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A survey on the application of oxide nanoparticles for improving concrete processing

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Abstract. The evolution of nanotechnology provides materials with advance properties. It's a fast growing area of research to introduce the oxide nanoparticles into the cement pastes to improve their performance. The purpose of this paper is to review the effects of oxide nanoparticles (such as SiO_2, TiO_2, Fe_2O_3, ZnO_2, Cr_2O_3 and Al_2O_3) on both of hardened concrete properties (i.e., compressive strength, split tensile strength and flexural strength, water permeability, Abrasion resistance and pore structure of concrete) and fresh concrete properties (i.e., workability and setting time). Graphical representations of all these parameters were presented to facilitate the comparison of the effect of oxide nanoparticles on concrete processing. The paper also introduces some discussion about future work in this direction by identifying some open research area.

Keywords: oxide nanoparticles; concrete; fresh concrete properties; hardened concrete properties

1. Introduction

Worldwide, around 2.6 billion tons of cement is prepared annually. This large amount of production consumes a lot of energy and is one of the largest sources in production of CO_2 gas (Aly *et al.* 2012, Gopalakrishnan *et al.* 2011, Zhang and Li *et al.* 2011*)*. Accordingly, there is a pressing demand to minimize the quantity of cement applied in the concrete (i.e., a composite mixture generally made of cement past and aggregates industry). The main drawback to this is to produce durable concrete with lower cement as well as a reasonable cost (Aly *et al.* 2012*)*.

Recently, nanotechnology has attracted considerable scientific interest due to a novel potential application of particles in nanometer (10^{-9}m) scale (Nazari *et al.* 2010*,* Sadrmomtazi *et al.* 2010, Sadrmomtazi and Barzegar 2010). The nano scale-size of particles can result in dramatically improved properties from conventional grain-size materials (Byung *et al.* 2007). Therefore, industries may be able to re-engineer many existing products and to fabricate a novel products that function at unprecedented levels (Bhuvaneshwari *et al.* 2013, Byung *et al.* 2007, Shekari *et al.* 2011).

Due to the special property such as high surface to volume ratios, the nanoparticles have gained more attentions in all the fields and also in civil engineering field (Bhuvaneshwari *et al.* 2012,

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Quercia *et al.* 2010). Accordingly, there is a great interest to modify the concrete structure by a new material to obtain more durable concrete. It is well documented in chemistry, physics and mechanics that concrete preparation with well-designed and advanced materials (i.e., nanoparticles) results in much harder and cheaper concrete (Khanzadi *et al.* 2010). Using of nano materials can significantly improve the mechanical and physical properties of concrete. Nanomaterials can alter the concrete properties due to their unique properties such as a high surface area to volume ratio (Naji *et al.* 2010, Cassar 2005). Nanoparticles were used either to replace as a part of cement such as preparing ecologic profile concrete, or as an admixtures in the cement pastes. In both cases, adding of nano-scale particles enhance the performance of cement in fresh mixtures (e.g., improvement of rheological properties) and hardened state (e.g., increasing of compressive strength) (Senff *et al.* 2012). Generally, the beneficial action of nanoparticles on properties of cement-based materials can be explained by following factors (Stefanidou *et al.* 2012, Nazari and Riahi 2011, Naji *et al.* 2011).

- Nanoparticles can be filled the void between the cement grains (Byung *et al.* 2007, Gaitero *et al.* 2008, Senff *et al.* 2009);

- Well-dispersed nanoparticles act as an appropriate site for crystallization of the cement hydrates, and consequently enhanced the hydration rate. It was necessary to note that; unsuitable dispersion of nanoparticles in the concrete matrix can act as macro particles and deteriorate the mechanical and physical properties of content in higher content of nanoparticles (Qing *et al.* 2007, Jalal *et al.* 2012, Lackhoff *et al.* 2003);

- Nanoparticles accelerate (SiO_2 and Al_2O_3) the pozzolanic transformations (reaction 1)

$$\text{Cement} + H_2O + \text{nanoparticles} \rightarrow Ca(OH)_2 + \text{C-S-H} + \text{C-S-H (additional)} + \text{heat} \qquad (1)$$

Hence, the presence of nanoparticles increase the consumption of $Ca(OH)_2$ and the creation of an “excess” C-S-H gel formation (Sadrmomtazi *et al.* 2010, Bhuvaneshwari *et al.* 2012, Gaitero *et al.* 2008, Senff *et al.* 2009);

-Nanoparticles modify the structure of aggregates contact zone, resulting in a better bond between aggregates and cement paste (Lázaro and Brouwers 2010, Li *et.al* 2006, Ji 2005, Naji *et.al* 2012);

-Nanoparticles prepared crack arrest and interlocking effects between the slip planes, which enhanced the toughness, shear, tensile and flexural strength of cement-based materials (Bhuvaneshwari *et al.* 2013).

To the best of our knowledge, There are several reports on the effect of nanoscale material on concrete specimens (Li *et al.* 2004) which most of them have focused on using of SiO_2 and TiO_2 nanoparticles (Shekari and Razzaghi 2011, Bhuvaneshwari *et al.* 2012, Khanzadi *et al* 2010). Also, some of the works have been conducted on utilizing of Al_2O_3, Fe_2O_3 nanoparticles (Bhuvaneshwari *et al*. 2012, Chen *et al.* 2012, Nazari and Riahi 2011).

According to literatures, the replacement of cement by other pozzolanic materials such as slag, silica fume or fly ash and ground granulated blast-furnace slag (GGBFS) are a very efficient method (Li 2004, Shi *et al.* 2012, Morsy *et al.* 2012, Nazari and Riahi 2011, Yuvaraj *et al.* 2012, Nazari and Riahi 2011). A number of publications appeared toward the application of nanopaticle in cementitious system is mainly due to the fact that concrete remains the most complex material and its hydration mechanism is still not totally understood.

The aim of this paper is to discuss on the mechanical and physical properties of concrete specimens containing various types and amounts of oxide nanoparticles which are cured in water or limewater. The effects of nanoparticles on pore structure have been summarized. Also, we did

Table 1 The characteristics of the most common oxide nanoparticles on concrete processing

Nanoparticles	Diameter (nm)	Surface volume ratio (m^2/g)	Density (g/cm^3)	Purity (%)
SiO_2 (Naji *et al.* 2010,	15±3	1333±50	<0.15	>99.9
Li and Zhang *et al.* 2006)	80±5	197±32	<0.19	>99.9
TiO_2 (Oltulu and Sahin 2011)	15±3	155±12	<0.13	>99.9
Fe_2O_3 (Khalaj and Nazari 2012)	15±2	159±18	<0.15	>99.9
ZnO_2 (Nazari and Riahi 2011)	15±3	155±12	<0.12	>99.9
Cr_2O_3 (Nazari and Riahi 2011)	15±5	150±10	<0.11	>99.9
Al_2O_3 (Senff *et al.* 2009)	15±3	155±12	<0.12	>99.9

an investigation for determination of the best and the most effective of conventional oxides nanoparticle in concrete processing.

2. Nanoparticles and concrete

The characteristics of the most common oxide nanoparticles applied on concrete processing are shown in Table 1.

The effects of these oxide nanoparticles on both of hardened concrete properties and fresh concrete properties have been discussed. These effects are shown in Fig. 1.

2.1 Hardened concrete

Generally, the mechanical and physical properties of hardened concrete including the compressive strength, splitting tensile strength, flexural strength and permeability (Jalal *et al.* 2012, Jalal *et al.* 2012).

2.1.1 Compressive strength

Compressive strength of any type of nanoparticles blended cement concrete cubes were measured according to the ASTM standard (Khanzadi *et al.* 2010, Naji *et al.* 2011, Raiess *et al.* 2010).

Tests were done on triplicate specimens and the mean compressive strength values were calculated (Nazari and Riahi 2011, Erdem *et al.* 2012, Diamantonis *et al.* 2010). It was necessary to note that before the determination of compressive strength, the mixtures series were cured in water, limewater or water with 1.0 wt.% polycarboxylate in admixture.

Fig. 2 compares the compressive strength of N-series and C0-series (zero content of oxide nanoparticles). Generally, the compressive strength of N-series is higher than the C0-series. The improvement of compressive strength in N-series blended concrete are related to the rapid consuming of $Ca(OH)_2$ (increases the pozzolanic reaction) (Lin *et al.* 2008, Nazari and Riahi 2011, Byung *et al.* 2007). Pozzolanic reaction was occurred at early ages of portland cement hydration

Table 2 Compressive strength of nano-Al_2O_3 particle blended concrete specimens

Specimens	C0-W	N1-W	N2-W	N3-W	N4-W	C0-LW	N1-LW	N2-LW	N3-LW	N4-LW
Compressive strength 28 days (MPa)*	34.48	39.19	40.39	39.73	37.004	34.43	41.25	42.45	43.23	45.26
Compressive strength 90 days (MPa)*	41.08	42.28	43.69	42.82	41.74	38.809	41.45	42.65	43.84	46.07

*: Compressive strength of nano-Al_2O_3 particle blended concrete specimens after 28 and 90 days of curing in water or limewater. N1, N2, N3 and N4 are the N-Series with 0.5%, 1.0%, 1.5% and 2.0% of nano-Al_2O_3, respectively. W denotes the specimens cured in water and LW denotes to those cured in saturated limewater.

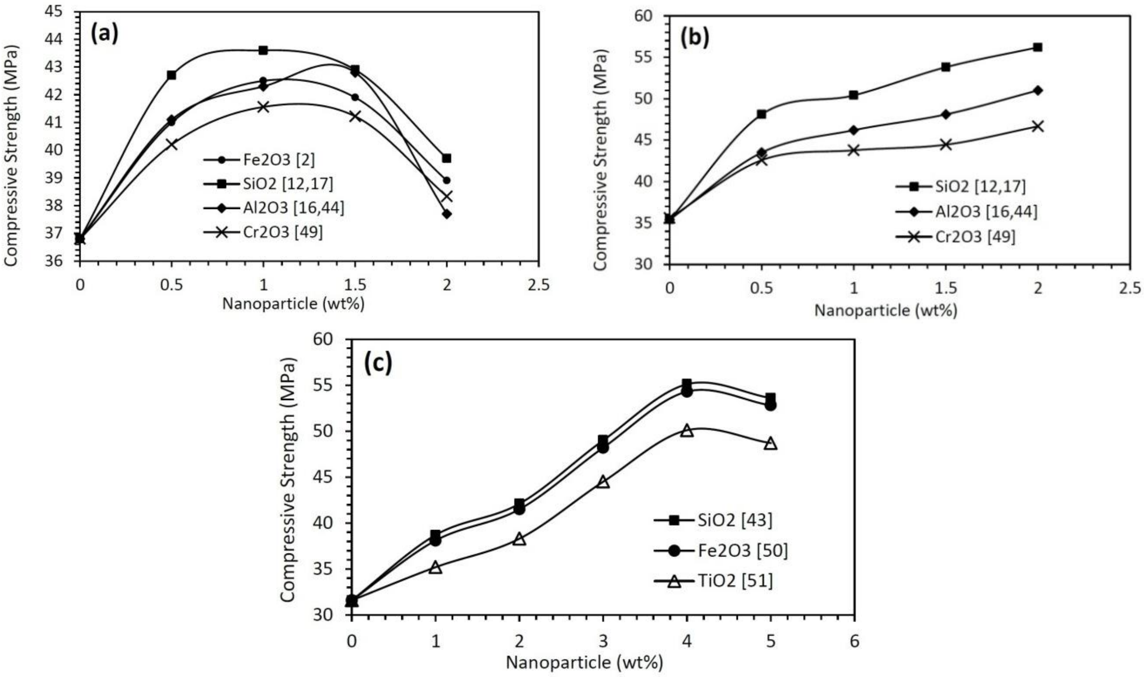

Fig. 2 Compressive strength of different specimens that are curing in (a) water (b) limewater and (c) water with 1.0 wt.% polycarboxylate in admixture, after 28 days

because of the high reactivity of oxide nanoparticles (Nazari and Riahi 2011, Morsy *et al.* 2012, Li *et al.* 2004). The other reason is that the oxide nanoparticles fill the cement pores, thus increasing the strength (Li *et al.* 2004, Nazari and Riahi 2011, Shebl *et al*. 2009). Moreover, due to very small sizes of the nanoparticles compared to the sizes of the cement particles, very large surface area is produced. This large surface area causes the oxide nanoparticles to react rapidly with the CH to form calcium silicate in alkaline environments such as the pore solution of portland cement paste (Shebl *et al*. 2009). Oxide nanoparticles recover the particle packing density of the blended cement, directing to a reduced volume of larger pores in the cement paste (Nazari and Riahi 2011, Morsy *et al*. 2012). From Figs. 2(a) and 2(b) can be concluded that the compressive strength of the N-LW series is more than those of N-W series. Once more this confirm the more strengthening gel formation in the presence of limewater in which the quantity of oxide nanoparticles present in the mix is close to the amount required to combine with the liberated lime within the hydration process. Thus, leading to a lesser silica leaching out in comparison of the specimens cured in water (Naji Givi and Abdul Rashid 2011, Nazari and Riahi 2011).

According to Figs. 2(a) and 2(c) by comparison the compressive strength of the specimens cured in water, it can be concluded that the presence of oxide nanoparticles up to a specific percent would increase the compressive strength and then it decreases, although the results of higher percent replacement is still higher than those of the C0-W concrete (Oltulu and Sahin 2011, Nazari and Riahi 2011). This may be related to this fact that the amount of oxide 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 cement material but does not contribute to the strength. Also, it may be correlated to the defects formed in dispersion of oxide nanoparticles that causes weak zones (Nazari and Riahi 2011, Riahi and Nazari 2011, Li *et al.* 2006). Typically, the compressive strength of nano-Al_2O_3 particle blended concrete specimens after 28 and 90 days of curing in water and limewater are given in table 2. As shown, the difference between the compressive strengths of the N-W and N-LW series after 28 days of curing was relatively high while, this difference in compressive strength after 90 days of curing is not significant. This may be related to the formation of crystalline $Ca(OH)_2$ in N-LW series after the 28 day causes reduction in compressive strength (Nazari and Riahi 2011).

It was necessary to note that, by decreasing the size of oxide nanoparticles, the rate of pozzolanic reaction was increased. The smaller the nanoparticle size, the more the heterogeneous nucleation sites results in faster early age strength as well as the more number of particles are available to act as nucleation sites for precipitation of hydration products (Naji *et al.* 2010, Li *et al.* 2004, Zhang *et al.* 2012).

2.1.2 Split tensile strength and flexural strength

Split tensile and flexural strength tests usually were performed in accordance with the ASTM standard. After a distinct curing period was over, the concrete cylinders were subjected to split tensile and flexural strength tests, using universal testing machine (Naji *et al.* 2011). Tests were done on the several specimens and the average split tensile strength values were reported (Naji *et al.* 2011, Nazari and Riahi 2011, Erdem *et al.* 2012, Soleymani 2012). Split tensile strength and flexural strength of N-series and C0-series are compared in Figs. 3 and 4, respectively. Similar to the compressive strength, the flexural and split tensile strength of N-series at final days of curing is more than that of C0-series (Naji *et al.* 2010, Hosseinpourpia *et al.* 2012, Qing *et al.* 2006). As shown in Figs. 3(b) and 4(b), the amount of nanoparticle for preparation of concrete with the best strength is significantly lower for the specimen are cured in saturated limewater (Soleymani 2012, Khoshakhlagh *et al.* 2012).

The mechanism of oxide nanoparticles effect on the flexural and the split tensile strength are similar to the effect of nanoparticles on compressive strength (Naji *et al.* 2010, Jalal *et al.* 2012, Nazari and Riahi 2011). Practically, the enhanced extent of concrete compressive strength is significantly higher than that of the flexural strength. This is essentially attributed to the presence of micro-cracks with various sizes in concrete. Also, the effect of micro-cracks on the flexural strength of concrete is higher than of the compressive strength. The presence of oxide nanoparticles have the same effect on the fracture behavior and the impact strength of concrete (Morsy *et al.* 2012, Li *et al.* 2006, Li *et al.* 2007).

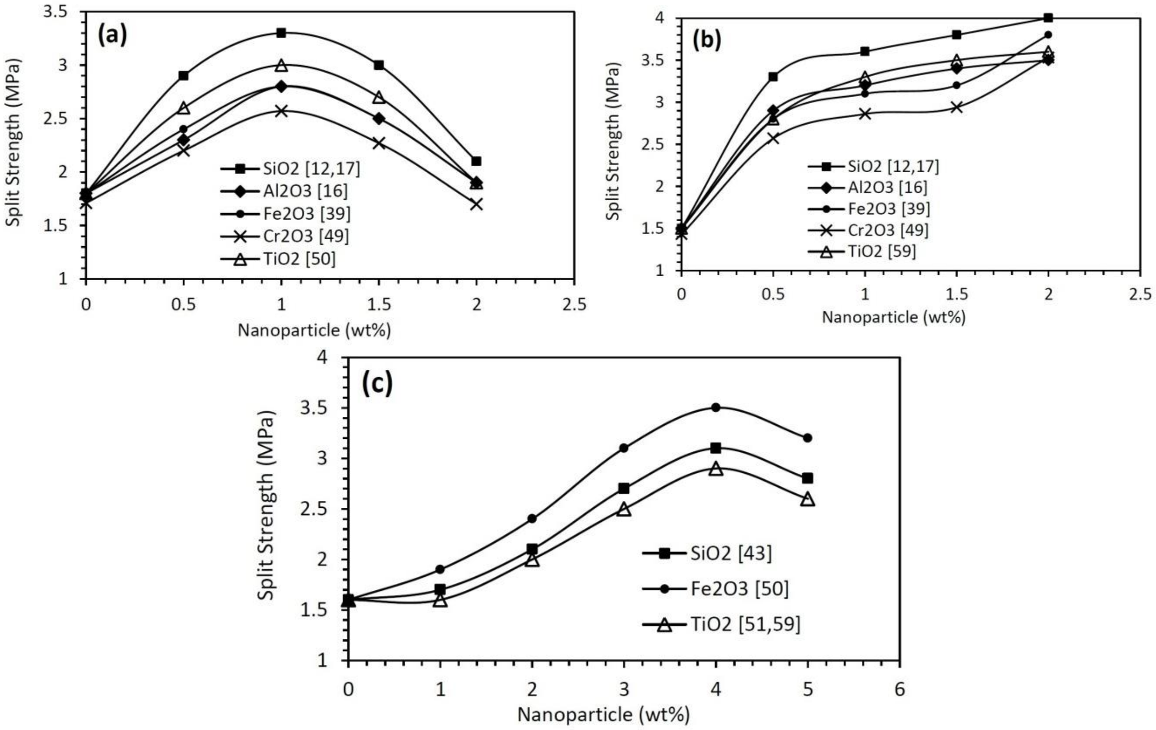

Fig. 3 Split tensile strength of different specimens that are curing in (a) water (b) limewater and (c) water with 1.0 wt.% polycarboxylate in admixture, after 28 days

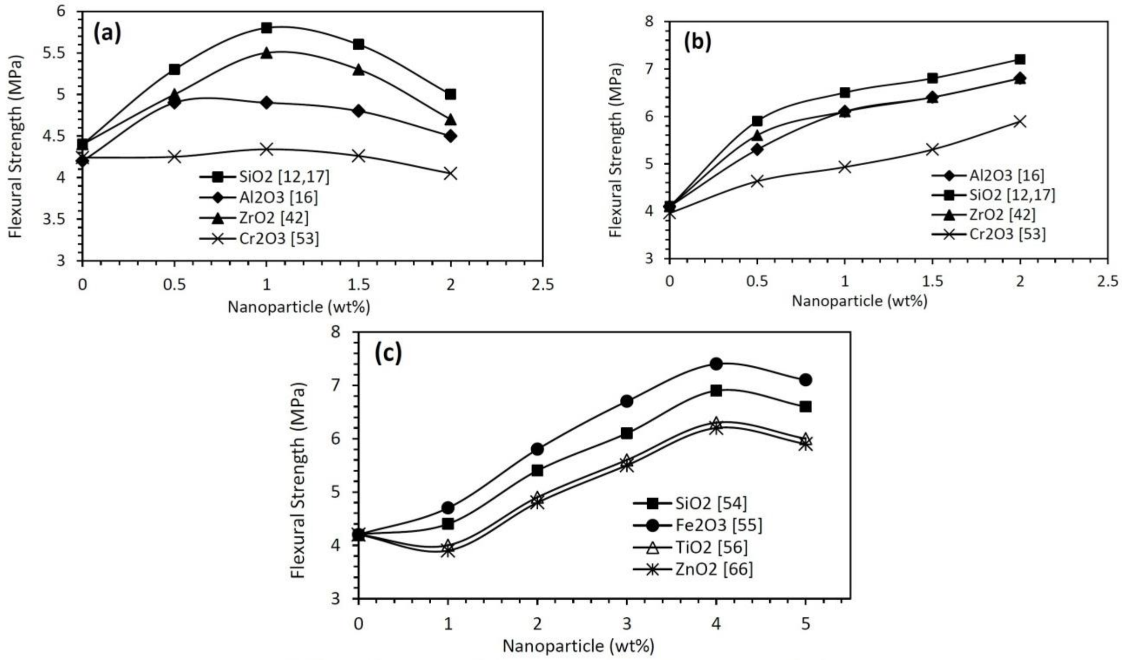

Fig. 4 Flexural strength of different specimens that are curing in (a) water (b) limewater and (c) water with 1.0 wt.% polycarboxylate in admixture, after 28 days

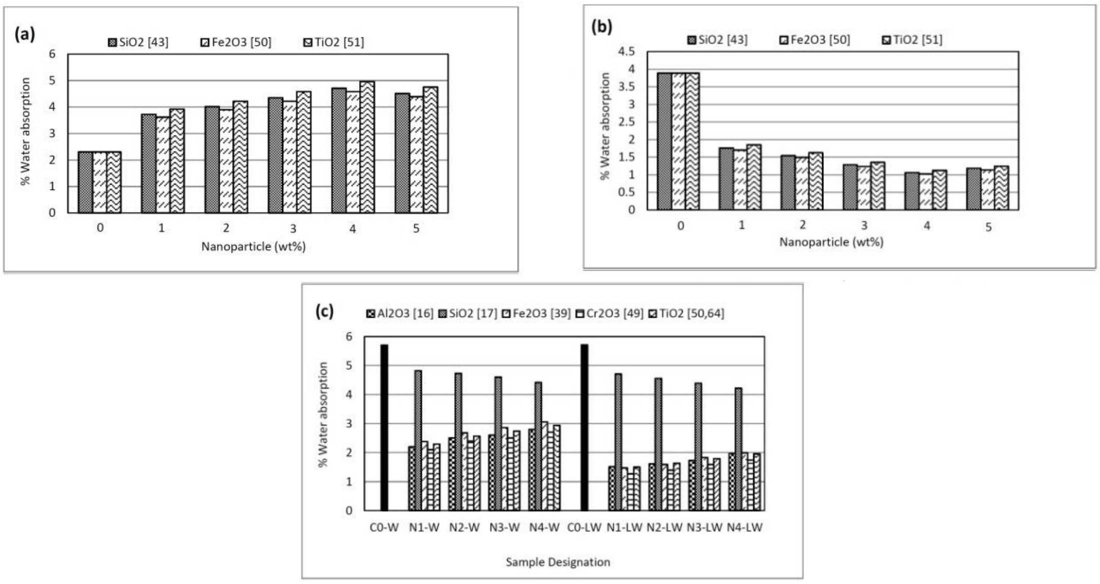

Fig. 5 Water absorption (%) of different specimens after (a) 2 days of curing in limewater (b) 28 days of curing in limewater and (c) 28 days of curing in water or limewater. N1, N2, N3 and N4 are the N-Series with 0.5%, 1.0%, 1.5% and 2.0% of nanoparticles, respectively. W denotes the specimens cured in water and LW denotes to those cured in saturated limewater

2.1.3 Water absorption (%) and Pore structure of concrete

The water absorption is criteria of the pore volume or porosity of concrete after hardening, which is occupied by the water or lime solution in saturated state. The percentage of water absorption of any type of nanoparticles blended concrete samples were calculated per ASTM standard after different days of moisture curing (Khanzadi *et al.* 2010, Naji *et al.* 2011, Raiess *et al.* 2010).

Fig. 5 compare the percentage of water absorption in N-series and C0-series. Accordingly, the percentage of water absorption in C0-series specimens at 7 days is lower than that of N-series while at 28 and 90 days of curing, this value is lower for N-series concrete. This may be explained by the formation of hydrated products in N-series at the early stages of curing. At 28 and 90 days of curing, the pore structure of N-series concrete is improved and water permeability of these series is diminished with respect to the C0-series concrete (Nazari and Riahi 2011). This behavior was shown in Figs. 5(a)-(b). As shown as in Fig. 5(b), the percentage of water absorption in N-series at 28 and 90 ages of curing is decreased by increasing the oxide nanoparticles content up to a specific percentage and then it is increased. This may be owing to the unsuitable dispersion of the oxide nanoparticles in the cement paste when the content of the oxide nanoparticles goes beyond 3 wt % (Khanzadi *et al.* 2010). High activity and filler effects of oxide nanoparticles caused that the same behavior for any type of nanoparticles.

Alireza Naji *et al.* (2011) reported the effect of limewater on the percentage of water absorption. The investigation was shown after 28 and 90 days of curing, the water absorption of N-LW series is lower than those of N-W series as a result of more C-S-H gel formation (Fig. 5(c)). While, at beginning days of curing the water absorption of N-LW series is higher than that of N-W series (Nazari and Riahi 2011).

In some references porosity is defining as pore structure of concrete. The pore structure of concrete is the general embodiment of porosity, pore size distribution, pore scale and pore geometry and is evaluated using the MIP test. The pore in concrete is categorized as harmless pore (<20 nm), few-harm pore (20-50 nm), harmful pore (50-200 nm) and multi-harm pore (>200 nm). By the presence of nanoparticles up to a specific percent, the total specific pore volumes of concretes is decreased, and the most probable pore diameters of concretes shift to the smaller pores and fall in to the range of few-harm pore, indicating that the presence of nanoparticles refines the pore structure of concretes. As shown in Fig. 6(a) by the addition of oxide nanoparticles, the amounts of pores decrease, which shows that the density of concretes is enhanced and the pore structure is modified. The modification of pore structure (general embodiment of porosity, pore size distribution, pore scale and pore geometry) in N-LW series is more drastic than the N-W series (Diamantonis *et al.* 2010). Also, by increasing of the amount of oxide nanoparticles in N-LW series the pore size amount decreased. While, in N-W series this trend was reversed after specific amount of nanoparticle content (Fig. 6(b)). The mechanism that the oxide nanoparticles modify the pore structure of concrete as the same as the effect of nanoparticles on the abrasion resistance of cement. This makes the cement matrix more homogeneous and compact (Nazari and Riahi 2011, Lin *et al*. 2008, Soleymani 2012).

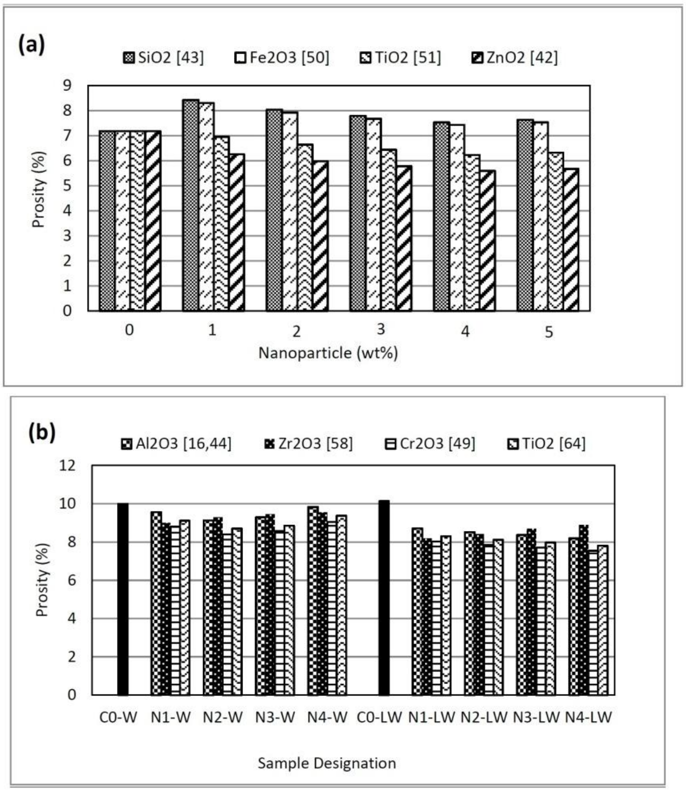

Fig. 6 Pore structure of different specimens that are curing in (a) water with 1.0 to 5.0 wt.% nanoparticles and 1.0 wt.% polycarboxylate admixture (b) water and lime without polycarboxylate admixture, after 28 days. N1, N2, N3 and N4 are the N-Series with 0.5%, 1.0%, 1.5% and 2.0% of nanoparticles, respectively. W denotes the specimens cured in water and LW denotes to those cured in saturated limewater

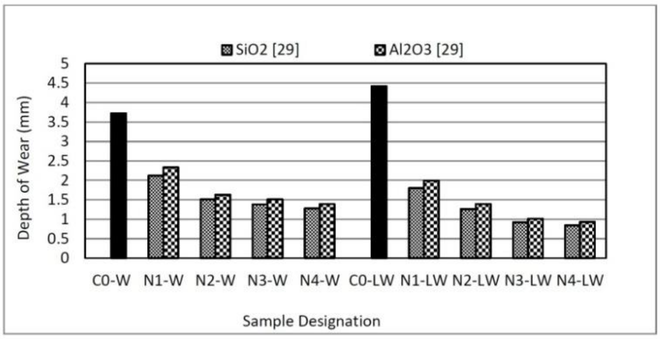

Fig. 7 The abrasion resistance of different specimens, after 28 days; N1, N2, N3 and N4 are the N-Series with 0.5%, 1.0%, 1.5% and 2.0% of nanoparticles, respectively. W denotes the specimens cured in water and LW denotes to those cured in saturated limewater

2.1.4 Abrasion resistance

To the best of our knowledge, there are a few numbers of investigations about the effect of oxide nanoparticles on the abrasion resistant of concrete. According to Nazari and Riahi (2011), the abrasion resistance of concretes containing oxide nanoparticles is remarkably improved; especially for concrete containing SiO_2 nanoparticles (Fig. 7).

Assume that the nanoparticles are regularly dispersed and each particle is contained in a cube pattern, the distance between nanoparticles can be determined. After hydration begins, hydrate products diffuse and envelop nanoparticles as kernel. If the amount of nanoparticles and the distance between them are suitable, the crystallization will be controlled to be an appropriate state through restricting the growth of $Ca(OH)_2$ crystal by nanoparticles (Li *et al*. 2006). In contrast with the compressive strength, the abrasion resistance of concrete specimens is enhanced with oxide nanoparticles content in N-W series (Jalal *et al*. 2012). It seems that the nanoparticles could act as an abrasive-resistant particle which prevents more erosion with respect to the C0-W and N-W series with lesser content of nanoparticles. As shown in Fig. 7, In C0-LW and N-LW series, abrasion resistance is increased up to a percent that higher than the percent of nanoparticles in C0-W and N-W series, similar to the compressive strength of these specimens (Nazari and Riahi 2011).

2.2 Fresh concrete

When the mixing procedure is completed, tests were conducted on the fresh concrete to determine the workability i.e., slump flow, and setting time (Jalal *et al*. 2012, Madandoust *et al*. 2011, Zaki *et al*. 2009).

2.2.1 Workability or slump flow

Workability or slump flow is the ability of concrete to flow easily but at the same time is free of segregation (Nazari and Riahi 2011, Nazari *et al.* 2010). Standard slump tests conforming to ASTM were used to determine the workability of the concrete (Nazari *et al.* 2010). The slump flow represents the mean diameter of concrete mass after release on standard slump cone (Jalal *et al.* 2012). Also, determination of slump flow (cm) is done according to the time usually required to flow through V-funnel (s) and filling height ratio of L-box test that is conducted immediately after

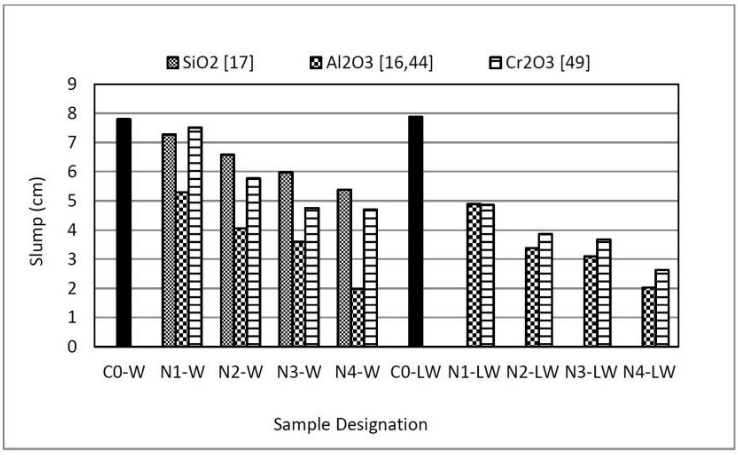

Fig. 8 Workability of concrete containing different nanoparticles. N1, N2, N3 and N4 are the N-Series with 0.5%, 1.0%, 1.5% and 2.0% of nanoparticles, respectively. W denotes the specimens cured in water and LW denotes to those cured in saturated limewater

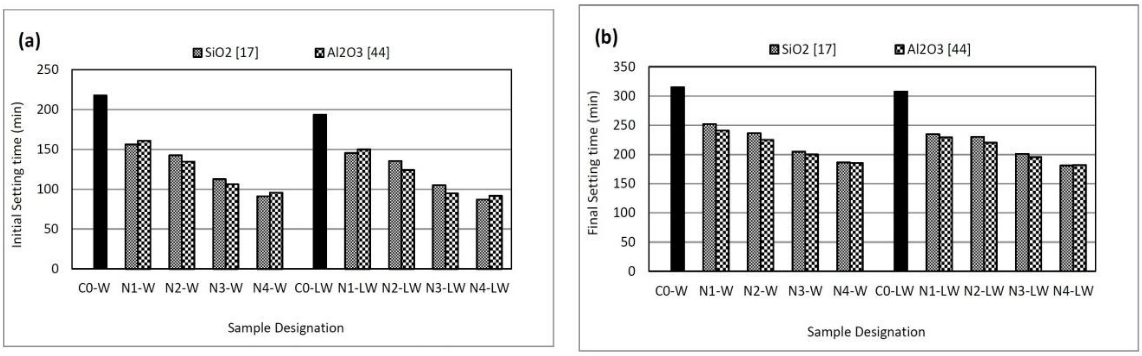

Fig. 9 The effects of nanoparticles on the (a) initial and (b) final setting time of concrete. N1, N2, N3 and N4 are the N-Series with 0.5, 1.0, 1.5 and 2.0 wt% of nanoparticles, respectively. W denotes the specimens cured in water and LW denotes those cured in saturated limewater

the mixing of the concrete (Sadrmomtazi and Barzegar 2010, Jalal *et al*. 2012, Madandoust *et al.* 2011).

Fig. 8 shows the effect of oxide nanoparticles content on workability of mixtures at constant water to binder ratio. Unlike the C0-series, all investigated oxide nanoparticles blended mixtures had low slump values and non-acceptable workability (Berra *et al.* 2012, Quercia *et al*. 2012). It might be explained that the increasing surface requires more water (Liu, *et al*. 2012). Moreover, because of the more rapid generation of C-S-H gel, a higher viscose mortar with reduced workability produced and consequently the reduction in workability of N-LW series is higher than that of N-W series (Ltifi, *et al*. 2011, Nazari and Riahi (2011). It can be considered that increasing of binder content such as slag modified the rheological properties due to increasing of the paste volume and consequently the flowability of fresh concrete is more uniform. In these conditions, the segregation probability is reduced significantly (Jalal *et al.* 2012).

2.2.2 Setting time

The standard consistence and setting time of the cement pastes were determined using a Vicat apparatus (Chen *et al*. 2012, Naji *et al*. 2011). Fig. 9 compares the effect of oxide nanoparticles on setting time of concrete.

As shown in Fig. 9(a) and 9(b), by increasing the content of oxide nanoparticles, the setting time is reduced, indicating that the oxide nanoparticles has a faster hydration reaction rate than the cement (Sadrmomtazi and Barzegar 2010, Chen *et al*. 2012, Ltifi *et al*. 2011, Zhang *et al*. 2012). Smaller particle sizes allow a rapid increase in surface area leading to a fast rise in the number of surface atoms. These surface atoms are significantly active and unstable, which results in a faster reaction speed. Consequently, the viscosity increased and solidification occurred earlier (Chen *et al.* 2012, Lin *et al.* 2008, Meng *et al.* 2012). Moreover, the reduction in setting time of N-LW series is higher than those of N-W series because of the higher rapid formation of C-S-H gel results in more viscose mortar with reduced setting time (Naji *et al.* 2011, Nazari and Riahi *et al.* 2011).

3. Conclusions

We have presented a survey and classification of the effect of oxide nanoparticles on hardened and fresh concrete properties. From this survey it can be seen that there is still a lot of work to be done in the field of the effect of oxide nanoparticles on concrete processing. It also observed from this survey that:

1- SiO_2 nanoparticles is the most effective on compressive strength and abrasion resistance of concrete (Figs. 2(a), 2(b), 2(c) and (6));

2- SiO_2 ,Al_2O_3 and in some conditions Fe_2O_3 nanoparticles are the most effective nanoparticles on split and flexural strength of concrete (Figs. 3(a), 3(b), 3(c), 4(a), 4(b), 4(c));

3- According to figure 2a, 2c, 3a, 3c, 4a and 4c by comparison the strength of the specimens cured in water, it can be concluded that the presence of oxide nanoparticles up to a specific percent would increase the strength and then it decreases. This may be related to this fact that the amount of oxide nanoparticles present in the mix is higher than the amount required to combine with the liberated lime during the process of hydration. Also, it may be correlated to the defects formed in dispersion of oxide nanoparticles that causes weak zones.

4- Water absorption is more impressible by Fe_2O_3 and Cr_2O_3 nanoparticles than the others (Figs. 5(a), 5(b) and 5(c));

5- The effects of ZnO_2 and Cr_2O_3 nanoparticles on porosity are higher than the other oxide nanoparticles (Figs. 7(a) and 7(b));

6- The effect of Cr_2O_3 nanoparticles on slump is more than the other oxide nanoparticles (Fig. 8);

7- SiO_2 nanoparticles reduced the setting time more than Al2O3 nanoparticles. So it seems that using of SiO_2 nanoparticles is better than Al_2O_3 (Figs. 9(a) and 9(b)).

8- Using of oxide nanoparticles on concrete processing can significantly improve the mechanical and physical properties of concrete. These effects are more serious in the presence of limestone.

At present time, the most of research works are concentrated on the application of the precious oxide nanoparticles such as SiO_2, TiO_2, Fe_2O_3, ZnO_2, Cr_2O_3 and Al_2O_3, separately. The studies on the application of other nanoparticles or the mixture of two or more type are needed to be carried out further.

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Abbreviations and definitions

OPC	Ordinary portland cement
MIP	Mercury intrusion porosimetry
C0-series concrete	A type of concrete is prepared by mixing of ordinary portland cement, fine or ultra-fine crushed limestone, polycarboxylate and water.
N-series concrete	A type of concrete is prepared by the addition of different size and amount of nanoparticles to C0-series.
N-W concrete	N-series concrete that are cured in water.
N-LW concrete	N-series concrete that are cured in limewater.
C0-W concrete	C0-series concrete that are cured in water.
C0-LW concrete	C0-series concrete that are cured in lime water.