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Enhancing the permeability and abrasion resistance of concrete using colloidal nano-SiO_2 oxide and spraying nanosilicon practices

R. Bani Ardalan [a], N. Jamshidi [b], H. Arabameri [c], A. Joshaghani [d], M. Mehrinejad [e], P. Sharafi [a,*]

[a] Center for Infrastructure Engineering, Western Sydney University, Australia
[b] CEO at FITEON Inc., Iran
[c] Faculty of Civil and Environmental Engineering, Tarbiat Modares University, Tehran, Iran
[d] Zachry Department of Civil Engineering, Texas A&M University, TX, United States
[e] School of Civil Engineering and Surveying, University of Southern Queensland, Australia

HIGHLIGHTS

- Reducing permeability and enhance the water resistance properties of concrete.
- Spraying nanosilicon to surface and treatment in water-diluted nano-SiO_2 oxide.
- Comparing mechanical & microstructure properties of treated and untreated concrete.
- Nano-SiO_2 as an additive after preparing concrete and during curing process.

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ABSTRACT

By protecting concrete from penetration of aggressive chemicals, *low permeability* is one of the most important contributory factors to the concrete's durability. In this paper the effects of nano-SiO_2 particles on concrete permeability are studied through employing the technique of spraying nanosilicon and treatment in the water-diluted nano-SiO_2 oxide. To this end, some mechanical and microstructure properties of concrete are investigated. The results show that the compression strength and the resistance of specimens to water penetration are significantly increased, whether in the mixtures cured in the colloidal solution or those being sprayed with nano-SiO_2. The minute dimensions of these particles allow them to penetrate up to a particular depth in a concrete panel. Hence, through improvement of concrete panel nanostructures, these particles participate in the completion of the hydration process, which in turn leads to a reduction in their permeability and development of a protective layer, and therefore the increase of bulk concrete panel durability. The experiment's outcomes also develop thorough understanding of the effects of nano-SiO_2 as an additive material after preparing the concrete and during the curing process.

1. Introduction

In recent years, there has been a growing interest in nanotechnological products, processes and applications due to their wide potential benefits [1]. In concrete technology, some nanoparticles, such as SiO_2, ZnO_2, Al_2O_3, CuO, $CaCo_3$, Fe_2O_3, and TiO_2 have been widely employed by many researchers to enhance the quality of cementitious materials, by modifying the microstructural, mechanical and durability properties of concrete or mortar [2–10]. When nanoparticles are integrated with cement-based building materials, the new materials can possess some outstanding properties. During previous studies, Nano-SiO_2 has been one of the most commonly used materials in comparison with the other nanomaterials [11–16]. However, the literature has been mainly focused on the study of the properties of concrete or mortar mixtures containing these nanoparticles as additives, and other techniques of treatments have not been adequately investigated. Qing et al. [11] showed that in comparison to adding silica fume, nano-SiO_2 influences compressive strengths of hardened cement paste and bond strengths of the paste-aggregate interface in a different way. Incorporating nano-SiO_2 into cement has stronger effects on cement properties compared to silica fume, especially at an early age. Jalal et al. [12,17] investigated the effects of micro SiO_2 and nanoparticles on the rheological, mechanical, durability and microstructural characteristics of high-performance self-

* Corresponding author.
E-mail address: P.Sharafi@westernsydeny.edu.au (P. Sharafi).

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compacting concrete. The results indicates that using micro and nano-silica can have a remarkable influence on improving the various properties of concrete [18]. The authors also investigated the split tensile strength along with the rheological, thermal, transport and microstructural properties of self-compacting concrete (SCC) containing low volume fly ash and TiO_2 nanoparticles. They showed TiO_2 nano-powder improves the microstructure of concrete by shifting the distributed pores to finer and less harmful pores [19]. The results of their study also showed that mechanical and transport properties improves in the mixtures containing admixtures especially blend of silica nanoparticles and silica fume [20].

Madandoust et al. [5] studied the effects of the addition of nano-SiO_2, nano-Fe_2O_3 and nano-CuO particles on the microstructural and durability performance of self-compacting mortar containing fly ash. According to their results, the properties of fresh and hardened samples are affected considerably by the nanoparticle ratio in the cement mortars. In their tests, the slump flow diameter increased by 4.2% and V-funnel flow time decreased by 13%. The specimen containing nano-SiO_2 had the highest strength compared to other specimens. For example, with 5% cement replacement, the compressive strength increases 18% at the age of 90 days. The addition of nano-SiO_2 also improves resistance to water permeability [14,16]. Naji et al. [15], discovered that curing in the limewater can reduce the strength of control concrete, but curing the specimens containing SiO_2 nanoparticles in saturated limewater causes a more rapid setting time as well as higher values of strength and resistance to water absorption. Findings from the literature indicate that the nano scale SiO_2 behaves not only as a filler to improve microstructure but also as an activator to promote the pozzolanic reaction [1]. Nano-SiO_2 particles enhance the density of cement paste in three ways: as a pozzolan, a core for forming C-S-H gel, and as a nano-scale filler for filling nano-scale pores. All these three mechanisms can act cooperatively at the same time [7].

The concrete durability critically influences the service life of the concrete structure [21], and consequently its life cycle costs [22]. In addition, concrete permeability is one of the most important parameters influencing the durability of concrete and its performance [23,24]. The most important factor in steel-reinforced concrete corrosion is diffusion of destructive ions to the concrete. Hence, reduction in permeability of the outer layer of the concrete can prevent these ions from reaching to reinforced-concrete [25] Given that permeability reduction in the back part of reinforced-concrete has no role in the prevention of its corrosion, focus on the decrease of permeability in the outer layer and reinforced-concrete cover can lead to a reduction in material cost [26–29]. A water permeability test shows that for concretes with similar 28-day strength, the incorporation of nano-SiO_2 particles can improve resistance to water permeability in concretes [30,31]. As Mehta et al. [32] reported, the permeability coefficient in day 6 is nearly 100 times higher than day 24. Moreover, many investigations on the abrasion resistance of concrete shows that it is strongly influenced by surface finishing techniques, compressive strength, aggregate properties, curing method, and testing conditions [1,2]. It is also demonstrated by previous studies that curing methods have an significant impact on the abrasion resistance of mortar or concrete [3]. In general, appropriate curing practices are proven to remarkably promote the abrasion resistance of concrete. Although some great advantages of nano-SiO_2 as an effective additive and partial replacement of cement have been investigated in the literature, their other practical applications in concrete technology have not been yet thoroughly surveyed.

Considering high costs of these materials compared with the other ingredients of concrete, this research study is an attempt to develop an economical method to employ nano-SiO_2 particles in order to reduce permeability and enhance the water resistance of concrete. This work is concentrated on evaluating the effect of curing concrete by colloidal nano-SiO_2 and nanosilicon spray, on water permeability and abrasion resistance. The nanoparticles' transfer with water or sprayer from concrete surface to its body is investigated through measuring permeability and abrasion changes. During the tests, permeability depth was frequently measured after applying water pressure. The experimental tests of slump, density, compressive strength, permeability, abrasion, and SEM were conducted in this study. The study shows how using curing concrete in colloidal nano-SiO_2 oxide and spraying nanosilicon practices to the surface of the concrete, can result in significant improvement in permeability and abrasion resistance. The findings can also contribute to determining the optimal nano-SiO_2 proportions.

2. Experimental work

2.1. Materials

For all samples, type II Ordinary Portland cement conforming to the requirements of the ASTM C150 was used [33]. The physical characteristics and chemical compositions of the Portland cementash are summarized in Table 1. Moreover, coarse aggregate size number 57 (2.5–4.75 mm) was designated, according to the ASTM C33 [34]. Also, fine aggregate meets the specifications mentioned in the ASTM C33 standard [35]. To increase workability in all mixtures, superplasticizer was added, which was a poly carboxylate-based high range water reducer (HRWR) with a density of between 1.06 and 1.08 g/cm^3 (at 20 °C) [21]. The specific gravity of the expander additive was 1200 kg/m^3. To produce sample mixtures with different properties in this research, various ratios of water to cementation materials are considered. SiO_2 nanoparticles with an average particle size of 50 nm were used.

2.2. Mixture proportions

A total of 4 mixtures containing 144 samples in 150 × 150 × 150 mm cubes were designed with the same materials and different water/binder ratios. Half of the samples were supposed to have 28 days of colloidal nano-SiO_2 curing with three different nano-SiO_2 contents (12%, 8%, and 4%). Meanwhile, some cubic specimens were kept in tap water as control samples. The other samples were sprayed with nanosilicon in two different contents (25% and 50%) at three different times; i) immediately after casting the mixture in the mold ii) after 1 h and 45 min iii) after 4 h of casting. For each mixture, 18 cubic samples were made. Nano-SiO_2 did not have any effect on the abrasion resistance and just influenced the cement paste. Therefore, in order to achieve

Table 1
Chemical composition and physical properties of cement.

Chemical analysis (wt%)	Cement
SiO_2	21.56
Al_2O_3	6.67
Fe_2O_3	6.17
Cao	49.88
MgO	4.51
SO_3	2.75
K_2O	0.76
Na_2O	0.43
LOI	2.79
Specific gravity (g/cm^3)	3.18
Specific surface area (cm^2/g)	4168