Alkali-Activated Concrete: Engineering Properties and Stress-Strain Behavior

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Abstract

This paper presents an investigation into the tensile strength, modulus of elasticity, Poisson's ratio, and stress-strain relationships of alkali-activated portland-cement-free concrete made with fly ash or ground granulated blast furnace slag (GGBFS) as the sole binder. Alkali-activated concrete is shown to be stronger in tension and have lower Poisson's ratio than portland cement concrete. Relationships are proposed to estimate the tensile strength and modulus of elasticity based on the compressive strength of alkali-activated concrete, which are of the same form as those currently employed for portland cement concrete.

Keywords: Alkali-activated concrete, modulus of elasticity, Poisson's ratio, stress-strain curve, tensile strength

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1. Introduction

Portland cement concrete (PCC) is the most widely used construction material, with production reaching one hundred million tonnes in the United States in 2005 [1, 2]. Even as domestic production declines, global consumption of portland cement grows significantly. Modern advancements to the portland cement manufacturing process have reduced associated energy consumption and emissions, but even the most modern operations use as much as 4 GJ of energy and emit nearly one tonne of carbon dioxide per tonne of cement produced [3–6]. This is by no means a new revelation; the concrete industry has long sought means to supplement or replace portland cement in concrete. Partial cement replacement with cementitious or pozzolanic industrial wastes like fly ashes and ground granulated blast furnace slag (GGBFS) has been employed with measurable success. These modifications not only improve the sustainability of concrete, but have also been shown to improve rheology, mechanical strength, and durability [7–10]. As an added benefit, repurposing industrial wastes reduces landfilling costs and associated environmental impact. Despite numerous and well-established benefits of partial cement replacement, fly ash and other pozzolans are typically limited to about 25% of total cementitious material, while GGBFS is often used in quantities as high as 50% of total cementitious material. A few studies have investigated the feasibility of high-volume cement replacement with some success, but these mixtures still require the use of a significant amount of portland cement [11, 12].

More recently, a number of studies have demonstrated the synthesis of portland cement-free binders by alkali activation of industrial byproducts and

26 natural pozzolans. Turner and Collins [13] recently suggested that alkali-
 27 activated binders can result in as much as 45% reduction in total carbon
 28 emissions associated with concrete production. The activation of GGBFS,
 29 fly ashes, and natural pozzolans with sodium and potassium alkalis has been
 30 shown by several studies to result in strong and durable binders [14–19]. Ar-
 31 guably the most common and effective activator used in relevant studies is
 32 sodium silicate, i.e., $\text{Na}_2\text{O} + m \cdot \text{SiO}_2$ where m is the silica modulus. Sodium
 33 silicate-activated fly ash and slag concretes have been shown to develop com-
 34 pressive strengths in excess of 30 MPa. Some formulations, particularly those
 35 based on fly ashes, require elevated temperature curing to develop apprecia-
 36 ble early-age strength [20–26]. Although the literature is somewhat conflicted
 37 with regard to durability, most available studies have shown activated con-
 38 crete to exhibit increased resistance to chloride penetration [20, 27, 28], acid
 39 attack [29–31], and sulfate attack [32], and reduced potential for deleterious
 40 alkali-silica reaction [33–35]. Despite the wealth of knowledge regarding the
 41 performance of alkali-activated concrete, very few studies have addressed the
 42 engineering properties of activated concrete, viz. the modulus of elastic-
 43 ity, Poisson’s ratio, tensile strength, and stress-strain relationships. Thor-
 44 ough understanding of these properties is essential to fully characterize the
 45 performance of alkali-activated concrete for the purpose of design and field
 46 implementation.

47 The engineering properties of PCC are generally well understood. The
 48 tensile strength f_{ct} , measured by the splitting tension (Brazilian) test, is
 49 typically 10–15% of the compressive strength f'_c . A number of more specific
 50 estimates have been proposed which have generally been of the form of Eq. 1,

51 where the splitting tensile strength f_{ct} and the compressive strength f'_c are
 52 in MPa. Typical fitting parameters are: $\frac{1}{5} \leq A \leq \frac{1}{2}$ and $\frac{5}{9} \leq B \leq \frac{7}{9}$ [36–
 53 41], although the power B is frequently constrained to a value of $\frac{1}{2}$, giving
 54 a function of the square root of the compressive strength [42–45]. Most
 55 notable is the equation for estimated splitting tensile strength given by ACI
 56 building code 318 [42] (Equation 2). High strength concrete often exhibits
 57 marginally higher tensile strength, and therefore the relationship proposed
 58 by Carrasquillo and Nilson [43] (Equation 3) applies.

$$f_{ct} = A (f'_c)^B \quad (1)$$

$$f_{ct} = 0.56 \sqrt{f'_c} \quad (2)$$

$$f_{ct} = 0.59 \sqrt{f'_c} \quad (3)$$

59 Young's modulus of elasticity E (MPa) of portland cement concrete is
 60 generally estimated as a function of the compressive strength f'_c (MPa) and
 61 the unit weight w_c (kg/m³) as in equation 4, after Pauw [46] and ACI building
 62 code 318 [42]. For normalweight concrete this reduces to equation 5 which,
 63 it should be noted, is of the same form as equation 1 with $B = \frac{1}{2}$.

$$E = 0.043 w_c^{3/2} (f'_c)^{1/2} \quad (4)$$

$$E = 4700 (f'_c)^{1/2} \quad (5)$$

64 The stress-strain behavior of concrete under uniaxial compression is rel-
 65 atively well understood, and is marked by nearly perfect linear elasticity up
 66 to the ultimate strength, followed by distinct strain softening [47, 48]. As
 67 the compressive strength increases, so does the brittleness; this manifests as
 68 an increasingly steep softening curve. Very high strength concrete exhibits
 69 highly brittle failure, with little or no softening behavior prior to complete
 70 rupture. Several authors have proposed analytical relationships to describe
 71 the stress-strain curve of portland cement concrete, although these relation-
 72 ships tend to be highly dependent on test conditions [49–51]. A reliable
 73 numerical stress-strain relationship was determined by Popovics [48] in 1973,
 74 wherein the stress σ (psi) at a given strain ϵ is estimated by a function of
 75 the ultimate stress σ_0 (psi), the corresponding strain ϵ_0 , and a constant n
 76 (Equation 6–8).

$$\sigma = \sigma_0 \frac{\epsilon}{\epsilon_0} \frac{n}{n - 1 + \frac{\epsilon}{\epsilon_0} n} \quad (6)$$

$$\epsilon_0 = 2.7 \times 10^{-4} \sigma_0^{\frac{1}{4}} \quad (7)$$

$$n = 0.4 \times 10^{-3} \sigma_0 + 1 \quad (8)$$

77 A few studies have discussed the tensile strength of alkali-activated and
 78 geopolymer concrete [22, 44, 45, 52, 53]. Several have suggested, based on
 79 somewhat limited data and without any proposed mathematical relation-
 80 ship, that alkali-activated concrete exhibits improved tensile strength over
 81 that typical of portland cement concrete [18, 22, 52, 53]. Specifically, Du-
 82 ran Atiş et al. [53] investigated the mechanical properties of alkali-activated

83 GGBFS mortar, concluding that sodium silicate-activated GGBFS mortar
 84 exhibited the best tensile strength, and that optimum solution parameters
 85 (i.e. silica modulus m and sodium oxide content) exist that provide the best
 86 tensile strength performance. A few other studies have shown contradict-
 87 ing results. Lee and Lee [44] found that the tensile strength of concrete
 88 made with alkali-activated fly ash/GGBFS mixtures was about 20% lower
 89 than that of portland cement concrete. Similarly, Sofi et al. [45] found that
 90 the tensile strength of high-compressive-strength geopolymer concrete made
 91 with fly ash and GGBFS was significantly lower than that of both normal
 92 and high strength portland cement concrete. The latter two studies proposed
 93 two very similar mathematical models to relate splitting tensile strength f_{ct}
 94 to compressive strength f'_c , which are given as Equations 9 [44] and 10 [45].

$$f_{ct} = 0.45\sqrt{f'_c} \quad (9)$$

$$f_{ct} = 0.48\sqrt{f'_c} \quad (10)$$

95 Several authors have reported the modulus of elasticity of various types
 96 of alkali-activated concrete in conjunction with other studies, but few have
 97 offered any substantial analysis or discussion of significant factors or their
 98 effects. These studies have all reported moduli of elasticity in the range of
 99 30–40 GPa [14, 18, 22] for activated fly ash and GGBFS concrete, which is
 100 in the same range as expected for portland cement concrete. Based on the
 101 results from experiments on alkali-activated natural geopolymer concrete,
 102 Duxson et al. [54] suggested that the modulus of elasticity of alkali-activated
 103 natural geopolymer concrete is strength-independent, at least within the

normal range of compressive strengths for structural concrete. Instead, it is suggested that the microstructural development has a more significant effect on the modulus of elasticity, which may be more or less the same for some alkali-activated binders [54]. Lee and Lee [44] proposed the relationship shown in Equation 11 for the modulus of elasticity of alkali-activated fly ash/GGBFS mixtures, finding that the ACI equation (Equation 4) overestimated the modulus of elasticity. Poisson's ratio has gone almost entirely unmentioned in conjunction with alkali-activated concrete in available literature, with the exception of Sofi et al. [45], who found Poisson's ratios in the range of 0.24 to 0.26 for inorganic polymer concretes.

$$E = 5300 (f'_c)^{\frac{1}{3}} \quad (11)$$

This study seeks to address the aforementioned gaps in knowledge and to cultivate a more thorough understanding of the engineering properties and stress-strain behavior of alkali-activated concrete for the purpose of design and field implementation. Specifically, this study evaluates the compressive strength, splitting tensile strength, modulus of elasticity, Poisson's ratio, and stress-strain response for alkali-activated class-C fly ash (FC) and GGBFS concrete; the results from this study are compared to the typical behavior of portland cement concrete (PCC). Additionally, this study evaluates the efficacy of using existing models for PCC to predict the behavior of alkali-activated FC and GGBFS concrete. Finally, improved models are proposed to predict the splitting tensile strength and modulus of elasticity of alkali-activated concretes. It should be noted that the models presented herein relate the splitting tensile strength and modulus of elasticity of alkali-activated con-

crete to the compressive strength, as is typical for cementitious composites. Since the strong dependence of compressive strength of alkali-activated concrete on the binder, activator, and curing condition have previously been established, the authors do not purport to address the effect of these mixture parameters on the engineering properties of alkali-activated concrete. That is to say, the aim of this paper is to propose relationships with which engineers can easily estimate the engineering properties of alkali-activated concrete without any detailed knowledge of the complex chemical makeup of alkali-activated formulations.

2. Research Significance

Although a wide body of literature is available describing the hydration products, reaction kinetics, mechanical strength, and durability of alkali-activated concrete, the engineering properties, viz., tensile strength, modulus of elasticity, and Poisson's ratio, have received only cursory attention, if any at all. Several papers have specifically called for additional investigations into these areas [44, 53]. Additionally, the authors are unaware of any studies that have investigated the stress-strain relationships of activated concrete. A complete understanding of these properties and how they relate to one another is vital for design and field implementation of alkali-activated concrete structures.

147 3. Experimental investigation

148 3.1. Materials

149 The binder materials used in this study were high-calcium ASTM C618
150 Class C coal fly ash (FC) and ASTM C989 Grade 100 granulated blast fur-
151 nace slag (GGBFS), both from reputable commercial suppliers. The oxide
152 composition, as determined by X-ray fluorescence spectrometry, and selected
153 physiochemical properties of the as-received binders are listed in Table 1.
154 The hydration products, reaction kinetics, and mechanical strengths of these
155 binders have been described by Deir et al. [19] and Gebregziabihier et al. [26].
156 The activator was a mixed solution of sodium silicate ($\text{Na}_2\text{O} + m \cdot \text{SiO}_2$) and
157 sodium hydroxide (NaOH). The Na_2O equivalent of the activator is reported
158 relative to binder mass (% Na_2O , by mass of binder), and the relative concen-
159 tration of silica to sodium oxide equivalent is reported as the silica modulus
160 m . Saturated surface-dry (SSD) natural fine aggregate with fineness mod-
161 ulus of 2.42 and specific gravity of 2.65 was used for all mixtures. Crushed
162 stone composed predominately of rose quartz with a nominal maximum par-
163 ticle size of 9.5 mm, bulk density of 1560 kg/m^3 , and specific gravity of 2.71
164 was used as coarse aggregate, and was used in SSD condition. Mixture pro-
165 portions were selected based on preliminary investigations which indicated
166 acceptable workability and appreciable compressive strength [55], and are de-
167 tailed in Table 2. Alkali-activated FC and GGBFS mixtures included 0.1%
168 dosage of rosin-based air-entraining agent for the purpose of workability im-
169 provement, as demonstrated elsewhere [55]. ASTM C150 Type I/II ordinary
170 portland cement concrete (PCC) control mixtures were selected to produce
171 similar compressive strengths as expected for the selected alkali-activated FC

172 and GGBFS mixtures.

Table 1: Chemical Oxide Composition and Selected Physical Properties of Binders

	GGBFS	FC
	% by mass	
SiO ₂	36.0	37.7
Al ₂ O ₃	10.5	20.0
CaO	39.8	23.4
MgO	7.9	4.3
Na ₂ O	0.3	1.7
SO ₃	2.1	2.4
K ₂ O	0.2	0.6
Fe ₂ O ₃	0.7	5.6

173 3.2. Specimen preparation

174 24 cylindrical concrete specimens measuring 150 mm in length and 75 mm
175 in diameter were cast in accordance with the specifications of ASTM C192 for
176 each mixture proportion as listed in Table 2. The specimen size was limited
177 to 75 mm due to the expense of the reagent-grade activators. Half of the spec-
178 imens were cured at elevated temperature (48±0.25 hours @ 50±0.1°C) and
179 the other half were cured at ambient temperature (28±0.5 days @ 22±1°C
180 and >95% RH). All specimens remained sealed for the duration of curing to
181 prevent moisture loss. After curing, specimens were de-molded and test faces
182 were ground flat and plane using a wet silicon carbide grinding belt.

Table 2: Mixture Proportions

ID	%Na ₂ O (binder mass)	m	%SiO ₂ (binder mass)	s/b (by mass)	Solution (kg/m ³)	Binder (kg/m ³)	Fine Aggr. (kg/m ³)	Coarse Aggr. (kg/m ³)
PCC1	—	—	—	0.40	228	570	658	780
PCC2	—	—	—	0.36	228	620	610	780
FC1	4.0	1.5	6.0	0.40	228	570	658	780
FC2	5.0	1.5	7.5	0.40	228	570	658	780
FC3	6.0	1.5	9.0	0.40	228	570	658	780
FC4	6.0	1.5	9.0	0.40	248	620	610	780
GGBFS1	4.0	0.75	3.0	0.40	228	570	658	780
GGBFS2	5.0	0.75	3.75	0.40	228	570	658	780
GGBFS3	6.0	0.75	4.0	0.40	228	570	658	780
GGBFS4	5.0	0.75	3.75	0.40	248	620	610	780
GGBFS5	2.0	1.5	5.0	0.40	228	570	658	780
GGBFS6	2.5	1.5	6.25	0.40	228	570	658	780

183 3.3. Test methods

184 The compressive strength, splitting tensile strength, modulus of elasticity,
185 Poisson’s ratio, and stress-strain relationship were experimentally evaluated
186 for each mixture at each curing condition, providing four replicates for each
187 measurement. The average unit weight of each batch was recorded to an
188 accuracy of 1 kg/m³. Compressive strength was determined in accordance
189 with the specifications of ASTM C39 using a stress application rate of 15
190 MPa/min. Splitting tensile strength, which is known to overestimate the
191 tensile strength of concrete when compared to direct tension testing [38],
192 was determined in accordance with the specifications of ASTM C496 using
193 a stress application rate of about 1 MPa/min. The width of the bearing
194 strips for the splitting test was less than 8% of the cylinder diameter in
195 order to achieve repeatable results, as Rocco et al. [56] showed significant

variation in tests results when bearing strips exceeded this limit. The static chord modulus of elasticity and Poisson's ratio were determined in general agreement with the specifications of ASTM C469, except for that the testing was performed under closed-loop displacement control. This modification in test procedure was made in order to allow evaluation of the post-failure strain response. Specimens were loaded in pure uniaxial compression at a constant displacement rate of 0.1 mm/min and were instrumented with an axial and radial extensometer, as shown in Figure 1. Post-failure strain measurements were also desired, and because failure typically causes the mounted gages to slip, two LVDT were also deployed in diametrically opposed positions in the axial direction.

4. Results and Discussion

The average compressive strength, tensile strength, elastic modulus, and Poisson's ratio for each mixture (4 replicates) are reported in Table 3. The unit weights of all concretes were within 2400 ± 27 kg/m³. Individual unit weights are not reported due to their similarity between mixtures.

4.1. Compressive strength

Ambient-temperature-cured (28 d @ 22°C) activated fly ash concrete exhibits very low compressive strength compared to identical specimens cured at elevated temperature (48 h @ 50°C). No such effect is observed in compressive strength results for alkali-activated GGBFS concrete, as has been reported by a few studies [19, 55]. For both binders, increased binder content results in reduced compressive strength as indicated by the strength reduction between FC formulations FC3 and FC4 and GGBFS formulations

Figure 1: Test configuration for determination of modulus of elasticity, Poisson's ratio, and stress-strain relationship.

Table 3: Summary of compressive strength f'_c , tensile strength f_{ct} , elastic modulus E , and Poisson's ratio μ results for all mixtures.

ID	Curing Condition	f'_c MPa	f_{ct} MPa	E GPa	μ
PCC1	28d @ 22°C	39.5	5.9	33.1	0.184
PCC2	28d @ 22°C	40.9	6.2	32.7	0.175
FC1	28d @ 22°C	16.2	2.9	17.7	0.126
	48h @ 50°C	31.5	6.1	28.8	0.128
FC2	28d @ 22°C	28.9	6.7	21.5	0.128
	48h @ 50°C	47.7	7.6	26.0	0.124
FC3	28d @ 22°C	22.9	3.8	22.6	0.127
	48h @ 50°C	50.3	7.5	35.5	0.124
FC4	28d @ 22°C	21.3	4.1	10.5	0.127
	48h @ 50°C	40.9	6.5	30.9	0.126
GGBFS1	28d @ 22°C	33.7	6.8	34.2	0.129
	48h @ 50°C	29.5	6.1	31.7	0.125
GGBFS2	28d @ 22°C	44.7	7.2	26.2	0.130
	48h @ 50°C	44.0	7.4	28.2	0.126
GGBFS3	28d @ 22°C	46.7	6.3	27.0	0.127
	48h @ 50°C	45.6	7.7	25.4	0.124
GGBFS4	28d @ 22°C	35.0	6.3	27.9	0.134
	48h @ 50°C	37.7	6.2	28.9	0.129
GGBFS5	28d @ 22°C	45.7	8.3	22.4	0.125
	48h @ 50°C	48.7	7.4	22.9	0.128
GGBFS6	28d @ 22°C	52.6	8.4	33.5	0.127
	48h @ 50°C	50.8	7.7	33.5	0.126

GGBFS2 and GGBFS4. Improved strength with increased binder content has been observed in PCC [57]. The propensity of activated concrete for microcracking, particularly under elevated-temperature-curing, has been discussed by Collins and Sanjayan [58]. It is likely that this microcracking, combined with increased volume fraction of the paste phase, leads to the reduction in strength of alkali-activated concrete with increased binder content.

4.2. Tensile strength

The average tensile strength of PCC control specimens is $14.1 \pm 0.6\%$ of the corresponding compressive strength, which is within the expected range of 10–15%. The tensile strengths of alkali-activated FC and GGBFS concrete observed in this study is marginally higher than those of PCC control mixtures. The average splitting tensile strength of alkali-activated GGBFS concrete is $17.0 \pm 2.1\%$ of the corresponding compressive strength, which is significantly higher than observed for PCC mixtures in a similar strength range. The sensitivity of the splitting tensile strength of activated fly ash concrete to the compressive strength appears to be affected by the curing condition; when cured at ambient temperature, the average splitting tensile strength is $19.4 \pm 2.8\%$ of the corresponding compressive strength, while the ratio is $16.5 \pm 1.9\%$ when cured at elevated temperature.

The splitting tensile strength and corresponding compressive strength of activated fly ash and GGBFS concrete are plotted in Fig. 2. Two prediction models are proposed which relate the splitting tensile strength to the compressive strength. The first, Equation 12, is of the general form of Equation 1 and fits the data quite well ($R^2 = 0.86$). A second proposed equation is also given, following the common convention of limiting the power B in Equation

1 to $\frac{1}{2}$, as in [42–45]. This square-root model (Equation 13) fits the data reasonably well ($R^2 = 0.80$), but not quite as well as with the unrestricted power (Equation 12). The goodness of fit of both proposed equations is considered quite acceptable due to the previously established variability of splitting tensile test results [56].

$$f_{ct} = \frac{2}{5} (f'_c)^{\frac{7}{9}} \quad (12)$$

$$f_{ct} = 1.08 \sqrt{f'_c} \quad (13)$$

In addition to the proposed models (Equations 12 and 13), several previously proposed models for splitting tensile strength of concrete are also included for comparison on Figure 2. These include the model proposed by Lee and Lee [44] for alkali-activated mixed fly ash/slag concrete, that proposed by Sofi et al. [45] for high-strength inorganic polymer concrete, the ACI 318 [42] model for normal strength PCC, and a model proposed by Carrasquilio and Nilson [43] for high strength PCC. The splitting tensile strengths observed here for alkali-activated FC and GGBFS concretes far exceed the predictions for both portland cement concrete [42, 43] and for alkali-activated and geopolymer concrete [44, 45] by a factor of nearly two. Lee and Lee [44] and Sofi et al. [45], despite using similar materials as used in the present study, used comparatively high solution-to-binder (s/b) ratios; the former did not specifically specify s/b , but in most cases specified mass ratios of water to fly ash greater than 1, and the latter used $s/b = 0.56$. The comparatively low ratio used in the present study ($s/b = 0.40$) is a likely reason for the discrepancy. A few other studies have suggested improved

266 tensile strength in alkali-activated concretes compared to PCC [22, 52, 53],
 267 as is seen in the present study.

Figure 2: Splitting tensile strength f_{ct} and compressive strength f'_c of alkali activated FC and GGBFS concrete along with proposed models (Eq. 12 and 13) and existing models proposed by Lee and Lee [44], Sofi et al. [45], ACI 318 [42], and Carrasquilio and Nilson [43]

268 4.3. Modulus of elasticity and Poisson's ratio

269 The axial and lateral strain relationships in the elastic region under uni-
 270 axial compression for alkali-activated concrete are highly linear, as expected.
 271 Representative curves are presented in Figures 3 and 4 for activated fly ash
 272 and GGBFS concrete, respectively. Poisson's ratio for alkali-activated FC
 273 and GGBFS concrete mixtures is 0.127 ± 0.003 , while PCC control specimens
 274 exhibited Poisson's ratio very near the expected value of 0.18. This is a very

275 surprising result which has gone unreported in the existing literature, and
 276 can be seen in Figures 3 and 4 where the lateral strain curve for PCC is
 277 very similar to those for alkali-activated FC and GGBFS concrete formula-
 278 tions even though the axial strain curve is much steeper. The modulus of
 279 elasticity of all alkali-activated FC and GGBFS concrete mixtures is within
 280 the expected range for concrete; observations are within $10 \leq E \leq 35$ GPa.
 281 The individual values observed for the modulus of elasticity of activated fly
 282 ash and GGBFS concrete are plotted against the corresponding compressive
 283 strengths in Figures 5 and 6.

Figure 3: Axial and lateral stress-strain relationships for alkali-activated fly ash concrete in pure uniaxial compression within the proportional limit.

Figure 4: Axial and lateral stress-strain relationships for alkali-activated GG-BFS concrete in pure uniaxial compression within the proportional limit.

284 The modulus of elasticity of activated fly ash concrete appears to vary di-
 285 rectly with the compressive strength, and this variation shows no discernible
 286 difference from that of PCC, as modeled by equation 5. Two models are
 287 proposed: the first, given by equation 14, is of the form of equation 1; the
 288 second, given by equation 15, is of the same form with the constraint that
 289 the power $B = \frac{1}{2}$, as in equation 5. The modulus of elasticity E and com-
 290 pressive strength f'_c are of course in MPa. The fitted equations vary only
 291 slightly from the ACI 318 equation (equation 5 in terms of both predicted

values and goodness of fit. Coefficients of determination (R^2) for equations 5, 14, and 15 are 0.54, 0.58, and 0.60, respectively. Despite these low coefficients of correlation which occur as a result of highly variable data and several potential outliers, all three equations do indeed provide a good representation of the trend. Additionally, because of the significant variation in the data, it is really impossible to conclude that one of these equations is a better predictor than another without additional studies. The model proposed by Lee and Lee [44] for alkali-activated fly ash/GGBFS mixtures is also plotted; this model drastically underestimates the modulus of elasticity of the alkali-activated FC mixtures tested here, which could again be due to the higher water content of those mixtures, or purely due to the use of mixed fly ash/GGBFS formulations. Additional models fit using curing condition as an additional predictor for the modulus of elasticity of activated fly ash concrete only marginally improve the goodness of fit. However, since the curing condition has been established as a significant effect in the compressive strength, it is likely that its use as a parameter in determining the modulus of elasticity represents the addition of a confounding variable. Furthermore, it should be noted that because mixture proportions in Table 2 are by weight and because the specific gravities of the binders are not the same, the volume fraction of aggregate is not constant between PCC and alkali-activated FC or GGBFS binders (ranging from 0.279 to 0.305). The aggregate volume fraction, as discussed by Hansen [59] is one of the main factors affecting the modulus of elasticity of concrete, although theoretically, the effect of such a

315 slight change in aggregate volume is fairly small.

$$E = 2900 (f'_c)^{\frac{3}{5}} \quad (14)$$

$$E = 4400 (f'_c)^{\frac{1}{2}} \quad (15)$$

316 The modulus of elasticity of activated GGBFS concrete, averages about
317 30 GPa, does not appear to vary with compressive strength over the range
318 $20 \text{ MPa} \leq f'_c \leq 60 \text{ MPa}$, as shown in Figure 6, nor is any significant variation
319 with curing condition observed. Attempting to fit a linear model to these
320 data results in a negative coefficient of determination ($R^2 < 0$). The practical
321 meaning of this is that a constant relationship (horizontal line) fits these data
322 better than the least-squares linear regression equation. Additionally, the
323 ACI 318 equation (equation 5) fits the data poorly. This is reminiscent of the
324 conclusions drawn by Duxson et al. [54] regarding the modulus of elasticity
325 of geopolymer concretes made with natural pozzolan binders, where it was
326 suggested that the microstructure, composition, and degree of hydration had
327 a more significant effect on the modulus of elasticity than the compressive
328 strength or solution parameters. This is due to the fact that the activator
329 and curing condition affect the composition, density, volume fraction, and
330 physical size of the product phases within the binder [19, 26], which can
331 have significant effects on the mechanical properties. This result could also
332 be a result of the significant microcracking that has been demonstrated in
333 sodium silicate-activated GGBFS concrete [58], which may be increasingly
334 prevalent as compressive strength increases. No significant correlation was
335 found between the modulus of elasticity of activated GGBFS concrete and

the activator concentrations (sodium oxide content $\%Na_2O$, silica modulus m , or silica content $m \cdot Na_2O$).

Figure 5: Modulus of elasticity and compressive strength of alkali-activated fly ash concrete.

4.4. Stress-strain relationships

A few representative stress-strain curves are shown for alkali-activated FC and GGBFS concrete in Figures 7 and 8. These experimental curves are compared with the numerically-derived curves for PCC after Popovics [48] (Equation 6). The stress-strain curves for alkali-activated FC concrete resemble the numerical estimates for PCC fairly closely. Minor differences in

Figure 6: Modulus of elasticity and compressive strength of alkali-activated GGBFS concrete.

the strain corresponding to the ultimate stress are observed under elevated-temperature curing, and the behavior is slightly more brittle. Additionally, alkali-activated FC concrete shows a more rapid decline in stress during post-peak strain softening. This suggests decreased toughness as compared to PCC. Overall, however, the stress-strain behavior of alkali-activated FC concrete is not much different than that typical of PCC. On the other hand, the stress-strain behavior of alkali-activated GGBFS concrete is starkly different than that of PCC. The strain corresponding to the ultimate stress is quite similar, but the post-peak behavior is drastically dissimilar. Where PCC displays gradual strain softening beyond the ultimate stress, alkali-activated GGBFS displays brittle fracture immediately following the peak. This increased brittleness has been observed by previous studies [53], and has generally been attributed to the high prevalence of microcracking in alkali-activated GGBFS [58]. Due to the limited number of test specimens evaluated here, no attempt is made to develop a numerical model of the stress-strain curve for alkali-activated FC and GGBFS concrete; some researchers have done so for PCC, but have generally used a very high sample size. For the purpose of this investigation, it is sufficient to conclude that the stress-strain behavior of alkali-activated fly ash concrete is similar to that of PCC, but that of alkali-activated GGBFS concrete exhibits high brittleness that is uncharacteristic of PCC.

5. Summary of Conclusions

The splitting tensile strength, modulus of elasticity, Poisson's ratio, and stress-strain relationships for alkali-activated FC and GGBFS concrete were

Figure 7: Representative stress-strain curves for alkali-activated fly ash concrete. Models for PCC after Popovics [48] are based on ultimate strength of given alkali-activated FC specimens

Figure 8: Representative stress-strain curves for alkali-activated GGBFS concrete. Models for PCC after Popovics [48] are based on ultimate strength of given alkali-activated GGBFS specimens

368 studied experimentally. The following conclusions are drawn from the results
369 of this study:

- 370 • The mechanical strength of alkali-activated fly ash concrete shows a
371 significant effect from curing condition; ambient-temperature-curing
372 (28d @ 22°C) resulted in significantly lower mechanical strength than
373 elevated-temperature-curing (48 h @ 50°C). In alkali-activated GGBFS
374 concrete, the two curing conditions resulted in no difference in mechan-
375 ical strength.
- 376 • The tensile strength of alkali-activated fly ash and GGBFS concrete is
377 significantly higher than that of portland cement concrete with similar
378 compressive strength.
- 379 • The splitting tensile strength of alkali-activated concrete is related to
380 the corresponding compressive strength by a power function of similar
381 form to those previously proposed for portland cement concrete. A
382 relationship with 86% correlation is proposed relating the tensile and
383 compressive strengths of alkali-activated FC and GGBFS concrete.
- 384 • Poisson's ratio for alkali-activated fly ash and slag concrete is about
385 two-thirds that typical of portland cement concrete with excellent re-
386 peatability.
- 387 • Young's modulus of elasticity varies linearly with compressive strength
388 for alkali-activated fly ash concrete, while the modulus remains rela-
389 tively constant for activated GGBFS concrete over the entire range of
390 compressive strengths represented in this study. Existing equations,

391 viz., equations 4 and 5 (ACI 318), fit reasonably well despite wide
392 variation in the data.

- 393 • Alkali-activated class-C fly ash concrete exhibits similar stress-strain
394 behavior to ordinary portland cement concrete, marked by imperfect
395 linear elasticity to failure followed by post-peak strain softening. Con-
396 versely, alkali-activated GGBFS concrete exhibits highly brittle behav-
397 ior marked by near perfect linear elasticity followed by sudden and total
398 failure.

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403 **References**

404 **References**

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