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# Stepwise regression modeling for compressive strength of alkali-activated concrete

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## HIGHLIGHTS

- Compressive strength of alkali-activated fly ash and slag concrete is tested.
- Effects of various mixture parameters are quantified.
- Predictive models for compressive strength are developed.

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## ABSTRACT

This paper presents the results from a parametric experimental investigation of the compressive strength of alkali-activated concrete. The effects of curing condition (moist-cured versus heat-cured), sodium oxide dosage, silica dosage, silica modulus (relative dosage of silica to sodium), solution/binder ratio, and free water/binder ratio on the compressive strength of sodium silicate-activated fly ash and slag cement concrete are evaluated. More than 5000 specimens with 676 unique combinations of mixture proportion and curing condition were tested. The marginalized effects of each parameter indicate effects similar to those identified by previous studies. Predictive models for the compressive strength of fly ash and slag cement-based concretes are developed by stepwise regression analysis. Although the specific models presented in this paper are applicable only for the materials and activators identified herein, the modeling procedures are generalized results are of doubtless utility for the design of alkali-activated concrete mixtures.



## 1. Introduction

Alkali-activated concrete is made by the chemical activation of aluminosilicate materials with strong metal alkalis. Activators like sodium or potassium hydroxide, sodium silicate, or sodium carbonate are commonly used in conjunction with industrial byproducts like fly ashes or slag cement to produce strong and durable binders. Although alkali-activation of aluminosilicates dates back to at least 1908 [1], alkali-activated concretes (AAC) have only recently emerged as potential replacements for portland cement concrete. The recent emergence of AAC stems mainly from increased concern over the environmental impact of portland cement manufacture. The embodied energy and carbon emissions associated with AAC are significantly lower than those associated with portland cement concrete (PCC) [2–4].

The compressive strength behavior of alkali-activated binders has been discussed at length in existing literature. The compressive strength of alkali-activated slag cement (AASC) is known to be influenced by binder composition, activator composition and concentration, water content, and curing condition. Several researchers have suggested that the optimal strength performance in AASC is obtained when sodium silicate is used as the activator [5–9]. The compressive strength is known to increase as the alkali concentration of the activator increases and as the ratio of silica to sodium oxide increases [5–12]. The compressive strength is known to decrease as the water/binder or solution/binder ratio increases, given sufficient water for adequate workability and consolidation [5]. The accelerating effect of heat-curing on strength gain in AASC concrete has been often reported [5,6,13–16]. [6] suggest that temperature is second only to activator concentration in terms of its effect on compressive strength. Additionally, the compressive strength of AASC concrete tends to increase with binder content [17].

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Similarly, the compressive strength of alkali-activated fly ash (AAF) concrete is known to vary with the composition of the binder, the composition and concentration of the activator, the water content, and the curing condition [18–26]. Extremely high compressive strengths, in the range of 70–100 MPa, have been achieved in AAF binders with very high alkali concentrations or elevated temperature [5,22,27,28]. Several studies have suggested an optimum silica modulus near 1.5 for AAF concrete when sodium silicate is used as the activator [25,26,29,30].

Despite the wealth of research describing the compressive strength behavior of alkali-activated binders and concrete summarized above, there have been few attempts to model the compressive strength as a function of the mixture parameters (e.g., activator concentration, water content). [6] presented some basic categorical models for the compressive strength of AAS concrete. [31] modeled the compressive strength of potassium hydroxide-activated natural pozzolans, which was based on chemical composition, alkali solubility, and pozzolan crystallinity. [32] evaluated various methods of predicting the compressive strength of AAF concrete. Those methods varied in reliability, but focused mainly on the physical and chemical properties of the binders as predictors of strength. Suggesting that it will be of more use to practitioners to predict the compressive strength of AAC made with a given binder based on mixture parameters, the present study purports to model the compressive strength of sodium silicate-activated fly ash and slag cement concrete as a function of activator composition, water content, and curing condition. Specifically, the effects of sodium oxide dosage, silica dosage, silica modulus (relative concentration of silica to sodium oxide), solution-to-binder ratio, free water-to-binder ratio are investigated for AAF and AASC concretes cured at ambient temperature (moist-cured at 23 °C for 28 d) and elevated temperature (heat-cured at 50 °C for 48 h).

## 2. Experimental

### 2.1. Materials

The binder materials were class C fly ash and slag cement. The former was sourced from the Belle River Power Plant, a subsidiary of Detroit Edison in St. Clair County, MI. The latter was sourced from Holcim USA at the Chicago Skyway Plant in Chicago, IL. The chemical composition is given in Table 1.

The activator was a compound aqueous solution of sodium silicate and sodium hydroxide. The sodium oxide dosage *N* and silica dosage *S* were specified by percent mass of binder. The silica modulus *m* is the mass ratio of silica to sodium oxide, $m = S/N$. Solutions were prepared by mixing deionized water, sodium oxide pellets, nanosilica powder, and a commercial sodium metasilicate solution in the prescribed ratios. The solution-to-binder ratio *s* is the mass ratio of activator solution to binder, and the free water-to-binder ratio *w* is the mass ratio of water in the activator solution to binder.

The fine aggregate was quartz sand with specific gravity 1.91 and fineness modulus 2.54. The coarse aggregate was quarried crushed stone composed predominately of pink limestone. The maximum aggregate size was 13 mm.

**Table 1**
Binder composition.

| | Slag cement | Fly ash |
|---|---|---|
| | (mass percent) | |
| $SiO_2$ | 36.0 | 37.7 |
| $Al_2O_3$ | 10.5 | 20.0 |
| CaO | 39.8 | 23.4 |
| MgO | 7.9 | 4.3 |
| $Na_2O$ | 0.3 | 1.7 |
| $SO_3$ | 2.1 | 2.4 |
| $K_2O$ | 0.2 | 0.6 |
| $Fe_2O_3$ | 0.7 | 5.6 |
| LOI | 0.00 | 0.31 |

### 2.2. Mixture proportioning and parameters

This study evaluated the effects of several mixture parameters. Mixture proportions were computed according to the absolute volume method with bulk volume of coarse aggregate of 0.5 [33]. Binder type was either fly ash or slag cement as previously described. The curing condition was either moist-curing ($23 \pm 2$ °C for 28 d) or heat-curing ($50 \pm 0.1$ °C for 48 h). This heat-curing regime was selected because it has been commonly used throughout the literature, and is the minimal temperature that will result in at least the same strength in 48 h as under moist-curing for 28 d [26,34,35]. The sodium oxide dosage *N*, silica dosage *S*, silica modulus *m*, the solution-to-binder ratio *s*, and the free water-to-binder ratio *w* were also varied. It should be noted that this shorthand nomenclature is somewhat nonstandard but has been adopted for the sake of brevity and clarity.

The range of parameters evaluated for each binder type is listed in Table 2. Activator compositions are typically specified by sodium oxide dosage *N*, silica modulus *m*, and solution-to-binder ratio *s*. As such, the silica dosage *S* and free water-to-binder ratio *w* were not directly varied. Quantification of the effect of these parameters was, however, still of interest. Based on preliminary experimentation [36], it was determined that mixtures with $w < 0.3$ were insufficiently workable. Additionally, mixtures with $S < 1$ were deemed unfairly representative of the behavior of the compound activator. The intermediate values $N = \{4.2, 4.4, 4.6, 4.8\}$ were included for AAF concrete based on preliminary investigations which suggested a sharp rise in strength between sodium oxide dosages of 4 and 5% [36].

### 2.3. Experimental methods

AAC mixtures were prepared in a standard bench top laboratory mixer. The binder and saturated surface dry aggregates were first charged into the mixing bowl and mixed for 60 s. The activator solution, prepared at least 24 h in advance of mixing, was charged into the mixing bowl over the course of 30 s with the mixer running at low speed. The batch was then mixed at medium speed for an additional two minutes. Following mixing, concrete was immediately cast into $\phi 76.2 \times 152.4$ mm cylinders and consolidated by mechanical vibration. Reagent-grade activators were used to keep precise control over the activator composition; the costs associated with these activators necessitated the use of specimens smaller than the standard $\phi 152.4 \times 304.8$ mm cylinders. Each specimen was sealed with plastic and placed in the prescribed curing condition. Eight specimens were cast from each batch; four were placed in each curing condition. Each batch was cast in two replicates; a total of 646 total batches and 5168 total specimens were

**Table 2**
Mixture proportion variables, ranges, and restrictions.

| Binder: | Fly ash C | Slag cement |
|---|---|---|
| Curing | Moist-cured, heat-cured | Moist-cured, heat-cured |
| *N* | 2, 3, 4, 4.2, 4.4, 4.6, 4.8, 5, 6, 7 | 1, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 7 |
| *m* | 0.5, 1, 1.5, 2.5 | 0.5, 0.75, 1, 1.5, 2.5, 3.5 |
| *S* | $\geqslant 1.0$ | $\geqslant 1.0$ |
| *s* | 0.35, 0.4, 0.425, 0.45, 0.5 | 0.35, 0.4, 0.425, 0.45, 0.5 |
| *w* | $>0.3$ | $>0.3$ |