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Research Article

Characterization of Nano-Silica Concrete for Nuclear Uses

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Abstract

Both radioactive materials and nuclear radiation are potentially hazardous to the environment especially of human beings. Thus in all nuclear facilities, provisions must made for the attenuation of incident nuclear radiation by means of shields. Gamma radiation have high penetrating powers and hence special shields must be constructed. In selecting the shielding materials, all the physical, mechanical, nuclear and engineering properties must be weighed carefully. On the other hand, the idea of using Nano-materials as partial replacement of cement in concrete, due to its great environment effect, became popular for producing infrastructures. This study aimed to investigate the influence of adding Nano-silica to the concrete as partial replacement of cement on the physical, mechanical and nuclear shielding properties. Nano-silica have been used with 1%, 3%, 5% and 7% percentages as partially replacement of cement. Results indicated that 3% of Nano-silica has improved such physical, mechanical and shielding properties to extent for use in some nuclear applications like shielding of γ-ray and for nuclear disposal packages.

Keywords: *Nano-silica, Porosity; Water absorption; Compressive strength; Splitting tensile strength; Nuclear shielding of concrete*

1. Introduction

Concrete is the most common used material for construction, and is primarily based on the cement industry. The cement industry is considered to be one of the most energy consuming industries, with a high rate of carbon dioxide (CO_2) emissions. Extensive research efforts have been directed to reducing the undesirable effect of the cement industry either by improving the efficiency of the cement manufacturing process (Barker *et al.* 2009, Deja *et al.* 2010) or by using supplementary cementitious materials which partially replace ordinary cement (Gartner 2004). Despite that, concrete is an excellent and versatile radiation shielding material as well as for safe storage of radioactive waste packages. The shielding properties of concrete may be adapted to a wide range of uses by modifying its composition.

On the other hand, Nano-technology has penetrated the construction industry at an accelerating rate in recent years. In this respect, the idea of using by-product as partial replacement of cement in concrete became popular recently. Nanomaterials (with at least one dimension between approximately 1 and 100 nanometers (nm)) (ASTM E2456-06 2012) have been gaining increasing attention and been applied in many fields to fabricate new materials with novelty function due to their unique physical and chemical properties. One of the most used Nano material in concrete admixtures, is Nano-silica (NS), which possesses more pozzolanic nature, it has the capability to react with the free lime during the cement hydration and forms additional C-S-H gel which gives strength, impermeability and durability to concrete (Hussain and Sastry 2014).

Ji (2005) has found that water permeability resistance and 28-days compressive strength of concrete were improved by using Nano-silica. Beside he found that, the microstructure of the Nano-silica concrete was more uniform and compact than that of the normal concrete. Lin *et al.* (2008) have observed the effect of Nano-silica addition on permeability and compressive strength of fly ash cement mortar. From the pore analysis study, it was reported that the relative permeability and pore sizes of concrete were decreased, whereas the compressive strength increased by adding more Nano-silica.

Abyaneh *et al.* (2013) have found that the concrete produced with Micro-SiO_2 and Nano-SiO_2 show higher degrees of quality in their compressive strength than the concrete which only have Micro-SiO_2 in their mixtures. Specimens with 2% Nano-SiO_2 and 10% Micro-SiO_2 had less water absorption and more electrical resistance. Abd El-Baky *et al.* (2013) concluded that compressive strength improved by 55.7% at 7% of cement replaced with Nano-silica in cement mortar. Also, the flexural strength of the cement mortar increased proportionally with

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increasing the amount of Nano-silica. Hussain and Sastry (2014) reported that cement replacement up to 7.5% with silica fume and up to 2% with Nano-silica, leads to increasing compressive strength, split tensile strength and flexural strength of concrete by 25.807%, 25.766% and 18.9% respectively.

Previous studies reported that, the microstructure of the mortar containing Nano-silica is denser and more uniform than that of the conventional mortar microstructure and that containing silica fume, (Rana *et al.* 2009, Mondal *et al.* 2010). The positive effects of using Nano-SiO_2 on the mechanical properties of concrete and cement mortar have been shown by other studies (Li 2004, Jo *et al.* 2007a, b).

Kharita *et al*. (2008) studied the shielding properties of six types of concrete and measured the attenuation coefficients for gamma rays (from Cs-137 and Co-60 sources). Results showed that the hematite concrete was the best composition for shielding purposes of γ-rays. Also, Yılmaz *et al*. (2011) measured the attenuation coefficients of gamma rays of 12 concrete samples with and without supplementary cementitious materials, at energies of 59.5 and 661 keV. They reported that, heavyweight concrete reduced the thickness of radiation shielding because of space considerations. Furthermore, Rajavikraman (2013) reported that nano concrete with the composite of galena (PbS) used for preventing radiation in radioactive zones. Finally, the obtained results by Hassan *et al*. (2015) depicted that addition of Nano-PbO to concrete can enhance its γ-ray mass attenuation coefficient.

The aim of the present work is to investigate the influence of adding Nano-silica as a partial replacement of cement on the physical and mechanical properties of concrete. In addition, its influence on the efficiency of concrete to be used in some nuclear applications such as γ-ray shielding and for safe storage of radioactive waste packages.

2. Testing Program

This section describes the experimental work performed through this study.

2.1 Properties of the Used Materials

The properties of the materials used in this work which are; Cement, Fine aggregate, Coarse aggregate, Nano-Silica and Super plasticizer are given below. All materials used are locally produced.

2.1.1 Cement

Ordinary Portland cement (CEM I-42.5) was used. The cement has specific gravity of 3.15 and fineness of $2.9x10^5$ mm^2/gm. The chemical composition of cement is shown in Table 1 (El-Sadani 2001).

Table 1 Chemical composition of OPC, weight %

Constituents	Weight (%)
CaO	62.5
SiO_2	21.0
Al_2O_3	6.5
Fe_2O_3	3.0
MgO	2.8
SO_3	2.1
Insoluble material	0.58
L.O.I.*	1.52

* Loss of Ignition

2.1.2 Fine aggregate

Natural sand with specific gravity of 2.61 was used as fine aggregate in the concrete specimens. It is clean and deleterious organic matter. The grading analysis of sand is presented in Table 2.

Table 2 Grading of sand

Sieve size (mm)	4.76	2.40	1.20	0.60	0.30	0.15
Sand (Passing %)	95 - 100	90 - 95	70 - 80	15 - 25	10 - 20	0

2.1.3 Coarse aggregate

Dolomite is a famous coarse aggregate which is used in usual ordinary concrete instead of the natural gravel. It is widely used as coarse aggregate because it possesses the ability to produce required sizes, ease of handling and satisfactory results obtained. Dolomite with specific gravity of 2.55 is used and the sieve analysis is presented in Table 3. The grading of coarse aggregate is in compliance with ACI 211.1- 91 (2002).

Table 3 Grading of coarse aggregate

Sieve size (mm)	38	19	9.5	4.75	2.36
Dolomite (Passing %)	100	95 - 100	20 - 30	0 - 5	0
ACI Limit (Passing %)	100	90 – 100	20 – 55	0 – 10	0 – 5

2.1.4 Nano-silica

The Nano-silica (NS) powder used in this work is provided from a local factory. It is off-white in color. The chemical and physical specifications are given in Table 4.

Table 4 Chemical and physical specifications of Nano-silica

Particle size	> 12 nm
SiO_2 content	< 99.8 %
Crystal structure	Amorphous
Density (g/cm^3)	~ 2.2

2.1.5 Water reducing admixture

In order to adjust workability of the fresh concrete, a commercial super plasticizer was used, which guarantees compatibility with the cement and the admixture used.

2.2 Mix Proportions

Five concrete mixes with different proportions of NS were optimized and used in the current study. The proportions of the mixtures are presented in Table 5. The specimens of standard cubes (150 mm x150 mm x150 mm), special cubes (100 mm x100 mm x100 mm) and standard cylinders of (150 mm Diameter x300mm height) were cast.

Table 5 Mix proportions of the concrete mixtures

No.	Nano-silica wt.%	Cement Kg/m³	w/c ratio	Fine Agg. Kg/m³	Coarse Agg. Kg/m³
S1	0	400	0.44	700	1110
S2	1	396	0.44	700	1110
S3	3	388	0.44	700	1110
S4	5	380	0.44	700	1110
S5	7	372	0.44	700	1110

Super plasticizer was added to adjust workability

2.3 Testing Procedures

All experiments were carried out on three samples and the average of the obtained results was considered.

2.3.1 Physical properties testing

The slump test was carried out according to ASTM C 143M-03 (2003). The percent of water absorption capacity, W_a%, and porosity percentage, n%, were calculated. In this respect, prepared cubes after 28 days were dried at 105 °C for 24 hr in a drying oven until their weight becomes constant then they were cooled in a desiccator. The dried specimens were weighed (W_d) then immersed in water. Specimen weight is checked every 24 hours until constant weight is recorded (W_w). Also, cylindrical specimens of different types of concrete were used after 28 days of preparation for the water permeability investigation. Surfaces of the specimens were smoothened and cleaned and the cylindrical side areas of specimens were painted with non-shrinkage epoxy resin to prevent the water leakage. The top face of the specimen was subjected to water pressure of 1 bar for 48 hr, followed by 3 bars for 24 hr, and finally 7 bars for 24 hr. The specimen was then split open by applying a lateral compression load. The penetration depth of the water was measured at several points and the average value was recorded.

2.3.2 Mechanical properties testing

Specimens were left to dry after extraction from the curing tank before testing. A 200-ton hydraulic compression testing machine has been used for determining the compressive strength for cubic specimens. While, cylindrical specimens have been used for determining splitting tensile strength according to ASTM C 496M-04 (2004).

2.3.3 Nuclear shielding properties testing

The shielding properties of mixed special cubes were studied using gamma rays photo peak energies emitted from Cs-137 (662 keV) and Co-60 (1173 keV and 1332 keV). The transmitted gamma ray intensity was measured using a gamma-ray spectrometer with NaI detector. Source-specimen holder is necessary to fix the sources and specimens in a defined position and distance from the detector as shown in Fig. 1(a). It is made from cast iron and set inside the shield house; Fig. 1(b).

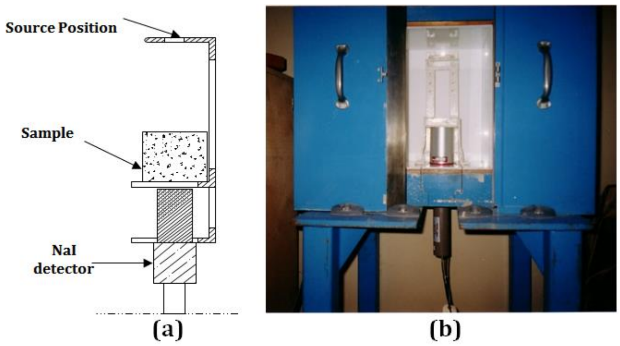

Fig. 1(a) Schematic diagram of the source-specimen holder, (b) source–specimen holder inside the shield house

Firstly, the two sources were put at the source position of the holder and the intensity of γ-radiations passed through air was detected for each γ ray photo peak energy; initial intensity (I_o). Then the concrete block was placed in its position at the holder and the γ radiations were allowed to pass through it. The intensity of the transmitted γ radiations for each concrete block was detected; I_x. Applying the measured values of I_o and I_x in the attenuation coefficient equation; Eq. (1) the linear attenuation coefficient (μ) of the concrete blocks are determined (Glasstone and Sesonske 2004),

$$I_x = I_o\, e^{-\mu x} \quad (1)$$

where x is the thickness of the concrete block.

3. Results and Discussions

3.1 Physical Properties

The results of the slump, the water absorption percentages and the porosity percentages for investigated specimens are shown in Table 6. Because of high specific surface area and the water absorption of NS, slump values seem to decrease with increase of NS percentage, but these values were controlled by super plasticizer. Table 6 illustrates that adding NS to concrete leads to much lower in both water absorption and porosity compared to plain concrete. This may be due to the small particles of Nano-silica which act as a filler to fill the interstitial spaces in the hardened concrete. While Tavakoli and Heidari (2013) reported that this behavior may be due to the pozzolanic effect, which combines glass-like silicon elements in Nano-silica with the lime elements of calcium oxide and hydroxide in cement to increase the bonding strength and solid volume.

Table 6 Slump, water absorption and porosity for all concrete mixtures

No.	Slump (cm)	Water Absorption (%)	Porosity (%)
S1	5.5	5.50	14.0
S2	5	4.11	10.5
S3	4.3	3.45	8.8
S4	4.5	3.22	8.2
S5	4.6	3.18	8.1

Figure (2) shows the results of the water penetration depth which indicates the permeability of studied specimens. From this figure it is clear that low penetration of water is allowed in S4 specimen where 5% cement was replaced with NS. The penetration depth decreases from 27 mm for S1 specimen to 12 mm for S4 specimen and it remains constant for S5. Which shows that, more than 55% reduction of water penetration can be achieved by adding 5% of NS which fill the little spaces in concrete. Accordingly, it results denser concrete than the plain concrete. These results have a positive effect in improving the leaching properties for the studied samples which are very important in the nuclear waste disposal packages.

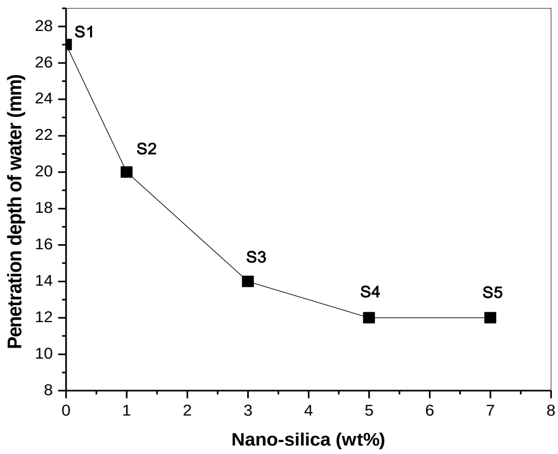

Fig. 2 Water penetration depth of all concrete mixtures

3.2 Mechanical Properties

Generally, silica has strong effect in compressive strength of concrete for ages of 7 and 28 days. The relations between various NS percentages and the corresponding compressive strength are presented in Fig. 3. This figure shows that, the compressive strength increases with increase NS percentage up to 3% replacement. This is follows by slight decrease with increasing the NS percentages up to 7%. Such increase in compressive strength is due to the high pozzolanic nature of Nano-silica and its filling ability. This finding is consistent with Hussain and Sastry (2014) and Tavakoli and Heidari (2013). While, the decreasing at 5% and 7% may be due to that the increasing amount of NS, which have low density than cement, affects the overall concrete density which consequently affects the compressive strength.

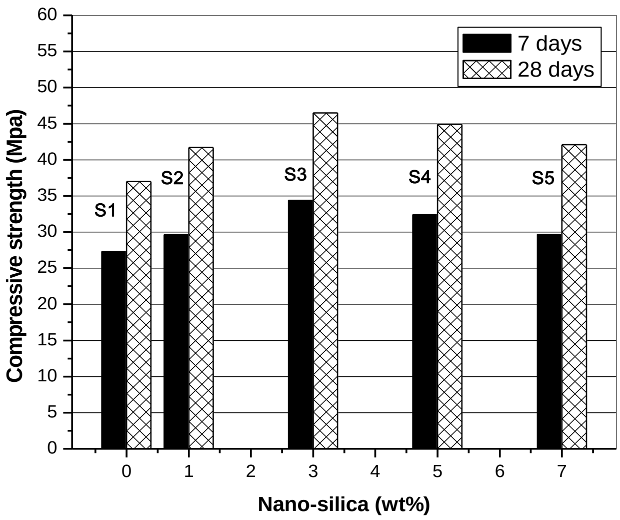

Fig. 3 Compressive strength of all concrete mixtures

The splitting tensile strength results for all mixes are studied and the obtained results are shown in Fig. 4. The results indicate that the tensile strength has the same trend like the compressive strength. It increases with NS percentage up to 3% replacement and then decreases slightly but still higher than tensile strength of plain concrete.

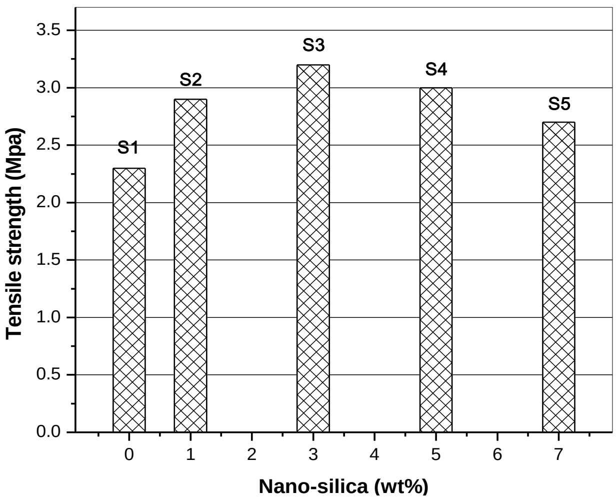

Fig. 4 Splitting tensile strength of all concrete mixtures

3.3 Nuclear Shielding Properties

The transmitted γ-rays intensity, I_x, has been measured for all investigated concrete mixtures. Hence, the linear attenuation coefficient (μ) are calculated using Eq. (1). The concrete thickness at which I_o reduces to its half value is named; half value thickness, $X_{1/2}$. It can be calculated from the following equation;

$$\frac{I_x}{I_0} = \frac{1}{2} = e^{-\mu x_{1/2}} \quad (2)$$

From mathematical calculations, $X_{1/2} = 0.693/\mu$. Table 7 presents the calculated values of the linear attenuation coefficient (μ) as well as the half value thickness ($X_{1/2}$) for the samples S1, S2, S3, S4 and S5 for each γ ray photo peak energy.

Table 7 Attenuation of γ-radiation of all concrete mixtures

No.	Source type	γ-Ray Energy (keV)	μ (cm^{-1})	HVT $X_{1/2}$ (cm)
S1	Cs-137	662	0.155	4.47
	Co-60	1173	0.127	5.46
		1332	0.121	5.73
S2	Cs-137	662	0.167	4.15
	Co-60	1173	0.137	5.06
		1332	0.130	5.33
S3	Cs-137	662	0.190	3.65
	Co-60	1173	0.147	4.71
		1332	0.139	4.99
S4	Cs-137	662	0.175	3.96
	Co-60	1173	0.141	4.91
		1332	0.132	5.25
S5	Cs-137	662	0.163	4.25
	Co-60	1173	0.133	5.21
		1332	0.125	5.54

From Table 7 it is clear that, S3 has the lowest $X_{1/2}$ for all the investigated γ energies while S1 has the highest values. This mean that, S3 has the best shielding properties in all investigated mixtures while S1 has the worst shielding properties. The changing behavior of shielding properties has the same trend as in the compressive strength. The shielding properties increase with NS percentage up to 3% replacement and then it decrease, although 5% and 7% are still better than shielding properties of plain concrete. This may be due to increasing in compressive strength and decreasing of pores consequently increasing in linear attenuation coefficient and decreasing in $X_{1/2}$. The obtained results depict that addition of Nano-silica to concrete can enhance its γ-ray linear attenuation coefficient to reach 23% of its value for plain concrete at 662 keV, 16% at 1173 keV and 15% at 1332 keV. Hassan *et al*. (2015) studied the effect of adding nano-PbO to concrete on its attenuation behavior of γ-rays. They found that, at 10% replacement the attenuation effect decreases by 3% of plain concrete at 662 keV and 9% at 1173 keV while, it increases by 4% of plain concrete at 1332 keV.

Conclusions

Based on the experimental results obtained the following conclusions can be drawn;

- Nano-silica as pozzolanic material has good influence on water permeability and mechanical properties of concrete.
- 5% replacement of cement weight by Nano-silica exhibited lowest penetration depth of water (12mm), where lowest porosity (8.1%) was obtained at 7% replacement.
- The maximum increase in compressive strength was 26% which obtained for 3% replacement of Nano-silica.
- The splitting tensile strength was improved by 39% for 3% replacement of Nano-silica.
- Reduction in porosity and penetration depth of water by Nano-silica replacement in concrete leads to reduction in leachability of the immobilized radioactive materials in the nuclear waste disposal packages.
- Replacement of cement weight by Nano-silica has a significant effect on increasing the attenuation of γ-radiation, consequently reducing the thickness required for shielding compared with plain concrete.
- From this investigation it can be recommended that Nano-silica in low amounts (3%-5% replacement of cement weight) can exert positive and desirable impacts on concrete.

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