

PERFORMANCE OF HIGH-STRENGTH CONCRETE MADE WITH BINARY AND TERNARY BLENDS OF NATURAL ZEOLITE AND NANO-PARTICLES IN AGGRESSIVE ENVIRONMENT

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In recent years, binary and ternary use of supplementary cementitious materials (SCMs) has received special attention by researchers throughout the world. This can combine the benefits of each SCM and minimize its adverse effects on the properties of concrete. The main purpose of this study was to investigate the performance of high-strength concrete (HSC) produced by the combined use of 0%, 5%, 10% and 15% natural zeolite (NZ) and different nano-particles including 2%-4% nano-SiO₂ and 0.5%-1.5% nano-CaCO₃ in aggressive environment. In this respect, different samples of HSC were made and besides slump and compressive strength; they are tested for chloride ion penetration depth and chemical resistance. The chemical resistance of HSCs were measured by evaluation the variations in the mass and crushing load of concretes after 28, 56 and 84 days of exposure to 5% sulfuric acid solution (H₂SO₄). Results showed that all HSC samples had a 28-day compressive strength greater than 81.36 MPa which passed the minimum strength value (≥ 60 MPa) considered in this study for HSC. Also, compared to using only NZ, by substituting the optimum level of nano-particles and NZ as SCM in HSC, lower depth of chloride ion penetration can be obtained. The results also revealed that the highest percentages of mass loss and crushing load loss were obtained for plain HSC which could decrease by the ternary incorporation of Portland cement, nano-particles and NZ.

Keywords: High-strength concrete, Nano-SiO₂, Nano-CaCO₃, Natural zeolite, Durability

1. Introduction

Nowadays, it is well established that supplementary cementitious materials (SCMs) as partial replacement of Portland cement (PC) in concrete can provide the advantages of a lowered economic and environmental unit cost. The most often used SCMs can be either natural origin (Natural perlite, etc) or an industrial (Silica fume, Fly ash, Slag, etc.). Natural zeolite (NZ) is among the most commonly used natural pozzolans. NZ, as volcanic or volcano-sediment materials, has a three-dimensional frame structure and is classified as a hydrated aluminosilicate of alkali and alkaline earth cations [1]. Besides of accessibility [2] and relatively low cost of NZ compared to traditional pozzolan in some countries, the pozzolanic properties of NZ due to the large quantity of reactive SiO₂ and Al₂O₃ have brought it into the attention of researchers. The soluble SiO₂ and Al₂O₃ could react with calcium hydroxide during cement hydration to produce C-S-H gel which densified the concrete matrix [3]. Although, the properties of NZ in concrete depend on its chemical composition and physical properties, the effectiveness of NZ at optimum replacement ratio on the oxygen permeability [1], electrical resistivity (at the later-ages) [4], chloride ion penetrability (based on ASTM C 1202) [5], expansion of mortar bars due to the ASR [1], corrosion rate [6] and drying shrinkage [6] is reported by researchers.

Over the past decade, a number of studies have been conducted with the suggestion of using binary and ternary blends of SCMs in concrete. Combined use of SCMs not only can facilitate the

benefits of each SCM, but also can minimize their adverse effects on the properties of concrete. In the meantime, there has been a growing interest in the combined use of nanomaterials and traditional pozzolanic materials. Table 1 lists some of the published papers dealing with the combined use of nanomaterials and traditional pozzolanic materials [7-16]. As shown in the table, these studies utilized a variety of nano-particles including nano-SiO₂, nano-CuO, nano-TiO₂, nano-Al₂O₃ and nano-clay. Meanwhile, nano-SiO₂ is the most commonly used nano-particles in the cement-based materials. Nano-SiO₂ can participate in the hydration process to generate C-S-H through reacting with CaOH₂ [17] that enhance the concrete's mechanical and durability properties. Beside this, the efficiently of using nano-CaCO₃ in mortar and concrete production has also been investigated. In this respect, Xu et al. [18] reported that by adding 2% nano-CaCO₃, slump was improved by 8.5%. Ge et al. [19] showed that the use of nano-CaCO₃ in the self-compacted concrete has resulted to a reduction in the average pore diameter. Wu et al. [20] showed that both nano-SiO₂ and nano-CaCO₃ demonstrated nucleation and filling effects and resulted in less porous and more homogeneous structure. In a study by Shaikh and Supit [21], it was reported that high volume fly ash (HVFA) concrete containing 1% nano-CaCO₃ have reasonably lower volume of permeable voids, porosity, higher resistance to water sorptivity, chloride permeability and chloride ion diffusivity than the counterpart HVFA concretes. The effect of adding either nano-silica (SiO₂) or nano-CaCO₃ on the performance of cement-silica fume-fly ash-based ultra-HSC was investigated by Wang et al.

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Table 1

Previous studies on combined use of nano-particles and traditional cementitious materials in mortars and concretes							
No.	Authors	SCMs	No	Authors	SCMs	No	Authors
1	Rao and Maruthi [7]	Nano-SiO ₂ and metakaolin	2016	6	Khotbehsara et al. [12]	2015	Nano-CuO and fly ash
2	Kara [8]	Nano-SiO ₂ and silica fume	2019	7	Miyandehi et al. [13]	2016	Nano-CuO and rice husk ash
4	Sivasankaran ¹ et al. [9]	Nano-SiO ₂ and fly ash	2004	8	Mohseni et al. [14]	2016	Nano-Al ₂ O ₃ and fly ash
3	Eskandari et al. [10]	Nano-SiO ₂ and micro zeolite	2018	9	Ma et al. [15]	2016	Nano-TiO ₂ and fly ash
5	Najjigivi et al. [11]	Nano-SiO ₂ and rice husk ash	2012	10	Langaroudi et al. [16]	2018	Nano clay, silica fume, fly ash, slag and rice husk ash

[22]. Additionally, Hosan et al. [23] investigated the effect of nano-CaCO₃ on compressive strength and microstructure of blended pastes containing high amounts of slag and fly ash. They found that using 1-4% nano-CaCO₃ enhanced the compressive strength of cement paste containing 70%, 80% and 90% slag. Such a trend was also observed in paste containing combined slag and fly ash content of 70% when adding 1% to 4% nano-CaCO₃. Furthermore, SEM images and EDS trace analysis of the specimens containing high amounts of slag and slag-fly ash showed a denser microstructure with fewer internal micro-cracks and more hydrated products in the presence of nano-CaCO₃. Authors in a previously published paper [24] explored the strength and durability of HSC made with binary and ternary blends of rice husk ash and nano-CaCO₃. Results showed nano-CaCO₃ in HSC containing rice husk ash could improve the electrical resistivity and reduce the water absorption as well as chloride ion penetration depth of HSC.

Although, there is a common agreement that ternary blends of nano-particles and traditional SCM in concrete could enhance the engineering properties and durability, the available research concerning the influence of binary and ternary blends of PC, NZ and nano-particles on the properties of HSC is limited. The current research addresses this gap in knowledge. For this purpose, various HSC mixes were designed in three groups, where 5%, 10% and 15% of cementitious materials were replaced with NZ. In each group, two types of nano-particles including nano-SiO₂ and nano-CaCO₃ were considered to produce ternary blend mixtures. Slump, compressive strength, chloride penetration depth and acid attack resistance of samples were determined and compared with those of plain HSC. The results of this study can provide useful information for civil engineers and contractors to utilized combined use of NZ and nano-particles in HSC which can facilitate its usage in full-scale field construction.

2. Experimental details

2.1. Materials

Type II Portland cement (PC) conforming to the ISIRI-389 with specific gravity of 3.14 was used for producing HSC samples. Additionally, a clinoptilolite type of NZ with specific gravity of 2.24

supplied from local company in Semnan province, centre of Iran was utilized as partial replacement of PC. The nano-SiO₂ used in this study was white in colour with purity greater than 99%, average particle size of 11 to 13 nm, and specific gravity of 2.4. The average particle size and specific gravity of nano-CaCO₃ was 15-40 nm and 2.93, respectively. The coarse aggregate was crushed gravel with a maximum size of 12.5 mm and well-graded sand with fineness modulus of 2.62 was used as fine aggregate. A superplasticizer (SP) with specific gravity of 1.1±0.02 was employed.

2.2. Concrete mixture proportions

Totally, 22 HSC mixtures were prepared with different NZ and nano-particles contents, as presented in Table 2. Accordingly, all mixtures were developed with a constant water/cementitious materials ratio of 0.26 and a total cementitious materials content of 500 Kg/m³. Moreover, the sand to gravel ratio in all mixes was constant at 0.63. The developed mixtures were:

- One reference mixture, called "Ctrl", was developed without incorporating NZ or nano-CaCO₃.
- Three mixtures called "NZ5", "NZ10" and "NZ15" with binary use of PC + 5%, 10% or 15% NZ were cast to examine the behaviour of NZ incorporated HSC.
- Nine mixtures were cast to study the performance of HSC made with ternary blends of PC+NZ+nano-SiO₂. These mixtures were formulated by varying the replacement of NZ at 5%, 10% and 15% and the replacement of nano-SiO₂ at 2%, 3% and 4%.
- Nine mixtures were also prepared in order to assess the ternary performance of PC+NZ+nano-CaCO₃ in HSC. In these mixtures, NZ were varied at 5%, 10% and 15% and the replacement of nano-CaCO₃ as SCM was 0.5%, 1% and 1.5%.

Ternary HSC mixtures were designated based on the NZ and nano-particle contents. For example, NZ10NS2 included 10% NZ and 2% nano-SiO₂. As can be seen in Table 2, besides of plain HSC, concrete mixtures were classified into three groups namely "S1", "S2" and "S3" for 5%, 10% and 15% replacement of NZ. Moreover, SP was added to the HSC mixture in order to obtain the slump value within the range of 50±10 mm.

Table 2
Details of Mixture proportions (kg/m³)

No.	Mixes	Cement	Natural zeolite	Nano-SiO ₂	Nano-CaCO ₃	Water	Gravel	Sand
1	Ctrl	500.0	-	-	-	130	1095.0	694.0
2	NZ5	475.0	25	-	-	130	1088.6	689.9
3	NZ5NS2	465.0	25	10	-	130	1087.0	688.9
4	NZ5NS3	460.0	25	15	-	130	1086.2	688.4
5	S1 NZ5NS4	455.0	25	20	-	130	1085.4	687.9
6	NZ5NC0.5	472.5	25	-	2.5	130	1088.5	689.9
7	NZ5NC1.0	470.0	25	-	5	130	1088.4	689.8
8	NZ5NC1.5	467.5	25	-	7.5	130	1088.3	689.7
9	NZ10	450.0	50	-	-	130	1082.1	685.8
10	NZ10NS2	440.0	50	10	-	130	1080.6	684.8
11	NZ10NS3	435.0	50	15	-	130	1079.8	684.3
12	S2 NZ10NS4	430.0	50	20	-	130	1079.0	683.8
13	NZ10NC0.5	447.5	50	-	2.5	130	1082.1	685.8
14	NZ10NC1.0	445.0	50	-	5	130	1081.9	685.7
15	NZ10NC1.5	442.5	50	-	7.5	130	1081.9	685.7
16	NZ15	425.0	75	-	-	130	1075.7	681.8
17	NZ15NS2	415.0	75	10	-	130	1074.1	680.8
18	NZ15NS3	410.0	75	15	-	130	1073.3	680.3
19	S3 NZ15NS4	405.0	75	20	-	130	1072.6	679.8
20	NZ15NC0.5	447.5	75	-	2.5	130	1082.1	685.8
21	NZ15NC1.0	445.0	75	-	5	130	1081.9	685.7
22	NZ15NC1.5	442.5	75	-	7.5	130	1081.9	685.7

2.3. Testing Method

After applying slump test (based on ASTM C143), the fresh concrete was poured into the moulds and compacted by using a vibrating table. The day after, the samples were de-moulds and specific curing was conducted until the testing age. Cubic samples with side lengths of 100 mm were used to evaluate the compressive strength at curing ages of 3, 7, 28 and 90 days. At each age, the average compressive strength of at least 3 samples measured by using a testing machine of 2000 kN capacity was considered as the criterion of compressive strength. Moreover, in order to evaluate the performance of concretes in aggressive environment the chloride penetration depth and chemical resistance tests were carried out. The chloride penetration depth was estimated by using AgNO₃ spraying method. For this purpose, HSC samples were initially cured for 28 days and then were kept in 5% NaCl solution for another 90 days. After that, three specimens of each mix were split into two halves and 0.1N AgNO₃ solution was sprayed on the freshly split surface. As presented in Figure 1, chloride penetration depth can be estimated by measuring the white color boundary resulting from the formation a white precipitate of AgCl. Various researchers have used this method to evaluate the chloride penetration depth [25-27]. Since, the



Fig.1 - Typical colorimetric pictures of HSCs after being sprayed with AgNO₃ solution.

resistance of concrete against acid attack is an important property for its performance in aggressive environment, in this study; HSC samples were tested to evaluate the resistance of concrete mixtures against acid attack. For this purpose, specimens were fully immersed in 5% sulfuric acid solution at the curing age of 28 days for another 84 days. In order to maintain the concentration of the acid solution, the H₂SO₄ solution was replaced at certain times. Three samples of each mix were removed after 28, 56 and 84 days of exposure to the acidic medium. Next, they were washed and weighed under SDD condition. The mass /crushing load loss at different times of exposure to the acidic medium was calculated through dividing the change in the mass/crushing load of each sample before and after exposure to acidic medium by the

mass/crushing load of samples at 28-days. It should be noted that the dimensions of specimens practically change once being placed in an acidic medium (difficulty in calculation of the cross-section area). Thus, the variation in the maximum load recorded in the compression test called the "crushing load" was determined [28].

3. Experimental details

3.1. Slump

Figure 2 reveals the changes in the SP demand to reach the specified slump value of 50±10 mm. As is shown in this figure, by increasing the replacement level of NZ to 5%, 10% or 15% the SP demand of plain concrete increased by 40%, 50% and 80%, respectively. These values show the higher the replacement of PC by NZ, the greater SP dosage is consumed. This can be attributed to the large amount of pores in NZ frame structure and high surface area of NZ [1]. Concerning the effects of nano-SiO₂, it can be observed that with the addition of nano-SiO₂ increased the amount of SP dosage by 33 to 111%. Furthermore, the addition of nano-CaCO₃ in HSC made with NZ resulted in a lower superplasticizer demand within the range of 0.3 to 0.7%.

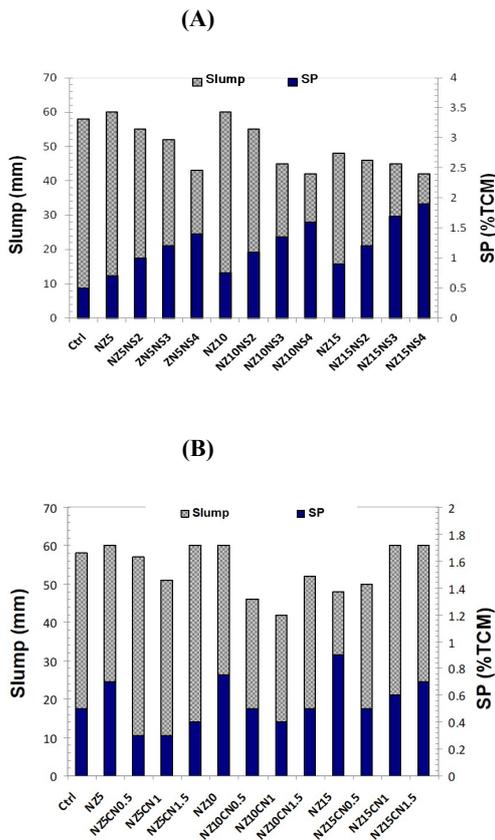


Fig. 2 - Slump vs. superplasticizer demand of HSC samples containing NZ and (A) nano-SiO₂, (B) nano-CaCO₃.

3.2. Compressive strength

Compressive strength of HSC mixtures were determined at different curing ages of 3, 7, 28 and 90 days and the results were presented in Figure 3 for HSCs made with binary blends use of PC+NZ, in Figure 4 for HSCs made with ternary blends of PC+NZ+nano-SiO₂ and in Figure 5 for HSCs containing PC+NZ+nano-CaCO₃. For comparison purpose, compressive strength of Ctrl mixture was also presented in these figures. According to these figures, all samples had a 28-day compressive strength higher than 81.36 MPa, which passed the minimum compressive strength requirement (≥60MPa) considered in this study for HSC. The effect of 5%, 10% and 15% NZ on the compressive strength of HSC in comparison with Ctrl mixture can be found in Figure 3. It can be observed that the maximum reduction in the compressive strength of plain HSC by incorporating 5% and 10% NZ was determined as 4.1% and 2.9%, respectively. This may suggest that up to 10% NZ usage had no significant effect on the compressive strength of HSC. This is while, although, the use of 15% NZ reduced the compressive strength of plain HSC by 11.7% at 3 days, this value decreased to 4.2%, 4.2% and 0.15% upon the increase in the curing age to 7, 28 and 90 days. This may be an indication of the pozzolanic activity of NZ.

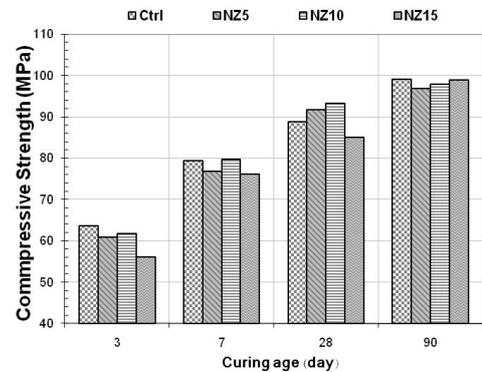
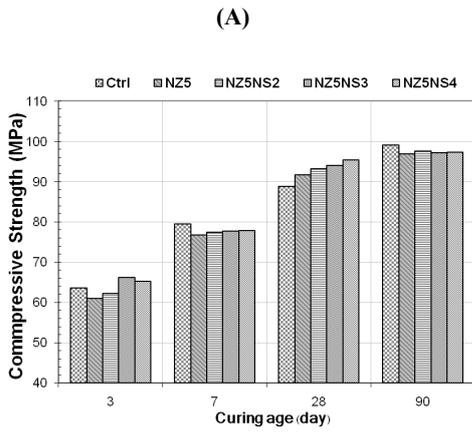
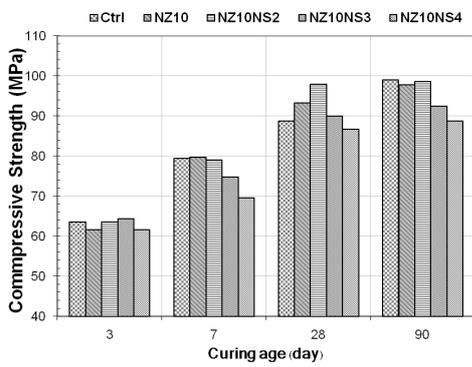


Fig. 3 - Compressive strength of HSC containing PC+NZ.

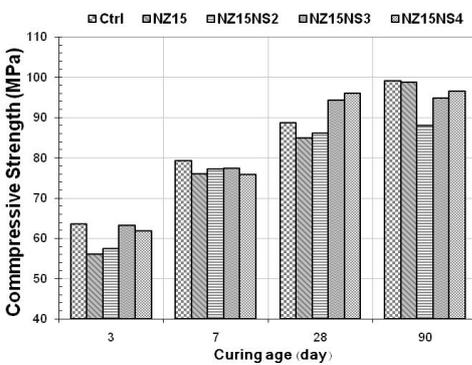
Based on the results presented in Figure 4, modifying HSC samples containing 5% NZ with 2%-4% nano-SiO₂ can result in the improvement of the compressive strength at all curing ages. The maximum compressive strength increment was 2.02%, 8.7% and 7.1% by the incorporation of 2%, 3% and 4% nano-SiO₂, respectively. This may be attributed to the pozzolanic activity and nano-filling property of nano-SiO₂ particles in concrete. Nonetheless, it can also be observed that 2% nano-SiO₂ can has a contribution to the strength development of HSC made with 10% or 15% NZ to some extent (except for NZ15NS2 at 90-days). As shown in Figure 5, at a constant NZ content, the presence of 1% or 1.5% nano-CaCO₃ in NZ



(A)



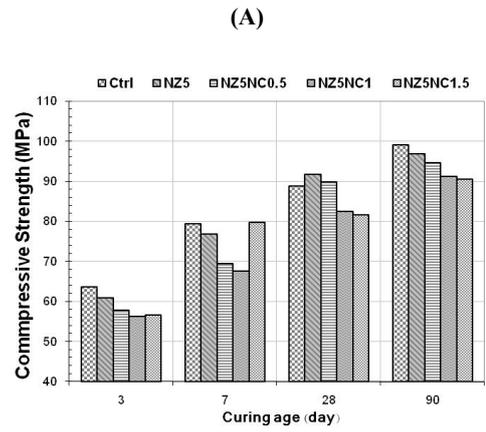
(B)



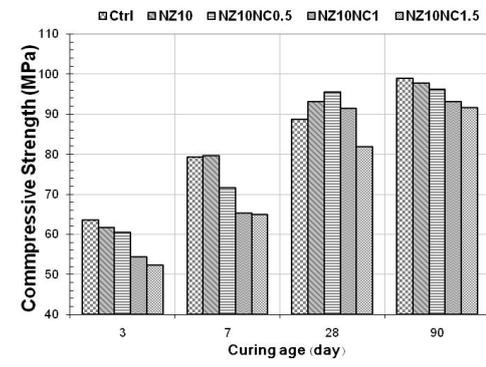
(C)

Fig. 4 - Compressive strength of nano-SiO₂ incorporated HSC containing NZ: A-5%, B-10% and C-15%.

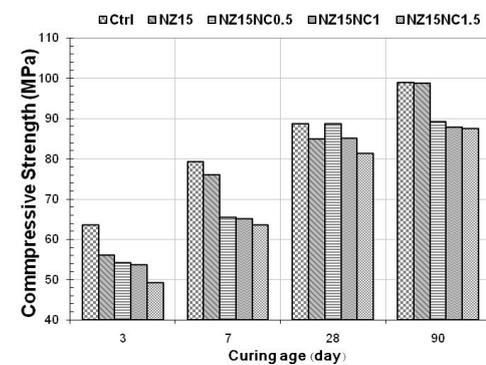
incorporated HSC mostly resulted in a lower compressive strength at all curing ages. Nonetheless, ternary blends of PC+0.5% nano-CaCO₃+ 5% or 10% NZ had a minor effect on the compressive strength of NZ5 and NZ10 mixtures at the ages of 28 and 90 days. For example, the 28-days compressive strength of NZ10NC0.5 increased by 7.67% and 2.51% over Ctrl and NZ10 mixtures, respectively. According to Shaikh and Supit [21], the addition of 1% nano-CaCO₃ to concrete containing 39% fly ash enhanced the compressive strength at different ages. The



(A)



(B)



(C)

Fig. 5 - Compressive strength of nano-CaCO₃ incorporated HSC containing NZ: A-5%, B-10% and C-15%

positive effect of nano-CaCO₃ on the compressive strength of the concrete containing high amounts of slag can be found in Ref. [23].

3.3. Chloride ion penetration depth

Chloride penetration depth of HSC samples after 90 days of exposure to 5% NaCl has been presented in Figure 6. It was observed that binary blends of PC+NZ shown a reduction of chloride penetration depth. The chloride penetration depth of NZ5, NZ10 and NZ15 were about 10.7%, 25.3%, and 26.3% of those of the control mixture.

These results may be in line with the study of Najimi et al. [6] who used rapid chloride penetration test (ASTM C1202) and reported that 15% and 30% NZ in concrete resulted to a lower the chloride ion permeability especially after 90 days of curing, compared to plain concrete. Concerning the effect of nano-SiO₂ on the chloride ion penetration depth of HSC, it can be concluded that replacing the Portland cement with nano-SiO₂ ensured a decrease in the chloride ion penetration depth of concrete made with NZ. For instance, as indicated in Figure 6, the incorporation of 2%, 3% and 4%

of PC+NZ. For instance, the chloride ion penetration depths of NZ5NC0.5, NZ5NC1 and NZ5NC1.5 mixtures were 10.3%, 15% and 48.1% lower compared to NZ5. A similar trend was observed when 0.5-1.5% nano-CaCO₃ was incorporated in HSC samples made with 10% or 15% NZ. According to Shaikh and Supit [21], this performance is related to the effects of nano-CaCO₃ in reducing the pore space and its conductivity within the concrete, which will reduce the chloride ion penetration.

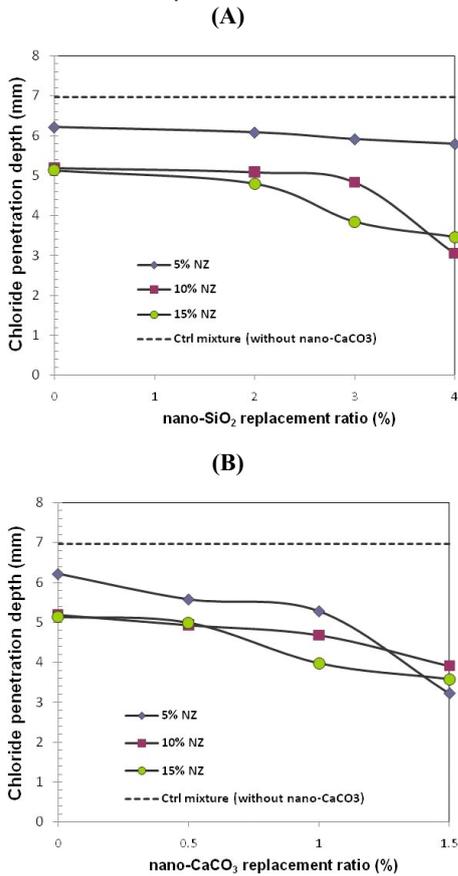


Fig. 6 - Chloride ion penetration depth of HSC samples containing NZ and nano-SiO₂ (A) and nano-CaCO₃ (B).

nano-SiO₂ decreased the chloride ion penetration depth of 15% NZ incorporated concrete by 6.5%, 25.1% and 32.6%, respectively. A similar pattern can also observe for the chloride ion penetration depth of the concretes containing 5% or 10% NZ when 2%-4% nano-SiO₂ particles were incorporated. This is an indication of the positive effect of ternary blends using of PC + NZ + nano-SiO₂ in the improvement of the chloride ion penetration resistance of HSCs in comparison with binary use of PC + NZ. It can be also concluded that the ternary combination of PC+NZ+nano-CaCO₃ is more effective in reducing the chloride ion penetration depth than the binary combination

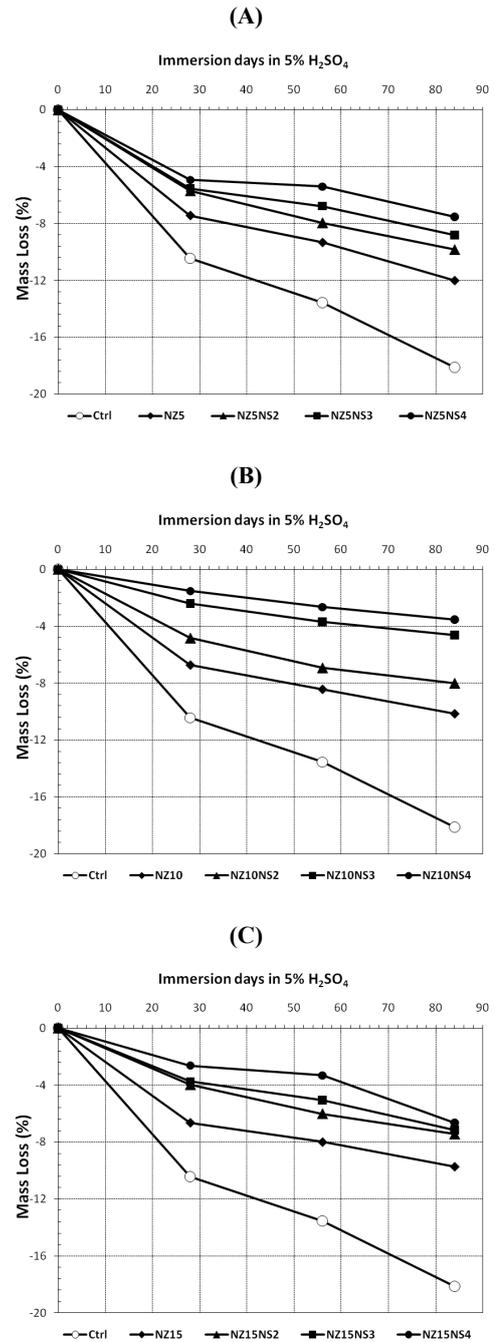


Fig. 7 - Mass loss of HSC made with nano-SiO₂ and NZ : A-5%, B-10% and C-15%, after exposure to H₂SO₄ solution.

3.4. Chemical resistance

3.4.1. Mass loss

The mass loss of the HSC mixes was determined after 28, 56 and 84 days of immersion in 5% H₂SO₄ solution and the results are shown in Figure 7 for HSC samples containing NZ + nano-SiO₂ and in Figure 8 for HSCs made with NZ + nano-CaCO₃. The mass loss of plain HSC were also presented in these figures. As can be observed, prolongation of the time of exposure to the acidic medium increased the mass loss of the samples.

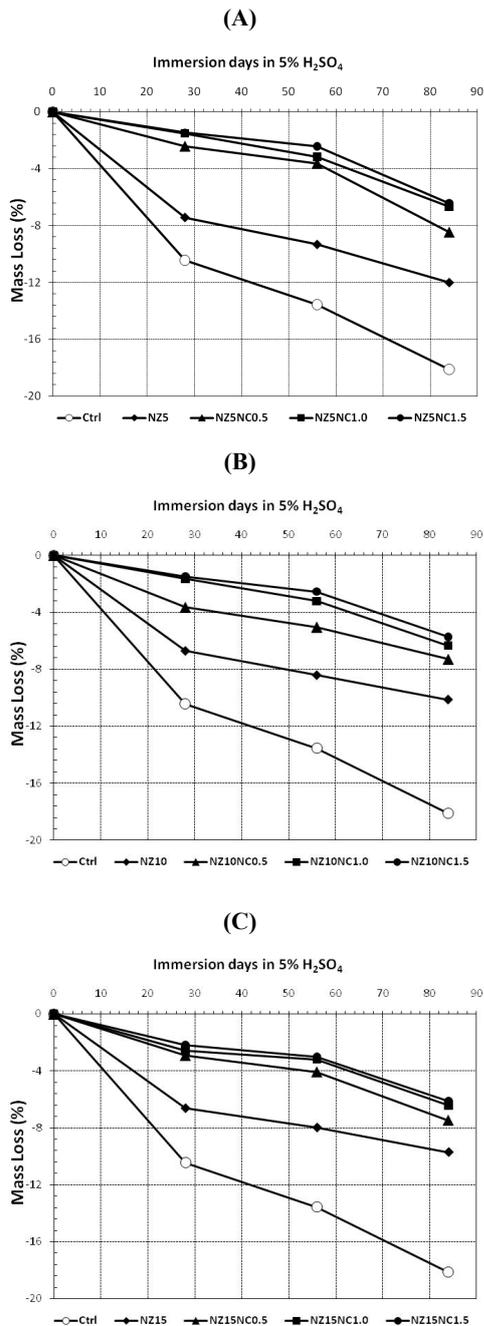


Fig. 8 - Mass loss of HSC made with nano-CaCO₃ and NZ: A-5%, B-10% and C-15%, after exposure to H₂SO₄ solution.

Binary blend of PC and NZ in HSC led to a lower mass loss after immersion in 5% H₂SO₄ solution in comparison to plain HSC. For example, the mass loss of the plain HSC after 84 days of exposure to the 5% H₂SO₄ solution was 18.13%, while the mixture with 5%, 10% and 15% NZ had mass loss of 12.02%, 10.13% and 9.71%, respectively. These values also suggest that higher NZ replacement ratio caused a lower mass loss. This can be attributed to the densification of the concrete microstructure by the incorporation of NZ as well as the pozzolanic consumption of calcium hydroxide component of PC hydration. This is while Samimi et al. [29] reported that while self-compacted concrete made with 15% zeolite exhibited the best resistance to acid attack, 10% zeolite in self-compacted concrete revealed behaviour very similar to that of the control self-compacted concrete and thus a lower chemical resistance.

Based on Figure 7, the ternary combination of PC+NZ+nano-SiO₂ exhibited better performance than the binary blends of PC+NZ, where the lowest mass loss values at all ages of exposure to the H₂SO₄ solution were obtained for mixtures made with NZ and 4% nano-SiO₂. The favourable effects of nano-CaCO₃ additions in improving the chemical resistance of HSC containing NZ can also be observed in Figure 8. For instance, the mass loss after 84 days of acid exposure is 10.13% for NZ10 which decreased to 7.3%, 6.34% and 5.73% by the incorporation of 0.5%, 1% and 1.5% nano-CaCO₃, respectively. According to these results, more nano-CaCO₃ in HSC, the lower reduction in mass loss is attained. In this respect, Senhadji et al. [30] explored that mortar specimens with the highest percentage of limestone (15% CaCO₃) had the minimum weight loss after exposure to sulfuric acid solution for three reasons: 1) its finer particles than cement, which fill the micropores and reduce porosity and permeability; 2) reduction in the amount of cement - reducing the amount of portlandite; 3) high amounts of calcium carbonate enhancing the capacity of limestone mortars to consume more aggressive acid.

3.4.2. Crushing load loss

Figure 9 display the variations in the crushing load of HSC samples containing binary and ternary combinations of PC, NZ and nano-SiO₂ after 28, 56 and 84 days of exposure to 5% sulfuric acid solution. Moreover, the crushing load loss of HSC samples made with PC, NZ and 0-1.5% nano-CaCO₃ were shown in Figure 10. As with what was observed for the mass loss, the crushing load loss also increased by increasing the time of exposure to the acidic medium.

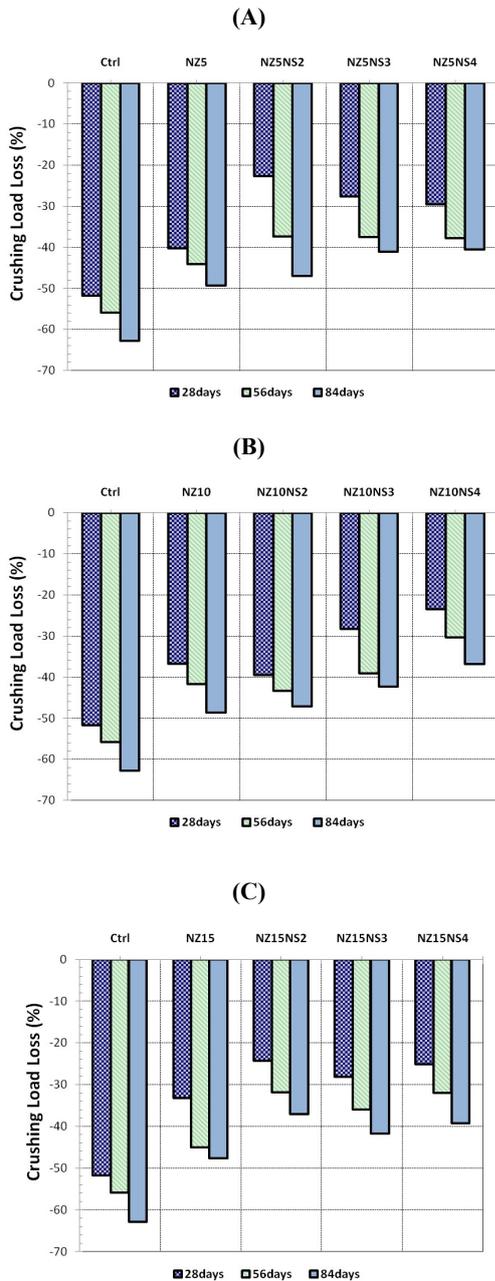


Fig. 9 - Crushing load loss of HSC made with nano-SiO₂ and NZ: A-5%, B-10%, C-15%, after exposure to H₂SO₄ solution.

Generally, it can be observed that the maximum crushing load loss has been achieved for plain HSC mixture while the addition of NZ and nano-particles reduced the crushing load loss. According to the results, the maximum differences in the crushing load loss of Ctrl mixture and NZ5, NZ10, NZ15 was 13.53%, 15.05%, 18.63%. By the incorporation of nano-SiO₂/CaCO₃, the crushing load loss of HSC containing NZ in most cases decreased after immersion to acid attack. For example, after 84 days of exposure to 5% H₂SO₄, the NZ10NC1.5 mixture had the minimum crushing load loss among the mix designs containing nano-CaCO₃, i.e. 43.36%, which was 10.8% lower than

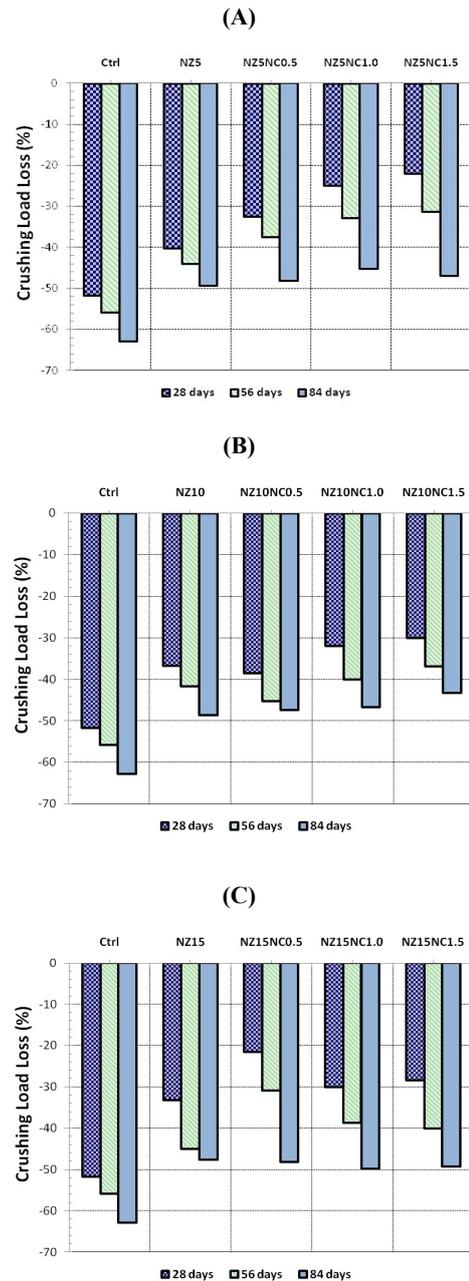


Fig. 10 - Crushing load loss of HSC containing nano-CaCO₃ and NZ: A-5%, B-10%, C-15%, after exposure to H₂SO₄ solution.

that of NZ10 and 31% lower than that of the Ctrl mixture. The relationship between the mass loss and the crushing load loss in HSC samples containing NZ and nano-particles after being immersed in 5% sulfuric acid solution is shown in Figure 11. The general trend indicates an increase in the crushing load loss with increasing mass loss. As presented in Figure 11, a linear relationship can be achieved in the form of $CL=2.13 \times ML - 22.78$ (with $R^2=0.72$) and $CL=2.39 \times ML - 22.21$ (with $R^2=0.75$) between the mass loss and the crushing load changes of HSC samples made with NZ+nano-CaCO₃ and NZ+nano-SiO₂, respectively.

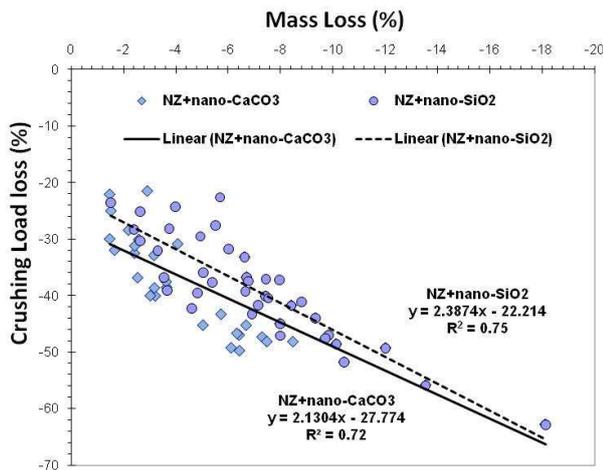


Fig. 11 - Relationship between mass loss and crushing load loss of HSC samples containing NZ and nano-SiO₂/CaCO₃

4. Conclusions

The performance of HSC containing NZ and nano-SiO₂/CaCO₃ was evaluated. The main points obtained can be summarized as follows.

- The compressive strength of all specimens was greater than 81.36 MPa at 28 days, which meets the minimum strength requirements considered in this study for HSC. Although, in comparison with plain HSC, insignificant changes were observed when 5-10% NZ was incorporated in HSC, the decline in the compressive strength of NZ15 mixture containing 15% NZ was attenuated over time.
- Although, the use of NZ in the HSC reduced the chloride ion penetration depth, the resistance to chloride ion penetration can also further improved by incorporating of nano-SiO₂/CaCO₃ in the NZ-containing mix designs. The NZ10NS4 containing 10% NZ and 4% nano-SiO₂ had the lowest chloride ion penetration depth, which was 41.3% lower than NZ10 and 56.2% lower than the plain HSC.
- The results indicated that the use of 5%, 10% and 15% NZ in HSC led to 12.02%, 10.13% and 9.71% mass losses after 84 days of immersion in 5% H₂SO₄ solution compared to 18.13% in the plain HSC. Ternary combination of PC+NZ+nano-SiO₂/nano-CaCO₃ exhibited the better performance in the reduction of mass loss of HSC samples in acid medium than the binary blends of PC+NZ.
- NZ10NS4 mixture showed the lowest the crushing load loss, i.e. 36.82%, among all mixture at 84 days of exposure to the 5% sulfuric acid. Furthermore, a linear relationship could be found between the mass loss and crushing load loss of HSC samples containing NZ and nano-particles after exposure to the 5% sulfuric acid solution.

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