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Influence of nanoparticles on performance of Portland cement paste and mortar

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ABSTRACT

In recent years, the use of nanoparticles has received particular attention in many applications to fabricate materials with new functionalities. When ultra-fine particles are incorporated into Portland-cement paste, mortar or concrete, materials with different characteristics from the conventional materials were obtained. For instance, nanoparticles of SiO_2 can fill the spaces between particles of gel of C–S–H, acting as a nano-filler. Furthermore, by the pozzolanic reaction with calcium hydroxide, the amount of C–S–H increases which results in a higher densification of the matrix that improves the strength and durability of the material. In this work we discus about Sol-Gel Chemistry Based Nanocomposites method and preparation of nanoparticles for addition into the Portland cement. Then the influence of nanoparticles on several Portland cements is investigated. Addition of nanoparticles to Portland cement can improve its physical properties such as compressive strength and permeability coefficient.

Keywords: *Nano-cement, Nano-silica, compressive strength, Sol-gel.*

1. INTRODUCTION

Portland cement is usually a mixture of limestone (calcium carbonate, $CaCO_3$) and a second material as a source of alumino-silicate. The principal clinker minerals of the Portland cement are Tri-calcium silicate, C3S (Alite), Calcium silicate, b-C2S (Belite), Tri-calcium aluminate, C3A, and Ferrite phase; Tetra-calcium alumino ferrite, C4AF (Celite). Alite compound is characterized by rapid rate of hydration within a few hours and rapid strength development during a few days, while Belite is characterized by slow rate of hydration within days and slow strength development within weeks. In contrast, Celite is characterized by a very rapid rate of hydration (a few minutes) and very rapid strength development as short as one day. Recently, the use of replacement materials such as silica fume, fly ash and metakaoline in Portland cement has been given much attention [1–2].

Nanoscience and nanotechnology refer to the exploration, innovation, and application of nanomaterials, which are characterized by at least one dimension in the nanometer (nm) range. The size range that evokes great attention is below 100 nm, and properties of materials in such scale differ from those of the atomic or the bulk materials of same composition [3-5]. In recent years, the use of nano-particles has received particular attention in many applications to fabricate materials with new functionalities. When ultra-fine particles are incorporated into Portland-cement paste, mortar or concrete, materials with different characteristics from the conventional materials were obtained [6–8].

Nano particles enhanced the compressive strength of cement paste much more than silica fume. It is due to the filling effect and pozzolanic reaction activation. It was concluded that the rate of pozzolanic reaction depends on the Blaine surface area available for reaction. Nano aluminate and silicate have been integrated with cement mortar as a new building material [6].

Nano-particles of SiO_2 (NS) can fill the spaces between particles of gel of C–S–H, acting as a nano-filler. Furthermore, by the pozzolanic reaction with calcium hydroxide, the amount of C–S–H increases which results in a higher densification of the matrix that improves the strength and durability of the material. Former researches indicate that the inclusion of nano-particles modifies fresh and hardened state properties even when compared with conventional mineral additives. Colloidal particles of amorphous silica appear to considerably impact the process of C3S hydration [9–14].

In this work we discus about Sol-Gel Chemistry Based Nanocomposites method and preparation of nano particles for addition into the Portland cement. Then the influence of nano particles on several Portland cements is investigated.

2. SOL-GEL CHEMISTRY BASED NANOCOMPOSITES

Applications of nanotechnology in coatings have shown remarkable growth in recent years. This is a result of two main factors: (1) increased availability of nano-scale materials such as various types of nanoparticles, and (2) advancements in processes that can control coating structure at the nano-scale. Another important reason for this growth is the nanotechnology potential to address many performance challenges presented by the vast range of products and structures that coatings are an integral part of them. A well-known approach to generate inorganic nano-phases within an organic matrix is to utilize sol-gel chemistry [15].

Typically, Silicon, Titanium, Aluminum, and Zirconium metal alkoxides are used as inorganic sol-gel precursors. Under controlled conditions, silanes and organic molecules can form coatings containing silica nanoparticles or nano-phases. In the presence of a coupling agent, the organic and inorganic phases can be covalently linked. This approach has been in practice, including in commercial products for nearly two decades [16, 17].

Feasibility of sol-gel derived organic/inorganic hybrid coatings as a replacement for aircraft aluminum alloy primers containing chromate corrosion inhibitors has been an active area of research [18–21]. Recently, a comprehensive review of sol-gel technology applications in anti-corrosion coatings is available [22].

3. TECHNICAL METHODS AND TEST RESULTS

Byung-Wan Jo et al. [13] studied characteristics of cement mortar with nano-sio2 particles. They used ordinary Portland cement, silica fume powder (SF) and nano-sio2 Particles (NS) as a case study. Figure 1 shows their X-ray diffraction (XRD) diagrams of silica fume and nano-SiO_2.

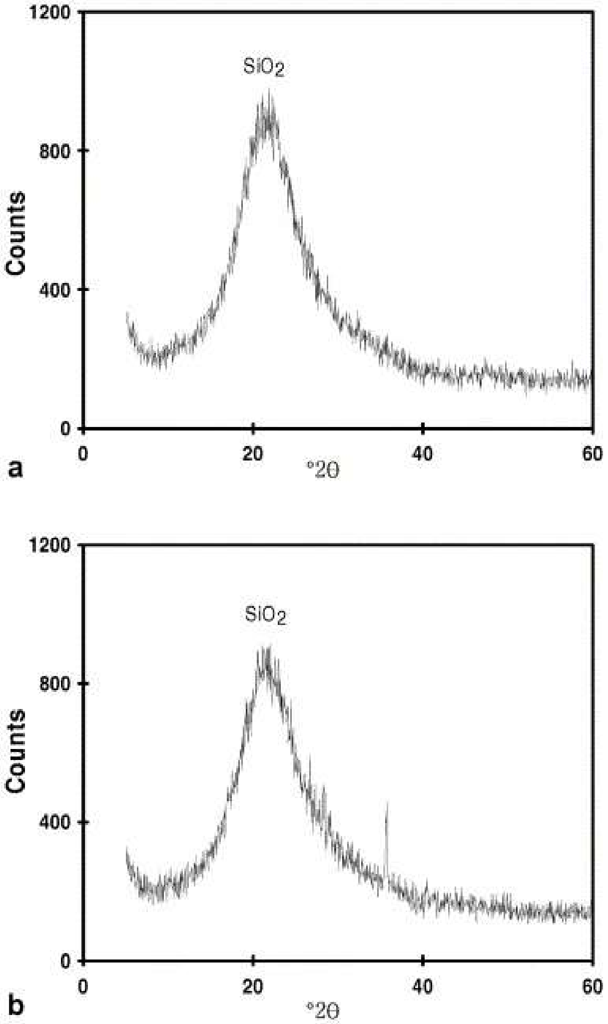

Figure 1. XRD analysis of materials: (a) silica fume and (b) nano-SiO_2 [*Reprinted from Jo B.W., Kim C.H., Tae G., Park J.B., Characteristics of cement mortar with nano-SiO_2 particles, Constr. Build. Mater, 21, 1351, 2007, with permission from Elsevier*].

They also added a polycarboxylate with a relative density of 1.06, which was incorporated into all mixes. The content was adjusted for each mix to ensure that no segregation would occur. Details of their mix proportions for mortars containing silica fume and nano-SiO_2 are given in Table 1.

In microstructure discussion their results show that addition of nano-SiO2 particles were found that influence hydration behavior and led to differences in the microstructure of the hardened pastes. On the other hand, the microstructure of the mixture containing nano-SiO_2 revealed a dense, compact formation of hydration products and a reduced number of Ca(OH)2 crystals. Figure 2 shows SEM images of paste containing nano-SiO2 particles.

Table 1. Mix proportion of the specimens.

Name of specimens	w/cm (%)	Water (g)	Cement (g)	Sand (g)	Silica fume (g)	Nano-SiO_2 (g)	SP. (%)
OPC	50%	128	255	625.0	–	–	1.2
SF5	50%	128	242.8	625.0	12.2	–	1.9
SF10	50%	128	231.8	625.0	23.2	–	2.1
SF15	50%	128	221.7	625.0	33.3	–	2.2
NS3	50%	128	247.5	625.0	–	7.5	1.8
NS6	50%	128	240.6	625.0	–	14.4	2.4
NS10	50%	128	231.8	625.0	–	23.2	2.9
NS12	50%	128	227.7	625.0	–	27.3	3.3

*OPC: ordinary portland cement mortar.
*SF: cement mortars containing silica fume (5%, 10%, 15%).
*NS: cement mortars containing nano-SiO_2 (3%, 6%, 10%, 12%).
*SP: superplasticizer.

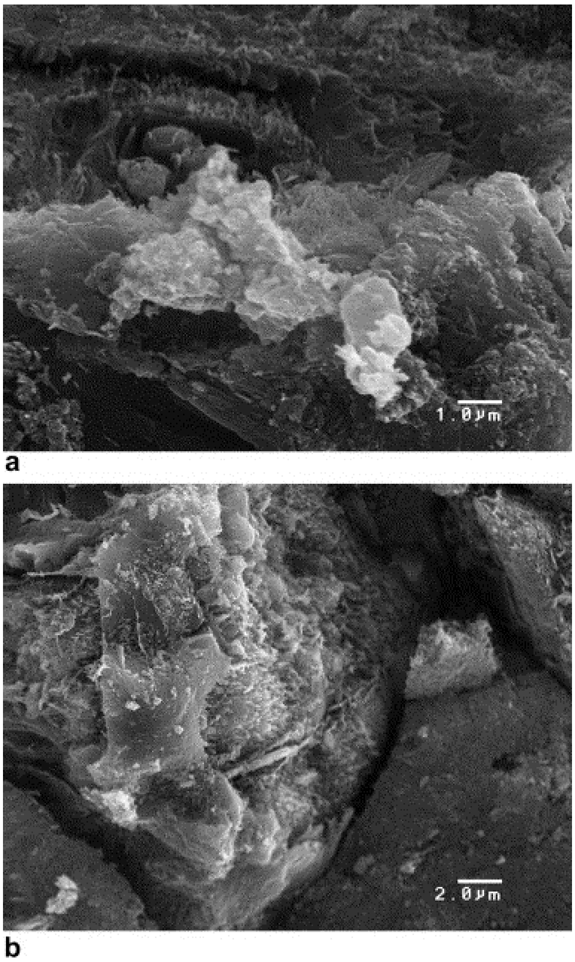

Figure 2. SEM micrographs of paste containing nano-SiO_2 particles: (a) 10,000× and (b) 5000× [*Reprinted from Jo B.W., Kim C.H., Tae G., Park J.B., Characteristics of cement mortar with nano-SiO_2 particles, Constr. Build. Mater, 21, 1351, 2007, with permission from Elsevier.]*

In mechanical properties discussion, their experimental results show that the compressive strength was developed in mortars containing nano-SiO2 particles in every case higher than that of control cement mortars. The difference in the strength development of the mortars can be attributed to pozzolanic reaction. As mentioned above, nano-particles are thought to be more effective in pozzolanic reaction than silica fume. Also, the nano-SiO_2 would fill pores to increase the mortar strength, as silica fume does. Therefore, it is confirmed that the addition of nano-SiO_2 to cement mortars improves their strength characteristics. Their compressive strengths after 7 and 28 days are shown in Table 2.

Table 2. Compressive strength (MPa).

Mix name	7 days	28 days
OPC	18.3	25.6
SF5	22.5	35.1
SF10	24.7	37.4
SF15	26.1	38.0
NS3	39.5	54.3
NS6	46.1	61.9
NS10	49.3	68.2
NS12	50.7	68.8

Ye Qing et al. [10] also studied the influence of nano-SiO2 addition on properties of cement paste and compared with silica fume. Their case study was A commercial ordinary Portland cement it with 310 m2/kg Blaine specific surface. Table 3 shows Chemical compositions and physical properties of clinker, slag, gypsum, silica fume and nano-SiO2.

Table 3. Chemical compositions and physical properties of clinker, slag, gypsum, silica- fume and nano-SiO_2

	Chemical composition (wt%)						Physical properties			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Average of diameter (nm)	Specific surface (m^2/g)	Density (g/cm^3)	Loose density (g/cm^3)
Clinker	21.05	5.56	4.03	64.3	1.02	0.75				
Slag	31.55	13.95	1.08	41.4	8.20	–				
Gypsum	4.96	0.46	0.26	29.6	1.45	37.56				
SF	92.1	2.04	1.08	0.45	0.58	0.44	180	21.5	2.22	0.21
NS	99.9	–	–	–	–	–	15	160		

They investigated 7 experimental procedures such as: (1) Preparation of paste specimen, (2) Test of paste compressive strength, (3) Test of consistency and setting time of fresh pastes (4) Preparation of paste–aggregate interface specimen for microstructure analysis, (5) Test of bond strength of paste–aggregate interface, (6) Microstructure analysis at interface and (7) Curing conditions for specimens over their mixtures. Table 4 shows their mix proportions, compressive and bond strengths of pastes made out of cement and NS or SF.

Table 4. Mix proportions, compressive and bond strengths of pastes made out of cement and NS or SF.

Sample	Mix proportion in mass					Consistency[a] (mm)	Setting time			Compressive strength (MPa) (%)				Bond strength (MPa) (%)	
	C	NS	SF	W	SM		Initial	Final	Δ*t*	1d	3d	28d	60d	7d	28d
CO	100	0	0	22	2.5	34	2h 57m	4h 23m	1h 26m	48.9 100	61.1 (100)	79.2 (100)	94.9 (100)	5.1 (100)	5.8 (100)
A1	99	1	0	22	2.5	34	2h 57m	4h 05m	1h 08m	49.2 101	71.6 (117)	94.7 (120)	101.6 (107)	5.9 (116)	7.3 (126)
A2	98	2	0	22	2.5	33	2h 55m	3h 50m	0h 55m	49.8 102	72.6 (119)	95.8 (121)	102.5 (108)	6.2 (122)	8.3 (143)
A3	97	3	0	22	2.5	33	2h 48m	3h 40m	0h 52m	52.0 106	82.2 (135)	97.6 (123)	105.8 (111)	6.6 (129)	10.0 (172)
A5	95	5	0	22	2.5	32	2h 16m	3h 06m	0h 50m	53.0 108	86.1 (141)	98.8 (125)	108.8 (115)	7.3 (143)	10.9 (188)
B2	98	0	2	22	2.5	35	3h 50m	4h 45m	0h 55m	47.5 97	61.0 (100)	84.2 (106)	101.5 (107)	5.2 (102)	6.3 (109)
B3	97	0	3	22	2.5	35	4h 35m	5h 20m	0h 45m	47.3 97	60.4 (99)	92.0 (116)	104.3 (110)	5.0 (98)	6.7 (116)
B5	95	0	5	22	2.5	36	4h 45m	5h 28m	0h 43m	47.0 96	60.0 (98)	95.3 (120)	106.9 (113)	4.9 (96)	7.1 (122)

[a] Penetration depth.

Their results show that when silica fume is added to cement or concrete, it acts both as chemical inert filler, improving the physical structure and providing nucleation sites for hydration products, and as a pozzolan. It also showed that the mechanism of addition of NS has different effects on the properties of the cement paste, as compared with addition of SF. When a material with high specific surface is added to cement or concrete, it acts as the micro-filler of the cement particles, which can reduce the amount of water that will fill in the void of the blending materials. However, replacing cement with a high specific surface material would increase the wettable surface area and the amount of water adsorbed. Figure 3 shows SEM image of $Ca(OH)_2$ crystals at the interface between aggregate and paste made from cement and nano-SiO_2.

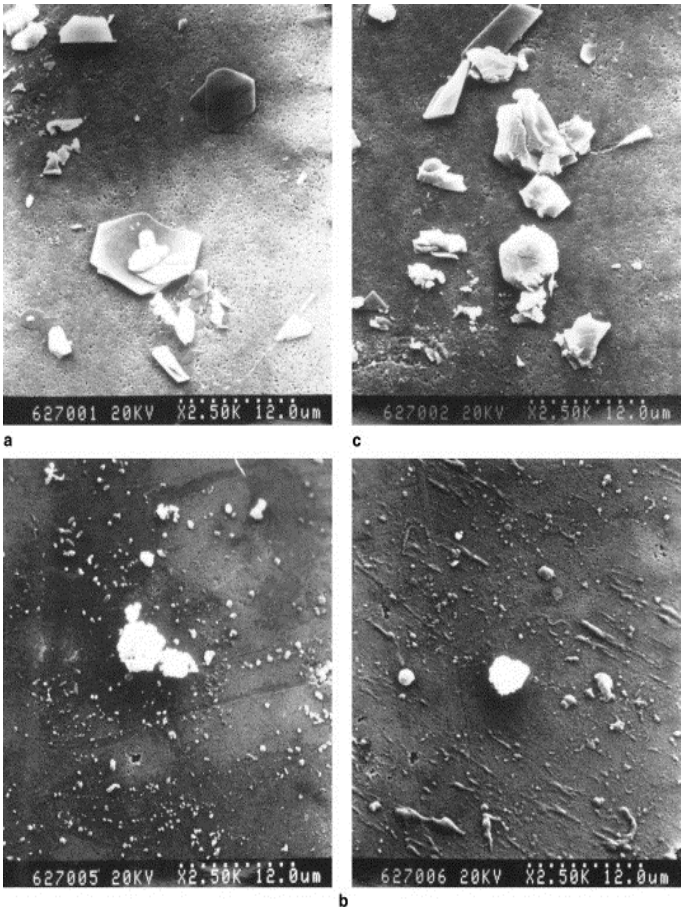

Figure 3. SEM micrographs of $Ca(OH)_2$ crystals at the interface between aggregate and paste made from cement and nano-SiO2 at 28 days: (a) without NS;(b) with 3% NS; (c) with 3% SF [*Reprinted from Qing Y., Zenan Z., Deyu K., Rongshen, influence of nano-SiO2 addition on properties of hardened cement paste as compared with silica fume C., Constr. Build. Mater, 21, 539, 2007*, *with permission from Elsevier*].

Zhenhua Li et al. [23] used ordinary Portland 325 cement to investigate the preparation and mechanical properties of the nano-alumina on it. Their results on effects of nano-alumina contents on mortars' elastic modulus and compressive strength are shown in Figures 4 and 5.

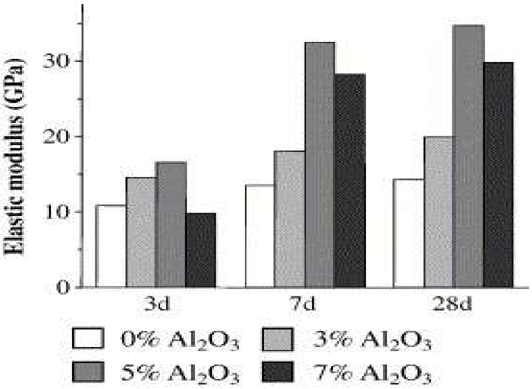

Figure 4. Elastic modulus of mortars [*Reprinted from Li Z., Wang H., He S., Lu Y., Wang M., Investigations on the preparation and mechanical properties of the nano-alumina reinforced cement composite, Mat. Letters, 60, 356, 2006.*, *with permission from Elsevier*].

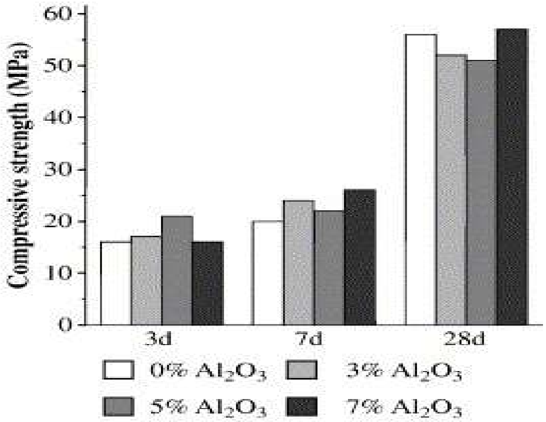

Figure 5. Compressive strength of mortars [*Reprinted from Li Z., Wang H., He S., Lu Y., Wang M., Investigations on the preparation and mechanical properties of the nano-alumina reinforced cement composite, Mat. Letters, 60, 356, 2006.*, *with permission from Elsevier*].

They deduced the results in a way that the added nano-alumina mainly acts as a super fine aggregate which fills the interfacial transition zone (ITZ) of cement and sand and some capillary in the matrix. As a result, the elastic modulus and compressive strength of mortar increased, respectively. Incorporating nano-alumina into mortars cannot significantly affect the compressive strength of mortar. The main reason is that the porosity of cement matrix cannot be significantly decreased under the experimental conditions of their work. There exists a big room to improve preparation technology.

Hui Li et al. [6] studied the microstructure of cement mortar with nano-particles. They studied the mechanical properties of nano-Fe_2O_3 and nano-SiO_2 cement mortars. They used a rotary mixer with a flat beater in their preparation method for mixing. Deformer and dispersant agent were dissolved in water and then the nano-particles were added and stirred at high speed for about 2 minutes. Then the cement and silica fume were added to the mixer and stirred for another 1 minute. Afterwards, sand was added into the mixture and auto-stirred for about 1.5 minutes. An external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were demolded after 24 hours and then cured in air at room temperature for 7 and 28 days, respectively.

Table 5 shows their eleven mixtures with different mix proportions.

Table 5. Mix proportion of the specimens.

Mixture no	*W/b*	*Mix proportion of the specimens (per768 cm^3)*						
		Water (ml)	**Cement (g)**	**Sand (g)**	**NS (g)**	**NF (g)**	**UNF (g)**	**SF (g)**
A	0.5	225	450	1350				
B1	0.5	225	436.5	1350		13.5	3.4	
B2	0.5	225	427.5	1350		22.5	6.5	
B3	0.5	225	405	1350		45	11.2	
C1	0.5	225	436.5	1350	13.5		6.8	
C2	0.5	225	427.5	1350	22.5		11.2	
C3	0.5	225	405	1350	45		22.5	
D	0.5	225	427.5	1350	9	13.5	7.9	
E1	0.5	225	427.5	1350		9	3	13.5
E2	0.5	225	405	1350		18	6	27
F	0.5	225	382.5	1350			3.4	67.5

Their result shows that C–S–H gel existed in the form of ‘stand-alone’ clusters, lapped and jointed together by many needle hydrates. At the same time, deposited Ca(OH)2 crystals were distributed among the cement paste. It also shows when a small quantity of the nano-particles was uniformly dispersed in the cement paste, the hydrate products of cement will deposit on the nano-particles due to their great surface energy during hydration and grow to form conglomeration containing the nano-particles as ‘nucleus’. The nano-particles located in the cement paste as nucleus will further promote and accelerate cement hydration due to their high activity. In the consideration of the nano-particles uniform disperse situation, a good microstructure could be formed with the uniform distributed conglomeration. The strength of the cement mortars with nano-particles has a preferable improvement, as demonstrated in this study. Furthermore, it can be predicted that the strengthening effect of nano-particles would be further enhanced in concrete because the nano-particles improve not only the cement paste, but also the interface between paste and aggregates. They deduced the results in such way that the strength of the cement mortars with nano-particles has a preferable improvement. Furthermore, it can be predicted that the strengthening effect of nano-particles would be further enhanced in concrete because the nano-particles improve not only the cement paste, but also the interface between paste and aggregates.
Jeng-Ywan Shih et al. [24] used Type I Portland cement complying with ASTM C150 standard, ordinary distilled water and nanosilica (NS) in liquid form used as the admixture as case study to investigate the effect of nanosilica on characterization of Portland cement composite. The chemical compositions and physical properties of Type I Portland cement and Basic material properties of nanosilica that they used are given in Table 5 and 6. They investigated 4 examinations on their mixed such as (1) Compressive strengths, (2) The interactions between the NS particles with Portland cement are assessed using the Zeta potential measurement, (3) The non-destructive and non-invasive measurement of nuclear magnetic resonance (NMR) and (4) The Brunauer–Emmett–Teller (BET) examination.

Table 6. Chemical composition of Portland cement CEM I – 52.5R.

Constituents	Content (wt%)
SiO_2	20.9
Al_2O_3	4.60
Fe_2O_3	3.15
CaO	62.0
MgO	2.00
SO_3	3.60

The compressive strengths of Portland cement composite at various additions of NS and ages are given in Figure 6.

They concluded that among four ages and five sets of mix proportions, the optimal mix proportion is the set of cement: water: nanosilica=1:0.55:0.006 which has the highest compressive strength of 65.62 MPa at age of 56 days. By comparing addition of nanosilica with the control set of cement paste without the addition of nanosilica, the ratio of maximum increase in compressive strength is about 60.6% at age of 14 days and is reduced to 43.8% at age of 56 days.

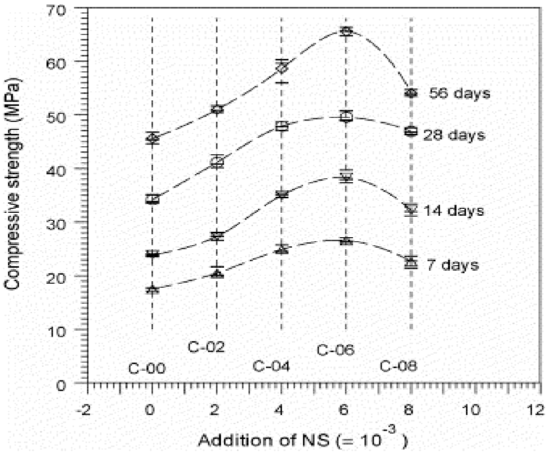

Figure 6. Compressive strengths of Portland cement composite at various additions of NS and ages [*Reprinted from Shih J.Y., Chang T.P., Hsiao T.C., Effect of Nanosilica on Characterization of Portland Cement Composite, Mat. Sc. Eng. A, 424, 266, 2006.***,** *with permission from Elsevier*].

Luciano Senff et al. [25] studied amorphous nano-silica (NS) particles which were incorporated in cement pastes and mortars, and their effect on the fresh state behavior. They used the Portland cement (CEM I – 52.5R) which its chemical composition is shown in Table 6.

The super plasticizer admixture that they used was a polycarboxylic acid based. They added the Nano-SiO2 particles that have an average size of 9 nm and specific surface area of 300 m^2/g. Table 7 shows their mixture composition.

Table 7. Mortar formulations.

NS (wt%)	W/B	Mixture components				
		Water (ml)	Cement (g)	Sand (g)	NS (g)	SP (g)
0	0.35	87.5	250.00	500	0	5.0
1.0	0.35	87.5	247.50	500	2.50	5.0
1.5	0.35	87.5	246.25	500	3.75	5.0
2.0	0.35	87.5	245.00	500	5.00	5.0
2.5	0.35	87.5	243.75	500	6.25	5.0

They concluded that when NS is incorporated into the mortar in the fresh state it has a direct influence on the water amount required in the mixture. This behavior confirms the fact that addition of high surface area mineral particles to cement mixtures causes the need for higher amounts of water or chemical admixtures in order to keep the workability of the mixture. If the water content is kept constant, as in the actual conditions, an increase of NS content will promote the packing of particles, decreasing the volume between them and decreasing the free water. Therefore, there is a higher internal friction between solid particles, which contributes to the increase of torque. Hence, values of yield stress are seriously affected and NS content can be considered as a limiting factor that shortens the open testing time. Setting time is also anticipated and the dormant period was decreased.

They also concluded that the increasing NS addition also decreases the fresh apparent density state of mortar. This reduction can be attributed to the combined effect of air-entraining and the replacement of denser cement particles (3.1 g/cm^3) by lighter NS particles (2.21 g/cm^3). With 2.5 wt% NS, there is an increase on the air-entrained content of 79%, when compared with mortars without NS.

Lin et al. [26] studied the influence of nano-SiO_2 and different ash particle sizes on Portland Type I cement and nano-SiO_2¬ which its physical properties are shown in Table 8.

Table 8. Properties of nano-SiO_2.

Properties	Content
Content of SiO_{2-x} (%)	99.9
Phase	Non-crystal white powder
Compaction density (g/cm^2)	0.14
Average particle size (nm)	10
Specific surface area (m^2/g)	670
Impurity (%)	
Cl	0.028
Cu	0.003
Al	0.002
Ca	0.002
Fe	0.001
Mg	0.001
Sn	0.001

A smooth spherical particle shape with few pores were observed for the 10 μm ash particle by optical microscope, and the effect of different sludge ash particle sizes with the additives of nano-SiO_2 on the setting time for the ash–cement mortar is also shown in Figures 7 and 8, respectively.

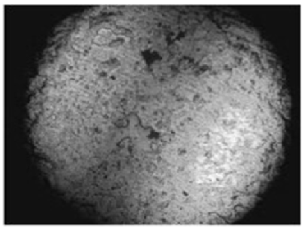

Figure 7. Shape of 10 mm ash particle observed by optical microscope [*Reprinted from Lin K.L., Chang W.C., Lin D.F., Luo H.L., Tsai M.C., Effects of nano-SiO2 and different ash particle sizes on sludge ash-cement mortar.J. Env. Manag, 88, 4, 708, 2008,* *with permission from Elsevier*].

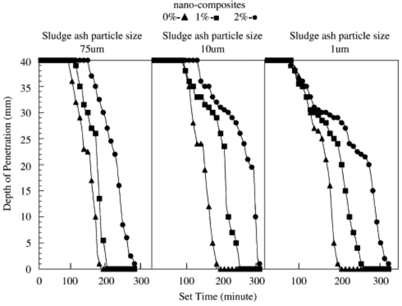

Figure 8. Effects of different sludge ash particle sizes and the additives of nano-SiO2 on the setting time for the ash–cement mortar [*Reprinted from Lin K.L., Chang W.C., Lin D.F., Luo H.L., Tsai M.C., Effects of nano-SiO2 and different ash particle sizes on sludge ash-cement mortar.J. Env. Manag, 88, 4, 708, 2008,* *with permission from Elsevier*].

They concluded that the addition of nano-SiO_2 can shorten the setting time. The reduction in setting time became noticeable for smaller sludge ash particle sizes. For mortar with 1% nano-SiO2 added, the pore radius decreased by about 6 nm for the 1 μm ash particles; 9 nm for the 10 μm ash particles; and 40 nm for the 75 μm ash particles. This implies that nano-SiO2 additives have a greater effect on larger ash particles than on smaller ash particles.

Ta-Peng Chang et al. [27] studied the influence of nano-montmorillonite on Portland cement paste. They used the Portland cement complying with ASTM C150 standard and ordinary tap water as mixing materials for the cement paste. Figure 9 shows the schematic diagram of sample preparation which they used for gas permeability test.

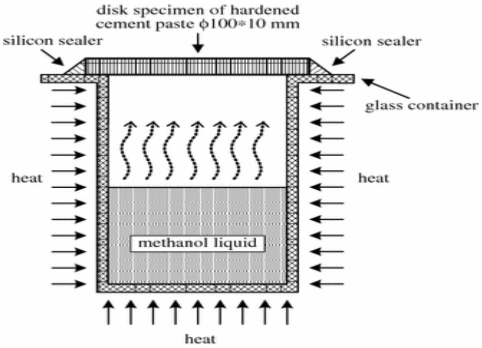

Figure 9. Schematic diagram of sample preparation for gas permeability test [*Reprinted from Chang T.P., Shih J.Y., Yang K.M., Hsiao T.C., Material properties of portland cement paste with nanomontmorillonite. J. Mater. Sci, 42, 17, 7478, 2007with permission from Springer*].

Their results showed that after the age of 28 days, optimal amounts of added nano-montmorillonite into the cement paste are found to be 0.6% and 0.4% by weight of cement, in which the cement paste composites have the highest compressive strength and the lowest permeability coefficient. Meanwhile, the addition of nano-montmorillonite into the Portland cement paste has shown a better improvement on the permeability coefficient than the compressive strength. Compressive strengths and permeability coefficients of cement paste at various additions of nano-montmorillonite and ages are showed in Figure 10 and Figure 11, respectively.

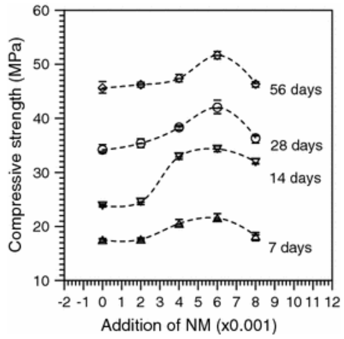

Figure 10. Compressive strengths of cement paste at various additions of NM and ages [*Reprinted from Chang T.P., Shih J.Y., Yang K.M., Hsiao T.C., Material properties of portland cement paste with nanomontmorillonite. J. Mater. Sci, 42, 17, 7478, 2007 with permission from Springer*].

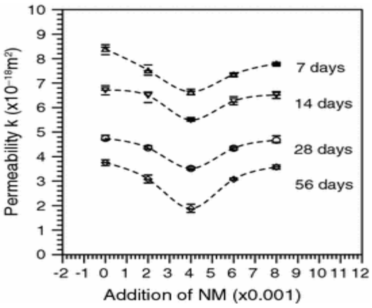

Figure 11. Permeability coefficients of cement paste at various additions of NM and ages [*Reprinted from Chang T.P., Shih J.Y., Yang K.M., Hsiao T.C., Material properties of portland cement paste with nanomontmorillonite. J. Mater. Sci, 42, 17, 7478, 2007with permission from Springer].*

4. CONCLUDING REMARKS

The Portland cement composite incorporating nanosilica reveals that the pore volume increases and the fractal dimension of microstructure decreases at regions where the pore size is smaller than 10 nm, but the results are reciprocal for regions where the pore size is larger than 10 nm.

The compressive and flexural strength of the cement mortars with nano-SiO_2 and with nano-Fe_2O_3 were both higher than that of the plain cement mortar with the same w/b.

The nano-particles were not only acting as filler, but also as an activator to promote hydration proves and to improve the microstructure of the cement paste if the nano-particles were uniformly dispersed. The optimum mixing volume of different nano-particles was not the same due to different functions. Further study in this direction is recommended.

The elastic modulus of mortar can significantly be enhanced by incorporating nano-alumina. The main reason is that the density degree of interfacial transition zone is enhanced.

The influence of nano-SiO_2 and silica fume on consistency and setting time are different. Nano-SiO_2 makes cement paste thicker and accelerates the cement hydration process.

Bond strengths of paste–aggregate interface incorporating nano-SiO_2 are higher than those of control samples and then those incorporating silica fume. By increasing the Nano-SiO_2 content, the rate of bond strength increase is more than that of their compressive strength increase.

The pozzolanic activity of nano-SiO_2 is much greater than that of silica fume. Nano-SiO_2 consumes CH crystals, decreases the orientation of CH crystals, reduces the size of CH crystals at the interface and improves the interface structure more effectively than silica fume.

Although, the addition of nano-montmorillonite to the Portland cement paste has shown some improvement on the material properties, it seems that a longer elapsed time is still needed to develop its final prospective potential. Further research on subtle improvements in the manufacture of better Portland cement composite, such as the technique of dispersion, curing condition, mixing ingredients, etc., is definitely necessary**.**

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