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The effect of nano silica on short term drying shrinkage of POFA cement mortars

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HIGHLIGHTS

- Nano silica decreased the permeability of POFA mortars.
- Nano silica increased the hydration rate in POFA mortars.
- Inclusion of nano silica decreased the drying shrinkage.

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ABSTRACT

This study investigates effects of nano silica on short-term drying shrinkage of mortars with palm oil fuel ash (POFA) during the first 28 days of curing. Furthermore, moisture content, hydration volume, and permeability were measured in order to study underlying mechanisms. It was revealed that addition of nano silica to samples with 30% POFA as cement replacement lowered the drying shrinkage by 7.5%. Also, it increased the strength development rate by 15% from 7 to 28 days of curing. Nano silica advantageously affected the shrinkage by refining the microstructure, increasing the hydration volume and lowering free water in cement matrix.

1. Introduction

One of the important factors in dimensional stability of concrete is drying shrinkage which is associated with moisture loss from the hydrated cement paste. The removal of interlayer water film from the C–S–H structure and tortuosity of the transport pass through the capillary network cause a strong driving force which ends to induce contraction of the matrix [1]. Drying shrinkage can be the origin of cracking, pre-stress losses, stress re-distribution, excessive deflection, and ingression of water and aggressive chemicals [2,3]. The crack formation is mostly because of quasi-brittle behavior of concrete in which the tensile stress develops due to restraints from sub-grade friction, end members, the reinforcing steel, and aggregates when contraction is induced [4,5]. So far, many studies have been conducted on aggregates [6,7] and mineral admixtures [8–11] to mitigate the drying shrinkage effect on concrete.

Mineral admixtures affect the drying shrinkage by increasing the formation of C–S–H, increasing the volume of fine pores in the matrix and densifying the interfacial transition zone. Previously, lower drying shrinkage especially at later ages of curing has been reported when mineral admixtures were added to concrete [12]. Katri et al. [13] reported that substitution of 10% of cement by silica fume increased the shrinkage at early ages but reduced its long term rate. Also, Jianyang and Yan [14] replaced cement with 10% silica fume, 30% slag and a combination of 30% slag and 10% silica fume. They realized that although shrinkage was similar at early ages, it was less in the ternary mix of silica fume and slag at 28 days. In another study, Atis et al. [15] studied the shrinkage evolution of mortars with 10%, 20% and 30% of fly ash. It was found that the shrinkage reduced by 25%, 37% and 43% at the later age of 5 months. However, in a study by Itim et al. [3], it was observed that even in the first week of curing age, the drying shrinkage of mortars with limestone powder and natural pozzolan was reduced. It was reported that fine pores and high impermeability of the binary mixed mortars reduced desiccation at early ages. For slag which is more active at early ages, both fineness and pozzolanic reaction were effective. Also, Guneyisi et al. [10] reported that the shrinkage of plain concrete was reduced at early ages when silica fume and Metakaolin were

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added to the mix. It was observed that the higher dosages (15%) of each added mineral admixture showed to have a better effect both at early ages and at ages of 45 days, especially after the first week of curing. The lower shrinkage rate was related to an increase in the amount of AFt crystal hydrates and the C–S–H gel in the cement paste which offers hardened concrete a stronger structure and higher resistance to deformation. Also, the filling effect and shifting size of pores to smaller ones were regarded as other reasons for the reduced shrinkage rate.

One of the recent used mineral admixtures in concrete is palm oil fuel ash (POFA) which is a by-product from biomass thermal power plants where oil palm residues are burned to generate electricity. The POFA has a large content of SiO_2 and can be used as a pozzolanic material [16]. However, studies have shown that the original size of POFA weakens the microstructure due to its large particle size with a porous structure [17–19]. Therefore, a grinding process has been suggested in many studies to enhance its reactivity and the filling function [20–22]. Tangchirapat et al. [19] studied effects of POFA with different fineness on concrete properties. They reported that a replacement of up to 10% ground POFA with median particle size of 7.4 μm had similar compressive strength values to the control concrete at 28 days. The utilization of POFA was also observed to improve resistance of concrete to chloride ion penetration [23,24], reduced heat development, increased resistance to acidic environment [18] and improved sulfate resistance of concrete [19,25]. Moreover, in a study by Tangchirapat and Jaturapitakkul [26], the drying shrinkage of concrete with POFA was investigated. Two sizes of POFA denoted as coarse and fine POFA were tested and the drying shrinkage was recorded in a period of 90 days. The test results showed that in the first 28 days of curing age, lower percentages of coarse POFA (10% and 20%) increased the drying shrinkage comparing to that of Ordinary Portland Cement (OPC) while 30% of coarse POFA lowered the shrinking rate. However, for the fine POFA, drying shrinkage was reported to be relatively low comparing to that of OPC. The lowest shrinkage was recorded for 30% POFA, albeit, the compressive strength decreased as a result of a higher level of the cement replacement. The study revealed that the shrinkage was less when finer POFA was used because of more pozzolanic reactivity and a higher packing effect, so the pore refinement reduced the water loss from the matrix.

Recently, Noorvand et al. [27] studied the inclusion of nano silica in unground POFA to enhance its mechanical properties. The study showed that admixing nano silica in the unground POFA cement mortars resulted in enhancement of compressive strength and reduction of water absorption and permeable voids in mortars. Nano silica is one of the most widely used nano materials with a high content of amorphous silica (>99%) and small sized spherical particles (1–50 nm) which can affect both fresh and hardened properties of concrete [28]. Previous studies mostly related the improved properties of paste, mortar, and concrete to rapid consumption of CH, especially at early ages as a result of high reactivity of SiO_2 nano particles and consequently a higher formation rate of C–S–H [29–35]. In a study by Tobón et al. [36], a larger quantity of hydration products was observed in cement pastes containing nano silica in first days of curing compared to that of the plain cement paste. It was also mentioned that at early ages, a good distribution of C–S–H caused higher compressive strength in the samples. In other studies, the good distribution of C–S–H was related to the nucleation effect by which hydration products enveloped nano particles and deposited on their large surface area [31–33,36]. The other mechanism by which nano silica may modify the hydration process in cement composites was explained by Bjornstrom et al. [37]. It was demonstrated that nano silica accelerated the dissolution of C_3S and rendered a more rapid formation of C–S–H due to the highly reactive and large surface area of its particles. It was also reported that nano silica could act as a nano filler, filling empty pores of C–S–H which may lead to densification in the interfacial transition zone (ITZ) [33]. In a study by Said et al. [34], it was observed that total porosity was reduced when up to 6% nano silica was added to the mix which was related to both the pozzolanic behavior of nano silica and the filling effect of its particles. On the other hand, nano silica decreased the volume between the cement and sand particles and hence, the free water in the matrix lowered [38]. The optimum amount of nano silica to advantageously affect the mechanical properties of cementitous composites was reported to be 1% for the smaller particle size (15 nm) and 2% when particles with 80 nm in size, were used in the binding matrix [39].

This study investigates the effect of nano silica on the short-term drying shrinkage of ground POFA cement mortars. The overarching purpose of this study is to investigate the underlying mechanisms by which nano silica affects the drying shrinkage at the first 28 days of curing by reducing free water, strengthening C–S–H network and decreasing the permeability of the matrix through hydration acceleration and filling effect. Also, the effect of nano silica inclusion on the compressive strength of POFA mortars was studied. Accordingly, the drying shrinkage rate, the compressive strength, and the moisture content were recorded for each sample during the curing age. Also, XRD and SEM tests were conducted to trace the chemical composition and microstructural changes when nano silica was added to the mix. The findings of this study may help to solve the problems related to the dimensional stability of concrete at early ages of curing when a high volume of mineral admixtures is used in concrete.

2. Experimental work

2.1. Materials

In this study, Ordinary Portland Cement (OPC) Type I (supplied by Phoenix Malaysia) was used. The POFA was provided from a plantation company located in Johor, the southern state of Malaysia. The collected POFA was dried in an oven at a temperature of 105 ± 5 °C for 24 h and then was sieved through a 300 μm sieve in order to remove the debris and extraneous materials such as unburned fibers and shells. The retained POFA was then ground and sieved through a 53 μm sieve. Scanning electron microscope (SEM) was used to investigate the particles morphology of the POFA as illustrated in Fig. 1. As can be seen in the figure, the unground POFA consisted of very irregular shaped particles with porous cellular surfaces. The grinding process changed the morphology of the particles to a crushed form with rough surface and porous texture. The median particle size and Brunauer–Emmett–Teller (BET) specific surface area of the ground POFA were 32.163 μm and 0.357 m^2/g, respectively, measured using a laser diffraction particle size analyzer – model Shimadzu 3001. X-ray fluorescence spectrometry scanning test (XRF) was also conducted to measure chemical composition of the POFA and cement illustrated in Table 1.

Amorphous nano silica (powder form) with spherical morphology and 99.5% purity was purchased from Nanostructured & Amorphous Materials, Inc. of USA. The average particle size of nano silica was 15 nm with a specific surface area of 640 m^2/g and density of 2.17–2.66 g/cm^3. Mining sand with maximum size of 2.36 mm and bulk density of 2.4 graded according to ASTM C 778 [40] was used to cast mortars.

2.2. Mortar preparation

In this study, cement mortars containing 0%, 10%, and 30% POFA as a partial replacement for cement were cast. To investigate the effect of nano silica on the drying shrinkage, 1% nano silica by weight of binder was also added to each mix and a total of 6 series of samples were cast. The water to binder (w/b) ratio of 0.5 and the sand to binder ratio of 2 were used in compliance to ASTM C 596-01 [41] and kept constant throughout the study. Dry mixing method was used as a mixing method in this study [42]. Powder components (nano silica, cement and the ground POFA) were vigorously mixed in six portions in a high speed mixer for 5 min. Then, the dry mix powder was added to the sand and mixed for 5 min in a drum mixer, and finally the water was added. After preparation of the mixes, they were moulded and covered with plastic sheets for 24 h to prevent water loss, and then demolded after 24 h of casting. All samples were cured in saturated lime water in accordance with ASTM C 511 [43]. Table 2 summarizes the dry mix composition of blended cement of all samples.