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Enhancing the engineering properties and microstructure of room temperature cured alkali activated natural pozzolan based concrete utilizing nanosilica

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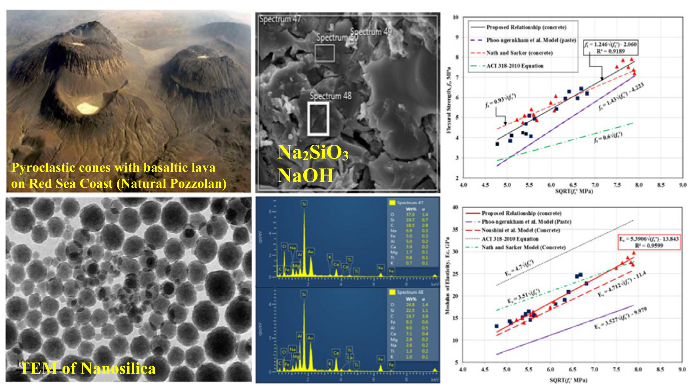
HIGHLIGHTS

- NP was partially replaced with NS in the synthesis of AAC to enable curing at room conditions.
- 5% and 7.5% NS addition resulted in remarkable enhancement in strength and microstructure of binder.
- AAC exhibited higher flexural strength and lower modulus of elasticity than OPC concrete.
- Constitutive models revealed that ACI 318 equations underestimate flexural strength and overestimate modulus of elasticity of AAC.
- Utilization of NS improved transformation of precursor material to form polymeric compounds.

GRAPHICAL ABSTRACT



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ABSTRACT

The strength gain of alkali-activated binders (AAB) when cured at room temperature is delayed due to the slow polymerization process. This is the major impediment in the utilization of this green concrete in cast in-situ concrete structures. In order to expand the applications of these binders to various fields of construction, attempts have to be intensified to overcome this obstacle. Incorporation of finer materials with high specific surface area to enhance the reactivity of alkali activated concrete (AAC) is one of the potential approaches to accelerate their strength gain. In this regard, nanomaterials, such as nanosilica (NS), can play a key role. Therefore, to enable curing at room temperature, incorporation of NS as partial replacement of natural pozzolan (NP) in developing AAC is the focus of this research work. AAC mixes were prepared by partially replacing NP with NS up to 7.5% by weight. The compressive strength development was monitored until 180 days of room temperature curing (23 ± 2 °C). Flexural strength and modulus of elasticity of concrete were also measured. Constitutive models relating the engineering properties of the developed AAC were formulated using regression analysis. In addition, SEM and XRD techniques were used to assess the nature of the binder formed during alkali activation. The data developed in the reported study indicated that NP, without incorporating NS, can be used as precursor material for producing AAC that could be potentially used as a construction material. However, AAC mixtures incorporating NS exhibited remarkable enhancement in the mechanical properties and microstructural

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characteristics. The addition of, 5% and 7.5% NS resulted in superior mechanical properties and a denser microstructure due to the greater transformation of precursor material in to polymeric compounds. The tangible outcomes of this research highlights the importance of nanomaterials in improving the properties of green building materials.

1. Introduction

As more punitive measures have been enforced by the international community to limit the greenhouse gas emissions, the focus of building materials research has shifted towards developing sustainable alternative binders. Among various options available, alkali activated binder (AAB) is evolving as the possible alternative to OPC. Materials that are predominantly composed of alumina and silica are the possible candidates for the development of an AAB [1–5]. Thus far, industrial byproducts, composed of aluminosilicates have been extensively used as source material in synthesizing AABs [6–8]. The utilization of these materials by fully replacing OPC in the production of concrete has multiple benefits including, appropriate usage of waste materials, lower environmental impact, high strength, low energy consumption, better chemical resistance and lower shrinkage characteristics [3,4,9]. The mechanism behind the development of AAB involves dissolution of aluminosilicate materials in the alkaline solutions resulting in the evolution of a three-dimensional polymeric chain [10]. However, the engineering properties and microstructure of AAB depends on several factors, including; composition of alkaline activators and their ratio, fineness and constituents of source materials as well as curing conditions [11–14]. Majority of the studies reported so far in this area focused on developing AABs utilizing fly ash as a source material cured at temperatures between 40 and 80 °C [15,16]. In order to improve the properties of AABs the source materials were partially replaced with mineral additives [16,17]. The strength gain of these binders is rapid when cured at elevated temperature, while, it is slow at room temperature cuing [16,18]. This is particularly true for low calcium precursor materials, due to the slow polymerization process. The elevated temperature curing has become a major limitation in utilization of this green concrete in cast in-situ applications [19,20]. On the other hand, high calcium fly ash could be cured at ambinet temperature to achieve reasonable mechanical properties [21].

In order to widen the practical application of AAC in the various fields of construction, particularly cast-in situ concreting applications, it is essential to overcome this limitation of curing at elevated temperature to obtain sufficient structural strength. Among several mix design parameters, chemical composition of the precursor material and its fineness significantly influences the evolution of mechanical properties of AAB as reported by several researchers [22–26]. Most significantly, the fineness of the precursor material has a profound effect on the rate of reactivity [27]. The finer materials dissolve easily in the alkaline solution leading to a higher conversion of the source materials to polymeric compounds which enhances the strength of these binders [28]. It is estimated that the dissolution of source materials having particle size of more than 20 μm is rather slow, whereas, materials with particle size of less than 2 μm react rapidly [27]. Nanomaterials were used, as partial replacement of fly ash, in earlier studies to accelerate the polymerization process in synthesizing these binders. For instance, Phoo-ngernkham et al. [28] studied the influence of incorporating NS and nanoalumina (NA) on the strength and microstructure of high calcium fly ash-based AAB cured under ambient conditions at a given alkaline activator concentration and ratio. It was reported that 2% nano material was sufficient to obtain enhanced strength due to the formation of calcium silicate hydrate (C-S-H) or calcium alumina silicate hydrate (C-A-S-H) gel along with sodium alumina silicate hydrate (N-A-S-H) gel [28]. In another study [29], fly ash was replaced with up to 10% NS in developing alkali activated mortar even though the source material was rich in silica and alumina. It was reported that the strength increased by 15% due to 6% replacement of fly ash with NS [29].

Considering the fact that the nature of the binder formed during alkali activation is quite different than that of OPC, the behaviour of AAC under different loading conditions could possibly be different than OPC-based concrete. Also, there are several mix design parameters that influence the nature and intensity of the binder produced in the synthesis of AAC apart from the bearing of curing conditions [30]. Hence, constitutive models specified for OPC concrete by the international standards and codes, such as ACI 318-10 [31], as well as equations proposed in previous studies may not accurately predict engineering properties of AAC. According to the results of a study [32], ACI 318-10 [31] underestimates the flexural strength of AAC, while, it overestimates the modulus of elasticity for similar grade concrete. For instance, based on Diaz-Loya et al. [32] proposal, the flexural strength estimated was 11% more than that computed by ACI 318-10 [31]. On the contrary, the modulus of elasticity of AAC reported by several researchers [33–35] was less than that estimated by ACI 318-10 equation for similar strength concrete.

Concrete with NP, used as a partial replacement of OPC, has exhibited excellent mechanical and durability characteristics [36]. It is abundantly available in several places in the world and on the Red Sea coast of Saudi Arabia (SA). It possesses great potential to be used as a precursor material for developing AAC. However, the chemical composition of NP varies widely from source to source. For instance, NP from Taftan, Iran is composed of 61.67% SiO_2 [37], which is quite high compared to the NP from SA which has only 40.48% SiO_2 [38]. Further, the reactivity is moderate, barely fulfilling the requirements of ASTM C618-10 [39]. The reactive silica in the source material is vital initially in the formation of polymeric compounds, and subsequently, in the development of mechanical and duarability characteristics of AAC [40]. As the NP from SA does not have sufficient quantity of reactive silica, compared to the low calcium precursor materials mentioned above [37], it is necessary to be supplemented with more reactive minerals, in order for it to be used as a precursor material for developing AAC possessing sufficient strength.

Therefore, to enable curing at room conditions, in this study NP from SA was substituted with up to 7.5% NS by weight for developing AAC containing 400 kg/m^3 binder content and Na_2SiO_3/NaOH by weight ratio of 2.5, which were found to be appropriate in achieving better strength in an earlier study conducted by the authors as a part of an on-going research activity [38]. The developed concrete was cured at room temperature (23 ± 2 °C). It is anticipated that the proposed study will help in understanding the effect of adding different percentages of NS on the properties of AAB prepared using NP as a percusor material. More importantly, the data obtained on the engineering properties in this study will be used to develop constitutive models describing the relationship between flexural strength, modulus of elasticity and compressive strength using a regression analysis by the method