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Effect of SnO_2, ZrO_2, and $CaCO_3$ nanoparticles on water transport and durability properties of self-compacting mortar containing fly ash: Experimental observations and ANFIS predictions

Mojdeh Mehrinejad Khotbehsara [a,b], Bahareh Mehdizadeh Miyandehi [b], Farzad Naseri [c], Togay Ozbakkaloglu [d,*], Faezeh Jafari [e], Ehsan Mohseni [b,f]

[a] Centre for Future Materials (CFM), School of Civil Engineering and Surveying, University of Southern Queensland, Toowoomba, QLD 4350, Australia
[b] Department of Civil Engineering, University of Guilan, Rasht, Iran
[c] Department of Civil Engineering, University of Islamic Azad University, Electronic Branch, Tehran, Iran
[d] School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, SA 5005, Australia
[e] Department of Civil Engineering, University of Malayer, Malayer, Iran
[f] School of Architecture and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia

HIGHLIGHTS

- Cement mortars incorporating different nano additives and fly ash were produced.
- Addition of nano SnO_2, ZrO_2 and $CaCO_3$ leads to improvements in the durability of self-compacting mortars.
- Porosimetry and SEM results show a better packed pore structure with the addition of nanoparticles.
- The chloride permeability of mortars decreases with an increase in the dose of nanoparticles.
- ANFIS predictions of the hardened mortar properties are in close agreement with the experimental results.

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ABSTRACT

This paper investigates the influence of the addition of nanoparticles, namely SnO_2, ZrO_2 and $CaCO_3$, at different doses on the durability and the microstructure of self-compacting mortar (SCM). Rheological characteristics were observed through mini slump flow diameter and mini V-funnel flow time. Transport properties were studied by the water absorption and capillary absorption tests. Mechanical properties were determined by the compression tests. Durability properties were examined by the electrical resistivity and rapid chloride permeability tests. Microstructure of SCMs was investigated through scanning electron microscopy (SEM). The mixtures containing nanoparticles exhibit improved transport properties, with increased compressive strengths and resistance to water and chloride ion penetration. These improvements are attributed to the compact microstructures, as the micro pore system was refined in the presence of nanoparticles. Based on fresh and hardened mortar properties, it is found that 5 wt% SnO_2, 4 wt% ZrO_2, and 3 wt% $CaCO_3$ would serve as suitable replacement levels in optimizing the overall performance. An adaptive neuro-fuzzy inference system (ANFIS) was employed to predict the SCM properties. The numerical results show that the metamodels provide accurate estimates of experimental results.

1. Introduction

The use of Portland cement in concrete is mainly responsible for the high environmental impact of concrete structures manufactured with Portland cement. Therefore, incorporation of supplementary cementitious materials, such as ground granulated blast furnace slag and fly ash, to reduce the carbon footprint of concrete has been studied extensively. It is predicted that the present day concrete technology would allow new buildings to be built with 60% less CO_2 emissions and energy use over the lifecycle of the building in comparison with the buildings constructed more than 20 years ago [1–4].

* Corresponding author.
E-mail addresses: Mojdeh.Mehrinejad@usq.edu.au (M.M. Khotbehsara), togay.ozbakkaloglu@adelaide.edu.au (T. Ozbakkaloglu), Ehsan.mohseni@uon.edu.au (E. Mohseni).

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Self-compaction of concrete can be achieved by restricting the content and size of coarse aggregates, while also using superplasticizers (SPs) to maintain a lower water-powder ratio [5–7]. This leads to a material that can be placed without any external vibration, which is recognized as a revolutionary technology in concrete industry. Because self-compacting concrete (SCC) has less coarse aggregates than regular concrete, mortar properties have a major influence on the overall performance of this material. Measuring the rheological properties of SCC is often challenging due to the need for sophisticated instruments, and for this reason the behavior of self-compacting mortar (SCM) is often studied (e.g. [5,8–10]) to gain insights into the behavior of SCC. Furthermore, assessing the properties of mortar can itself be useful, as this forms a main component of SCC mix design processes. Based on these considerations SCMs were used in the current study.

In recent years, numerous studies have been undertaken to investigate the incorporation of nanoparticles including nano-SiO_2 [11–15] and nano-TiO_2 [16–19] as well as a few other particles, such as nano-Al_2O_3, nano-CuO and nano-Fe_2O_3 [20–22] in mortar and concrete. Most of these studies examined the effect of nanoparticles on the compressive strength and water transport of new cement-based composites. Quercia et al. [11] reported the effect of 3.8% colloidal nano-SiO_2 on the durability properties of self-compacting concrete. The results indicated that the use of nanoparticles led the pores become finer and less connected. Moreover, the paste-aggregate interface was modified and became more compact to provide a higher resistance against harmful agents. As a result, the chloride diffusion, water resistance under pressure, and migration coefficient were decreased by 63.1%, 88.5%, and 63.6%, respectively. Du et al. [12] investigated the transport properties of concrete containing 0.3% and 0.9% of nano-SiO_2. The calcium hydroxide was quickly consumed with the addition of nano-SiO_2. Furthermore, the paste pore systems were refined even at the small nano-SiO_2 addition of 0.3%. Owing to the fewer connected holes and pores, the water penetration depth, chloride migration and diffusion, and rate of water absorption significantly decreased. Hou et al. [13] assessed the effect of surface-treatment of nano-SiO_2 on the transport characteristics of hardened cement pastes, and reported a linear correlation between the transport property and the volume of capillary pores. This was attributed to the reduced transport properties of hardened cement pastes. The advantages of concrete containing nano-TiO_2 over conventional concrete in resisting combined effects of chloride diffusion and scouring was studied by Li et al. [14]. It was reported that the concrete containing 1% nano-TiO_2 by mass of Portland cement showed an improvement in microstructure and porosity, resulting in better impermeability as well as durability. It was reported that there existed a critical nano-SiO_2 or nano-TiO_2 content beyond which the properties of concrete containing nanoparticles could not be further enhanced as more air voids would be dragged out through the system. Mohseni et al. [16] found that 1–3% colloidal nano-SiO_2 and 5% colloidal nano-TiO_2 could lead to the best durability and mechanical properties.

The influence of nanoparticles studied in the current study, namely nano-SnO_2, nano-ZrO_2, and nano-$CaCO_3$, on the mechanical properties of cement-based materials has also been investigated in a couple of previous studies [23–28]. Among these few studies, Nazari et al. [25] reported that ZrO_2 nanoparticles up to 4% by mass of Portland cement could improve the mechanical and physical properties of the concretes. He experimentally showed that the compressive strength, flexural strength and split tensile strength of SCC mixes were increased with the incorporation of nano-ZrO_2 due to more formation of hydrated products. The positive effect of SnO_2 nanoparticles the mechanical and physical properties of the high-strength SCCs has been also reported by him [27]. The results showed that incorporation of up to 2% SnO_2 nanoparticles could significantly increase the compressive strength. Liu et al. [28] conducted a research on investigation of the compressive strength and flexural strength, at ages of 7 and 28 days, of cement pastes modified with nano-$CaCO_3$. Cement was partially replaced with nano-$CaCO_3$ at levels of 0%, 1%, 2% and 3%, by weight. An increase in the compressive strength was observed with the addition of nano-$CaCO_3$, and the optimum content of nano-$CaCO_3$ providing the highest compressive strength was 2%. However, investigations with regard to the effect of these nanoparticles on the water transport properties, microstructure, and durability of self-compacting cementitious materials have been limited. In addition, the effects of nanoparticles on the rheological and physical properties of self-compacting mortar (SCM) have so far received very limited attention.

Adaptive neuro-fuzzy inference system (ANFIS) is a powerful method for prediction concrete properties. ANFIS that was first applied by Jang [29], has the capability to approximate real continuous functions. The structure consists of a number of nodes, which are connected through directional links, and each node has a function comprising adjustable or fixed parameters. Recently, a number of studies have been reported on the application of this method [30–39]. Nataraja et al. [32] presented the development of ANFIS method for predicting proportioning of standard concrete mixes. For achieving that three layers back propagation neural network were applied to obtain the relationship between 28 days compressive strength and w/c ratio. Emiroğlu et al. [33] used ANFIS to predict the peak loads of the glass fiber-reinforced concrete pipes with good accuracy. In 2012, Mohammadhassani et al. [34] applied ANFIS to estimate deflections in high-strength SCC deep beams. Vakhshouri et al. [35] investigated the nonlinear relationship between the splitting tensile strength and modulus of elasticity with the compressive strength of high-strength concrete. Chou et al. [36] suggested ANFIS algorithm as a method to predict the carbonation depth of a reinforced concrete member. However, ANFIS predictions of the rheological, physical, water transport and durability properties of self-compacting cementitious materials containing nanoparticles and fly ash have not been previously reported in the literature.

The main aim of the work reported in this paper is to study, for the first time, the influence of three different types of nanoparticles, viz. nano-SnO_2 (NS), nano-ZrO_2 (NZ) and nano-$CaCO_3$ (NC), on the microstructure, rheology, water transport, and durability of SCMs containing fly ash. To this end, water transport and durability properties of the mortars were investigated together with their workability and compressive strength. The water transport properties were determined by the capillary and water absorption tests, whereas the durability performance was assessed by the electrical resistivity and rapid chloride permeability tests. Finally, the application of ANFIS method to predict the properties of SCM was presented.

2. Experimental program

2.1. Materials

Type II Portland cement in accord with ASTM C150 [40] standard was used in the mortar mixes together with river sand that was employed as the fine aggregate. Fly ash classified as Class F was also added to the mix at a constant rate (i.e. 175 kg/m^3). The physical characteristics and chemical compositions of the Portland cement and fly ash are summarized in Table 1. To enhance the flowability of the mixes, a polycarboxylic-ether (PCE) type super plasticizer (SP) with a density of 1030 kg/m^3 conforming to ASTM C494 TYPE F [41] was used. SP was added at different dosages to achieve the workability recommended by EFNARC [42]. SnO_2,