 2 Physical properties on cement and nano- and micro-SiO_2 [10]

Product name	Ingredients		Size (nm)	Specific surface area (m^2/g)	Specific gravity
OPC	CaO, SiO_2, Al_2O_3, Fe_2O_3, etc.		20,000	0.38	3.10
Silica fume	SiO_2	99.6	100–150	18–20	2.22
Micro-silica		96.08	22.65	20.8	2.11
Nano-silica		99.78	14.05	203.8	1.40
Fumed silica		99.75	13.60	144.0	1.51

Table 3 Cement paste mixing table of volume proportion

Specimens	*W/B*	Binder volume (%)				
		Cement	Silica fume	Micro-silica	Nano-silica	Fumed silica
OPC	0.30	100	–	–	–	–
SF-1		99	1	–	–	–
SF-3		97	3	–	–	–
MS-1		99	–	1	–	–
MS-3		97	–	3	–	–
NS-1		99	–	–	1	–
NS-3		97	–	–	3	–
FS-1		99	–	–	–	1
FS-3		97	–	–	–	3

OPC ordinary Portland cement, *SF* silica fume, *MS* micro-silica, *NS* nano-silica, *FS* fumed silica

(a) Micro silica (b) Nano silica (c) Fumed silica

Fig. 1 Nano- and micro-SiO_2 materials

by mixing with silica fume, a conventional binder used in the construction industry.

2.2 Nanomaterial Reactivity Analysis (*K*-value)

For the reactivity of the nanomaterials, the *K*-value of BS EN 196-1 (2016), which is used as a method to identify the reactivity of fly ash, was used. The properties of the nanomaterials were taken directly from Kim et al., (2021, Table 2). The compressive strength and the volume of the material were used determine *K*-value. In this study, the volume of sand was excluded, and the following equation was used to examine reactivity in cement paste (BS EN 196-1, 2016):

$$S = K\left(\frac{C+f}{C+f+W}\right)^2, \quad (1)$$

where S is the compressive strength of cement paste, C is the volume of cement, f is the volume of the nanomaterial to be used as an admixture, and W is the volume of water. For the compressive strength of cement paste, the *W/B* ratio was fixed at 0.3, and the nano- and micro-SiO_2 substitution rate for cement was set to 1 and 3% based on the cement volume (Table 3). Nano-SiO_2 used for binder has a large specific surface area, it has a high influence on the decrease in flowability. In this study, it was determined to be up to 3% for specimen production. And the mixing amount recommended by existing researchers is also about 0.5 to 2% (Naji Givi et al., 2010; Stefanidou & Papayianni, 2012).

The compressive strength measurement specimens were prepared as 50×50×50 mm cubes. The compressive strengths of the specimens were measured on the 7 days after one day of dry curing and water curing at 80 °C, and they were substituted into Eq. (1). The *K*-value calculation results are shown in Fig. 2.

In the *K*-value calculation results, the mixes with the nano- and micro-SiO_2 exhibited high reactivity. When the nanomaterial substitution rate was 1%, nano-silica showed the highest reactivity. When the substitution rate was 3%, the reactivity was lower than a substitution rate of 1%, but it was still higher than that of OPC. Fumed

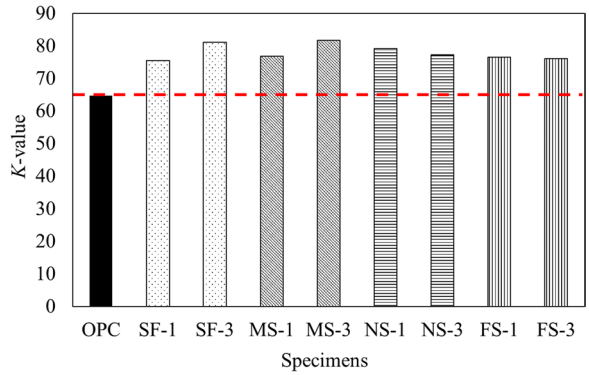


Fig. 2 *K*-value calculation result of nano- and micro-materials

silica showed a tendency similar to nano-silica, but its reactivity was relatively low. Silica fume and micro-silica exhibited similar reactivity, and their reactivity increased when the substitution rate increased from 1 to 3%. It appeared that nano-silica and fumed silica showed similar tendencies, and similar results were measured from silica fume and micro-silica because the content of the nano- and micro-SiO_2 was significantly affected by their average size and specific surface area value. Fumed silica showed a tendency similar to that of nano-silica, but it was excluded from this study due to its relatively low reactivity compared to nano-silica.

2.3 Mix Design

It is challenging to apply a weight mix design to nano-scale materials because they have lower specific gravity and larger specific surface area than typical binders for construction (kim et al., 2021). Therefore, the binder was designed by calculating the volume ratio, as shown in Table 3. The specific gravity values in Table 2 were used for volume conversion. In the case of silica fume, a substitution rate of 10% by weight of cement has been used in many studies on high-strength concrete mixes (Dong et al., 2020; Lee et al., 2018; Terence, 2005; Yu et al., 2022). Therefore, in this study, a substitution rate of 10% was set as a variable, and it was calculated to be approximately 7.5% when converted into the volume ratio. Because micro-silica showed a tendency similar to that of silica fume in the *K*-value reactivity test, the same substitution rate was applied. For nano-silica with relatively small particle size, low specific gravity value, and large specific surface area, the substitution rate was determined to be 1% because its reactivity decreased when the substitution rate exceeded 1% in the *K*-value reactivity test. The mixing amount recommended by existing researchers is also about 0.5 to 2% (Naji Givi et al., 2010; Stefanidou & Papayianni, 2012). In addition, an experiment was also performed by adding 1% of nano-silica to the mix in which 7.5% of silica fume and micro-silica were substituted to examine the material characteristics.

The cementitious composites were prepared using a paddle mixer following the ASTM C 305 (2020) and KS L 5109 (2017) standards, and the nano- and micro-SiO_2 were sufficiently mixed with the cement (Table 4, Figs. 3, 4).

3 Experimental Method

3.1 Flow (Flow Table) Measurement

A flow table was used for the flow test on cement paste mixes containing pozzolanic admixtures (KS L5111, 2022). In the test, the degree of flow under non-vibration conditions and 25 impacts was measured using a vernier caliper on the flow table, and the average of two measurements was used for each mix.

3.2 Setting Time (Vicat) Measurement

The setting time was measured using the Vicat needle test method on the cement paste, and Vicamatic 2 automatic measurement equipment from CONTROLS (Fig. 4) was used following the ASTM C 191 standard (2021). To measure the setting time (initial and final setting times) for each cement mix, the penetration resistance depth was measured every 30 min after the start of the test. Since the penetration resistance depth sharply

Table 4 Cement paste mixing table of volume proportion

Specimens	*W/B*	Binder volume (%)			
		Cement	Silica fume	Micro-silica	Nano-silica
OPC	0.30	100	–	–	–
SF		92.5	7.5	–	–
MS		92.5	–	7.5	–
NS		99.0	–	–	1
SFNS		91.5	7.5		1
MSNS		91.5	–	7.5	1

OPC ordinary Portland cement, *SF* silica fume, *MS* micro-silica, *NS* nano-silica

Fig. 3 Mixing of cement paste with SiO_2 materials

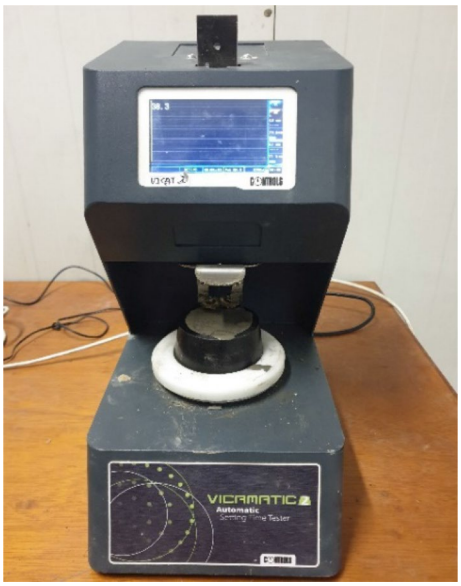


Fig. 4 Automatic vicat equipment

Fig. 5 Compressive strength test equipment

decreased as the initial setting time was approached, the penetrating needle was set to fall every 5 min when the penetration resistance depth was 30 mm or less automatically. The penetration resistance depth began at 38 mm, and the final setting time was determined based on the penetration depth of 2.5 mm or less because it was difficult to measure up to 0 mm due to the characteristics of the equipment. All the measurements were performed at a temperature of 20 °C and a humidity of 85% using a constant temperature and humidity chamber.

3.3 Compressive Strength Measurement

The compressive strength of cement paste was measured to verify mechanical properties according to the addition of nano- and micro-SiO_2. 50×50×50 mm cubic specimens were prepared to measure the compressive strengths of the cementitious composites. The compressive strength was measured using a 300 kN universal testing machine (Fig. 5) in accordance with the ASTM C 109 standard (2021) at 7 and 28 days of age after one day of dry curing at 20 °C and water curing.

3.4 Microstructure (MIP) Measurement

Cement microstructure is a main factor that affects the durability and compressive strength of concrete. In general, the porosity of cementitious materials is measured through Brunauer, Emmett, and Teller (BET) and mercury intrusion porosimetry (MIP) methods. The BET method determines pores in the cement hydrate microstructure through the amount of gas or water vapor adsorbed based on the gas adsorption theory. Similar to the BET method, the MIP method also measures the porosity of the microstructure in cement paste by injecting mercury with the equipment used for microporosity and pore size distribution measurement. BET can be favorable for measuring micropores in a specific portion but cannot measure pores beyond a certain size as its measurement range is limited. Therefore, this study conducted MIP tests that measure a relatively wide range of pore structures in cement paste. 50×50×50 mm cubic specimens were prepared for the compressive strength of the cementitious composites. MIP tests were conducted after interrupting the hydration of the specimens crushed at 28 days of age after water curing through immersion in acetone.

4 Experimental Results and Discussion

4.1 Flow

Fig. 6 shows the flow property of the cement paste. Depending on the content of the pozzolanic binders, the flow of the mixes other than that containing silica fume showed decreasing trend. Flow measured of nano- and micro-SiO_2 cement paste on non-vibration conditions by Fig. 7a and 25 impacts after by Fig. 7b.

OPC showed a flow of approximately 190 mm, and the flow was measured to be 192 mm for the silica fume mix, 163 mm for the micro-silica mix, and 138 mm for the nano-silica mix. It appears that the flow of the nano-silica mix sharply decreased because nano-silica has a low density and a large specific surface area compared to other pozzolanic binders, even at a 1% ratio. The mixes containing silica fume and micro-silica also exhibited flow at a level similar to that of the nano-silica mix, but

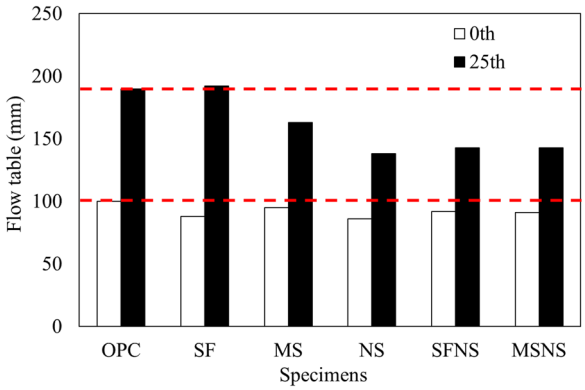


Fig. 6 Flow table of nano- and micro-SiO_2 on cement binder

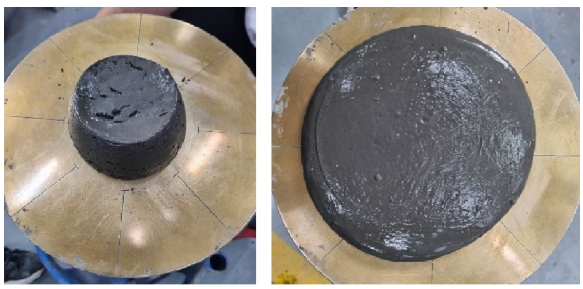


Fig. 7 Flow table of nano- and micro-SiO_2 on cement binder

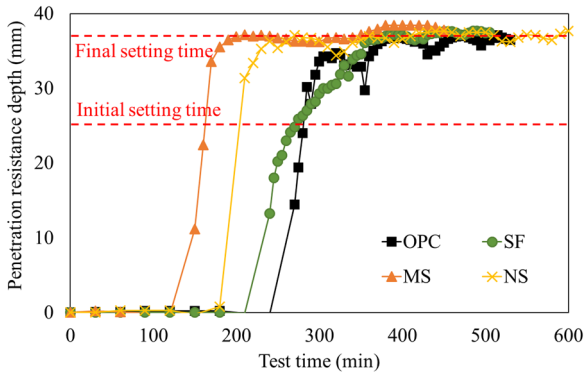


Fig. 8 Vicat test result of nano- and micro-SiO_2 on cement binder

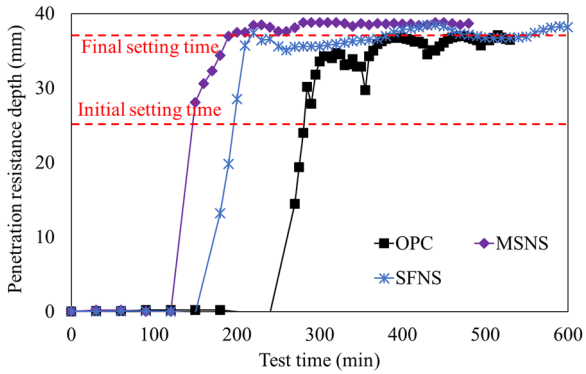


Fig. 9 Vicat test result of nano- and micro-combined SiO_2 on the cement binder

no additional reduction in flow was observed. This is because silica fume and micro-silica did not affect the flow due to their relatively small specific surface area. Therefore, when nano-silica is mixed as a binder, the use of binder must be considered to prevent a reduction in flow.

4.2 Setting Time Measurement Results

Fig. 8 shows the setting time variation by adding the pozzolanic binders as a function of penetration depth over time. The experiment results of Kim and Yang (2022) were cited for the penetration resistance test results of OPC and silica fume. The initial and final setting times of the OPC mix were measured to be 268 and 380 min, respectively. Depending on the nano- and micro-SiO_2 type, the initial and final setting times were reduced compared to OPC. In the case of the mix containing silica fume, the initial and final setting times were measured to be 240 and 360 min, respectively. The initial and final setting times were measured to be 157 and 190 min for the micro-silica mix and 190 and 265 min for the nano-silica mix. Nano-silica exhibited a faster setting acceleration effect than silica fume with relatively small content. This is because nano-silica accelerated the pozzolanic reaction and caused rapid initial cement hydration with its small particle size and large specific surface area compared to its relatively small content. Similarly, it is judged that micro-silica had a relatively higher pozzolanic reaction acceleration effect than silica fume due to its smaller particle size, and it caused the filler effect that fills pores in the composite.

To analyze the effect according to the particle size, the mixes that contained nano-silica, which had a specific surface area at a level of approximately ten times compared to silica fume and micro-silica, together with silica fume and micro-silica, were prepared and compared. Nano-silica (1%) was added to the mixes that contained 7.5% of silica fume and micro-silica, respectively, and the setting time was analyzed. The results are shown in Fig. 9. The initial and final setting times were reduced by adding 1% nano-silica. In the case of the silica fume mix, the initial and final setting times were 181 and 220 min, respectively, showing that the final setting time was shortened by approximately 160 min. In the case of the micro-silica mix, the initial and final setting times were shortened to 138 and 190 min, respectively. It was found that adding a small amount of nano-silica reduced the setting time, and

the reduction was less significant for the micro-silica mix than the silica fume mix.

In the mix that contained both silica fume and nano-silica, it is found that the setting time was shortened because nano-silica with a particle size of approximately 14.05 nm accelerated the pozzolanic reaction and filled internal pores as it was evenly dispersed among silica fume particles in a size of approximately 150 nm and cement particles in a size of approximately 20,000 nm. On the other hand, it is judged that micro-silica did not significantly affect the filling of internal pores because the particle size (approximately 22.65 nm) is not significantly different from that of nano-silica. Similar results can be found in the experiment results according to the particle size distribution in UHPC mixes (Richard & Cheyrezy, 1995).

4.3 Compressive Strength Measurement Results

Fig. 10 shows the compressive strength measurement results according to the content of the nano- and micro-SiO_2 binders. All of the specimens tended to show higher compressive strength than OPC. At 7 days of age, the compressive strength of silica fume increased by approximately 1.10 times compared to that of OPC. When micro-silica and nano-silica were added, the compressive strength increased by approximately 1.09 and 1.04, respectively. At 28 days of age, a tendency similar to that at 7 days was observed, and the strength increase rate compared to OPC was approximately 3 to 8% higher. At 28 days of age, the mix containing micro-silica also showed the highest strength increase rate of 1.13 times compared to OPC when nano- and micro-SiO_2 were used alone. When nano- and micro-SiO_2 were used alone, the mixes containing silica fume and micro-silica could improve strength. In the case of nano-silica, it was shown that a small amount effectively improved strength. This means that adding smaller particles that can trigger the pozzolanic reaction accelerates the hydration reaction and has a strength improvement effect as in the previous setting test results. Nano-silica had a higher setting time reduction effect than silica fume, even with a small amount, but exhibited a low strength increase rate. This appears to be due to the imbalance in particle size distribution, as there is a significant difference between the cement and nano-silica particle size. It should be noted that preparing compressive strength specimens was difficult due to the reduction in flow caused by nano-silica.

The influence of the particle size distribution could be determined through the mixes in which a small amount of nano-silica was added to silica fume and micro-silica. For the mix containing both silica fume and nano-silica, the strength increased by approximately 1.04 times at 7 days of age and 1.08 times at 28 days compared to the mix containing silica fume alone. In the case of the mix containing both micro-silica and nano-silica, however, the strength at 7 days was similar to that of the mix containing only micro-silica as it increased by only 1.01 times. The strength at 28 days increased by approximately 1.04 times, half the level of the mix containing both silica fume and nano-silica. The experiment results suggested that using micro-silica is effective in strength improvement when nano- and micro-SiO_2 are used alone, and that adding both silica fume and nano-silica can maximize strength improvement due to the pore-filling effect when nano- and micro-SiO_2 are used in consideration of the particle size distribution. While the filling effect of nano-silica with an average particle size of approximately 14 nm was maximized for silica fume with an average particle size of approximately 150 nm, it is judged that the strength improvement effect was insignificant for micro-silica with a similar average particle size (approximately 22 nm). Our results also suggest that they will be effective in long-term strength improvement because the strength increase rate at 28 days was measured to be higher.

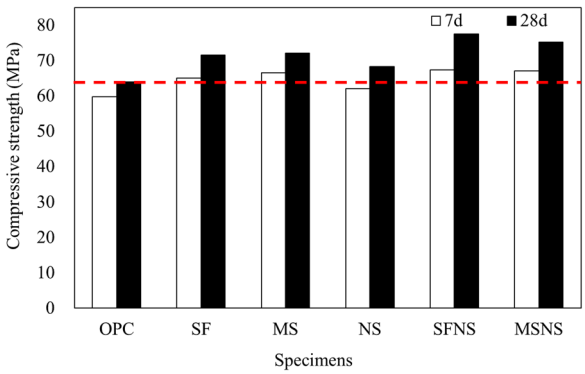
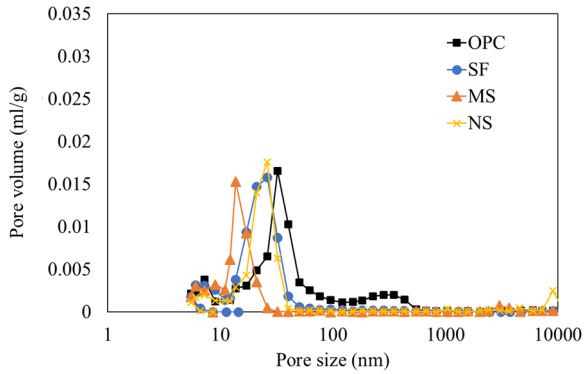


Fig. 10 Compressive strength of nano- and micro-SiO_2 on cement binder

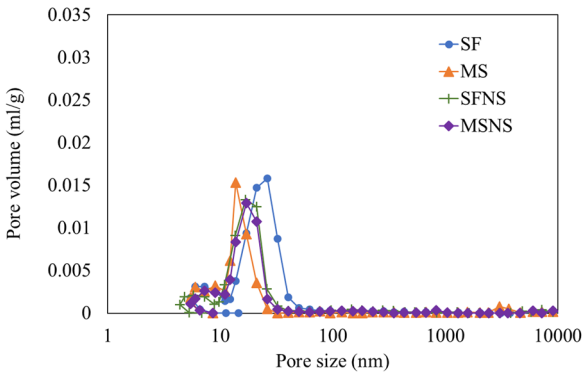
4.4 Microstructure (MIP) Measurement Results

MIP tests were conducted on nano-silica, micro-silica and silica fume which exhibited relatively high compressive strength test results. Fig. 11 shows the test results at 28 days of age. When the microstructure at 28 days was analyzed, the highest porosity was measured from OPC, and the pore size was distributed in the 5–400 nm range. The porosity decreased for all of the mixes containing the nano-silica and micro-SiO_2 (micro-silica or silica fume), and the mix containing both micro-silica and nano-silica exhibited the most significant reduction in porosity.

Fig. 12 shows the test results of nano-silica at 1 day and 28 days of age, and Fig. 13 shows the test results of nano- and micro-silica mixture. Both the 1-day and 28-day ages showed a smaller pore distribution when nano- and



(a) Nano SiO_2



(b) Nano and micro SiO_2

Fig. 11 Pore size distribution for nano- and micro-SiO_2 on cement binder composites at 28 days

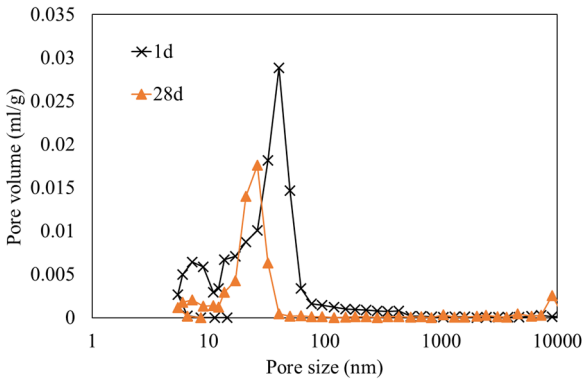


Fig. 12 Pore size distribution for nano-SiO_2 on cement binder composites

micro-silica were incorporated, and the decrease in pore amount and pore distribution with age was greater than only nano-silica. On the other hand, nano-silica effectively reduced porosity, but resulted in relatively large pores in the 10–40 nm. This result is caused by the increase in pore size in the microstructure due to the imbalance in particle size distribution and can explain

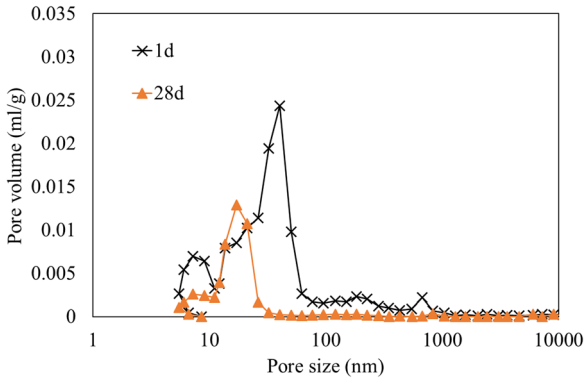


Fig. 13 Pore size distribution for nano- and micro-SiO_2 mix contain on cement binder composites

the finding that mixing nano-silica with cement leads to a low compressive strength development rate while increasing reactivity and shortening the setting time even with a small amount due to the small particle size. The mix containing silica fume was similar results.

It was also found that using both micro-silica and nano-silica was most effective in reducing porosity and resulted in the narrowest pore size range. This results regardless of micro-silica or silica fume. This is because the filling effect in the microstructure was largest as the internal microstructure was filled with nano- and micro-particles. The result was shown in the compressive strength experiment, and the size distribution of the particles constituting the microstructure had effect on the compressive strength.

5 Conclusion

In this study, the setting time, mechanical properties, and microstructure of OPC were evaluated using micro-silica and nano-silica as binders. The nano- and micro-SiO_2 binders were selected by examining reactivity using *K*-value, and the effects of nano- and micro-SiO_2 on initial cement hydration reaction were investigated. Performance was compared and analyzed when the nano- and micro-SiO_2 binders were used alone and together. In addition, the effects on mechanical properties were evaluated through the setting time reduction and microstructure change, and the following conclusions were drawn:

1. When the nano-silica (nano-SiO_2) were mixed, a reduction in flow was observed. When the substitution rate of nano-silica for cement exceeded 1%, the flow was reduced due to the large specific surface area, and the limit of work performance was observed.
2. The measurement of the setting time showed that the initial and final setting times were shortened com-

pared to OPC when the nano- and micro-SiO_2 were mixed. In particular, using micro-silica was effective in developing initial hydration as the initial and final setting times were shortened to 50 to 58%. It was also found that nano-silica had an excellent setting time reduction effect even with a low substitution rate of 1% due to its small particle size and large specific surface area.

3. When a test was conducted by adding nano-silica to the silica fume and micro-silica mixes, considering the particle sizes of the nano- and micro-SiO_2, it was found that the initial and final setting times were further shortened. In particular, the setting time was sharply reduced in the silica fume and nano-silica mix. This is due to the fact that the filling effect was maximized as the pores in silica fume with micro-sized particles were filled with nano-silica with nanoscale particles.
4. In the case of the mix containing both micro-silica and nano-silica, the effect on the setting time was relatively insignificant. This is because the internal pore-filling effect was insignificant due to the imbalance in pore size distribution in the composite, as there was no significant difference in particle size between micro-silica and nano-silica.
5. The compressive strength test results showed similar results to the setting time development effect. In particular, the mix containing silica fume and nano-silica increased the strength by approximately 112% compared to OPC, even with a small amount of nano-silica. This indicates that the particle size distribution must be considered when nano- and micro-admixtures are used.
6. Similar results were also derived from the microstructure measurement. The addition of nano- and micro-SiO_2 reduced porosity. In particular, the porosity reduction effect was large when the nano- and micro-SiO_2 binders were substituted.
7. Since the average particle size of cement was approximately 1400 times larger than that of nano-silica, the pore size was measured to be relatively large due to the imbalance in particle size distribution in the microstructure. The compressive strength increase rate was relatively insignificant due to the imbalance in particle size distribution. This indicates that the particle size distribution plays an important role when nano- and micro-materials are used.
8. It can be found that when the particle size is balanced, the internal dispersion is also affected. This was also confirmed in the flow experiment results. If the particle was well distributed in the cement paste, the reactivity of pozzolane naturally increases. As a result, the reduced the setting time and increased compressive strength.
9. It was found that nano- and micro-SiO_2 affect initial cement hydration, shorten the setting time with an internal pore-filling effect, and increase compressive strength by decreasing the porosity of the internal microstructure. Therefore, these materials can maximize durability through strength enhancement effects, pozzolanic reaction activation, and microstructure densification at high-performance cementitious composites.

This research was evaluated to setting time, mechanical properties, and microstructure of cement paste mixing nano- and micro-sized pozzolanic reactive binders. Based on the experimental results, the deeper understanding about the effects of nano- and micro-pozzolanic particles on cement hydration could be obtained. Furthermore, the current research would also be used in the development of nano- and micro-cement hydration model.

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Author contributions
WW performed most of test and analysis works; main writer of the paper. JH supported the writing the paper. All authors read and approved the final manuscript.

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Declarations

Competing interests
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Won-Woo Kim Ph.D, Research Specialist, Structural Research Division, Korea Institute of Civil Engineering and Building Technology, Republic of Korea.

Jae-Heum Moon Ph.D, Research Fellow, Structural Research Division, Structural Research Division, Korea Institute of Civil Engineering and Building Technology, Republic of Korea.