Modern Methods and Advances in Structural Engineering and Construction
Cheung, S. O., Yazdani, S., Ghafoori, N., and Singh, A. (eds.)
ISEC-6, Zürich, June 21–26, 2011

CONSTITUTIVE MODELS FOR PREDICTING MECHANICAL PROPERTIES OF NATURAL POZZOLAN-BASED ALKALI ACTIVATED CONCRETE

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A large variety of mix design variables and environmental conditions in which alkali activated concretes (AAC) are cured, influences the nature and intensity of the binder formed. Equations developed for OPC-based concrete in various codes and published work may not accurately predict engineering properties of these AAC. AAC in this study was synthesized utilizing natural pozzolan (NP) in the presence of alkaline activators. Nano-SiO2 was added for enhancing the strength development at room temperature curing as NP is a low calcium precursor material. Development of compressive strength, flexural strength and modulus of elasticity were investigated. Using the data generated, two constitutive models, relating the compressive strength to flexural strength and modulus of elasticity were developed and compared with the equations specified in international codes for OPC-based concrete and previous studies in the area. The results show that the ACI 318, underestimates the flexural strength and overestimates the modulus of elasticity of alkali activated concrete. However, constitutive models developed in this study are in good agreement with the equations proposed in the previous works for AAC. Only the limited data available to date on the engineering properties of AAC cannot be used to establish robust constitutive relationships and more research is required in this area.

1 INTRODUCTION

Alkali activated binders (AABs) are evolving as the possible alternative to OPC due to its multiple benefits [Rovnanik 2010]. Thus far, industrial byproduct, such as fly ash, has been extensively used as source material in synthesizing AABs and cured at temperatures between 40 to 80 °C [Hardjito et al. 2005.]. 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 [Duxson et al. 2007]. The strength gain of these binders is rapid when cured at elevated temperature, while, it is slow at room temperature curing [Pangdaeng et al. 2014]. In order to widen the practical application of AAB in this study natural pozzolan (NP) was partially replaced with nanosilica (NS) to enable it to be cured at room temperature. Considering the fact that the nature of the binder formed during alkali activation is quite different than that of OPC, the behavior of AAC under different loading conditions could possibly be different than OPC-based concrete. Hence, constitutive models specified for OPC concrete by the international standards and codes, such as ACI 318-10 [ACI 318 2010], as well as equations proposed in the previous studies may not accurately predict engineering properties of NP-based AAC. According to the results of a study [Diaz-Loya et al. 2011], ACI 318-10 [ACI 318 2010] 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. proposal, the flexural strength estimated was 11% more than that computed by ACI 318-10 [ACI 318 2010]. On the contrary, the modulus of elasticity of AAC reported by several researchers [Olivia and Nikraz 2012] was less than that estimated by ACI 318-10 equation for similar strength concrete. Therefore, the data obtained on the engineering properties in this study were used to develop constitutive models describing the relationship between compressive strength with flexural strength and modulus of elasticity using a regression analysis by the method of least squares.

2 MATERIALS AND METHODS

2.1 Materials

Natural pozzolan (NP), the main precursor material used in the study, was in a powdered form of volcanic rock. The chemical composition of NP is given in Table 1. The physical properties of the NS used in the study are shown in Table 2. 14 M NaOH solution and Na_2SiO_3 of 3.3 silica modulus were used as alkaline activators. The composition of sodium silicate includes: H_2O: 62.5%, SiO_2: 28.75% and Na_2O: 8.75%. Crushed limestone, having specific gravity of 2.56, was used as coarse aggregate while dune sand having specific gravity of 2.62 was utilized as fine aggregate in the concrete mixtures.

Table 1: Chemical composition of NP.

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	TiO_2	LOI
Weight, %	40.48	12.90	17.62	11.83	8.33	1.67	3.60	1.37	0.60	1.6

Table 2: Physical properties of NS.

Property	Solid content, %	Avg. Particle size, nm	Bulk density, g/cm^3	Specific surface area, m^2/g	Na_2O content, %	Viscosity cps	pH
Value	50	35	1.4	80	0.2	15	9.5

2.2 Methods

Table 3 shows the quantities of constituent materials of mixes prepared by incorporating NS. All the AAC mixtures were prepared with a constant Na_2SiO_3/NaOH weight ratio of 2.50. Additionally, OPC concrete was prepared using mix proportions generally adopted in the construction industry.

Table 3: Quantities of AAC mix constituents.

Mix #	Legend	NP, kg/m^3	NS, kg/m^3	Na_2SiO_3, kg/m^3	NaOH, kg/m^3	FA, kg/m^3	CA, kg/m^3
M0	0%-NS	400	0	150	60	650	1206
M1	1%-NS	396	8	150	60	646	1200
M2	2.5%-NS	390	20	150	60	640	1188
M3	5%-NS	380	40	150	60	630	1170
M4	7.5%-NS	370	60	150	60	620	1152

The concrete specimens were de-molded after 1 day of casting, placed in plastic bags to avoid evaporation of moisture, and kept in the laboratory that was maintained at 23$\pm$2 $^\circ$C until the predetermined curing period. OPC concrete was cured under wet burlap. The compressive strength of concrete was measured after 3, 7, 14, 28, 56, 90 and 180 days of curing on 50 mm cube specimens. Prismatic specimens measuring 50 x 50 x 200 mm were prepared to determine the flexural strength of concrete using third point loading in accordance with ASTM C78 [ASTM C78

2010]. The modulus of elasticity of concrete was measured on 75 mm diameter and 150 mm high cylindrical concrete specimens in accordance with ASTM C469 [ASTM C469 2010]. In order to ensure the accuracy of results three specimens for each period were prepared and tested.

3 RESULTS AND DISCUSSION

3.1 Compressive Strength

The compressive strength development in the AAC prepared with NS varying from 0 to 7.5% by weight and OPC concrete is depicted in Fig. 1. The compressive strength was low at the onset of curing in the concrete specimens prepared with NS compared to those prepared without it, particularly after three days of curing. However, as the period of room curing continued, the strength gain was remarkably high in the concrete mixes containing NS than in the control specimens. For instance, the compressive strength after seven days of curing in the AAC mixes containing 0%, 1%, 2.5%, 5% and 7.5% NS was 13.87, 14.20, 11.57, 9.44, and 7.76 MPa, respectively, which increased to 25.55, 28.45, 29.84, 44.97 and 37.92 MPa, respectively, after 28 days of curing. After 90 days of curing, the compressive strength of concrete mix without NS was 27.93 MPa, whereas, it was 31.40, 36.32, 60.65 and 58.78 MPa, in the AAC mixtures containing 1%, 2.5%, 5% and 7.5% NS, respectively. According to these results, there was about 117% and 110% increase in the strength in the concrete containing 5% and 7.5% NS, respectively, compared to the control samples (0% NS), at 90 days. The remarkable improvement in the performance of the AAC containing NS, in terms of compressive strength, particularly with 5% NS, could be attributed to the enhanced transformation of source materials to the polymeric gel in the presence of highly reactive NS as well as due to possible particle packing effect of nanoparticles in the binder structure [Yip *et al*. 2005].

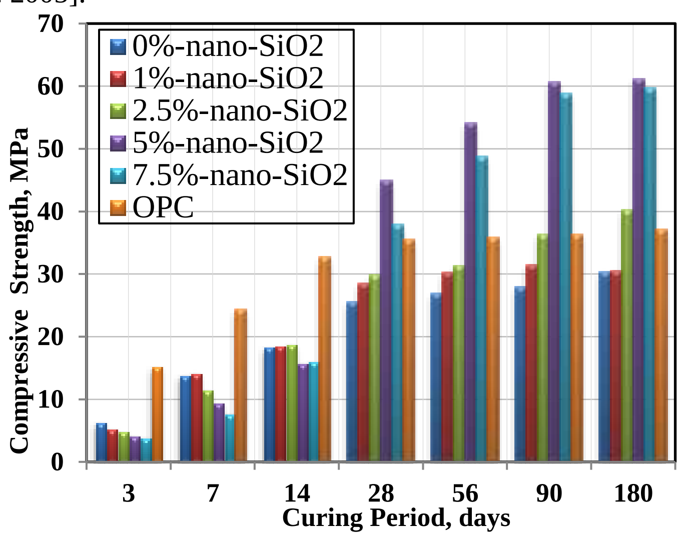

Fig. 1: Compressive strength development of the concrete.

3.2 Flexural Strength

The flexural strength of the AAC mixtures varied from 3.88 to 6.20 MPa and 4.92 to 7.59 MPa, after 28 and 90 days of curing, respectively. The maximum value was observed in the AAB with 7.5% NS. After 90 days of curing, there was about 4.47%, 11.99%, 53.25% and 54.27% increase in the flexural strength in the AAC mixtures incorporating 1%, 2.5%, 5% and 7.5% NS, respectively, over the control mixture prepared without NS. These findings were consistent with that of compressive strength results, which exhibited a similar trend. Largely, the flexural strength data obtained in the reported research work is in good agreement with the findings of other researchers, wherein, partial replacement of binders with nanoparticles resulted in an improvement in the mechanical properties [Phoo-Ngernkham *et al*. 2014]. The compressive and flexural strength after 28 and 90 days of curing were utilized to develop a correlation between them by plotting square root of compressive strength on abscissa and flexural strength as ordinate, as shown in Fig. 2. The correlation between compressive and flexural strength can be expressed by Eq. 1 obtained by regression analysis of the obtained data. In order to compare the relationship developed in this study with other statistical models, the flexural strength was also computed using relationships proposed by Phoo-ngernkham et al. and Nath and Sarker, that are given in Eq. 2 and Eq. 3, respectively, which are also plotted in Fig. 2. The flexural strength was also calculated using Eq. 4 as specified in ACI 318-10 [ACI 318 2010] and plotted in Fig. 2.

$$ft = 1.246\sqrt{f'c} - 2.060 \quad (1)$$
$$ft = 1.430\sqrt{f'c} - 4.223 \quad (2)$$
$$ft = 0.93\sqrt{f'} \quad (3)$$
$$ft = 0.6\sqrt{f'c} \quad (4)$$

Where; ft is the flexural strength and $f'c$ is the compressive strength, both in MPa.
The flexural strength of AAC after 28 and 90 days of room curing computed, as a function of compressive strength was greater than that estimated using ACI 318-10 equation, particularly correct for those AAC mixes containing higher NS content. The flexural strength predicted using the model developed by Phoo-ngernkham et al. was also less than that obtained in this study which could be attributed to the absence of coarse and fine aggregates in the mixtures. However, the flexural strength calculated using the statistical model proposed by Nath and Sarker gives values of similar order. For example, at 28 days of curing, for about 40 MPa strength concrete the flexural strength from the Nath and Sarker model was 5.88 MPa, which is about 1% less than the experimental value obtained in this study, while, it was more than 35% above the value estimated using ACI 318-10 equation. Based on these results, it can be concluded that ACI 318-10 equation did not accurately predict the flexural strength of AAC.

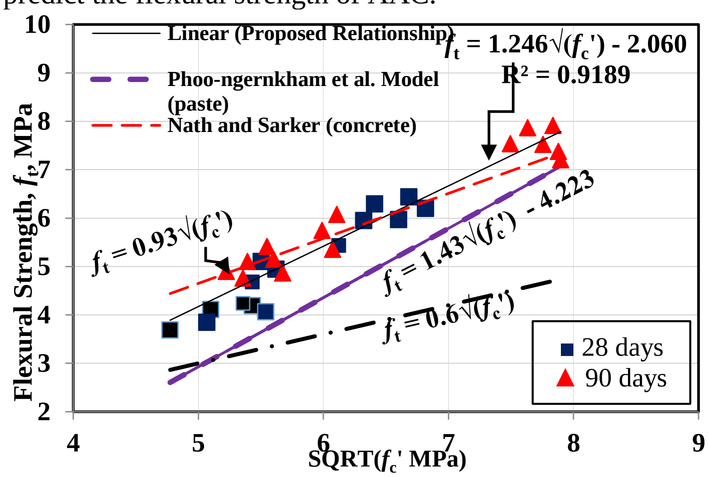

Fig. 2: Correlation between flexural strength and compressive strength.

3.3 Modulus of Elasticity

The modulus of elasticity increased with increasing curing period as well as the quantity of NS in the AAC. It ranged between 13.80 to 24.00 GPa and 14.53 to 28.70 GPa, after 28 and 90 days of curing, respectively. AAC prepared with 5% NS resulted in the highest modulus of elasticity at both curing periods, whereas, it was the lowest in the concrete mixture prepared without NS. The increase in the modulus of elasticity of NS modified AAC mixes may be attributed to the greater transformation of amorphous and semi-crystalline phases in the precursor material to the polymeric compounds, including C-A-S-H as well as N-A-S-H [Phoo-Ngernkham 2014]. In this study an attempt was made to develop a statistical model for computation of modulus of elasticity and to compare it with the models available in the literature using the obtained data. Fig. 3 provides the correlation between compressive strength with that of modulus of elasticity using regression analysis by the method of least squares. The equation for predicting modulus of elasticity for OPC as per ACI 318-10 and the equations proposed by Phoo-ngernkham et al., Noushini et al., and Nath and Sarker for AAC are given in Eq. 6, Eq. 7 and Eq. 8 and Eq. 9, respectively. The moduli of elasticity predicted by these equations utilizing compressive strength results obtained experimentally in this study are also plotted in Fig. 3. Based on the data obtained in this study a relationship between elastic modulus with the square root of compressive strength is proposed in Eq. 10 for AAC with NP as precursor material which was partially replaced with NS.

$$Ec = 4.7\sqrt{(fc')} \tag{6}$$
$$Ec = 3.527\sqrt{(fc')} - 9.979 \tag{7}$$
$$Ec = 4.712\sqrt{(fc')} - 11.4 \tag{8}$$
$$Ec = 3.51\sqrt{(fc')} \tag{9}$$
$$\mathrm{Ec} = 5.390\sqrt{(\mathrm{fc}')} - 13.843 \tag{10}$$

Where; Ec is the modulus of elasticity in GPa and $f'c$ is the compressive strength in MPa
It is evident from the figure that the modulus of elasticity calculated using ACI 318-10 is significantly more than that predicted by other models as well as proposed model by the authors. With regard to the model presented by Phoo-ngernkham et al., it under estimates the modulus of elasticity of AAC compared to the value obtained in this study. However, statistical models proposed by Noushini et al. and Nath and Sarker match very well with the experimental results of this investigation. Based on the results presented here, it can be summarized that the equation given in ACI 318-10 overestimates the modulus of elasticity and it is not suitable for predicting these values for AAC.

4 CONCLUSIONS

The compressive strength, flexural strength and modulus of elasticity of NP and NS-based AAC increased with the period of curing. At the onset of curing, the compressive strength of AAC was less than that of OPC. However, it significantly improved as the room curing continued. The partial replacement of NP with 5% and 7.5% NS significantly improved the mechanical properties due to the enhanced transformation of source material to C-S-H or C/N-A-S-H gel. Constitutive models developed in this research utilizing modest data generated on the engineering properties were in good agreement with some of the other models proposed by previous researchers. However, ACI 318-10 equation underestimated the flexural strength compared to the experimental value, while, it was contrary in the case of modulus of elasticity. It is important to highlight that considering the large number of mix design variables and limited availability of engineering properties of AAC, the proposed statistical model in this study as well as suggested by other researchers, mentioned earlier, cannot be used as a general correlation between the compressive strength and other engineering properties of AAC. Consequently, there is a need to develop models correlating the engineering properties of AAC by undertaking future research studies.

Acknowledgments

The authors gratefully acknowledge the Center for Engineering Research (CER) of the Research Institute, King Fahd University of Petroleum and Minerals and the School of Civil Engineering, Universiti Sains Malaysia for providing the necessary support for this work.

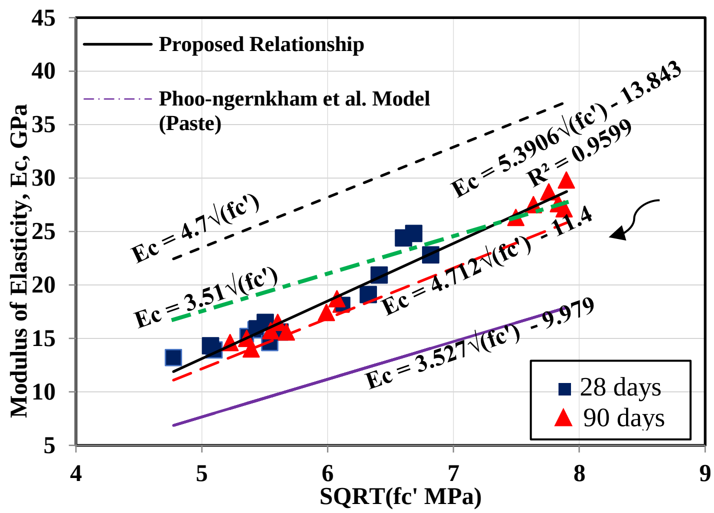

Fig. 3: Correlation between modulus of elasticity and compressive strength.

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