Chapter 90
Effect of Incorporating Nano-silica on the Strength of Natural Pozzolan-Based Alkali-Activated Concrete

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A new class of concrete with precursors such as fly ash and pozzolan, totally replacing ordinary Portland cement (OPC), together with alkaline activators is being extensively researched in producing alkali-activated concrete (AAC). The strength development of AAC depends on curing temperature, composition, and fineness of the source materials. Reactivity of the binders with the alkaline activators increases with the fineness, leading to the improved mechanical and microstructural properties. This study focuses on the development of AAC utilizing natural pozzolan (NP) as source material. In order to enhance the properties, NP is partially replaced with nano-silica up to 7.5% in the AAC mixes. Compressive strength was measured on the specimens cured for 0.5, 1, 3, 7, 14, and 28 days in the oven maintained at 60 °C. Scanning electron microscopy (SEM) was used to determine the morphology of the developed alkali-activated paste (AAP). The results indicated that AAC with NP as a binder gained reasonable strength after 3 days of curing at elevated temperature. Further, NP replaced with nano-silica (NS) exhibited improved strength and microstructural characteristics. AAC with 5% nano-silica showed better compressive strength results and denser microstructure compared to the ones prepared with other replacement levels.

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M. M. Reda Taha (ed.), *International Congress on Polymers in Concrete (ICPIC 2018)*, https://doi.org/10.1007/978-3-319-78175-4_90

1 Introduction

Concrete research is currently focused on developing sustainable alternative binders to OPC to enable mitigation of greenhouse gas emissions associated with the production of OPC. Making headway in this research is the development of alkali-activated binder in which OPC is replaced totally with supplementary cementitious materials (SCMs) that are rich in silica and alumina [1]. The majority of research studies conducted utilized fly ash as precursor in developing AAC [2]. The key engineering properties of AAC depend on the chemical composition and fineness of the source materials as well as concentration of alkaline activators [3]. As the fineness of source material increases, so does the reactivity with the alkaline activators, resulting in improved properties [4]. In this respect nanomaterials can play a significant role as they are highly reactive due to their enormous specific surface area. Natural pozzolan is another class of naturally available SCM, which has a strong potential for use as a source material in synthesizing AAC. Therefore, this study focusses on developing NP-based alkali-activated concrete, and subsequently the properties of this concrete were improved by partially replacing it with nano-silica.

2 Materials and Methods

Natural pozzolan used in this study is a powder form of volcanic rock available locally in the Western Saudi Arabia. The nano-silica used is an aqueous dispersion of colloidal silica approximately 50% solids by mass supplied by AkzoNobel Germany. The chemical composition of NP as determined by X-ray fluorescence (XRF) technique is shown in Table 90.1. The specific surface area and average particle size of NP used are 442 m^2/kg and 30 μm, respectively. The alkaline activators used are a combination of aqueous sodium silicate (SS) and 14 M sodium hydroxide (SH) solution. Silica modulus of sodium silicate was 3.3, and its composition was H_2O, 62.50%; SiO_2, 28.75%; and Na_2O, 8.75%. Dune sand with a specific gravity of 2.62 in saturated surface dry (SSD) condition was used as fine aggregate. Limestone

Table 90.1 Chemical composition of natural pozzolan

Constituent	Weight (%)
Silica (SiO_2)	40.48
Alumina (Al_2O_3)	12.90
Ferric oxide (Fe_2O_3)	17.62
Lime (CaO)	11.83
Magnesia (MgO)	8.33
Potassium oxide (K_2O)	1.67
Sodium oxide (Na_2O)	3.60
Phosphorus oxide (P_2O_5)	1.37
Loss on ignition	1.6

Table 90.2 Constituent materials for AAC mixtures with nano-silica (in kg/m^3)

Mix	Natural pozzolan	Nano-silica	Sodium silicate	Sodium hydroxide	Fine aggregate	Coarse aggregate
M0	400	0	150	60	650	1206
M1	396	8	150	60	646	1200
M2	390	20	150	60	640	1188
M3	380	40	150	60	630	1170
M4	370	60	150	60	620	1152

aggregate having a specific gravity of 2.56 in SSD condition was used as coarse aggregate.

All concrete mixes were prepared with a constant binder content of 400 kg/m^3 having SS/SH by weight ratio of 2.5. Table 90.2 summarizes constituent materials for preparing AAC specimens incorporating nano-silica for compressive strength tests. For SEM analysis AAP specimens were prepared. Coarse aggregate to total aggregate and fine aggregate to total aggregate ratios were 0.65 and 0.35, respectively. Free water to pozzolanic material ratio of 0.25 was used in all the AAC mixtures. Alkaline activator to binder ratio was 0.525.

After 24 h of casting, specimens were de-molded, placed in plastic bags to avoid evaporation of moisture, and kept in the oven maintained at 60 °C. AAP specimens were cured for 7 days in the oven after which morphological studies were carried out. Compressive strength of concrete was determined on 50 mm cube specimens according to ASTM C 150 after 0.5, 1, 3, 7, 14, and 28 days of curing at 60 °C.

3 Results and Discussion

Figure 90.1 shows the compressive strength development in the nano-silica-modified AAC. The data indicate that the strength development in the AAC specimens prepared with higher dosage of nano-silica was slow as compared to that of the lower ones in the initial stages of curing. For instance, 1-day compressive strength of AAC prepared with 0%, 1%, 2.5%, 5%, and 7.5% nano-silica was 22.92 MPa, 22.32 MPa, 14.24 MPa, 12.04 MPa, and 7.32 MPa, respectively. About 90% of strength development was recorded after 3 days of curing in the concrete without nano-silica when compared with that of 7 days strength. However, further curing of AAC specimens, particularly containing nano-silica, remarkably improved its strength. Seven-day compressive strength of specimens prepared with varying dosage of nano-silica was in the range of 37.52–44.52 MPa, maximum value being for the mixture prepared with 5% nano-silica replacement, whereas the lowest was in the control mix. Compared to the strength of concrete, prepared without nano-silica, there was about 18% higher strength recorded in the specimens containing 5% nano-silica. It is interesting to note that the 7-day strength was 12.6%, 34.4%, 43.3%,

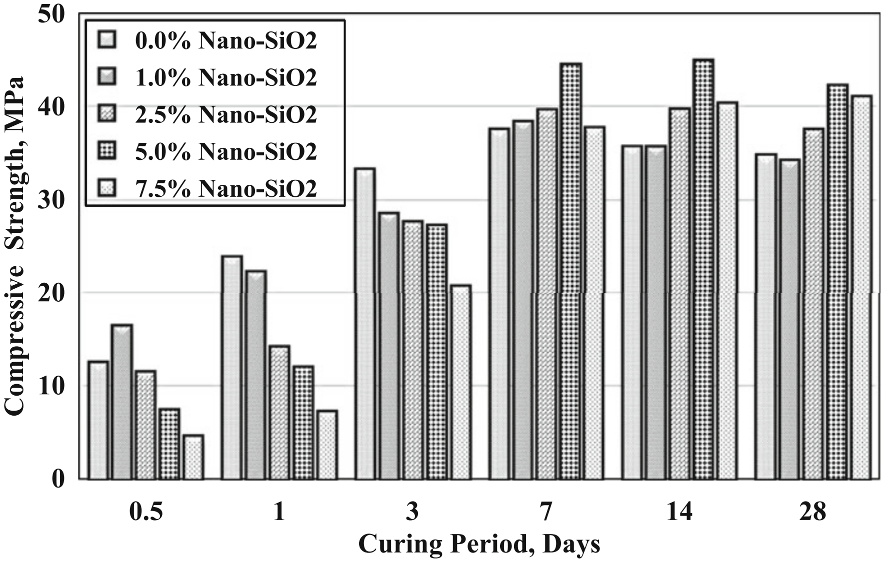

Fig. 90.1 Compressive strength development in the AAC specimens

63.0%, and 81.5% higher as compared to 3 days, respectively, for the specimens prepared with 0%, 1%, 2.5%, 5%, and 7.5% nano-silica.

What appears from the findings is that as the dosage of nano-silica increased, compressive strength development was delayed. This phenomenon is attributed to the increase in the amount of silica in the system for a given alkaline activator content resulting in delayed polymerization of these particles. When the pozzolanic material containing nanoparticles encounters the alkaline solution, dissolution of the base material takes place initially, and the resulting products are deposited on the highly reactive nanoparticles leading to the formation of nucleation sites. Nucleation of hydration products on the nanoparticles further nurtures and accelerates the dissolution of pozzolanic material, due to which properties of the materials improve significantly [5].

Figure 90.2 illustrates SEM images of NP-based AAP prepared with varying dosages of nano-silica. The NP-based AAP without nano-silica has a porous microstructure, and the matrix was coarser in nature with widespread micro-cracks and voids compared to that containing nano-silica. As the NP was partially replaced with nano-silica from 1.0% to 7.5% by weight, the microstructure started densifying with a reduction in the pore volume. Compared with other replacement levels of nano-silica, the microstructure of 5% was more homogenous and denser having less unreacted particles with continuous gel matrix without clear particle boundaries. This more homogenous gel-like matrix without distinct voids is constituted of pure polymeric binder. On the other hand, the SEM micrograph of AAP containing 7.5% nano-silica, shown in Fig. 90.2, appeared to be also dense with unreacted particles embedded in the structure indicating that the quantity of nano-silica was excessive,

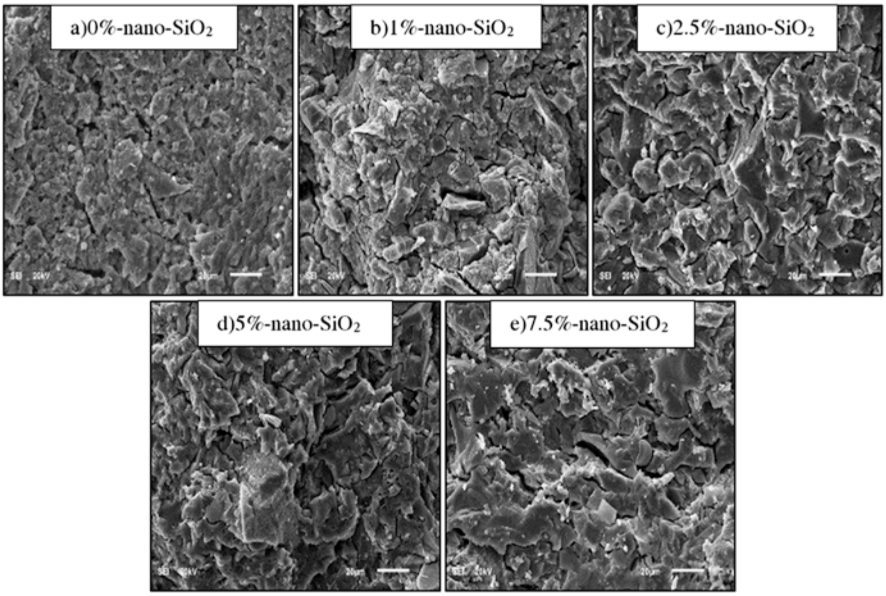

Fig. 90.2 SEM of AAP specimens prepared with and without nano-silica

and it remained unreacted together with the particles of NP. Unreacted particles are identified clearly in the matrix with the boundaries. Therefore, it appears from the microstructure that there was only partial filling of voids in the specimen prepared with nano-silica up to 2.5% replacement, while the addition of 7.5% of it caused agglomeration of the nanomaterial, which in turn did not beneficially assist the microstructural development and strength.

The microstructure of AAP specimens prepared by partial replacement of NP with nano-silica became homogenous and denser due to increase in the Si species, which enhanced polymerization in the system generated in the process of reaction between Si, Al, and highly alkaline materials [6]. In case of AAP prepared with 5% nano-silica, all the aluminosilicate materials are consumed in the process of alkali activation leaving minimal unreacted particles in the mixture resulting in the enhancement of microstructure. These findings are complemented by the compressive strength results.

These results are in good agreement with the data presented by Adak et al. [7] in which 6% of nano-silica replacement of fly ash resulted in better compressive strength and compact microstructure in comparison to the other replacement levels due to enhanced transformation of amorphous compounds to the crystalline. The significant improvement in the compressive strength and microstructure of specimens containing 5% and 7.5% nano-silica is attributed firstly, to the enhancement in the reaction products in the process of polymerization due to the presence of highly reactive nano-silica yielding additional CSH or CASH gels along with NASH and secondly due to the filler effect [8].

AAC using NP as a main binder has strong potential for a concrete without OPC, with nano-silica contributing to significant strength enhancement. The advantages of the developed concrete include reduction in greenhouse gas emissions, utilization of natural and industrial byproducts, superior strength, and durability characteristics. The concrete, however, has disadvantages, as it requires heat curing, and polymerization process is sensitive to the concentration of alkaline materials. The cost impact of nano-silica could be another minus point.

4 Conclusions

The aim of this study was to improve the properties of NP-based AAC by incorporating nano-silica. The investigation conducted shows that:

- Strength development was slow in the mixes containing higher amounts of NS as compared to the lower levels at the onset of curing. As the curing progressed, concrete specimens prepared with NS exhibited a significant enhancement in the compressive strength and microstructural characteristics as compared to the specimens prepared without NS.
- Replacement of NP by 5% NS in the AAC was an optimal level, achieving superior strength as well as homogenous and denser microstructure.
- NP-based AAC is suitable for construction applications without incorporating NS. However, NP partially replaced with NS exhibited significant improvement in the properties of the final product.

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