

Abrasion resistance of concrete containing SiO₂ nanoparticles in different curing media

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Abstract: In the present study, abrasion resistance and compressive strength of concrete specimens containing SiO₂ nanoparticles which are cured in different curing media have been investigated. SiO₂ nanoparticles were partially replaced by Portland cement up to 2.0 wt% and mechanical properties of the produced specimens were measured. Increasing the nanoparticles content have found to increase the abrasion resistance of the specimens which were cured in water and saturated limewater, while this condition was not observed for compressive strength in both curing media. The enhancement of abrasion resistance was more for the specimens containing SiO₂ nanoparticles in both curing media. Since, abrasion resistance and compressive strength of the specimens follow a similar regime by increasing the nanoparticles content when they are cured in saturated limewater, some experimental relationships has been presented to correlate these two properties of concrete for this curing medium. On the whole, it has been concluded that the abrasion resistance of concrete does not only depend on the corresponding compressive strength. [Farzad Soleymani. **Abrasion resistance of concrete containing SiO₂ nanoparticles in different curing media.** *J Am Sci* 2012;8(8):171-178]. (ISSN: 1545-1003). <http://www.jofamericanscience.org>. 26

Keywords: A. Ceramic-matrix composites (CMCs); B. Mechanical properties; B. Strength; D. Thermal analysis.

1. Introduction

Numerous studies on the abrasion resistance of concrete have been carried out show that the abrasion resistance of concrete is strongly influenced by compressive strength, surface finishing techniques, curing types, aggregate properties and testing conditions [1, 2]. There are two views on the relationship between compressive strength and abrasion resistance of concrete specimens. The first is that compressive strength is the most important factor governing the abrasion resistance of concrete [3], and the abrasion resistance of concrete follows its compressive strength [1, 2, 4, 5]. For instance, Naik et al. [1] and Gjorv et al. [4] indicated that the relationship between compressive strength and abrasion resistance of concrete is linear while, Cengiz [2] pointed out that this relation is hyperbolic. The second view is that the abrasion resistance of concrete is independent on its compressive strength [6, 7].

Regardless of aggregates and admixtures, nano-additives could mainly influence upon the mechanical properties of concrete. There are several reports on incorporation of nanoparticles in concrete specimens which most of them have focused on using SiO₂ nanoparticles [8-17]. In addition, some of the works have conducted on utilizing nano-Al₂O₃ [18, 19], nano-Fe₂O₃ [20] and zinc-iron oxide nanoparticles [21].

As authors' knowledge, incorporating of nanoparticles to evaluate abrasion resistance of

concrete has only evaluated by Li et al. [12]. They chose SiO₂ and TiO₂ nanoparticles and replaced them partially by Portland cement. The results indicated that both SiO₂ and TiO₂ nanoparticles could improve the abrasion resistance of concrete. However, TiO₂ nanoparticles had superior influence on abrasion resistance of the specimens. They constructed a hyperbolic relationship between abrasion resistance and compressive strength of the specimens.

The aim of this study is to compare the abrasion resistance of concrete incorporating SiO₂ nanoparticles which are cured in different curing media. The nanoparticles were partially replaced by Portland cement and the prepared specimens were cured in two different media (i.e. water and saturated limewater) and abrasion resistance of the concrete specimens was measured after 7, 28 and 90 days of curing. In addition, thermal behavior and microstructure of the prepared specimens has been explored to compare the change occurred throughout curing.

2. Materials and Methods

Ordinary Portland Cement (OPC) conforming to ASTM C150 [22] standard was used as received. The chemical and physical properties of the cement are shown in Table 1. In addition, the distribution pattern of cement particles is illustrated in Fig. 1.

Table 1. Properties of Portland cement (Wt%)

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	Loss on ignition
Cement	21.89	5.3	3.34	53.27	6.45	3.67	0.18	0.98	3.21

Specific gravity: 1.7 g/cm³

Table 2. The properties of nanoparticles

Nanoparticle type	Diameter (nm)	Surface Volume ratio, m ² /g	Density, g/cm ³	Purity (%)
SiO ₂	15 ± 3	165 ± 17	< 0.15	>99.9

Table 3. Mixture proportion of nanoparticles blended concretes

Sample designation	Nanoparticles wt%	Quantities, kg/m ³	
		Cement	nanoparticles
C0 (control)	0	450	0
N1	0.5	447.75	2.25
N2	1.0	445.50	4.50
N3	1.5	443.25	6.75
N4	2.0	441.00	9.00

Water to binder [cement + nanoparticles] ratio of 0.40, sand 492 kg/m³, and aggregate 1148 kg/m³.

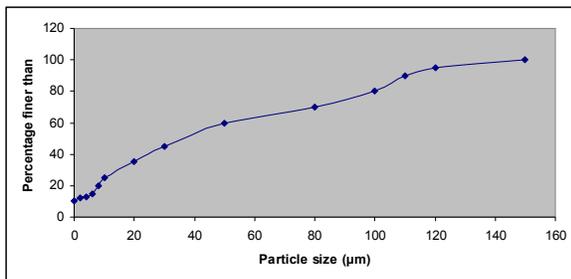
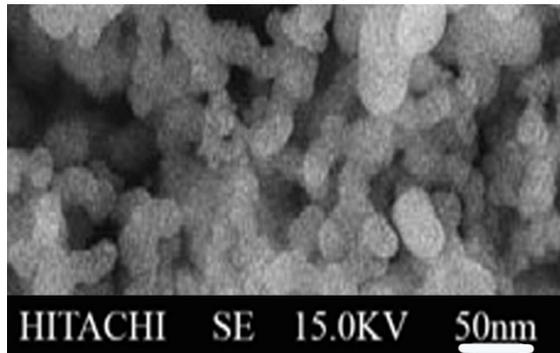
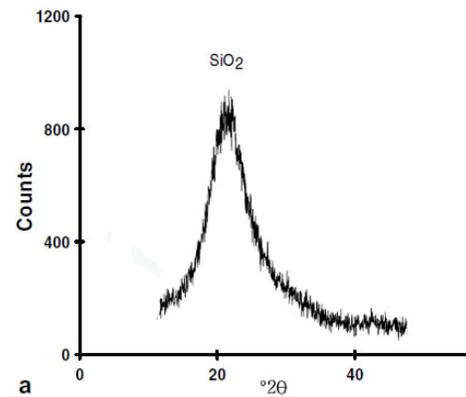


Fig. 1. Particles distribution pattern of ordinary Portland cement.

Fig. 2. SEM micrograph of SiO₂ nanoparticles.

Nanoparticles with the average particle size of 15 nm producing from Suzhou Fuer Import&Export Trade Co., Ltd were used as received. The properties of nanoparticles are shown in Table 2. Scanning electron micrographs (SEM) and powder X-ray diffraction (XRD) diagrams of nanoparticles are shown in Figs. 2 and 3.

Fig. 3. XRD analysis of SiO₂ nanoparticles.

Locally available natural sand with particles smaller than 0.5 mm and fineness modulus of 2.25 and specific gravity of 2.58 g/cm³ was used as fine aggregate. Alushed basalt stored in the laboratory with maximum size of 15 mm and specific gravity of 2.96 g/cm³ (loose form) was used as coarse aggregate.

Two series of mixtures were prepared in the laboratory trials. C0 Series mixtures were prepared as control specimens. The control mixtures were made of natural aggregates, cement and water. N series were prepared with different contents of nanoparticles with average particle size of 15 nm. The mixtures were prepared with the cement replacement of 0.5%, 1.0%, 1.5% and 2.0% by weight. The water to binder ratio for all mixtures was set at 0.40. The aggregates for the mixtures consisted of a combination of crushed basalt and of fine sand, with 30 wt% of sand. The binder content of all

mixtures was 450 kg/m^3 . The proportions of the mixtures are presented in Table 3.

N series mixtures were prepared by mixing the course aggregates, fine aggregates and powder materials (cement and nanoparticles) in a laboratory concrete drum mixer. The powder material in the C0 series mixtures was only cement. They were mixed in dry condition for two minutes, and for another three minutes after adding the water. Cubes of 100 mm edge for compressive strength tests and cylindrical specimens with 300 mm diameter and 100 mm height for abrasion resistance test were cast and compacted in two layers on a vibrating table, where each layer was vibrated for 10 s. The moulds were covered with polyethylene sheets and moistened for 24 h. Then the specimens were demolded and cured in water (N-W series) and saturated limewater (N-LW series) at a temperature of 20°C prior to test days. To produce saturated limewater, the lime powder was solved in tap water and dispersed until the excess lime powder was precipitated. The strength tests of the concrete samples were determined at 7, 28 and 90 days after curing. After each time of the curing, the old limewater media was renewed to maintain saturated limewater.

Compressive strength of nanoparticles blended cement concrete cubes was determined in accordance to the ASTM C 39 [23] after 7, 28 and 90 days of moisture curing. Tests were carried out on triplicate specimens and average compressive strength values were considered.

The abrasion test was conducted in accordance with ASTM C 1138 [24] and measured in terms of depth of wear at 7, 28 and 90 days.

Conduction calorimetry test was run out on a Wexham Developments JAF model isothermal calorimeter, using IBM program AWCAL-4, at 22°C for a maximum of 70 hours. Fifteen grams of cement was mixed with water and saturated limewater and admixture before introducing it into the calorimeter cell.

A Netzsch model STA 409 simultaneous thermal analyzer equipped with a Data Acquisition System 414/1 programmer was used for thermogravimetric analysis. Specimens which were cured in water and saturated limewater for 90 days were heated from 110 to 650°C , at a heating rate of $4^\circ \text{C}/\text{min}$ in an inert N_2 atmosphere.

SEM investigations were conducted on a Hitachi apparatus. Backscattered electron (BSE) and secondary electron (SE) imaging was used to study the samples, which were prepared under conditions that ensured their subsequent viability for analytical purposes.

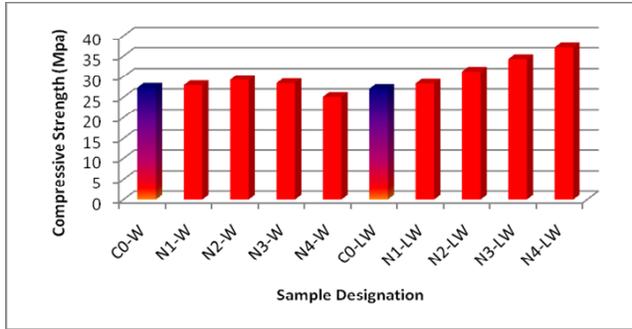
A Philips PW-1730 unit was used for XRD analysis which was taken from 4 to 70° .

3. Results and discussion

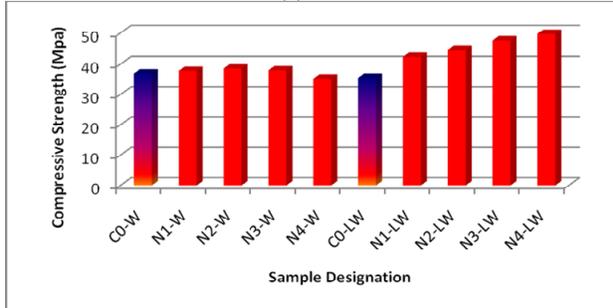
3.1. Compressive strength

The compressive strength results of C0-W and N-W series mixtures are shown in Fig.4. By comparison the compressive strength of the specimens cured for 7, 28 and 90 days, it could be observed that the compressive strength is increased with nanoparticles up to 1.0% replacement (N2-W) and then it is decreased, although the results of 2.0% replacement (N4-W) is still higher than those of plain concrete specimen (C0-W). It is shown that using 2.0% nanoparticles in N-W series decreases the compressive strength to a value which is near to the control concrete. This may be as a result of this fact that the quantity of nanoparticles present in the mix is higher than the amount required to combine with the liberated lime during the process of hydration thus leading to excess silica leaching out and causing a deficiency in strength as it replaces as a part of the cementitious material but does not contribute to strength [25]. Also, it may be related to the defects generated in dispersion of nanoparticles that causes weak zones. The high enhancement of compressive strength in the N series blended concrete is due to the rapid consuming of $\text{Ca}(\text{OH})_2$ which is formed during hydration of Portland cement specially at early ages related to the high reactivity of nanoparticles. As a consequence, the hydration of cement is accelerated and larger volumes of reaction products are formed. Also nanoparticles recover the particle packing density of the blended cement, directing to a reduced volume of larger pores in the cement paste. The higher compressive strength of the specimens containing SiO_2 nanoparticles may be due to contribution of SiO_2 nanoparticles as a pozzolan to formation C-S-H gel.

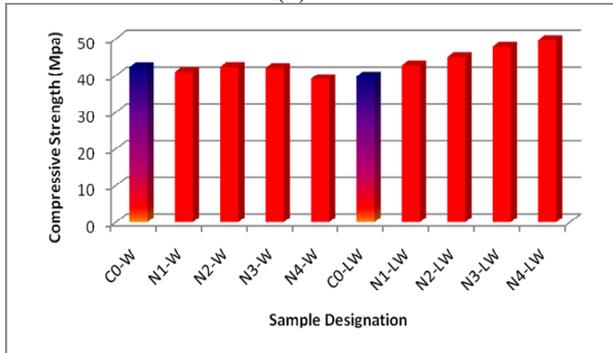
Figs. 5 and 6 respectively show the SEM micrograph of concrete without and with nanoparticles after 7 days of curing in water. C-S-H gel which is existed in isolation is enclosed by some of needle-hydrates in the SEM micrograph of cement paste (Fig. 5). On the other hand, the micrograph of the mixture containing nanoparticles revealed a compact formation of hydration products and a reduced content of $\text{Ca}(\text{OH})_2$ crystals (Fig. 6). In addition XRD results of the cement pastes with and without nanoparticles after 15 h of curing in water has been illustrated in Fig. 7. The results show that after 15 h of curing, $\text{Ca}(\text{OH})_2$ crystals which needs to formation of C-S-H gel appears in concrete with nanoparticles while for concrete without nanoparticles it is not appeared indicating synergic effects of nanoparticles on formation of subsequent C-S-H gel.



(a)



(b)



(c)

Fig. 4. Compressive strength of C0 and W series concrete specimens at a) 7, b) 28 and c) 90 days of curing.

Fig. 4 also shows the compressive strength of C0-LW and N-LW series. The results show that the replacement of cement by nanoparticles up to 2.0 Wt% (N4-LW) in N-LW series produces concrete with high strength with respect to N-LW concrete. By comparison the compressive strength results of C0-W and C0-LW series, it shows that after 7, 28 and 90 days of curing the concrete in the saturated limewater, the compressive strength of the C0-LW series is smaller than the corresponding strength of C0-W series. This may be due to more formation of crystalline Ca(OH)_2 in the presence of limewater which reduces the compressive strength in C0-LW series with respect to C0-W series. On the other hand, the compressive strength of the N-LW series is more than those of N-W series. Lime reacts with water and

produces Ca(OH)_2 which needs to form strengthening gel [26]:

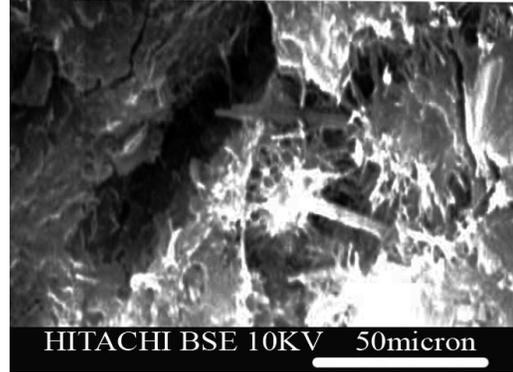
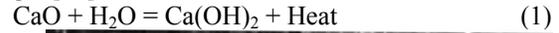


Fig. 5. SEM micrograph of cement paste without nanoparticles.

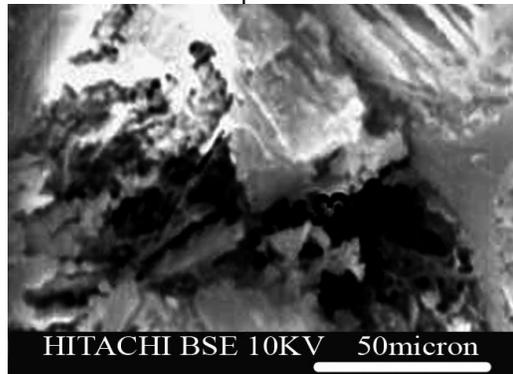


Fig. 6. SEM micrograph of cement paste with SiO_2 nanoparticles cured in water.

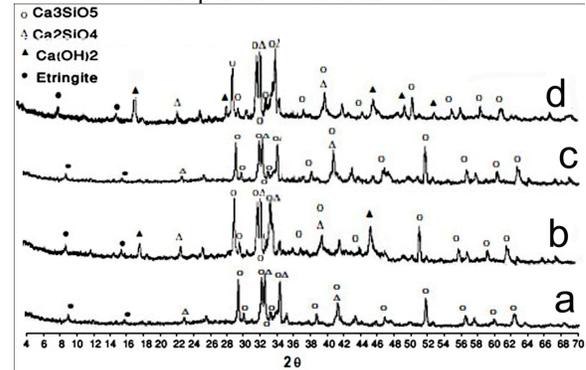


Fig. 7- XRD results of cement pastes at 15 h of curing for the specimens containing SiO_2 nanoparticles. a) Without nanoparticles cured in water, b) with nanoparticles cured in water, c) without nanoparticles cured in saturated limewater and d) with nanoparticles cured in saturated limewater

When nanoparticles react with Ca(OH)_2 produced from saturated limewater, the content of strengthening gel is increased because of high free energy of nanoparticles which reduces significantly

when reacts by $\text{Ca}(\text{OH})_2$ [27]. The compressive strength of N-W and N-LW series should be compared from two viewpoints:

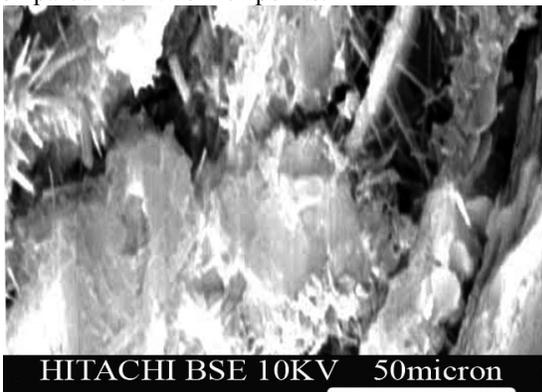


Fig. 8. SEM micrograph of cement paste without nanoparticles cured in saturated limewater.

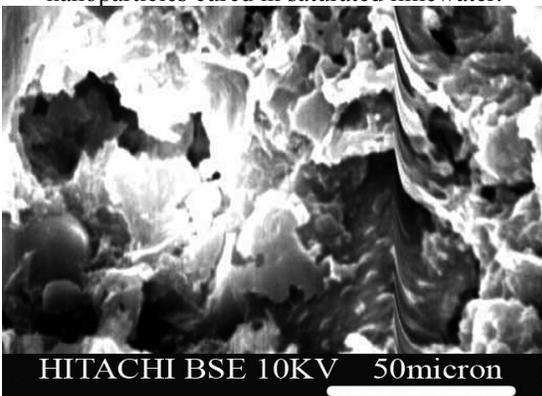


Fig. 9. SEM micrograph of cement paste with SiO_2 nanoparticles cured in saturated limewater.

1. The compressive strength of N-LW series increases by partial replacement of cement with nanoparticles up to 2.0 wt% (N4-LW) while for N-W series it increases by partial replacement of cement with nanoparticles up to 1.0 wt% (N2-W) and then decreases. Once more this confirm the more strengthening gel formation in the presence of saturated limewater in which the quantity of nanoparticles present in the mix is close to the amount required to combine with the liberated lime during the process of hydration thus leading to lesser silica leaching out with respect to the specimens cured in water [27].

2. The difference between compressive strengths of the N-W and N-LW series after 28 days of curing is relatively high while this difference in compressive strength after 90 days of curing is not high. This may be due to formation of crystalline $\text{Ca}(\text{OH})_2$ in N-LW series after the 28 day causes reduction in compressive strength.

Once again, SiO_2 nanoparticles make the concrete stronger and after that TiO_2 nanoparticles produce more strengthened specimens when the concretes are cured in saturated limewater.

Figs. 8 and 9 show the SEM micrograph of concrete without and with nanoparticles at 7 days of curing in saturated limewater. Once again, the micrograph of the mixture containing nanoparticles revealed a compact formation of hydration products and a reduced content of $\text{Ca}(\text{OH})_2$ crystals. Moreover, No significant differences is evident between the microstructure of concrete without nanoparticles cured in water or saturated limewater. In addition XRD results of the cement pastes with nanoparticles at 15 h of curing in saturated limewater have been illustrated in Fig. 7. The longer pick intensity show that the amount of $\text{Ca}(\text{OH})_2$ crystals which needs to formation of C-S-H gel is more for the specimens cured in limewater rather the specimens cured in water when nanoparticles are used.

3.2. Conduction calorimetry

Two signals can be distinguished on all test results: a peak corresponding to the acceleration or post-induction period, associated with the precipitation of C-S-H gel and CH , and a shoulder related to a second, weaker signal with a later peak time, associated with the transformation from the ettringite (AF_1) to the calcium monosulphoaluminate (AFm) phase via dissolution and reaction with $\text{Al}(\text{OH})_4^-$ [28]. The numerical values corresponding to these two signals (heat release rate, peak times) and the total released heat are shown in Table 4. The time period over the total heat was measured until the heat release rate was below 1% of the maximum of the second peak.

The heat release rate values in Table 4 show that decreasing the percentage of nanoparticles in the pastes retards peak times and raises heat release rate values. In addition, the specimens which have been cured in saturated limewater show a decreased peak time and heat release rate values with respect to the corresponding specimens cured in water. This is indicative of a delay in initial cement hydration due to lesser content of nanoparticles and the lesser content of $\text{Ca}(\text{OH})_2$ in the specimens cured in water. The retardation is much less marked in the second peak. The total heat released under identical conditions (at times when the heat release rate is less than 1% of the maximum amount of heat released in the first peak) decreases with higher percentages of nanoparticles in the mix.

Table 4. Calorimetric results of cement pastes.

Mixture	Total heat		First peak		Second peak	
	kJ/kg	Time (h)	Rate (W/kg)	Time (h)	Rate (W/kg)	
C0-W (control)	299.8	1.4	0.6	15.1	2.5	
N1-W	265.4	1.3	0.5	14.3	2.3	
N2-W	244.2	1.2	0.4	14.0	2.1	
N3-W	256.8	1.3	0.5	14.2	2.2	
N4-W	280.3	1.3	0.5	14.6	2.3	
C0-LW (control)	312.5	1.6	0.6	15.8	2.6	
N1-LW	260.7	1.2	0.5	14.1	2.2	
N2-LW	234.2	1.1	0.4	13.9	2.1	
N3-LW	228.6	1.0	0.4	13.8	1.9	
N4-LW	219.4	1.0	0.3	13.5	1.9	

Water to binder [cement + nanoparticles] ratio of 0.40

W denotes the specimens cured in water and LW denotes to those cured in saturated limewater

3.3. Thermogravimetric analysis results

Table 5 shows the weight loss measured in the 110-650 °C range in which dehydration of the hydrated products occurred. The results show that after 90 days of curing, the loss in weight of the specimens is increased by increasing the nanoparticles content in concretes. This is more evident in N2-W and N4-LW series. This may be due to more formation of hydrated C-S-H gel in N2-W and N4-LW series.

3.4. Abrasion resistance

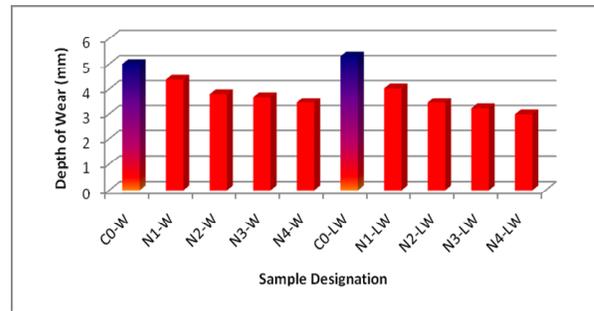
Fig. 10 shows the results of abrasion resistance of all specimens at the 7, 28 and 90 days of curing in water and saturated limewater. It can be seen that the abrasion resistance of concretes containing nanoparticles is remarkably improved, in particular the abrasion resistance of concrete containing SiO₂ nanoparticles.

Table 5. Weight loss (%) of the pastes in the range of 110-650 °C after 90 days of curing.

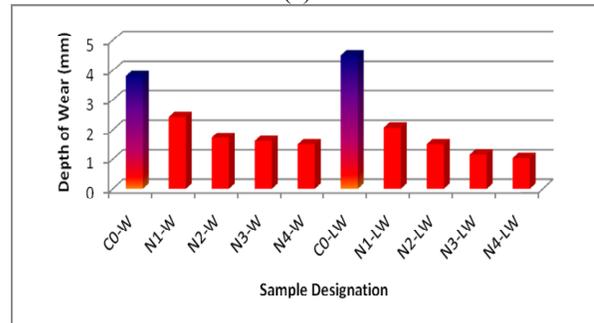
Mixture	Total heat kJ/kg
C0-W (control)	12.2
N1-W	12.8
N2-W	13.0
N3-W	12.9
N4-W	12.5
C0-LW (control)	12.7
N1-LW	13.0
N2-LW	13.3
N3-LW	13.1
N4-LW	12.9

Water to binder [cement + nanoparticles] ratio of 0.40

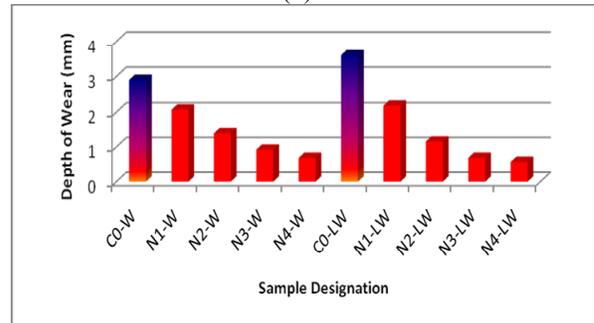
W denotes the specimens cured in water and LW denotes to those cured in saturated limewater



(a)



(b)



(c)

Fig. 10. Abrasion resistance of C0 and W series concrete specimens at a) 7, b) 28 and c) 90 days of curing.

The mechanism that nanoparticles are able to improve the abrasion resistance of concrete can be

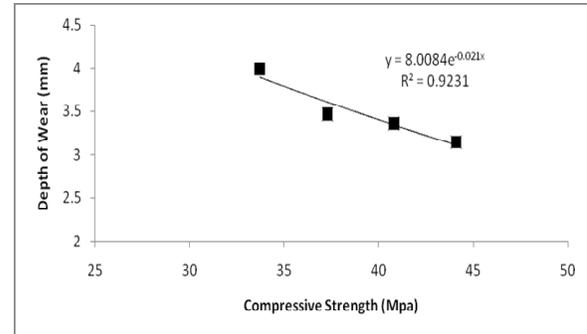
interpreted as follows [12]: suppose that nanoparticles are uniformly dispersed and each particle is contained in a cube pattern, the distance between nano-particles can be specified. After hydration begins, hydrate products diffuse and envelop nanoparticles as kernel. If the content of nanoparticles and the distance between them are appropriate, the crystallization will be controlled to be a suitable state through restricting the growth of $\text{Ca}(\text{OH})_2$ crystal by nanoparticles [12]. This makes the cement matrix more homogeneous and compact. As a consequence, the abrasion resistance and strength are improved evidently such as the concrete containing 1% nano- TiO_2 . With increasing content of nano-particles, the distance between nanoparticles decreases, $\text{Ca}(\text{OH})_2$ crystal cannot grow up enough, which leads to the ratio of crystal to C-S-H gel small and the microstructure of cement matrix is loose. The abrasion resistance and strength of concrete decrease relatively [12].

In addition, because cement and water content in this study are relatively low, the slump of fresh concrete, especially the concrete containing nanoparticles is less than 60 mm, which leads to a thin mortar layer on the surface of concrete forming. The thin mortar layer is favorable to the improvement of abrasion resistance of concrete [12].

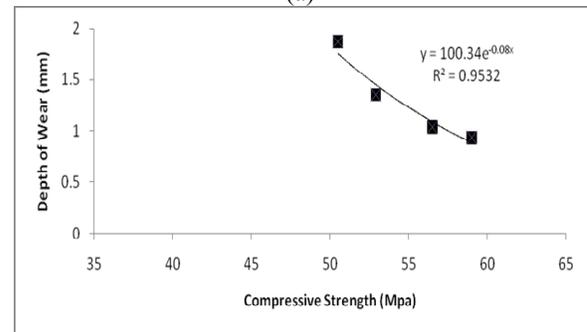
The abrasion resistance of the specimens in contrast with the compressive strength of concrete specimens is increased with nanoparticles content in W series. It seems that nanoparticles could act as a abrasive-resistant particle which prevent more erosion with respect to the C0-W series and W series with lesser amount of nanoparticles. In LW series, abrasion resistance is increased up to 2.0 wt% similar to the compressive strength of these specimens.

Finally, we have tried to relate the compressive strength of the specimens to their abrasion resistance. For N-W series, since the variations are not continuous and after specific nanoparticle content it is decreased, we could not correlate this property to the abrasion resistance of these specimens which is continuously increased by increasing nanoparticle content. We could only obtain this correlation for N-LW series and the relation between compressive strength and abrasion resistance of N-LW series with SiO_2 nanoparticles has been illustrated in Fig. 11. The best fit equation and R^2 value of each curve has been illustrated in the corresponding figure. It seems that there is a relatively good relationship between the results in most cases. However, in some cases, the agreement is relatively low. In the whole, the abrasion resistance of N-LW specimens could be predicted by their compressive strength. However, for N-W series specimens this prediction could not be applied. In the other words, we can conclude that the

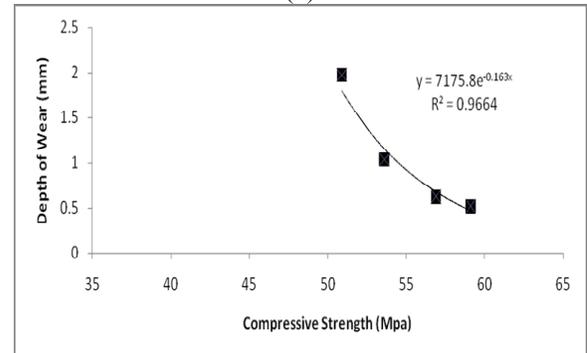
abrasion resistance of the concrete depends on several factors (like curing medium which has been investigated in this work) and does not only depend on compressive strength of concrete [6, 7].



(a)



(b)



(c)

Fig. 11. The relationship between abrasion resistance and compressive strength of N-LW series concrete specimens at a) 7, b) 28 and c) 90 days of curing.

4. Conclusions

From the present work, the following conclusions were obtained:

- The abrasion resistance and the compressive strength of the specimens could be improved by partially replacing of Portland cement with SiO_2 nanoparticles.
- The compressive strength of the specimens is increased for the specimens cured in water by using up to 1.0 wt% nanoparticles and then it

is decreased while for the specimens cured in saturated limewater even using 2.0 wt% nanoparticles improve the compressive strength.

- The abrasion resistance of the specimens is enhanced by increasing the nanoparticles content in both curing media.
- Although, some experimental relationships have been presented to correlate compressive strength and abrasion resistance of the specimens cured in saturated limewater, the abrasion resistance of concrete does not only depend on the compressive strength of the specimens.

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5/2/2012