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The influence of nano-silica and barite aggregate on properties of ultra high performance concrete

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HIGHLIGHTS

- Ultra high performance concrete (UHPC) for multipurpose.
- Porosity decrease with increasing nano-silica (nS) content.
- Strength increased with addition of 2% nS in UHPC with up to 50% barite sand.
- Resistance to radiation was improved with the addition of barite aggregate.

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ABSTRACT

The development of building materials with improved characteristics and their application for increasing structure durability and sustainability is one of the goals in construction sector. The main objective of this paper is to evaluate the influence of nano-silica replacement of cement (2% or 5%) and aggregate type (quartz, barite or its combination 50:50 by volume) on the properties of ultra high performance concrete (UHPC). UHPC with nano-silica and combination of barite and quartz aggregate is composite which has finer pore-size distribution, improvement in compressive and flexural strength and in radiation protection characteristics, with potential usage as building material for hospitals and nuclear facilities.

1. Introduction

The development of more durable and sustainable concrete in order to decrease life cycle cost of structures is an important trend in modern civil engineering. Nanotechnology opened a new world in the field of construction and building materials [1,2]. Numerous nanomaterials such as nanosilica, nanoclays, calcium carbonate nanoparticles, nanotitania, nanoaluminia and carbon nanotubes have been investigated [3,4]. Significant increases in mechanical properties of cementitious materials have been achieved by incorporating nanosilica [4]. Nanoparticles have a high cost and that leads to an increase in concrete cost [5].

In order to understand the characteristics of the pozzolanic reactivity of nano-SiO_2, its pozzolanic reaction kinetics, morphology and structure of the hydrates and the influences of these features on the properties of cement-based materials were investigated [6]. Land and Stephan studied effect of different nanoparticles on cement hydration [7]. The acceleration of cement hydration was dependant of the total surface size of nano-silica particles that were added [8].

The test results obtained by Li [9] indicate that nano-SiO_2 can improve concrete microstructure and its water permeability resistant capacity. A large amount of $Ca(OH)_2$ crystal is produced due to the hydration reaction between water and cement. $Ca(OH)_2$ crystal is hexagonal and is arrayed in the interfacial transition zone (ITZ) between aggregates and binding paste matrix, which adversely affects the water permeability resistant capacity. Nano-SiO_2 has very high activity because of its galactic specific surface area. Nano-SiO_2 can react with $Ca(OH)_2$ crystal quickly, and the product of this reaction is C–S–H gel. That is to say, the $Ca(OH)_2$ crystal can be absorbed. That reduces the size and amount of the calcium hydroxide crystals. The C–S–H gel fills the voids, which improves the density of the interfacial transition zone (ITZ) and the binding paste matrix. C–S–H gel is about 70% of hydration products. The average diameter of C–S–H gel is approximately 10 nm. The nano-SiO_2 particles can fill the voids of C–S–H gel structure, which makes the binding paste matrix denser. A nano-SiO_2 particle can

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act as a nucleus in the C–S–H gel structure to make a tight bond with C–S–H gel particles. Therefore, the integration and stability of the hydration product structure are improved, and long-term mechanical properties and durability of concrete are expected to be increased [9].

The influence of colloidal nano-silica (nS) on ultrafine cement and the microstructure of the hardened cement pastes were investigated. It was found that optimal mix proportion was the one with 4% nS [10]. The pore size distribution also indicated that the large capillary pores were refined by nano-silica, due to the combined contribution of the nano-filler effect and the pozzolanic reaction [11]. The reduction in pore volume, the fact that pore-size distribution was becoming finer and the improvement in physico-mechanical properties of the mortars after the addition of nano-powders could be explained by the filler effect or the amount of hydration products of cement. However, the addition of the powders at proportions in excess of 1.25% resulted in an increase in the pore volume of some mortars due to agglomeration [12].

The specimens which contained higher amount of palm oil fuel ash (POFA) had less surface water absorption and higher durability under acid and sulfate attack when compared to the normal SCC excluding POFA. Incorporation of palm oil fuel ash reduced the amount of portlandite in the system to produce C–S–H gel which led to densification of the matrix and blocking of open porosity networks The reduction in initial surface absorption that was observed could be connected to fine close porosity of POFA contained matrix which resulted in omitting pore networks in concrete matrix. Furthermore, the palm oil fuel ash with smaller particle size was placed between cement particles which enhanced the matrix microstructure and filled the pores in POFA based self-compacting concrete [13].

Nano-silica is similar to silica fume in a way that it increases the packing density, particularly interface between the pastes and aggregate. 1% of nanosilica has an effect almost equal or near to that of 10% of microsilica at 90 days. On the other hand, with more addition of nano-silica than 2%, e.g., 3%, the results were still higher than those of the control concrete (without nano-silica). It was observed that the binary use of nano and microsilica had better performance on the characteristics of UHPCs when compared to the individual incorporation [14].

Nanoparticles can act as nuclei for cement phases, further promoting cement hydration due to their high reactivity, as nanoreinforcement, and as filler, densifying the microstructure and the ITZ, which leads to reduced porosity. Effective dispersion is the most significant issue for all nanoparticles. Although it is particularly significant at high loadings, even low loadings have problems with self-aggregation, which reduces the benefits of their small size and creates unreacted pockets, and that leads to a potential for the concentration of stresses in the material. It was found that nano-SiO_2 improves concrete workability and strength, increases resistance to water penetration, and helps to control the leaching of calcium, which is closely associated with various types of concrete degradation. Additionally, it was shown that nano-SiO_2 accelerates the hydration reactions of both C_3S and an ash–cement mortar as a result of the large and highly reactive surface of the nanoparticles. It was found that Nano-SiO_2 is more efficient in strength enhancement than silica fume. It was noticed that the obtained results depended on the production route and conditions of the nano-SiO_2 synthesis (e.g., type of reaction media, molar ratios of the reagents, and duration of the reaction for the sol–gel method) and that dispersion of the nano-SiO_2 in the paste plays an important role. In addition to behaving as a filler to improve the microstructure, Nano-SiO_2 also behaved as an activator in promoting pozzolanic reactions [15].

The indirect tensile strength was improved by about 40% compared with referent blended white cement pastes with the increase in the replacement content of inactivated nS up to 2% [16]. The effect of the addition of nano-silica, Cu-Zn ferrite and Ni ferrite on the compressive strength, flexural strength, splitting tensile strength and the modulus of elasticity of concrete manufactured with two types of coarse aggregate (dolomite and granite) was studied. Nanomaterials were added in five percentages (1%, 2%, 3%, 4% and 5%) of the weight of cementitious materials (cement and silica fume). The results showed that the optimum dose of nano-silica is 3% by weight [17]. The pullout of the fibers increased significantly in the fiber-cement composites with the additions of between 3% and 10% w/w of colloidal silica suspension [18].

The addition of nS also resulted in the increase in compressive strength as well as in the transport properties of UHPC. To achieve the best performance, the optimum amount of cement replacement by nS in cement paste was 3 wt.%. However, the improper dispersion of nS was found as a deterrent factor to introduce higher percentage of nS into the cement paste [19].

The results showed that with the increase in the nano-SiO_2 content up to 3% the compressive and flexural strength of UHPC increased, and due to agglomeration of nano-SiO_2 particles the mechanical properties decreased slightly when the nano-SiO_2 content was more than 3%. The addition of nano-SiO_2 resulted in the acceleration of the hydration process. The increase of the nano-SiO_2 content resulted in the decrease in porosity and average pore diameter. The microstructure was more homogenous and dense for nano-SiO_2 specimens comparing to the control specimen [20].

Yu et al. investigated influence of fly ash, ground granulated blast-furnace slag and limestone powder as a partial cement replacement on the properties and hydration kinetics of the UHPC with nS. They found that hydration heat development curves are similar during the initial five days for all types of UHPC [21].

The incorporation of small amounts of nano-silica can lead to the decrease in the total carbonation of cement paste. Nano-silica could significantly reduce carbonation (decalcification) of C–S–H and the depth of carbonation [22]. Frost resistance and mechanical properties of concrete containing nano-silica and nano-alumina were studied. Nano-particles were used as a partial substitute for cement. Experimental results showed that, as result of a more compacted microstructure, the frost resistance of concrete containing nano-particles considerably improved [23]. Nano-silica improved mechanical properties and durability of self-compacting concrete [24]. The results of the influence of class F fly ash and silica nano-micro powder on the properties of high performance cementitious composites showed that the pozzolanic admixtures, especially a blend of silica fume and SiO_2 nanoparticles, have a significant effect on thermal properties and particularly capillary water absorption [25].

New nanomaterials will allow higher temperatures and hence a more efficient operation of power plants, and enable the development of new energy production systems based on solar, nuclear and renewable sources [26]. Due to its dynamical behavior ultra high performance concrete can be used in nuclear power plants and defensive facilities [27].

Barite aggregate is used to produce heavyweight concrete which application concerns radiation shielding in hospitals and nuclear facilities. Concrete with barite powder as sand substitution in range between 0% and 25% has decreased the compressive strength at 28 days only by 10% and elastic modulus at one year by 20%, while tensile strength has been reduced up to 50% [28]. Mixing process modifies the grading curve of barite at a higher extent than for other aggregates. This influenced the properties of concrete in a way that it increased workability, but decreased compressive strength and the modulus of elasticity [29]. Concrete made with magnetite fine aggregate showed better physico-mechanical properties than the corresponding concrete containing barite and goethite. The compressive strength of high-performance