On drying shrinkage in alkali-activated concrete: Improving dimensional stability by aging or heat-curing

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Abstract

The problem of excessive drying shrinkage in alkali-activated concrete (AAC) is well-documented in the literature. The magnitude of drying shrinkage is often three or more times that in portland cement concrete. This study investigates the effects of binder type, activator concentration, strength, age, and curing method on the manifestation of drying shrinkage in alkali-activated fly ash and slag cement concrete. Early-age shrinkage strains in excess of $1200 \mu\epsilon$ (0.12 percent strain) are observed in AAC. This is attributed to delayed hydration, microstructure refinement, and strength development. The resulting damage is far more significant than in portland cement concrete. Shrinkage and resulting damage are greatly reduced when specimens are dried at later age and after heat-curing. Alkali-activated slag cement concrete is more sensitive to water loss than portland cement or alkali-activated fly ash concrete. This results from a finer pore structure in alkali-activated slag binders.

Keywords: Alkali-activated concrete, drying shrinkage, autogenous

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1. Introduction

Alkali-activated fly ash and slag cement concrete are promising sustainable alternatives to ordinary portland cement concrete (PCC). The improved sustainability of alkali-activated concrete (AAC) is based on: (1) The beneficiation of industrial byproducts which would otherwise be landfilled, and (2) the reduction of carbon emissions associated with portland cement production. Estimates for the reduction in carbon emissions associated with the use of alkali-activated or geopolymer binders in place of portland cement vary wildly from 9 % [1] to 80 % [2], but most studies estimate a reduction of at least 40 % [2–7]. The reduction in emissions is not only dependent on the chemistry of the alkaline activator, but also on the availability of raw materials, fuel costs, and the efficiency of the clinkering operation in a particular geographical location. This provides some context for the lack of consensus within the literature.

Although alkaline activation of aluminosilicates is by no means a new technology [8–12], alkali-activated fly ash (AAF) and slag cement (AASC) binders have only recently emerged as viable alternatives to portland cement. A number of studies describe the activation chemistry, product formation, reaction kinetics, and mechanical properties of AAF and AASC concrete [13–22]. Despite this, the long-term durability of AAC is not summarily proven [12, 23–25]. Several questions remain with regard to the durability of AAC. These mainly relate to carbonation, chloride permeability, alkali-silica reactivity, resistance to chemical attack, and shrinkage. This study

24 investigates the last.

25 *1.1. Drying and autogenous shrinkage*

26 Volume instability in hardened cement or concrete may occur due to
27 carbonation, thermal effects, drying, or self-dessication. The latter two are
28 of concern for the present study. Drying and autogenous shrinkage both
29 result from the removal of pore water from within the hardened binder. The
30 former is due to the loss of internal water to the external environment through
31 evaporation. The latter is due to self-dessication, i.e., the consumption of
32 pore water by the continuing hydration reaction. Only autogenous shrinkage
33 can occur if the specimen is sealed to prevent moisture egress, but autogenous
34 and drying shrinkage occur simultaneously if the specimen is unsealed.

35 Drying shrinkage is approximately proportional to water loss [26]. Since
36 aggregates are highly dimensionally stable, shrinkage is dominant within the
37 binder paste. An increase in binder content in concrete, which leads to
38 an increase in the paste volume, naturally leads to an increase in drying
39 shrinkage [27, 28]. With sufficient shrinkage strains, cracking occurs. This
40 can result in weakening of concrete structures, but the formation of cracks is
41 more significant to the durability of concrete [28].

42 Since autogenous shrinkage results from the consumption of water by the
43 continuing hydration reaction, it is only of concern when the binder does
44 not reach its full hydration potential. In the case of portland cement, com-
45 plete hydration requires $w/cm > 0.42$ [29–31]. Above this value, at which
46 sufficient water is provided for complete hydration, autogenous shrinkage is
47 theoretically nonexistent. It should be noted that there is some disagree-
48 ment on the value of w/cm which results in complete hydration of portland

49 cement [32, 33], but this is of no consequence to the present study.

50 Three predominate mechanisms are known to contribute to drying shrink-
51 age: Surface energy, capillary stress, and disjoining pressure [34–41]. The
52 effects of surface energy (or surface tension) are explained by the Bangham
53 equation and Gibb’s free energy [35, 40, 42, 43], which describe the shrinkage
54 resulting from a reduction in surface energy due to the spreading of phys-
55 ically adsorbed water within the pore volume. Surface energy effects are
56 significant below 45 %RH [44]. Disjoining pressure arises from a cohesive
57 interaction—mainly due to Van der Waals forces—between the pore water
58 and the surface within the pore volume [40, 45–48]. Disjoining pressure is
59 significant only above 45 %RH [44].

60 Shrinkage induced by capillary stresses is a function of the volume of
61 capillary pores, the capillary stress, and the compliance of the medium [49].
62 The volume of capillary pores in PCC is sensitive to w/cm and the degree of
63 hydration [34, 50, 51]. The capillary pressure P_{cap} is related to the surface
64 tension of the pore fluid γ and the pore radius r according to Equation 1 [44,
65 52, 53].

$$P_{cap} = \frac{2\gamma}{r} \quad (1)$$

66 As the surface tension increases, so does the capillary pressure. Larger
67 pores develop lower capillary stresses since the ratio of pore volume to surface
68 area is lower. Capillary stresses are significant only above 45 %RH due to
69 instability of menisci below this humidity level [44].

70 *1.2. Drying and autogenous shrinkage in AAC*

71 The problem of excessive drying shrinkage strains in AASC is well docu-
72 mented [12, 14, 54–62]. Bakharev et al. [55] showed that curing at elevated
73 temperature effectively reduced the magnitude of drying shrinkage strain in
74 AASC concrete. Additions of gypsum, common air-entraining admixtures
75 (AEA), and shrinkage-reducing admixtures (SRA) have also been shown to
76 temper the magnitude of drying shrinkage in AASC [57, 59]. Atiş et al. [61]
77 found that the use of sodium carbonate as an activator instead of sodium sil-
78 icate or sodium hydroxide also resulted in reduced shrinkage. Several studies
79 have also demonstrated increased autogenous shrinkage in AASC relative to
80 comparable portland cement [55, 57, 60, 62].

81 In accordance with the previous discussion, the pore structure has a sig-
82 nificant effect on drying shrinkage in concrete. Collins and Sanjayan [58]
83 attributed the increased drying shrinkage in AASC concrete to a finer over-
84 all porosity. AASC binders are known to include a higher percentage of
85 mesopores ($2\text{ nm} \leq r \leq 50\text{ nm}$) than portland cement [58, 63–65]. Shi [63]
86 posited that sodium silicate-activated slag cement binders resulted in the
87 finest pore structure of any AASC binders. Bakharev et al. [55] showed that
88 the relatively localized hydration in heat-cured AASC resulted in a coarser
89 porosity. Reduced drying shrinkage in heat-cured AASC concrete was at-
90 tributed to this change in pore structure [55]. Furthermore, Palacios and
91 Puertas [59] attributed reduced drying shrinkage in AASC with SRA to a
92 coarsening of the pore structure and a reduction in pore fluid surface tension.

93 Comparatively few studies have discussed the manifestation of drying or
94 autogenous shrinkage in AAF. Fernández-Jiménez et al. [66] reported that

the drying shrinkage in AAF mortar was less than that observed in comparable OPC mortar. Several studies have reported similar results for fly ash-based geopolymer binders [67, 68], but geopolymers are chemically and mechanically distinct from AAF binders. In a study of the properties of alkali-activated blended fly ash/slag cement mortars, Chi and Huang [69] showed that a higher proportion of fly ash led to a decrease in the observed drying shrinkage strain. That same study also indicated that an increase in the dosage of sodium oxide in blended alkali-activated binders led to a decrease in the observed shrinkage [69].

The porosity and pore size distribution in alkali-activated binders has been studied somewhat intensely using micro-computed tomography (μ CT), mercury intrusion porosimetry (MIP), Wood’s metal intrusion porosimetry (WMIP), nitrogen sorption, water sorption, and microscopy; much of this research is neatly summarized by Provis et al. [70]. The high degree of heterogeneity and chemical complexity of alkali-activated binders results in a wide distribution of pore sizes, which can range from the order 10 nm to the order 10 μ m [70]. As a result of very small pore sizes and the ink-bottle effect, standard techniques like MIP, WMIP, and water sorption give incomplete information regarding the porosity and pore structure in alkali-activated binders [70–73]. More advanced techniques like μ CT and nitrogen adsorption using Brunauer-Emmet-Teller (BET) theory [74] give more complete information.

Very high porosity has been observed in AAF binders [75–78], which are devoid of large capillary pores but include some very large cavities [78]. In comparison, the pore structure of AASC binders is much finer and more

120 tortuous [70]. Some conflicting results have indicated only minor differences
121 in the porosity and pore structure with curing time [79], but most studies
122 suggest that the porosity and pore connectivity in AAC decrease with both
123 curing time and curing temperature [70, 78, 80, 81].

124 1.3. Research objectives

125 The problem of excessive drying shrinkage in AASC concrete is well-
126 documented. However, there is limited information about how the activator
127 concentration in AAC affects the susceptibility to drying shrinkage. The
128 effect of heat curing on the manifestation of drying shrinkage has been doc-
129 umented to some extent, but the effect of age at drying has not. Finally,
130 the damage that occurs as a result of drying shrinkage in AAC has not been
131 fully investigated. This study seeks to address these gaps in knowledge.

132 2. Materials and methods

133 2.1. Materials and mixture proportions

134 The binder materials used in this study were class C fly ash meeting
135 the specifications of ASTM C618, grade 100 ground granulated blast-furnace
136 slag (slag cement) meeting the specifications of ASTM C989, and Type I
137 ordinary portland cement (OPC) meeting the specifications of ASTM C150.
138 The oxide composition of the fly ash and slag cement is listed in Table 1.

139 The activator was an aqueous sodium silicate solution ($\text{Na}_2\text{O} + m \cdot \text{SiO}_2$).
140 The silica modulus m is the mass ratio of silica to sodium oxide in the
141 activating solution. Activator concentrations were specified by the silica
142 modulus m and the dosage of sodium oxide in percent by mass of binder.

143 The solution-to-binder ratio s/b is the mass ratio of activator solution (or
144 water, in the case of OPC concrete) to binder. The solution-to-binder ratio
145 s/b was 0.40 throughout. Activator concentrations are given in Table 2. The
146 fine aggregate was a natural quartz sand. The specific gravity was 2.71 and
147 the fineness modulus was 2.36. The coarse aggregate was a quarried crushed
148 stone composed mainly of rose quartz. The nominal maximum aggregate
149 size was 12.5 mm (0.5 in). The binder content was 570 kg/m³, the coarse
150 aggregate content was 780 kg/m³, the fine aggregate content was 658 kg/m³,
151 and the activator solution content was 228 kg/m³.

152 For comparative purposes, an effort was made to replicate the activator
153 concentrations used for fly ash mixtures (FC1–FC3) using slag cement as the
154 binder. The solutions concentrations for FC1 and FC2 are thus replicated
155 for SC1 and SC2. The solution concentration used for FC3 (i.e., 6% Na₂O,
156 $m = 1.5$) resulted in a mixture that was poorly workable and difficult to
157 consolidate when used with slag cement as the binder, and was therefore
158 excluded.

159 2.2. Experimental methods

160 Concrete was cast into $\phi 101.6$ mm x 203.2 mm ($\phi 4$ in x 8 in) cylinders
161 for the determination of compressive strength and 50.8 x 50.8 mm (2 x 2 in)
162 mortar bars with gage length 254 mm (10 in) for shrinkage evaluation. The
163 latter were in accordance with the specifications of ASTM C157. Specimens
164 were cast in three equal lifts and consolidated between lifts using a vibrating
165 table. Cast specimens were double-sealed with plastic film to limit moisture
166 loss. Moist-cured specimens were stored at 23±2 °C and >95 %RH. Heat-
167 cured specimens were stored in an oven at 50±0.1 °C. Compressive strength of

Table 1: Oxide composition of binders

	Slag cement	Fly ash
	(percent composition 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
LOI	0.0	0.31

168 moist-cured concrete was evaluated at 1, 3, 7, 14, 28, and 90 d. Compressive
169 strength of heat-cured concrete was evaluated at 24, 48, and 72 h. Each
170 compressive strength test included a minimum of four replicates.

171 Since alkali-activated binders have exhibited slow hydration and strength
172 gain (depending on activator composition and concentration) [82–84], moist-
173 cured shrinkage specimens remained in their molds for 72 h, instead of the
174 standard 24 h as prescribed by ASTM C157. Heat-cured shrinkage specimens
175 were demolded after 48 h. Following demolding, the initial length, mass, and
176 dynamic modulus of elasticity of each specimen was measured. Specimens
177 were then submerged in saturated limewater for either 72 h or 90 d. Following
178 the saturation period, the specimen length, mass, and dynamic modulus of
179 elasticity were again measured. Specimens were then dried on stainless steel

Table 2: Mixture proportions and activator solution concentrations (*Note: PC indicates portland cement, FC indicates fly ash, and SC indicates slag cement*)

ID	Activator		
	% Na ₂ O	m	s/b
PC1	—	—	0.4
FC1	4.0	1.5	0.4
FC2	5.0	1.5	0.4
FC3	6.0	1.5	0.4
SC1	4.0	1.5	0.4
SC2	5.0	1.5	0.4
SC3	4.0	0.75	0.4
SC4	5.0	0.75	0.4
SC5	6.0	0.75	0.4

180 wire racks at 50 ± 5 %RH and 22 ± 2 °C to ensure equal drying on all sides.
181 Measurements of length, mass, and dynamic modulus of elasticity in drying
182 specimens were taken daily for one week, and then at 14, 28, 56, 90, 180, 270,
183 and 365 d. Several cylindrical specimens were exposed to identical conditions
184 and the compressive strength of those specimens was measured after drying
185 for 90 d.

186 For the sake of clarity in the following discussion, some nomenclature
187 is defined. Specimens which were moist-cured for 72 h and submerged in
188 saturated limewater for 48 h prior to drying are said to be dried at early
189 age. Specimens which were moist-cured for 72 h and submerged in saturated
190 limewater for 90 d prior to drying are said to be dried at later age. Fi-
191 nally, specimens which were heat-cured for 48 h and submerged in saturated
192 limewater for 48 h prior to drying are said to be dried after heat-curing.

193 Compressive strength was evaluated in accordance with the specifications
194 of ASTM C39. Drying shrinkage was measured as length change relative to
195 the initial specimen length in accordance with the specifications of ASTM
196 C596. Specimen length was measured using a standard length comparator
197 and invar reference rod in accordance with the specifications of ASTM C490.
198 Dynamic modulus of elasticity E_d was determined from Equation 2, where
199 C is a geometric factor found from ASTM C215, M is the specimen mass,
200 and n is the fundamental transverse resonant frequency.

$$E_d = CMn^2 \quad (2)$$

201 **3. Results and Discussion**

202 *3.1. Drying shrinkage*

203 *3.1.1. Early-age drying shrinkage*

204 The drying shrinkage strain and water loss in specimens dried at early
205 age are plotted in Figures 1 and 2 for AAF and AASC concrete, respectively.
206 Drying shrinkage in PCC occurred gradually, reaching a terminal value of
207 about $700 \mu\epsilon$ (0.07 percent strain). The accompanying water loss was about
208 2.7 percent by mass. About half the total shrinkage was observed in the
209 first 7 d. This is consistent with expectations based on existing literature
210 [14, 54–62].

211 The drying shrinkage in AAF concrete was much greater, in the range
212 of $800\text{--}1300 \mu\epsilon$ (0.08–0.13 percent strain). Additionally, that shrinkage oc-
213 curred much more rapidly. This is in contrast to previously reported re-
214 sults [66, 69]. More than 90 percent of the ultimate shrinkage value was
215 observed in the first 7 d, with about half in the first 24 h. A high degree
216 of dimensional stability was reached within 90 d. The magnitude of shrink-
217 age decreased as the sodium oxide dosage in the activator increased, which
218 follows Chi and Huang [69]. Increased sodium oxide concentration improves
219 compressive strength and modulus of elasticity within the represented range,
220 and has also been shown to reduce porosity in AAC [54, 58, 59, 63, 82, 85, 86].
221 A stiffer and less porous concrete will logically be more dimensionally stable.

222 The water loss in AAF concrete was similarly high, in the range of 3–6
223 percent by mass. Most of the water loss was at early age, and the shrinkage
224 strain showed a direct correlation to the water loss. Much more water was
225 lost from AAF concrete than PCC, which suggests that the availability of

226 water for evaporation is higher in AAF. Since it is known that the total
227 porosity in AAF binders is relatively high, this logically follows.

228 The drying shrinkage strain in AASC concrete was also very high. The
229 rate of shrinkage was faster than in PCC, but not quite as fast as in AAF
230 concrete. About two-thirds the ultimate shrinkage was realized within 7 d.
231 Although the magnitude of shrinkage strain was higher in AASC concrete
232 than in PCC, the water loss was about half or less. Furthermore, the water
233 loss was not directly related to the shrinkage strain in AASC concrete. For
234 example, the shrinkage strain was greater in mixture SC2 than in SC1, but
235 less water was lost. The magnitude of shrinkage is normally well-correlated to
236 the percent water loss [26]. Both of these conclusions are therefore somewhat
237 counter-intuitive.

238 The observed shrinkage was higher in magnitude when the silica modulus
239 increased from 0.75 to 1.5. With constant silica modulus, the magnitude of
240 shrinkage increased with sodium oxide concentration. Increases in both silica
241 modulus and sodium oxide are known to improve the strength and stiffness
242 of AASC concrete within the represented range [54, 61, 63, 85, 86]. Sodium
243 oxide tends to accelerate activation, while silica tends to retard it [82–84, 87–
244 90]. If changes in the mechanical properties (strength, stiffness, or compli-
245 ance) were responsible for the observed shrinkage reduction then increased
246 sodium oxide or silica modulus would be expected to result in lower shrink-
247 age. However, mixtures with higher sodium oxide and silica modulus actually
248 experienced higher-magnitude shrinkage. It is therefore likely that changes
249 in porosity or the pore structure are a more likely culprit. In fact, Collins
250 and Sanjayan [58] argued that the pore structure was more important in

Figure 1: Early-age drying shrinkage and water loss in AAF concrete

251 determining the shrinkage in AASC concrete than the water loss. Shi [63]
 252 showed that when silica was included in the alkaline activator, the pore struc-
 253 ture in AASC binders became much finer. The increased shrinkage in AASC
 254 concrete with higher silica modulus must therefore result from a finer pore
 255 structure. In accordance with Equation 1, this increases the capillary ten-
 256 sile stress. In addition, this makes diffusion through the binder matrix more
 257 difficult.

258 3.1.2. Later-age and heat-cured drying shrinkage

259 Drying shrinkage strains and water loss in specimens dried at later age
 260 and after heat-curing are plotted in Figures 3 and 4. Drying shrinkage in
 261 AAC at later age was much less than at early age. The maximum shrinkage
 262 strain recorded in AAC at later age was about $500 \mu\epsilon$ (0.05 percent). That

Figure 2: Early-age drying shrinkage and water loss in AASC concrete

shrinkage was still far more rapid in AAC than in PCC, especially for AAF concrete. The shrinkage was slightly reduced in PCC at later age, but only by a small margin. The water loss in PCC and AAF concrete was approximately the same as at early-age, but was greatly reduced in AASC concrete. Since there was little change in water loss in AAF concrete, the change in shrinkage must arise from some change in the pore structure or mechanical properties. The strength at 90 d is much higher than at 3 d, and the stiffness is known to follow the strength [86]. In addition, some significant changes in the microstructure can be expected after 3 d due to the relatively slow kinetics of the activation reaction [82–84, 87–90]. A dramatic reduction in water loss is at least partially responsible for the reduction in shrinkage in AASC concrete, but it is very likely that changes in mechanical properties and porosity also contribute. The microstructure of AASC binders are known to experience

276 gradual refinement [82–84, 87–90]. Reduced water loss is therefore a likely
277 result of lesser total porosity at later age [70, 81]. This limits the pore volume
278 and therefore the water within the pore structure.

279 At elevated temperature, the reduction in shrinkage is even greater. The
280 maximum drying shrinkage observed in AAC cured at elevated temperature
281 was about $350 \mu\epsilon$ (0.035 percent). The water loss in AAF concrete was
282 approximately the same as under ambient curing at early age and at later age.
283 The water loss was greatly reduced in AASC concrete, which is again likely
284 a result of a lower total porosity. Hydration, and therefore refinement of the
285 microstructure, are of course greatly accelerated at elevated temperature [82–
286 84, 90]. Significant strength development can then be expected in AAC even
287 when heat-cured for shorter durations. It is therefore likely that the benefits
288 of heat-curing in terms of shrinkage mitigation could be realized even under
289 heat-curing regimes of much shorter duration than those employed here.

290 It is also important to consider the changes in product phase composition
291 that occur in AAF and AASC binders with age. Portland cement binders
292 are very stable in phase composition, and reach that stability fairly early in
293 the curing period. Alkali-activated binders, on the other hand, are known to
294 change in both composition and concentration throughout their curing pe-
295 riod. Furthermore, the product phase composition in alkali-activated binders
296 may be significantly altered by carbonation, efflorescence, or other phenom-
297 ena [23, 91–93]. These changes in phase composition may also have a signif-
298 icant effect on the water loss and resulting shrinkage.

299 Some limited information regarding the water-permeable porosity of AAC
300 mixtures identical to those discussed in this paper has been presented by some

Figure 3: Shrinkage and water loss after 90 d limewater curing

Figure 4: Shrinkage and water loss after 48 h heat curing

301 of the authors [94, 95]. The water-permeable porosity and accompanying
 302 electrical conductivity data indicate that the porosity and pore connectivity
 303 and AAS is significantly lower when slag cement is used as the binder. Fur-
 304 thermore, these data indicate that heat-curing tends to reduce the permeable
 305 porosity and reduce the electrical conductivity, suggesting a net reduction in
 306 porosity and pore connectivity. Although these data are an admittedly poor
 307 description of the pore structure in AAC, they do give some context for the
 308 above discussion. Furthermore, a few previous studies by other authors have
 309 reported on the pore structure of similar concrete mixtures. In particular,
 310 Provis et al. [70] reported on the porosity and tortuosity of the pore network
 311 in sodium metasilicate-activated binders made with fly ash, slag cement, and
 312 blends thereof using three-dimensional μ CT mapping of the pore structure.
 313 That study indicated a significantly lower porosity and high tortuosity in
 314 AASC binders than in AAF; longer curing times were shown to decrease the
 315 porosity and increase the tortuosity in both AAF and AASC binders [70].
 316 Sindhunata et al. [79] reported contrary results for fly ash-based geopolymers
 317 based on nitrogen adsorption, indicating only a slight reduction in porosity
 318 with increased curing time. A few other studies have shown decreased poros-
 319 ity and pore connectivity in AAF and AASC binders with increased curing
 320 temperature or curing duration [78, 80, 81, 96]. These results are mostly
 321 consistent with the above arguments.

322 3.1.3. *Sensitivity to water loss*

323 The sensitivity of length change to water loss at early age, late age, and
 324 after heat curing is shown in Figure 5. Here, we define sensitivity as the slope
 325 of the curve where the abscissa is water loss and the ordinate is shrinkage,

326 i.e., the length change per unit water loss. Evaluating the sensitivity provides
327 clues about the mechanism involved in changes in shrinkage. Since the cap-
328 illary tensile stress, and therefore the magnitude of shrinkage resulting from
329 a unit water loss, is dependent on the pore radius, a change in sensitivity
330 suggests a change in the pore size distribution. Increased sensitivity suggests
331 a finer porosity, while decreased sensitivity suggests a coarser porosity.

332 The sensitivity of PCC was about the same at early and later age. At
333 early age, the sensitivity of AAF concrete was about the same as that of PCC.
334 This suggests that the pore size distribution was relatively similar. This is in
335 good agreement with existing literature [75–78]. The increased shrinkage in
336 AAF concrete dried at early age therefore resulted from increased water loss.
337 It is known that the total porosity in AAF concrete is very high [75–78],
338 allowing for more water absorption during saturation and more water loss
339 during drying.

340 The sensitivity of AAF concrete was reduced at later age and after heat-
341 curing, although the water loss was not greatly affected. It has been sug-
342 gested that both the porosity and pore size in AAF binders are reduced
343 with age and under heat-curing [78]. The minimal reduction in water loss
344 observed here suggests only a minor reduction in porosity. The reduced sen-
345 sitivity suggests a coarsening of the pore structure, rather than the expected
346 refinement. It has been shown that AAF binders are highly susceptible to
347 microcracking, particularly when heat-cured [82]. In fact, micrographs of
348 similar binder systems (except with higher s/b) presented by Deir et al. [82]
349 show abundant microcracking, particularly when heat-cured. The presence of
350 microcracks could account for this reduced sensitivity, since water lost from

351 very fine microcracks would not likely generate appreciable stress. Addition-
352 ally, the drastic improvement in strength in AAF concrete at later age and
353 after heat-curing is accompanied by a likewise improvement in the modulus
354 of elasticity [86]. This results in a stiffer concrete which is more resistant to
355 length change as a result of internal stresses.

356 Length change in AASC concrete was more sensitive to water loss than
357 PCC and AAF concrete under all curing conditions. Not only is the poros-
358 ity in AASC concrete generally less than that of PCC, the pore structure is
359 finer [55, 58, 59, 63–65, 85]. This is likely the reason for the increased sensi-
360 tivity to water loss observed in AASC concrete. The sensitivity was similar
361 when dried at early age, later age, and after heat-curing. Reduced shrinkage
362 under the latter two conditions is therefore a result of reduced water loss.
363 This is in agreement with previous observations which indicate a reduction
364 in total porosity in AASC concrete at later age and after heat-curing [55].

365 3.1.4. *Ultimate shrinkage*

366 The ultimate drying shrinkage is that value at which the shrinkage mea-
367 surement stabilized, i.e., did not change by more than 0.0025 mm (0.0001 in)
368 between successive readings. All specimens reached this point within one
369 year. The ultimate drying shrinkage values in AAC and PCC are compared
370 in Table 3. The table lists the ultimate drying shrinkage for specimens dried
371 at early age, later age, and after heat-curing. The ultimate drying shrink-
372 age for PCC dried at early age was only marginally higher than under other
373 conditions. This indicates that aging PCC or curing at elevated temperature
374 did little to improve resistance to drying shrinkage. On the contrary, the ter-
375 minal early-age drying shrinkage in AAC was three to five times that at later

Figure 5: Sensitivity of length to water loss under varying curing conditions

Table 3: Terminal drying shrinkage values for specimens dried at early and late ages. **Ratio* refers to the ratio of late-age or heat-cured drying shrinkage to early-age drying shrinkage

	Ultimate drying shrinkage ($\mu\varepsilon$)		
Mixture	Early-age	Late-age (*Ratio)	Heat-cured (*Ratio)
PC1	710	575 (0.81)	550 (0.77)
FC2	975	340 (0.35)	210 (0.22)
SC2	1380	510 (0.37)	355 (0.26)
SC4	890	280 (0.31)	195 (0.22)

age or after heat-curing. Therefore, both heat-curing and aging effectively reduced the susceptibility of AAC to drying shrinkage. The former is more effective by a noticeable margin. This again likely results of the documented improvements in porosity at later age and after heat-curing [55].

3.2. Damage during drying

Damage in concrete due to drying shrinkage occurs mainly due to cracking. Typical cracking patterns for AAF and AASC concrete dried for 90 d at early age and after heat-curing are shown in Figure 6. Specimens were dusted with blue chalk to highlight the appearance of cracks. Cracking was much more severe in AAF concrete, especially when dried at early age. Only

Figure 6: Typical cracking patterns in (a) AAF concrete dried at early age, (b) AAF concrete dried after heat-curing, (c) AASC concrete dried at early age, and (d) AASC concrete dried after heat-curing

386 very minor surface cracks were observed in AASC concrete, despite some very
 387 large drying shrinkage strains observed. Specimens dried after heat curing
 388 exhibited some significant surface cracking, despite minimal drying shrinkage
 389 strain. These cracks were visible immediately after heat curing and prior to
 390 drying. This suggests that the cracking occurred during heat-curing, indi-
 391 cating that some autogenous or drying shrinkage must be occurring during
 392 the initial curing period.

393 Cracking reduces both the compressive strength and the dynamic mod-
 394 ulus of elasticity in concrete. The extent of damage can therefore be evalu-
 395 ated by measuring both properties before, during, and after drying. Baseline
 396 strength values are listed in Table 4 for moist-cured and heat-cured cylin-

397 ders. The 28 d moist-cured compressive strengths of all concrete mixtures
398 used in this study are presented in Table 4. The compressive strength of AAF
399 concrete was greatly improved by curing at elevated temperature for 48 h.
400 The compressive strength of AASC concrete was approximately equivalent
401 under both curing conditions. The compressive strength of PCC after 48 h
402 heat-curing was not recorded. Although PCC does gain appreciable strength
403 in 48 h at 50 °C, the strength gain is not accelerated nearly as much as in
404 AAC.

405 The strength development of selected mixtures is shown in Figure 7.
406 Strength gain in AAC at ambient temperature is slower than in PCC, par-
407 ticularly for AAF concrete. The 1 d compressive strength of PCC is about
408 one-third the strength at 28 d. AASC concrete develops strength relatively
409 slowly. The 1 d strength is between one-tenth and one-fourth the strength
410 at 28 d. Strength development in AAF concrete is even slower; the strength
411 after 3 d is only one-fifth the 28 d compressive strength. Strength develop-
412 ment in AAC cured at elevated temperature was much more rapid. In AASC
413 concrete, the compressive strength after 48 h heat-curing was approximately
414 equal to the 28-d ambient-cured strength. AAF concrete develops approxi-
415 mately double the 28 d ambient-cured compressive strength after heat-curing
416 for 48 h. In both cases, about 75 percent of that strength was developed in
417 the first 24 hours.

418 Strength development is mostly a function of activation kinetics, which
419 have been described in great detail by a number of studies [12, 82–84]. The
420 activation reaction is greatly accelerated at elevated temperature and with
421 increased sodium oxide dosage in the activator [12, 83, 84]. The reaction

Table 4: Compressive strength f'_c and dynamic modulus of elasticity E_d under various curing conditions

	%Na ₂ O	m	f'_c (MPa [psi])			E_d (GPa [10^6 psi])		
			28-d ($f'_c{}^*$)	90-d	Heat-cured	28-d (E_d^*)	90-d	Heat-cured
PC1	—	—	39.5 [5730]	42.6 [6180]	—	33.2 [4.81]	36.7 [5.32]	—
FC1	4.0	1.5	16.2 [2350]	22.5 [3260]	31.5 [4570]	18.1 [2.62]	21.4 [3.10]	17.9 [2.60]
FC2	5.0	1.5	22.9 [3320]	26.4 [3830]	47.7 [6920]	22.4 [3.25]	25.3 [3.67]	21.2 [3.07]
FC3	6.0	1.5	28.9 [4190]	33.4 [4840]	50.3 [7290]	23.9 [3.47]	26.7 [3.87]	26.4 [3.83]
SC1	4.0	1.5	41.2 [5970]	43.6 [6320]	39.7 [5760]	34.9 [5.06]	35.7 [5.18]	33.5 [4.86]
SC2	5.0	1.5	46.2 [6700]	49.1 [7120]	46.6 [6760]	37.1 [5.38]	39.2 [5.68]	35.6 [5.16]
SC3	4.0	0.75	33.7 [4890]	36.2 [5250]	29.5 [4280]	31.8 [4.61]	32.1 [4.65]	32.1 [4.65]
SC4	5.0	0.75	44.7 [6480]	46.3 [6710]	44.0 [6380]	33.5 [4.86]	34.6 [5.02]	31.4 [4.55]
SC5	6.0	0.75	46.7 [6770]	48.5 [7030]	45.6 [6610]	36.2 [5.25]	38.3 [5.55]	35.7 [5.18]

422 is slightly retarded by increased silica in the activator, but the compressive
423 strength at later age is generally improved [12, 83, 84].

424 The compressive strengths of AAC and PCC are presented in Table 5 for
425 specimens dried at early age, later age, and after heat-curing. The relative
426 compressive strength $f'_c/f'_c{}^*$ and dynamic modulus E_d/E_d^* , where $f'_c{}^*$ and E_d^*
427 are the moist-cured compressive strength and dynamic modulus of elastic-
428 ity, respectively, and f'_c and E_d are the compressive strength and dynamic
429 modulus of elasticity, respectively, after drying at either early or late age, are
430 shown in Figure 8. This figure shows the strength and modulus reductions
431 that resulted from drying under each condition. The strength and dynamic
432 modulus in PCC of elasticity were only slightly reduced by drying at either
433 early or later ages. When dried at early age, PCC retained about 85 percent
434 of the 28 d strength. Meanwhile, AAC dried at early age exhibited about
435 half the 28-d moist-cured compressive strength. That was accompanied by
436 a reduction in dynamic modulus of 20–30 percent, which indicates extensive

Figure 7: Compressive strength development of selected concrete mixtures cured at ambient and elevated temperature

437 cracking. The reductions in strength and dynamic modulus in AAC were
 438 tempered at late age and after heat-curing. In most cases, the strength and
 439 dynamic modulus were very near the 28 d values when dried at late age or
 440 after heat curing. The strength of AAF concrete dried after heat-curing was
 441 much higher than the 28 d strength due to the dramatic effect of heat-curing
 442 on the compressive strength of AAF concrete. This shows that aging and
 443 heat-curing not only effectively mitigate the manifestation of drying shrink-
 444 age in AAC, but also effectively mitigate the associated damage.

Table 5: Compressive strength f'_c and dynamic modulus of elasticity E_d after 90 d drying with various curing conditions

	f'_c (MPa, [psi])			E_d (GPa [10^6 psi])		
	Early age	Late age	Heat-cured	Early age	Late age	Heat-cured
PC1	33.7 [4890]	37.6 [5450]	—	32.0 [4.64]	34.1 [4.94]	—
FC2	13.5 [1960]	19.2 [2780]	41.4 [6000]	11.5 [1.67]	20.9 [3.03]	19.9 [2.89]
SC2	21.4 [3100]	42.3 [6130]	44.5 [6450]	29.3 [4.25]	37.6 [5.45]	33.1 [4.80]
SC4	22.6 [3280]	41.4 [6000]	43.8 [6350]	28.8 [4.18]	33.2 [4.81]	30.0 [4.35]

Figure 8: Compressive strength f'_c and dynamic modulus of elasticity E_d after drying relative to 28-d moist-cured compressive strength f'_c^* and dynamic modulus of elasticity E_d^*

4. Conclusions

The drying shrinkage characteristics of AAF and AASC concrete under various conditions were investigated. The effects of activator concentration,

448 heat-curing, and age were evaluated. The shrinkage characteristics of AAC
449 were compared with those of PCC. Several interesting conclusions are drawn.

450 AAC is in general less volumetrically stable and more prone to damage
451 than PCC under normal testing conditions (i.e., cured at ambient temper-
452 ature and exposed to drying environment at early age). The magnitude of
453 early-age drying shrinkage is sometimes in excess of $1000\ \mu\epsilon$ (0.1 percent
454 strain). In AASC concrete, this results from a finer pore structure which
455 greatly increases capillary stress. The dimensional stability of AASC con-
456 crete is, in turn, more sensitive to water loss. In AAF concrete, this is a
457 result of higher total porosity which increases the pore volume and water
458 loss. This shrinkage is accompanied by a strength loss of nearly 50 percent
459 compared to the 28 d moist-cured strength.

460 The volumetric stability of AAC is greatly improved at later age. The
461 drying shrinkage is reduced by two-thirds or more. The resulting damage
462 is similarly tempered. When heat-cured, the volumetric stability is further
463 improved. The magnitude of drying shrinkage is reduced by 75 percent or
464 more, and the resulting damage is again reduced. Therefore, while AAC is
465 highly susceptible to drying shrinkage at early age, the problem is easily mit-
466 igated without the use of chemical admixtures. This results from reductions
467 in total porosity at later age and after heat-curing. This suggests that the
468 poor early-age dimensional stability of AAC under drying conditions results
469 mainly from delayed product formation and microstructure development.

470 In AAF concrete, an increase in sodium oxide concentration led to a
471 reduction in the observed shrinkage. This is likely a result of reduced porosity
472 and improved strength and stiffness. In AASC concrete, increases in both

473 sodium oxide and silica modulus led to increased shrinkage, despite improving
474 the strength. This could be due to a reduction in the porosity or an increase
475 in pore fineness, which affect the sensitivity to water loss.

476 In general, the susceptibility of AAC to early-age drying shrinkage lim-
477 its its applicability in the field. However, the effective mitigation of that
478 shrinkage by either curing for a longer duration or at elevated temperature
479 is summarily proven. These curing regimes are obvious unrealistic in-situ.
480 However, a practical interpretation of these results is that AAC may be par-
481 ticularly well-suited for precast applications wherein these curing regimes are
482 not necessarily prohibitive.

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