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Engineering Properties of Ambient Cured Alkali-Activated Slag-Fly Ash Concrete Reinforced with Different Types of Steel Fiber

Abstract

This paper investigates the influence of different types of steel fibers on the engineering properties of ambient cured alkali-activated slag-fly ash concrete. The engineering properties investigated include workability, compressive strength, splitting tensile strength, flexural strength, direct tensile strength, and stress-strain response under axial compression. Three types of steel fibers, i.e., straight micro steel fiber, deformed macro steel fiber and hybrid steel fiber, were added to the alkali-activated slag-fly ash mixes. It was found that the workability of the alkali-activated slag-fly ash concrete mixes decreased with the increase in the volume fraction of steel fibers. It was also found that the compressive strength, splitting tensile strength, flexural strength, and direct tensile strength of alkali-activated slag-fly ash concrete mixes increased with the addition of steel fibers. The stress-strain response of alkali-activated slag-fly ash concrete mixes changed from brittle to ductile by the addition of steel fibers. Significant improvements in the mechanical properties of alkali-activated slag-fly ash concrete were observed for the addition of 2% by volume of all three types of steel fiber. The addition of hybrid steel fiber (1% straight micro steel fiber plus 1% deformed macro steel fibers) showed the highest improvement in the mechanical properties of ambient cured alkali-activated slag-fly ash concrete.

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1 **Engineering Properties of Ambient Cured Alkali-Activated Slag-Fly Ash**
2 **Concrete Reinforced with Different Types of Steel Fiber**
3

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14 **Abstract**

15 This paper investigates the influence of different types of steel fibers on the engineering
16 properties of ambient cured alkali-activated slag-fly ash concrete. The engineering properties
17 investigated include workability, compressive strength, splitting tensile strength, flexural
18 strength, direct tensile strength and stress-strain response under axial compression. Three
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24 mixes increased with the addition of steel fibers. The stress-strain response of alkali-activated
25 slag-fly ash concrete mixes changed from brittle to ductile by the addition of steel fibers.

26 Significant improvements in the mechanical properties of alkali-activated slag-fly ash
27 concrete were observed for the addition of 2% by volume of all three types of steel fiber. The
28 addition of hybrid steel fiber (1% straight micro steel fiber plus 1% deformed macro steel
29 fibers) showed the highest improvement in the mechanical properties of ambient cured alkali-
30 activated slag-fly ash concrete.

31 **Keywords:** Alkali-activated; Ambient cured; Engineering properties; Strength; Steel fiber

32 **Introduction**

33 Rapid urbanization worldwide places a significant demand on infrastructure development.
34 Increasing infrastructure development causes increasing demand of concrete and hence
35 increasing demand of cement in the construction industry. Cement production is associated
36 with the emission of greenhouse gases including carbon dioxide, methane and nitrous oxide
37 into the atmosphere. It is estimated that the production of one ton of cement releases about
38 0.7 to 0.8 ton of carbon dioxide (CO₂) into the atmosphere (Peng et al. 2013). Hence, the
39 need for alternative binders for reducing the carbon dioxide (CO₂) emissions is paramount.
40 One of the possible solutions is to use industrial by-product materials as alternative binders to
41 cement. Alkali-activated binder is considered as a promising alternative binder to cement. It is
42 estimated that alkali-activated concrete emits about 26-45% less CO₂ than cement (Habert et
43 al. 2011; McLellan et al. 2011). The alkali-activated binder has other advantages including
44 better mechanical properties, better resistance to chemical attack, lower chloride diffusion
45 and higher fire resistance than cement (Bakharev et al. 1999; Bakharev et al. 2003; Roy et al.
46 2000; Rashad et al. 2012).

47 Alkali-activated concrete can be prepared by using aluminosilicate materials such as fly ash
48 (FA) and ground granulated blast furnace slag (GGBS). Alkali-activated concrete is obtained

49 by activating an aluminosilicate material with a strong alkaline activator either at high
50 temperatures or ambient conditions (Duxson et al. 2007). The chemical reaction and the
51 strength development of alkali-activated concrete are influenced by several factors including
52 chemical compositions of the aluminosilicate material, alkaline activators and curing
53 conditions (Yip et al. 2008). Islam et al. (2014) observed that the compressive strength of
54 alkali-activated concrete increased by increasing of GGBS content in the binder containing
55 FA. The addition of GGBS with alkali-activated concrete achieved setting time and
56 compressive strength equivalent to Ordinary Portland Cement (OPC) (Nath and Sarker
57 2014). Ryu et al. (2013) studied the effect of the chemical composition of alkaline activators
58 on the compressive strength of alkali-activated concrete. The results showed that chemical
59 composition of the alkaline activators had a significant influence on the early strength of the
60 alkali-activated concrete.

61 The performance of alkali-activated concrete cured at high temperatures was investigated in
62 recent research publications (Palomo et al. 1999; Bakharev 2005). These studies indicated
63 that alkali-activated concrete achieved high compressive strength, high tensile strength and
64 low porosity, which are beneficial for concrete in aggressive marine and corrosive
65 environments. Fernandez-Jimenez et al. (2006) studied the mechanical properties of alkali-
66 activated concrete and observed that alkali-activated concrete obtained comparable
67 compressive strength, higher splitting and flexural tensile strengths, and lower modulus of
68 elasticity than OPC concrete. Thomas and Peethamparan (2015) investigated the tensile
69 strength, modulus of elasticity, Poisson's ratio, and stress-strain relationships of alkali-
70 activated concrete made with FA or GGBS. Thomas and Peethamparan (2015) found that
71 alkali-activated concrete obtained higher tensile strength and lower modulus of elasticity and
72 Poisson's ratio than OPC concrete. Alkali-activated concrete was found to be more durable

73 than conventional concrete in aggressive marine and corrosive environments (Olivia and
74 Nikraz 2012). Most of the research studies on heat-cured alkali-activated concrete considered
75 limited applications of alkali-activated concrete in the construction of precast concrete
76 members. The development of alkali-activated concrete at ambient curing condition will
77 increase its application in the construction of a wide range of structural members. The
78 reduction in the CO₂ emissions, cost saving due to ambient curing and cast in-situ
79 constructions are the main drivers for the development of ambient cured alkali-activated
80 concrete (Hadi et al. 2017).

81 Although alkali-activated concrete possesses many desirable engineering properties, it lacks
82 adequate ductility (Lokuge and Karunasena 2016). Moreover, alkali-activated concrete
83 exhibits low tensile and flexural strengths (Shaikh 2013; Bhutta et al. 2017). However, the
84 tensile strength, flexural strength and the ductility of the alkali-activated concrete can be
85 enhanced by the addition of fibers. Fiber reinforced alkali-activated concrete was first
86 investigated in Davidovits (1991). Afterwards, alkali-activated concrete with different types
87 of fibers was investigated including carbon fiber (Ranjbar et al. 2015), polyvinyl alcohol fiber
88 (Yunsheng et al. 2008), polypropylene fiber (Ranjbar et al. 2016) and steel fiber (Nataraja et
89 al. 1999; Ng et al. 2013; Bernal et al. 2010). It was reported that the increase in the tensile
90 and flexural strengths of alkali-activated concrete depends on the volume fraction, geometry
91 and type of fibers. The addition of carbon fiber, polyvinyl alcohol fiber and polypropylene
92 fibers in alkali-activated concrete are usually associated with poor fire resistance, poor bond
93 with concrete and high sensitivity to sunlight and oxygen. A detailed literature review
94 indicated that only a limited number of studies investigated the addition of steel fibers in heat
95 cured alkali-activated concrete. Al-Majidi et al. (2017) investigated the effect of the addition
96 of various type (steel, polyvinyl alcohol and glass) and various volume fraction (1%-3%) of

97 fibers on the mechanical properties of alkali-activated concrete. It was found that the
98 compressive strength of alkali-activated concrete improved significantly when 2% steel fibers
99 by volume were added to the alkali-activated concrete mix. The use of hooked end and
100 straight steel fibers (0.5%- 1.5%) improved the load carrying capacity, cracking strength,
101 crack width and rate of crack growth in fiber reinforced heat cured alkali-activated concrete
102 (Ng et al. 2013). Incorporation of steel fiber (0.5% and 1.5%) considerably improved splitting
103 tensile strength and flexural strength of heat cured alkali-activated concrete (Bernal et al.
104 2010).

105 To the knowledge of the authors, none of the research studies investigated the addition of
106 straight micro steel fibers, deformed macro steel fibers and hybrid steel fibers (combination
107 of straight micro and deformed macro steel fibers) in ambient cured alkali-activated concrete.
108 Also, none of the available studies investigated the direct tensile strength of alkali-activated
109 concrete with different type of steel fibers. The direct tensile strength of the ambient cured
110 alkali-activated concrete is significantly important for the analysis of the cracking and post-
111 cracking response of reinforced concrete elements constructed with alkali-activated concrete.
112 This study investigates the mechanical properties of ambient cured alkali-activated slag-fly
113 ash concrete with straight micro steel fibers, deformed macro steel fibers and hybrid steel
114 fibers. The objective of this study is achieved through extensive experimental studies. The
115 investigation on the microstructural characteristics of the specimen using scanning electron
116 microscope is considered beyond the scope of the paper.

117 **Experimental details**

118 ***Materials***

119 Ground granulated blast furnace slag (GGBS) and fly ash (FA) were used as source materials
120 to prepare the alkali-activated slag-fly ash concrete. The GGBS was supplied by the
121 Australian (Iron & Steel) Slag Association (ASA 2017). The FA Classified as Class F
122 according to ASTM C618-08 (ASTM 2012) was supplied by Eraring Power Station,
123 Australia (EPSA 2017). The chemical compositions of the GGBS and the FA are reported in
124 Table 1.

125 Crushed aggregate with a maximum size of 10 mm was used as coarse aggregate and river
126 sand was used as fine aggregate. The alkaline activator consisted of combining sodium
127 silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions. The Na_2SiO_3 solution was
128 supplied by PQ Australia (PQ 2017) with a specific gravity of 1.53 and an activator modulus
129 (M_s) of 2.0 ($M_s = \text{SiO}_2/\text{Na}_2\text{O}$; $\text{SiO}_2 = 29.4\%$ and $\text{Na}_2\text{O} = 14.7\%$). The sodium silicate
130 (Na_2SiO_3) and sodium hydroxide (NaOH) solutions were blended for a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ mass
131 ratio of 2.5. The amount of activator was 35% of the amount of binder. Hence, the amount of
132 activator was $157.5 \text{ kg/m}^3 (=0.35 \times \text{combined amount of fly ash and GGBS of } 450 \text{ kg/m}^3)$.
133 The sodium hydroxide (NaOH) solution was prepared by dissolving the NaOH pellets in
134 potable water. The mass of NaOH pellets varied depending on the concentration of the
135 solution. For example, for preparing the NaOH solution with a concentration of 14 mole/l,
136 560 grams (14 pellets @ 40 grams = 560 grams) NaOH solid was mixed with potable water,
137 where 40 is the molecular weight of NaOH. In order to mix the NaOH pellets with water, a
138 magnetic stirrer was used. The mix was stirred until the pellets were fully dissolved in the
139 water. The NaOH solution was prepared 24 hours before the mixing of concrete. The
140 Na_2SiO_3 and NaOH solutions were blended together for a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ mass ratio of 2.5.
141 In order to improve the workability, a commercially available high range water reducer,
142 Glenium 8700, supplied by BASF, Australia was used.

143 In this study, three types of steel fibers were used, i.e., straight micro steel (MS) fibers,
144 deformed macro steel (DS) fibers and hybrid steel (HS) fibers. The straight micro steel (MS)
145 fibers were 6 mm in length and 0.2 mm in diameter. The nominal tensile strength of MS
146 fibers was 2600 MPa. The DS fibers were 18 mm in length and 0.55 mm in diameter with a
147 nominal tensile strength of 800 MPa. The HS fibers were a combination of MS fibers and DS
148 fibers. The MS fibers were provided by Ganzhou Daye Metallic Fibers Company, China. The
149 DS fibers were provided by Fibercon Company, Australia. Figure 1 shows the MS fibers and
150 DS fibers.

151 *Preparation of specimens*

152 In the production of the alkali-activated slag-fly ash concrete, the component materials
153 (GGBS, FA, coarse aggregate, and sand) were initially mixed in a pan mixer without steel
154 fibers. The alkaline activators were prepared by combining Na_2SiO_3 and NaOH. High range
155 water reducers and water were then added to the dry mix. Afterwards, the steel fibers were
156 added gradually in order to avoid fiber balling and to produce an alkali-activated slag-fly ash
157 concrete mix with reasonable workability. In this study, a total of three types of steel fibers
158 with different volume fraction were used. The first type included 1%, 2%, and 3% by volume
159 of MS fibers. The second type included 1%, 1.5% and 2% by volume of DS fibers. The third
160 type included 2% by volume of HS fibers, which was a combination of 0.5% MS+1.5% DS
161 fibers, 1% MS+1% DS fibers, and 1.5% MS+0.5% DS fibers. The weight of steel fiber with
162 2% by volume was equal to $7800 \text{ kg/m}^3 \times 0.02 = 156 \text{ kg/m}^3$, where 7800 kg/m^3 is the density
163 of steel fibers. Also, plain alkali-activated slag-fly ash concrete without steel fiber was
164 prepared as a control mix. The engineering properties investigated in this study include
165 workability, compressive strength, splitting tensile strength, flexural strength, direct tensile

166 strength and stress-strain response under compressive axial load. The alkali-activated slag-fly
167 ash concrete was cured under ambient conditions.

168 Table 2 shows the mix proportions of alkali-activated slag-fly ash concrete adopted from a
169 previous study by Hadi et al. (2017). Ground granulated blast-furnace slag (GGBS) and Fly
170 ash (FA) were used as binders for alkali-activated slag-fly ash concrete. A combination of
171 sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was used as alkaline activators.
172 Crushed aggregate with a maximum size of 10 mm and river sand were used as coarse and
173 fine aggregates, respectively.

174 In this study, polyvinyl chloride (PVC) cylindrical molds of 100 mm × 200 mm were used for
175 casting the alkali-activated slag-fly ash concrete specimens to measure the compressive
176 strength according to AS 1012.9-1999 (AS 1999). In addition, polyvinyl chloride (PVC)
177 cylindrical molds of 150 mm × 300 mm were used for casting the alkali-activated slag-fly ash
178 concrete specimens to measure the splitting tensile strength and stress-strain response
179 according to AS 1012.10-2000 (AS 2000) and AS 1012.17 (AS 2014), respectively. Plywood
180 molds of 100 mm × 100 mm × 500 mm were used for casting alkali-activated slag-fly ash
181 concrete specimens to measure the flexural strength and direct tensile strength. All alkali-
182 activated slag-fly ash concrete specimens were cast in three layers and each layer was
183 compacted for 10 seconds with an electric vibrator. After casting, the alkali-activated slag-
184 fly ash concrete specimens were kept under ambient conditions at a temperature of 23 ± 3 °C
185 and a relative humidity of $60 \pm 10\%$ for 24 hours. Afterwards, the specimens were removed
186 from the mold and left under ambient conditions until the time of testing.

187 ***Labelling of alkali-activated slag-fly ash concrete mixes***

188 In this study, each alkali-activated slag-fly ash concrete mix has been labelled with an
189 acronym (Table 3). The symbols REF, ACMS, ACDS and ACHS refer to plain alkali-
190 activated slag-fly ash concrete mix, alkali-activated slag-fly ash concrete mix with MS fibers,
191 alkali-activated slag-fly ash concrete mix with DS fibers and alkali-activated slag-fly ash
192 concrete mix with HS fibers, respectively. The numbers (1, 1.5, 2, and 3) afterwards refer to
193 the percentages of steel fibers by volume used in alkali-activated slag-fly ash concrete mix.
194 The ACHS mixes included 2% HS fibers by volume. The ACHS2a included 0.5% MS+1.5%
195 DS fibers, ACHS2b included 1% MS+1% DS fibers and ACHS2c included 1.5% MS+0.5%
196 DS fibers.

197 *Test methods*

198 Table 3 shows the test matrix for alkali-activated slag-fly ash concrete with and without steel
199 fibers. All the specimens were tested in the Structural Engineering Laboratories at the
200 University of Wollongong, Australia. For determining the consistency of the alkali-activated
201 slag-fly ash mixes, slump tests were performed according to AS 1012.3.1-1998 (AS 1998).

202 The compressive strength tests of alkali-activated slag-fly ash concrete were conducted
203 according to AS 1012.9-1999 (AS 1999) at 7 and 28 days. A compression testing machine
204 with a capacity of 1800 kN was used to conduct the compressive strength tests. Before
205 testing, the cylinders were capped with a high strength plaster to ensure uniform loading face.
206 For each mix, three specimens were tested and the average compressive strengths have been
207 reported.

208 The splitting tensile strength tests were performed according to AS 1012.10-2000 (AS 2000a)
209 at 28 days. Two timber strips (5 mm thick × 25 mm wide × 400 mm long) were placed
210 between the loading plate and the cylinder surface. A compression testing machine with a

211 capacity of 1800 kN was used to conduct the splitting tensile tests. The specimens were tested
212 at loading rate of 106 kN/min until the specimen failed. For each mix, three specimens were
213 tested and the average splitting tensile strengths have been reported.

214 The flexural strength tests were performed under four-point bending according to AS
215 1012.11-2000 (AS 2000b) at 28 days. The prism specimens were tested under force
216 controlled load applications at 2 kN/sec until the prism specimen failed. For each mix, three
217 prism specimens were tested and the average flexural strengths have been reported.

218 Different test methods were used in the literature to measure the direct tensile strength of the
219 concrete (Alhussainy et al. 2016). However, most of the test methods for direct tensile testing
220 of concrete are associated with major drawbacks including load eccentricity, slippage and the
221 fracture at the ends of the tested specimens. However, the test method developed in
222 Alhussainy et al. (2016) was successful in overcoming the major drawbacks associated with
223 the direct tensile testing of concrete. Hence, this test method was used to test the direct tensile
224 strength of alkali-activated slag-fly ash concrete. The test was performed on alkali-activated
225 slag-fly ash concrete prism specimens with a cross-section of 100 mm × 100 mm and a length
226 of 500 mm. A wooden box, as shown in Fig. 2 was used as formwork for the specimens. To
227 ensure failure in the middle of the specimen, the cross-sectional area of the specimen was
228 reduced by using two timber triangular prisms with a height of 10 mm and a base of 20 mm.
229 The triangular prisms were glued inside the wooden formwork vertically at the middle of the
230 specimens, as shown in Fig. 2.

231 In order to apply the direct tensile force on the alkali-activated slag-fly ash concrete
232 specimens, two steel gripping claws were embedded for 125 mm at both ends of the
233 specimen. The gripping claws were made from a 20 mm diameter threaded steel bar which

234 had four steel pins with 30 mm length and 8 mm diameter. These pins were welded to the
235 threaded steel bar at 90 degrees with a spacing of 20 mm, as shown in Fig. 2.

236 To prevent any misalignment of the gripping claws and to ensure the application of the axial
237 tensile loading during the testing, two universal joints were used. The universal joints were
238 also used to hold the ends of specimens by the testing machine. Figure 3 shows the setup for
239 direct tensile tests. All the specimens were tested using the 500 kN Universal Instron testing
240 machine. The specimens were tested up to failure under a displacement controlled loading at
241 0.1 mm/min and the data were recorded at every two seconds.

242 In order to investigate the stress-strain response of the ambient cured alkali-activated slag-fly
243 ash concrete mixes, tests were carried out according to the AS 1012.17 (AS 2014). The
244 cylindrical specimens of 150 mm diameter and 300 mm height were tested in a 5000 kN
245 Denison compression testing machine. At the middle half of the specimens, a standard
246 compressometer with one linear variable differential transducer (LVDT) was used to measure
247 the axial deformation of the specimens, while the axial load was obtained directly from the
248 compression testing machine. The compression tests were performed under displacement
249 controlled loads at 0.3 mm/min. To record the axial load and the corresponding axial
250 deformation, an electronic data acquisition system was used. Before testing, the specimens of
251 alkali-activated slag-fly ash concrete were capped with a high strength plaster to ensure
252 uniform loading faces. Figure 4 shows the test arrangements for stress-strain response under
253 compressive axial load.

254 **Results and discussion**

255 Ten alkali-activated slag-fly ash concrete mixes were designed to study the influence of
256 different types of steel fibers on the engineering properties of ambient cured alkali-activated

257 slag-fly ash concrete. The test results of alkali-activated slag-fly ash concrete mixes are
258 reported in Table 4. The test results included the workability, compressive strength, splitting
259 tensile strength, flexural strength, direct tensile strength and stress-strain response of ambient
260 cured alkali-activated slag-fly ash concrete.

261 ***Workability***

262 The slump test results are reported in Table 4. The addition of MS, DS, and HS fibers in
263 alkali-activated slag-fly ash concrete mixes reduced the workability. The reduction in the
264 workability increased with the increase in the volume fraction of different types of steel fibers
265 in the ambient cured alkali-activated slag-fly ash concrete. Figure 5 shows the influences of
266 different types of steel fibers on the workability of ambient cured alkali-activated slag-fly ash
267 concrete.

268 Based on the test results, it can be found that the increase in the volume fraction of MS fibers
269 from 0 (REF) to 3% (ACMS3), the slump of the ambient cured alkali-activated slag-fly ash
270 concrete decreased by 35.6%. The slump for ACMS3 mix was only 76 mm. The ACMS3
271 mix was found to be difficult to cast and also the vibration during casting was not efficient.
272 Therefore, some voids were observed when the specimens were de-molded. However, no
273 flash set occurred during casting. It can also be observed that the increase in the volume
274 fraction of DS fibers from 0 (REF) to 2% (ACDS2), the slump of the ambient cured alkali-
275 activated slag-fly ash concrete decreased by 30.5%.

276 Finally, the addition of HS fibers exhibited a significant decrease in the slump of the ambient
277 cured alkali-activated slag-fly ash concrete. The reduction in the slump was more for
278 ACHS2a mix in which the reduction in the slump was 36.4% compared to the REF mix.
279 From Fig. 5, it can be found that the trend for the decrease in the slump with an increase in

280 the volume fraction of steel fibers was almost similar for all mixes. The decrease in the slump
281 of the mixes with high steel fibers content could be attributed to the balling of steel fibers
282 during the mixing process, which restrained the followability of the mixes.

283 *Compressive Strength*

284 The compressive strength of various mixes tested at 7 and 28 days are shown in Table 4. The
285 compressive strength of ambient cured alkali-activated slag-fly ash concrete mixes was not
286 significantly influenced by the addition of steel fibers, similar to the observations reported for
287 OPC concrete (Bhargava et al. 2006; Ou et al. 2011). Figure 6 illustrates that the effect of the
288 addition of different types of steel fibers on the compressive strength. The average
289 compressive strength of the alkali-activated slag-fly ash concrete with steel fibers was
290 slightly higher than the average compressive strength of alkali-activated slag-fly ash concrete
291 without steel fibers. The alkali-activated slag-fly ash concrete without steel fiber (REF)
292 achieved the average compressive strength of 40.1 MPa and 44.1 MPa on the 7 days and the
293 28 days, respectively.

294 It can be found that the increase in the volume fraction of MS and DS fibers from 0 to 2%,
295 the compressive strength of ambient cured alkali-activated slag-fly ash concrete increased by
296 8.6% for ACMS2 mix and 4.1% for ACDS2 mix compared to the reference alkali-activated
297 slag-fly ash concrete mix (REF). This increase could be attributed to the good distribution of
298 steel fibers in alkali-activated slag-fly ash concrete mix which led to increasing in the
299 bonding between the steel fibers and the alkali-activated slag-fly ash concrete mix and
300 subsequently increased the compressive strength of alkali-activated slag-fly ash concrete.
301 However, the compressive strength of alkali-activated slag-fly ash concrete decreased by
302 4.8% with the increase in the volume fraction of MS fiber from 2% (ACMS2) to 3%
303 (ACMS3). The reduction in compressive strength was because of the reduction in the

304 workability of the alkali-activated slag-fly ash concrete mix, as steel fibers created internal
305 voids in alkali-activated slag-fly ash concrete. The internal voids were created due to
306 insufficient vibration during casting. These voids reduced the density of alkali-activated slag-
307 fly ash concrete, which resulted in a significant decrease in the compressive strength of
308 alkali-activated slag-fly ash concrete. The optimum content of steel fiber that provided the
309 maximum compressive strength was 2% for MS fibers and 2% for DS fibers.

310 Finally, the addition of HS fibers resulted in an increase in the compressive strength of
311 ambient cured alkali-activated slag-fly ash concrete compared to the reference mix (REF).
312 The improvement in the compressive strength of ACHS mix ranged from 4.5% to 10.8%. The
313 highest compressive strength was achieved for the ACHS2b mix. The compressive strength
314 of ACHS2b mix was 10.8% higher than the compressive strength of REF mix. The increase
315 in the compressive strength was most likely because HS fibers with different sizes and shapes
316 offered a combination of different restraint conditions. The micro steel fibers (MS) arrested
317 the micro cracks and prevented the expansion of cracks. The DS fibers arrested the macro
318 cracks and substantially improved the compressive strength of alkali-activated slag-fly ash
319 concrete (Chen and Liu 2004).

320 *Splitting tensile strength*

321 The splitting tensile strengths of the ambient cured alkali-activated slag-fly ash concrete mix
322 at 28 days are shown in Table 4. The experimental results demonstrated that the addition of
323 steel fibers significantly influenced the splitting tensile strength of alkali-activated slag-fly
324 ash concrete, similar to the observation reported for OPC concrete (Song et al. 2004; Yusof et
325 al. 2011). Figure 7 shows the effect of the volume fraction of different types of steel fibers on
326 the splitting tensile strength. It can be observed that the splitting tensile strengths of alkali-
327 activated slag-fly ash concrete containing steel fibers were higher than the splitting tensile

328 strength of alkali-activated slag-fly ash concrete without steel fibers. The average splitting
329 tensile strength of REF mix was 3.50 MPa.

330 It can be seen that with the increase in the volume fraction of MS and DS fibers from 0 (REF)
331 to 2%, the splitting tensile strength of alkali-activated slag-fly ash concrete increased by
332 51.4% for ACMS2 mix and 57.1% for ACDS2 mix. The increase in splitting tensile strength
333 of alkali-activated slag-fly ash concrete can be attributed to the randomly oriented and the
334 good distribution of steel fibers. Also, an increase in the bond strength between alkali-
335 activated slag-fly ash concrete and steel fiber was achieved, which increased the splitting
336 tensile strength of alkali-activated slag-fly ash concrete. However, increasing the volume
337 fraction of MS fiber from 2% to 3% led to a decrease in the splitting tensile strength of alkali-
338 activated slag-fly ash concrete by 9.2%. The decrease in the splitting tensile strength with the
339 increase in the volume fraction of MS fibers from 2% to 3% was because the increase in the
340 steel fiber increased voids in the alkali-activated slag-fly ash concrete. Consequently, the
341 splitting tensile strength of alkali-activated slag-fly ash concrete decreased. The optimum
342 volume fraction of steel fibers that provided the maximum splitting tensile strength was 2%
343 for MS and 2% for DS fibers.

344 Finally, the addition of 2% HS fiber by volume increased the splitting tensile strength. The
345 increase in the splitting tensile strength ranged between 48.6% and 80% compared to the
346 reference alkali-activated slag-fly ash mix (REF). The highest splitting tensile strength of
347 alkali-activated slag-fly ash concrete was achieved for ACHS2b mix. The splitting tensile
348 strength of ACHS2b mix was 80% higher than the splitting tensile strength of REF mix.

349 ***Flexural strength***

350 The flexural strengths of ambient cured alkali-activated slag-fly ash concrete at 28 days are
351 shown in Table 4. The average flexural strength of ambient cured alkali-activated slag-fly ash
352 concrete without steel fibers was 4.4 MPa. The experimental results illustrated that the
353 addition of steel fibers significantly influenced the flexural strength of alkali-activated slag-
354 fly ash concrete, similar to the observation reported for OPC concrete (Park et al. 2012; Kim
355 et al. 2011; Yusof et al. 2011). Figure 8 shows the effect of the volume fraction of different
356 types of steel fibers on the flexural strength of ambient cured alkali-activated slag-fly ash
357 concrete. It can be observed that a significant increase in the flexural strength of alkali-
358 activated slag-fly ash concrete was obtained by the addition of steel fibers.

359 It can be observed that for the increase in the volume fraction of MS and DS fiber from 0
360 (REF) to 2%, the flexural strength of alkali-activated slag-fly ash concrete increased by
361 22.7% for ACMS2 mix and 38.6% for ACDS2 mix. The increase in the flexural strength was
362 attributed to the randomly oriented steel fibers crossing the cracked section, which resisted
363 the propagation of micro and macro cracks. The arrest in the propagation of cracks increased
364 the load-carrying capacity (Faisal and Ashour 1992). However, the increase in the volume
365 fraction of MS fibers from 2% to 3%, the flexural strength decreased by 9.4%. The reason for
366 the decrease in the flexural strength could be because the high volume fraction of steel fibers
367 reduced the workability of the alkali-activated slag-fly ash concrete mix, which resulted in
368 the nonhomogeneous distribution of steel fibers crossing the cracked section. The optimum
369 volume fraction of steel fibers for the maximum flexural strength was 2% for MS and 2% for
370 DS fibers.

371 Finally, the addition of 2% HS fibers by volume increased the flexural strength compared to
372 the reference alkali-activated slag-fly ash concrete mix (REF). The improvement in the
373 flexural strength of HS fibers reinforced alkali-activated slag-fly ash concrete ranged from

374 27.3% to 52.3% compared to REF alkali-activated slag-fly ash concrete mix. The highest
375 flexural strength of alkali-activated slag-fly ash concrete obtained for the ACHS2b mix. The
376 flexural strength of ACHS2b mix was 52.3% higher than the flexural strength of REF mix.
377 This is because HS fibers with different sizes and shapes offered a combination of different
378 restraint conditions. After test, a number of steel fibers crossing the cracked section were
379 observed. The MIS fibers substantially influenced the bridging of micro cracks, while the
380 DES fibers significantly influenced the bridging of macro cracks. Hence, greater efficiencies
381 in delaying the growth of micro and macro cracks was achieved, which improved the flexural
382 strength. Similar observations were reported in Sivakumar and Santhanam (2007) for high
383 strength concrete reinforced with hybrid fibers.

384 *Direct tensile test*

385 Figure 9 shows the typical failure mode of ambient cured alkali-activated slag-fly ash
386 concrete specimens with different types of steel fibers under direct tensile load. The failure of
387 the reference plain alkali-activated slag-fly ash concrete mix (REF) occurred in a brittle
388 manner with a complete fracture of the concrete specimens in the middle without prior signs
389 of failure. On the other hand, the failure of all the specimens reinforced with 2% steel fibers
390 (MS, DS and HS) by volume started with formation of cracks in the middle of the specimens.
391 The presence of the steel fibers effectively prevented the sudden failure of alkali-activated
392 slag-fly ash concrete specimens. As expected, the failures occurred in the middle of all the
393 specimens as the cross section of the specimens was reduced by 20%. For all specimens
394 tested under direct tensile load, no claw slippage was observed and no cracking occurred at
395 the end of the specimens. This indicates that a proper alignment was achieved during testing.
396 The direct tensile strength was calculated as the maximum tensile load divided by the reduced
397 cross-sectional area of the specimens (100 mm × 80 mm). Figure 10 shows the effect of the

398 volume fraction of different types of steel fibers on the direct tensile strength of alkali-
399 activated slag-fly ash concrete mix. It can be observed in Fig. 10 that the direct tensile
400 strength is significantly increased by the addition of steel fibers compared to the direct tensile
401 strength of plain alkali-activated slag-fly ash concrete mix (REF). It can be observed in Table
402 4 that the addition of 1%, 2% and 3% MS fibers by volume increased the direct tensile
403 strength by about 8.3%, 20.8% and 16.6%, respectively, compared to the REF mix. The
404 addition of 1%, 1.5% and 2% DS fibers by volume increased the direct tensile strength by
405 8.3%, 12.5% and 20.8%, respectively, compared to the REF mix. The addition of 2% HS
406 fibers by volume significantly increased the direct tensile strength. The increase in the direct
407 tensile strength ranged between 20.8% and 37.5% compared to the REF mix. The addition of
408 2% HS (1% MS and 1% DS) fiber by volume achieved the highest increase in the direct
409 tensile strength. The increase in the direct tensile strength was about 37.5% compared to the
410 REF mix. This is because high volume fraction of steel fibers with different sizes and shapes
411 increased the availability of fibers crossing the cracked section. Hence, greater efficiency in
412 delaying the growth of micro and macro cracks and the improvement in the direct tensile
413 strength were achieved.

414 *Stress-strain response under compressive axial load*

415 The stress-strain response of ambient cured alkali-activated slag-fly ash concrete was
416 determined by testing cylinder specimens with 150 mm in diameter and 300 mm in height.
417 The stress-strain response of the cylinder specimens was evaluated at 28 days. The stress-
418 strain curves of the specimens are shown in Fig. 11. It can be observed from Fig. 11 that the
419 stress-strain response in both the ascending and descending branches of the curves were
420 influenced by the addition of steel fibers. However, the most significant effect was noticed in
421 the descending branch of the stress-strain curve. When the ascending branch of the stress-

422 strain curves was almost linear until the peak axial load, the slope of the post-peak
423 descending branch decreased significantly with the increase in the volume fraction of steel
424 fibers. The addition of steel fibers to alkali-activated slag-fly ash concrete increased the peak
425 stress and the strain corresponding to the peak stress. The increase in peak strain
426 corresponding to the peak stress was more for mixes with higher volume fraction of steel
427 fibers.

428 For the increase in the volume fraction of MS and DS fibers from 0 (REF) to 2%, the peak
429 stress increased by 11.1% for the addition of 2% MS fibers by volume (ACMS2) and 5.9%
430 for the addition of 2% DS fibers by volume (ACDS2) (Figure 11). However, increasing the
431 MS fiber content from 2% to 3% by volume led to a reduction in the peak stress. This may be
432 due to the high-volume fraction of steel fibers which led to a reduction in the workability of
433 alkali-activated slag-fly ash concrete mix and resulted in a non-uniform distribution of the
434 MS fibers during the mixing process. In addition, the high-volume fraction of steel fibers
435 created voids in alkali-activated slag-fly ash concrete mixes.

436 The peak stress, strain corresponding to the peak stress and modulus of elasticity of the
437 specimens are reported in Table 5. It was observed that the increase in the volume fraction of
438 MS fibers from 0 (REF) to 3% (ACMS3), the strain corresponding to the peak stress
439 increased by 57.1% (Table 5). It was also observed that the increase of DS fiber content from
440 0 (REF) to 2% (ACDS2), the strain corresponding to the peak stress in the alkali-activated
441 slag-fly ash concrete increased by 42.8% (Table 5).

442 For HS fibers, the addition of 2% HS fibers by volume showed a significant influence on the
443 stress-strain response compared to the reference mix (REF). The peak stress for alkali-
444 activated slag-fly ash concrete with 2% HS fibers was higher than the peak stress of the
445 reference mix (REF). The strain corresponding to the peak stress of alkali-activated slag-fly

446 ash concrete was increased by 32.1%, 46.4%, and 35.7% for ACHS2a, ACHS2b, and
447 ACHS2c, respectively compared to the reference mix (REF) (Table 5). It can also be
448 observed that slopes of the descending branches (softening response) of the stress-strain
449 curve for alkali-activated slag-fly ash concrete with HS fibers were very similar. The slope of
450 the descending branches of the stress-strain response of the alkali-activated slag-fly ash
451 concrete with HS fibers was significantly less steep than the slope of the reference mix
452 (REF). This is because of the high-volume fraction of HS fibers in the alkali-activated slag-
453 fly ash concrete mix. The presence of steel fibers in different mixed sizes and shapes
454 improved the post-peak stress by bridging the small cracks at an early stage. At the beginning
455 of macro cracking, the opening and growth of cracks were controlled by the bridging action
456 of fibers. This mechanism increased the demand of energy for the cracks to
457 propagate. Therefore, the improvement was achieved in the post-peak response of alkali-
458 activated slag-fly ash concrete with HS fibers.

459 The area under the stress-strain curve represents to the toughness of the material. Figure 11
460 shows that the area under the stress-strain curve increased with the increase in the volume
461 fraction of steel fibers, which indicated an increase in the toughness. The average toughness
462 of the alkali-activated slag-fly ash concrete mixes was calculated and shown in Table 5. The
463 limiting strain for the toughness was considered as 0.015, which is five times the ultimate
464 concrete strain of 0.003 as specified in ACI 318-11 (ACI 2011) for conventional concrete.
465 The toughness of different alkali-activated slag-fly ash concrete mixes was evaluated and the
466 results are presented in Table 5. It can be seen from Table 5 the increase in the volume
467 fraction of steel fibers led to a significant increase in the toughness of the alkali-activated
468 slag-fly ash concrete. Similar to the observation reported for OPC concrete (Banthia et al.
469 2007; Yao et al. 2003). The highest improvement of the toughness of the alkali-activated

470 slag-fly ash concrete was achieved for Mixes ACHS2b and ACHS2c. The toughness of
471 Mixes ACHS2b and ACHS2c was approximately 400% higher than the toughness of REF.
472 This may be because the concrete with different types and shapes of steel fiber provided a
473 combined effect to the ability of fibers in arresting cracks at both micro and macro levels.
474 Consequently, the toughness of alkali-activated slag-fly ash concrete increased.

475 **Conclusion**

476 This study evaluated the engineering properties of ambient cured alkali-activated slag-fly ash
477 concrete mixes with different types of steel fibers i.e., micro-steel fibers (MS), deformed
478 macro steel fibers (DS) and the combination of micro and deformed steel fibers, termed as
479 hybrid steel fibers (HS). The engineering properties of ambient cured alkali-activated slag-fly
480 ash concrete mixes were assessed in terms of a slump, compressive strength, splitting tensile
481 strength, flexural strength, and direct tensile strength. The stress-strain response of ambient
482 cured alkali-activated slag-fly ash concrete mixes with MS, DS and HS fibers was also
483 investigated. The following conclusions are drawn from the test results presented in this
484 study:

- 485 1. The addition up to 2% MS, DS, and HS fibers by volume in ambient cured alkali-activated
486 slag-fly ash concrete mixes did not significantly affect the workability of alkali-activated
487 slag-fly ash concrete mixes. However, the addition of 3% MS fibers by volume affected the
488 workability of alkali-activated slag-fly ash concrete and led to less workable concrete.
- 489 2. The addition of 2% steel fibers (MS, DS and HS) by volume increased the compressive
490 strength of ambient cured alkali-activated slag-fly ash concrete mixes. The highest
491 compressive strength of alkali-activated slag-fly ash concrete was obtained for the addition of
492 2% HS (1% MS and 1% DS) fiber by volume in the alkali-activated slag-fly ash concrete

493 mixes. The increase in the compressive strength was about 10.8% compared to the reference
494 alkali-activated slag-fly ash concrete mix (REF) without any fiber.

495 3. The splitting tensile strength and flexural strength of ambient cured alkali-activated slag-
496 fly ash concrete mix significantly improved by the addition of MS, DS, and HS fibers. The
497 addition of 2% HS (1% MS and 1% DS) fiber by volume achieved the highest splitting
498 tensile strength and flexural strength. The increases in the splitting tensile strength and
499 flexural strength were about 80% and 52.3% respectively, compared to the reference alkali-
500 activated slag-fly ash mix (REF) without steel fiber.

501 4. The direct tensile strength of ambient cured alkali-activated slag-fly ash concrete increased
502 with the increase in the addition of the volume fraction of steel fibers. The addition of 2% HS
503 (1% MS and 1% DS) fiber by volume achieved the highest increase in the direct tensile
504 strength. The increase in the direct tensile strength was about 37.5% compared to the
505 reference alkali-activated slag-fly ash concrete mix (REF).

506 5. The addition of steel fibers into the ambient cured alkali-activated slag-fly ash concrete
507 mixes changed the basic characteristics of the stress-strain response under axial compression.
508 The ascending branch of the stress-strain curve was slightly influenced, but the descending
509 branch (softening response) of the stress-strain curve was significantly influenced by the
510 addition of steel fibers. The slope of the descending branch decreased significantly with the
511 addition of steel fibers compared to the reference alkali-activated slag-fly ash concrete mix
512 (REF).

513 6. The toughness of alkali-activated slag-fly ash concrete mixes increased with the increase in
514 the volume fraction of steel fibers in the alkali-activated slag-fly ash concrete. The highest
515 toughness was obtained by the addition of 2% HS (either 1% MS and 1% DS or 1.5% MS
516 and 0.5% DS) fiber by volume in the alkali-activated slag-fly ash concrete mixes. The

517 additions of 2% HS (either 1% MS and 1% DS or 1.5% MS and 0.5% DS) fiber by volume
518 achieved an increase in the toughness by 400% compared to the reference mix (REF).

519 Finally, the test results indicated that the addition of steel fiber improved the engineering
520 properties of ambient cured alkali-activated slag-fly ash concrete mix. The highest
521 improvement in the mechanical properties of the alkali-activated slag-fly ash concrete mix
522 was achieved by the addition of 2% MS, 2% DS and 2% HS fibers by volume. The HS fiber
523 reinforced alkali-activated slag-fly ash concrete mix with 1% MS and 1% DS fibers by
524 volume achieved the optimum improvement in mechanical properties compared to the alkali-
525 activated slag-fly ash concrete mix reinforced with other types of steel fibers.

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716 Table 1. Chemical composition (mass %) for GGBS (ASA 2017) and FA (EPSA 2017)

Component	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	TiO ₂	P ₂ O ₅	Mn ₂ O ₃	SO ₃	LOI*
GGBS	32.4	14.96	0.83	40.7	5.99	0.29	0.42	0.84	0.38	0.40	2.74	NA
FA	62.2	27.5	3.92	2.27	1.05	1.24	0.52	0.16	0.30	0.09	0.08	0.89

717 *LOI: Loss on ignition

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743 Table 2. Mix proportions of ambient cured alkali-activated slag-fly ash concrete (Hadi et al.
744 2017)

Mix	Quantity
FA (kg/m ³)	225
GGBS (kg/m ³)	225
Al/Binder	0.35
Aggregate (kg/m ³)	1164
Sand (kg/m ³)	627

Na ₂ SiO ₃ /NaOH	2.5
Na ₂ SiO ₃ (kg/m ³)	112.5
NaOH (kg/m ³)	45
NaOH (mole/l)	14
Superplasticizer (kg/m ³)	22.5
Water (kg/m ³)	45

745 Note: Al/Binder represents alkaline activator to binder content ratio.

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760 Table 3. Test matrix

Alkali-activated concrete mix	Type of steel fiber	Percentage by volume
REF	Plain Concrete	-
ACMS1	Micro steel fiber (MS)	1%
ACMS2		2%
ACMS3		3%
ACDS1	Deformed steel fiber (DS)	1%

ACDS1.5		1.5%
ACDS2		2%
ACHS2a	Hybrid steel fiber (HS)	2% (0.5% MS+1.5% DS)
ACHS2b		2% (1% MS+1% DS)
ACHS2c		2% (1.5% MS+0.5% DS)

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775 Table 4. Test results of ambient cured alkali-activated slag-fly ash concrete

Alkali-activated concrete mix	Slump (mm)	Compressive Strength (MPa)				Splitting Tensile Strength (MPa)		Flexural Strength (MPa)		Direct Tensile Strength (MPa)	
		7 days		28 days		Average	S.D	Average	S.D	Average	S.D
		Average	S.D	Average	S.D						
REF	118	40.1	1.11	44.1	1.12	3.5	0.20	4.4	0.26	2.4	0.15
ACMS1	105	41.7	1.12	46.5	1.20	3.9	0.26	4.6	0.17	2.6	0.14
ACMS2	85	44.1	1.06	47.9	1.20	5.3	0.22	5.4	0.13	2.9	0.16
ACMS3	76	40.7	0.79	45.6	0.93	4.8	0.15	5.0	0.32	2.8	0.10
ACDS1	102	40.8	1.07	44.3	0.86	4.4	0.16	4.7	0.18	2.6	0.14
ACDS1.5	95	41.6	0.90	44.8	1.56	4.5	0.25	4.9	0.25	2.7	0.12
ACDS2	82	42.7	1.50	45.9	0.80	5.5	0.24	6.1	0.15	2.9	0.14
ACHS2a	75	42.2	1.26	46.1	1.39	5.2	0.19	5.6	0.24	2.9	0.15
ACHS2b	80	45.0	1.02	48.9	1.47	6.3	0.17	6.7	0.21	3.3	0.15
ACHS2c	82	42.7	1.59	46.6	0.98	5.6	0.16	5.9	0.21	3.0	0.18

776 Note: S.D represents standard deviation

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779 Table 5. Axial stress-axial strain response of ambient cured alkali-activated slag-fly ash
 780 concrete under axial compression

Alkali-activated concrete mix	f'_{cf} (1)	ϵ'_{cf} (2)	Toughness	Toughness relative to the REF	Modulus of elasticity (GPa)
REF	42.4	0.0028	0.10	1	22.6
ACMS1	45.1	0.0033	0.36	3.6	24.7
ACMS2	47.1	0.0037	0.42	4.2	24.9
ACMS3	44.3	0.0044	0.48	4.8	23.9
ACDS1	42.5	0.0036	0.36	3.6	22.7
ACDS1.5	42.6	0.0039	0.42	4.2	22.8
ACDS2	44.9	0.0040	0.46	4.6	23.0
ACHS2a	45.7	0.0037	0.44	4.4	24.1
ACHS2b	48.0	0.0041	0.50	5.0	25.7
ACHS2c	44.9	0.0038	0.50	5.0	23.7

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 782 *Note:* (1) Average peak compressive stress in MPa. (2) Average strain corresponding to
 783 average peak stress.

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(a)

(b)

Fig. 1. Steel fibers: (a) MS fibers and (b) DS fibers

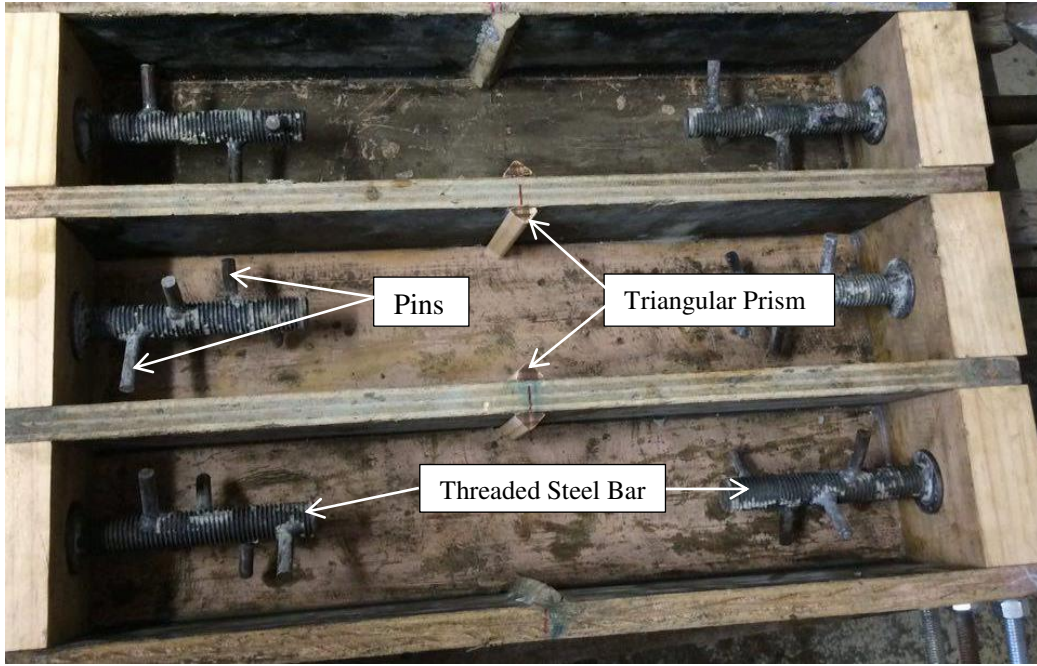


Fig. 2. Formwork of direct tensile test specimens

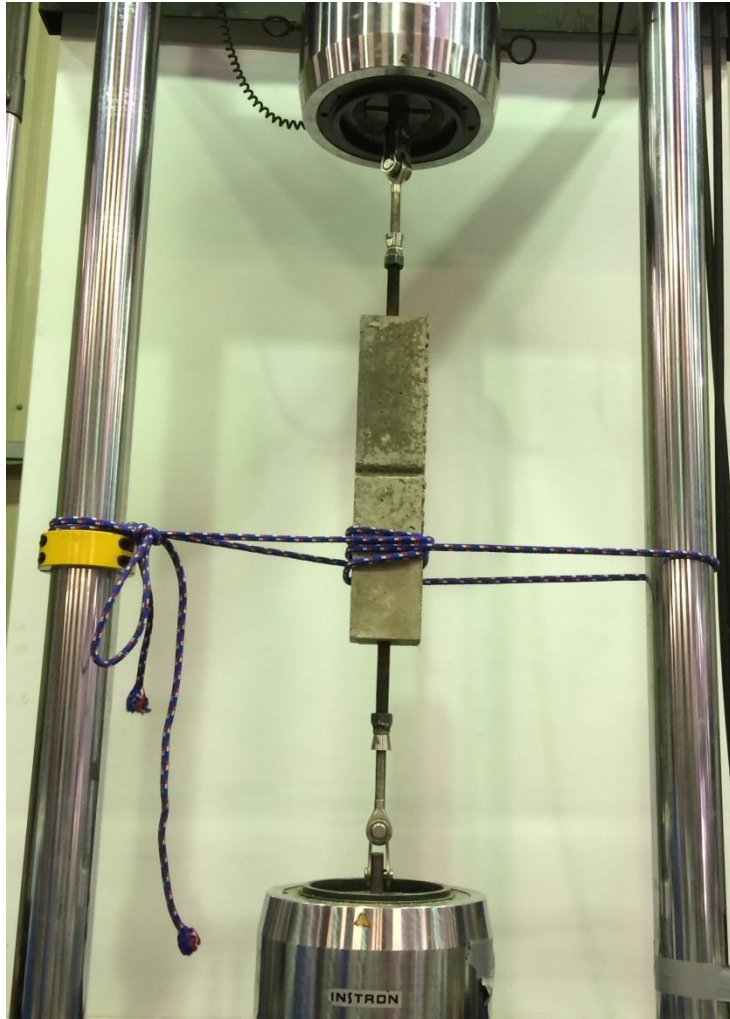


Fig. 3. Direct tensile testing setup

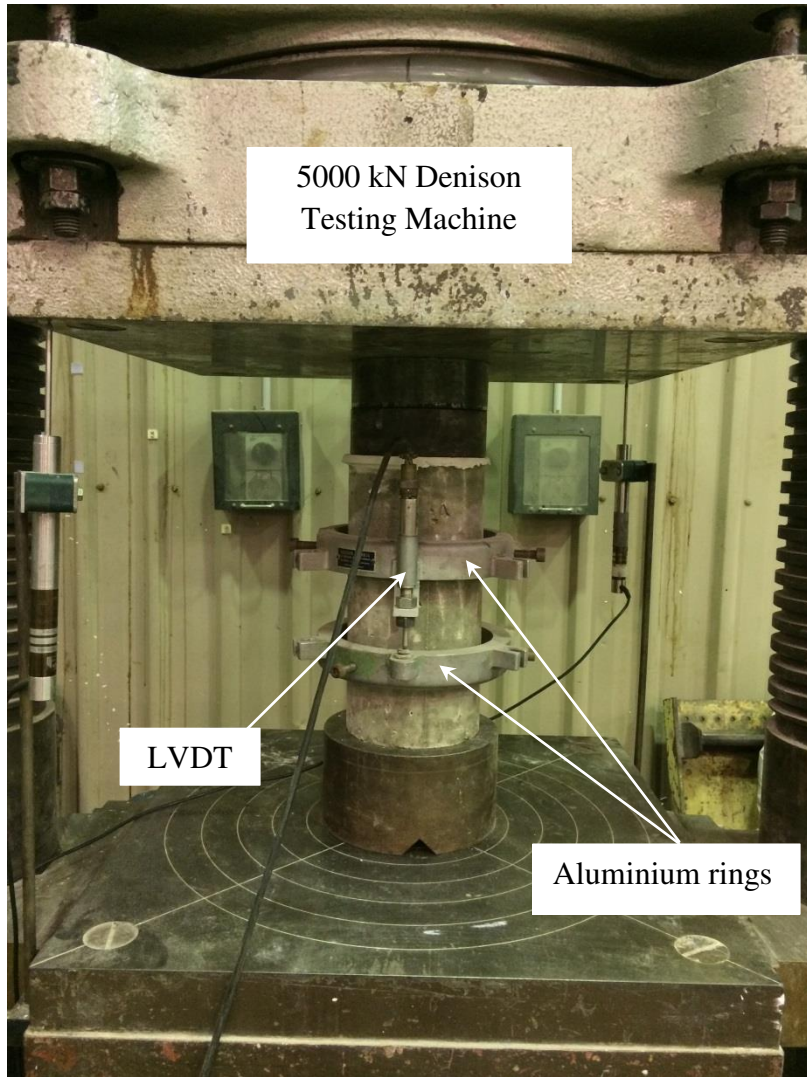


Fig. 4. Test setup for stress-strain response

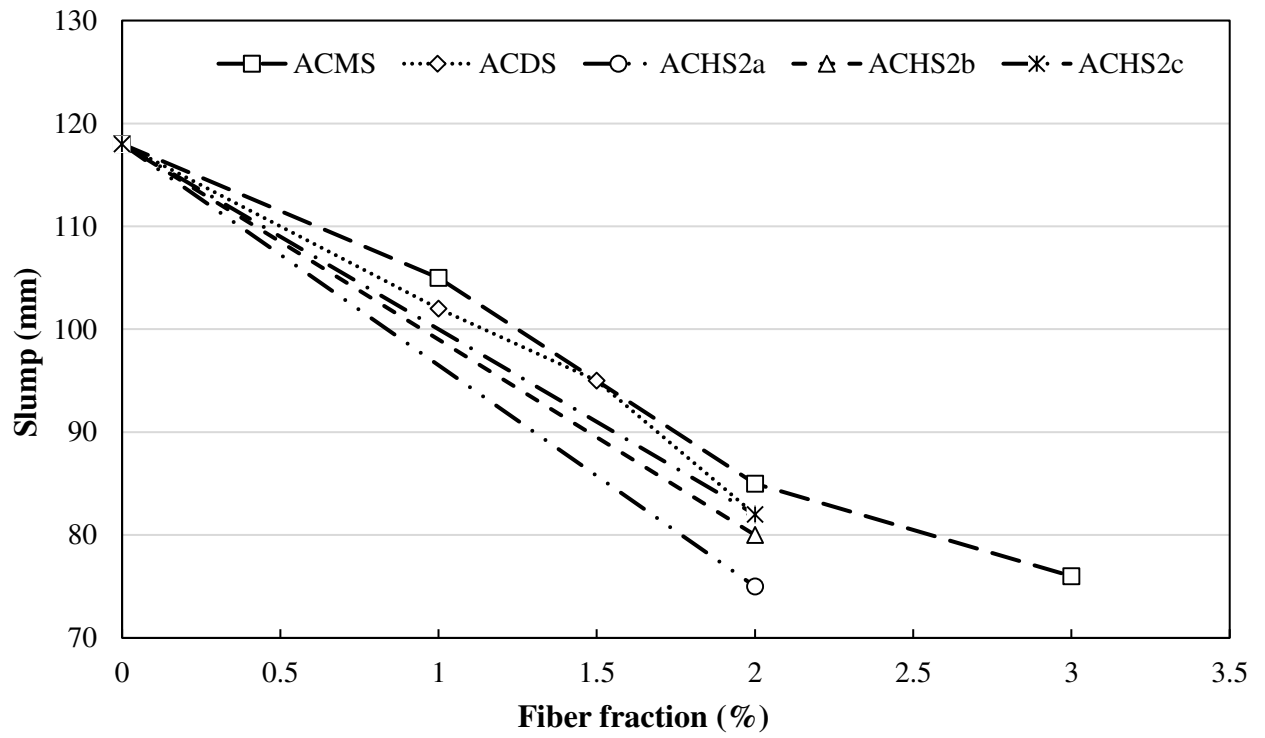


Fig. 5. Slump test results of alkali-activated slag-fly ash concrete mixes

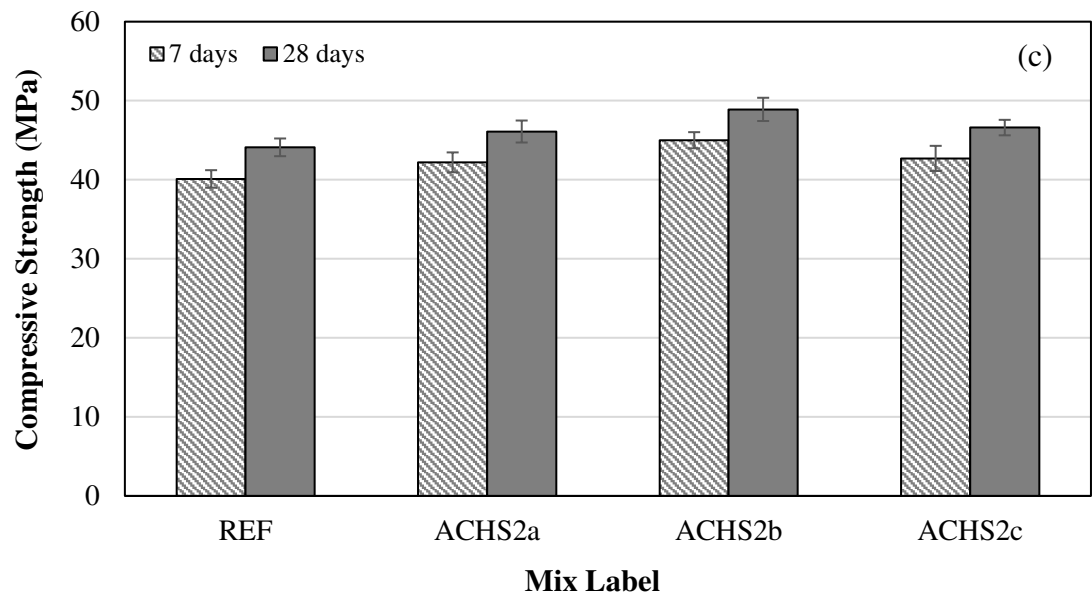
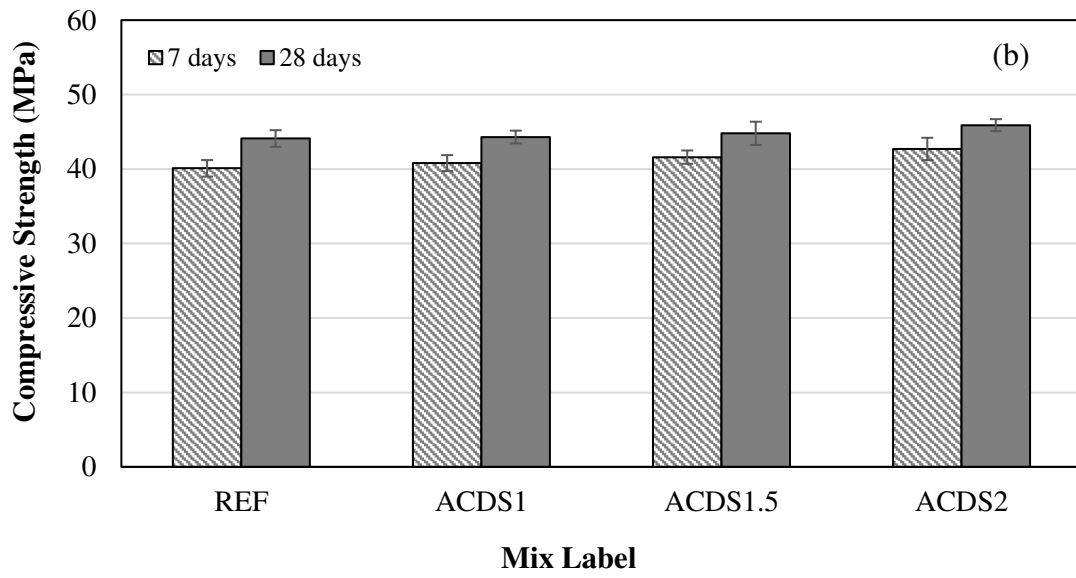
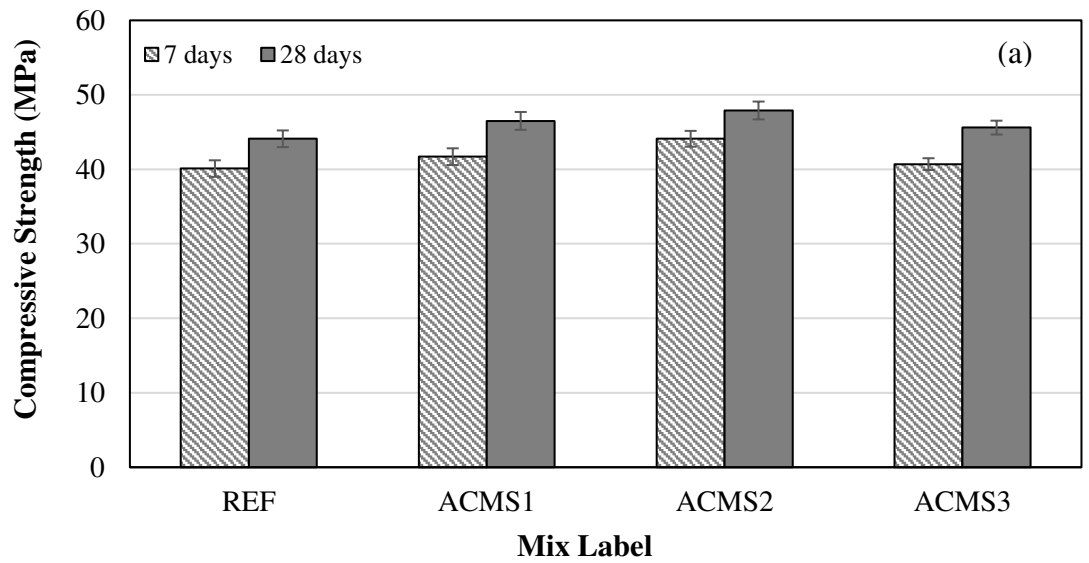


Fig. 6. Average compressive strength of ambient cured alkali-activated slag-fly ash concrete mixes: (a) ACMS, (b) ACDS and (c) ACHS

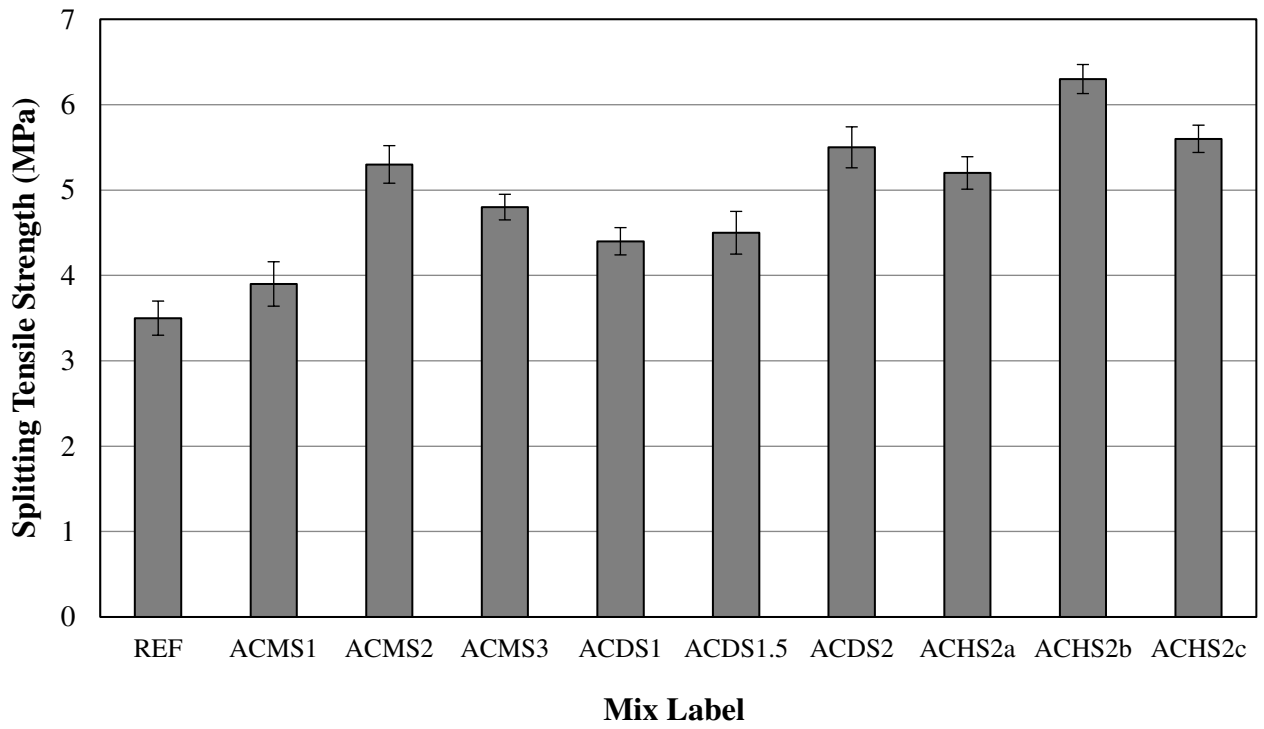


Fig. 7. Average 28-day splitting tensile strength of ambient cured alkali-activated slag-fly ash concrete mixes (REF, ACMS, ACDS and ACHS)

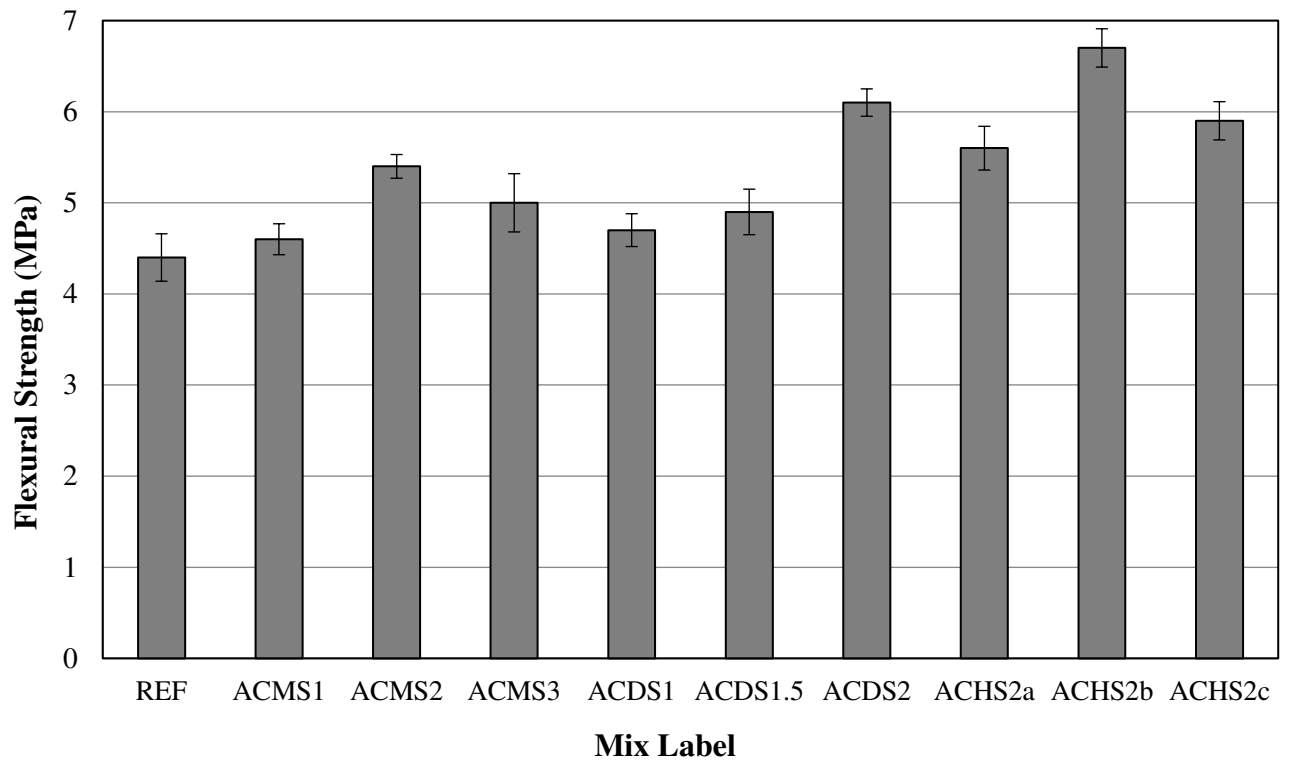


Fig. 8. Average 28-day flexural strength of ambient cured alkali-activated slag-fly ash concrete mixes (REF, ACMS, ACDS and ACHS)

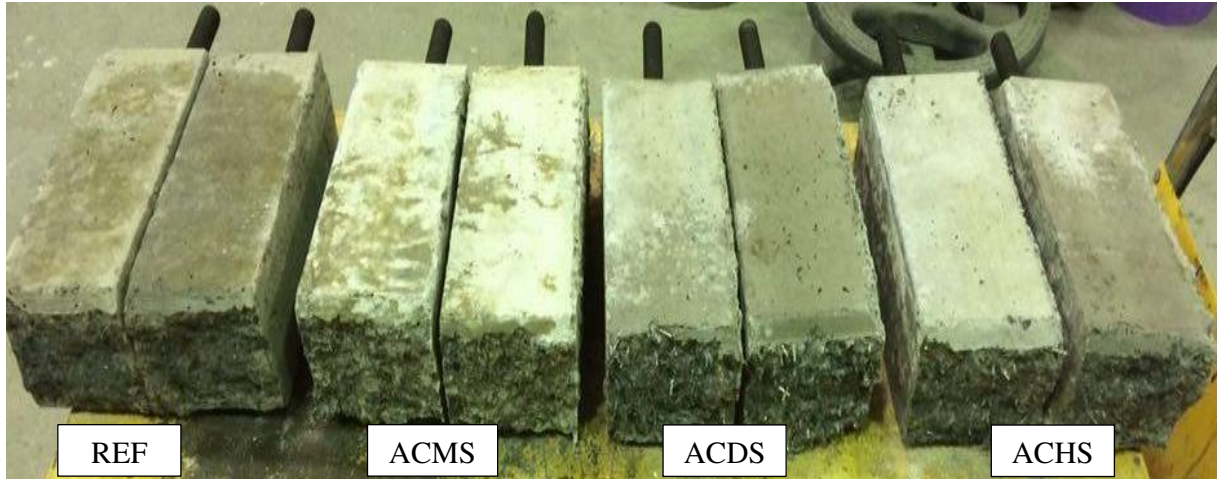


Fig. 9. Typical failure mode of ambient cured alkali-activated slag-fly ash concrete mixes under direct tension (REF, ACMS, ACDS, and ACHS)

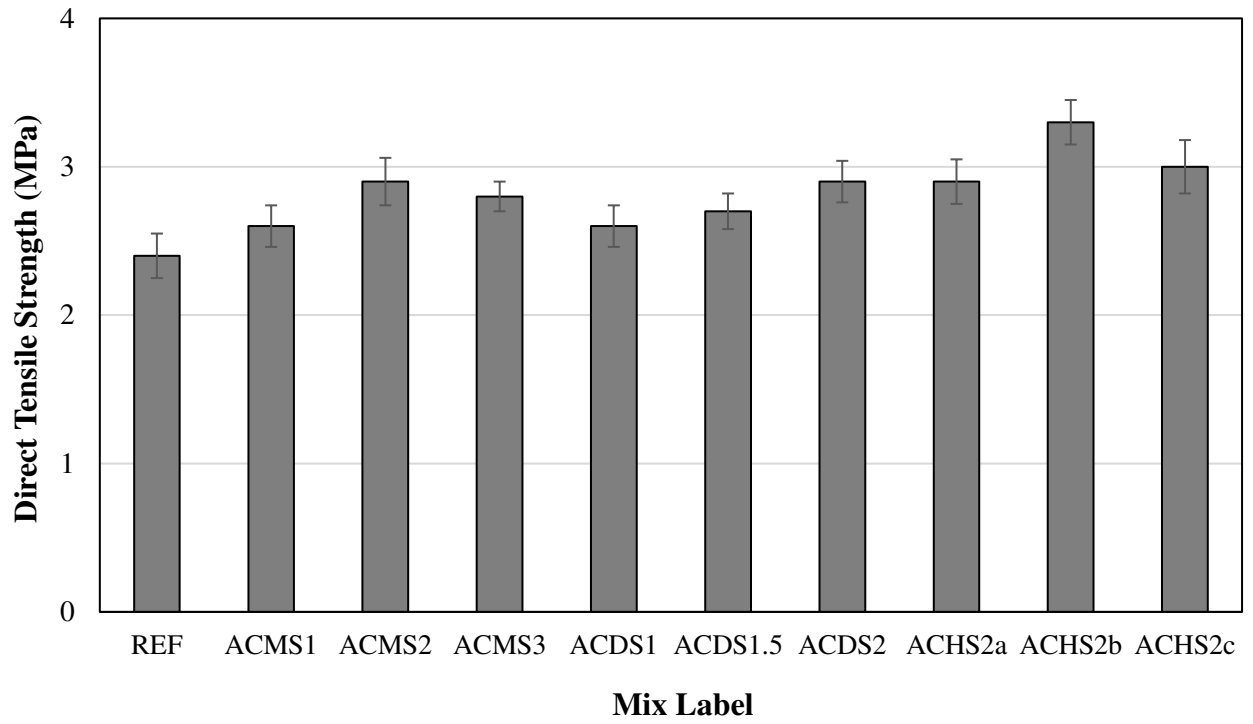


Fig. 10. Average 28-day direct tensile strength of ambient cured alkali-activated slag-fly ash concrete mixes (REF, ACMS, ACDS and ACHS)

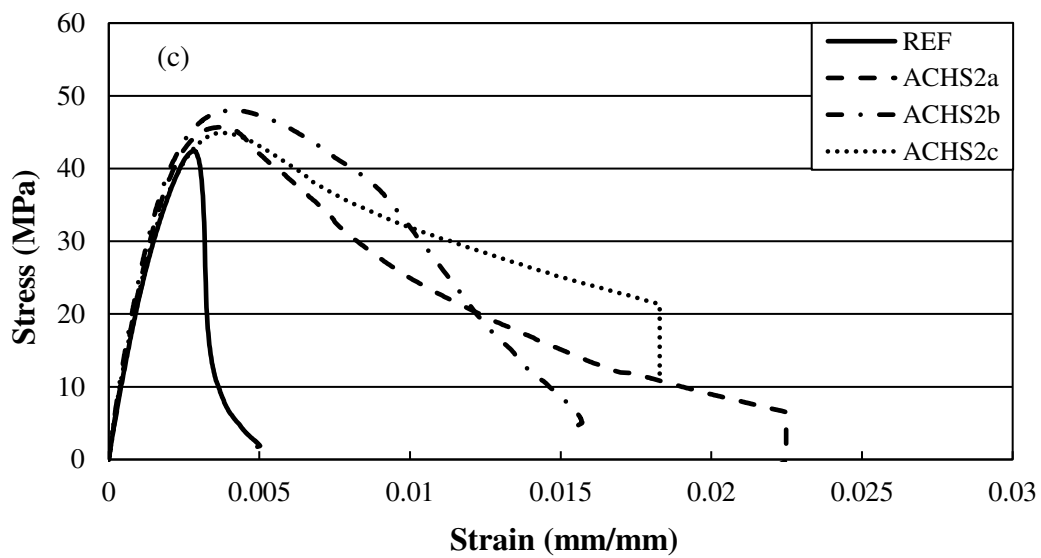
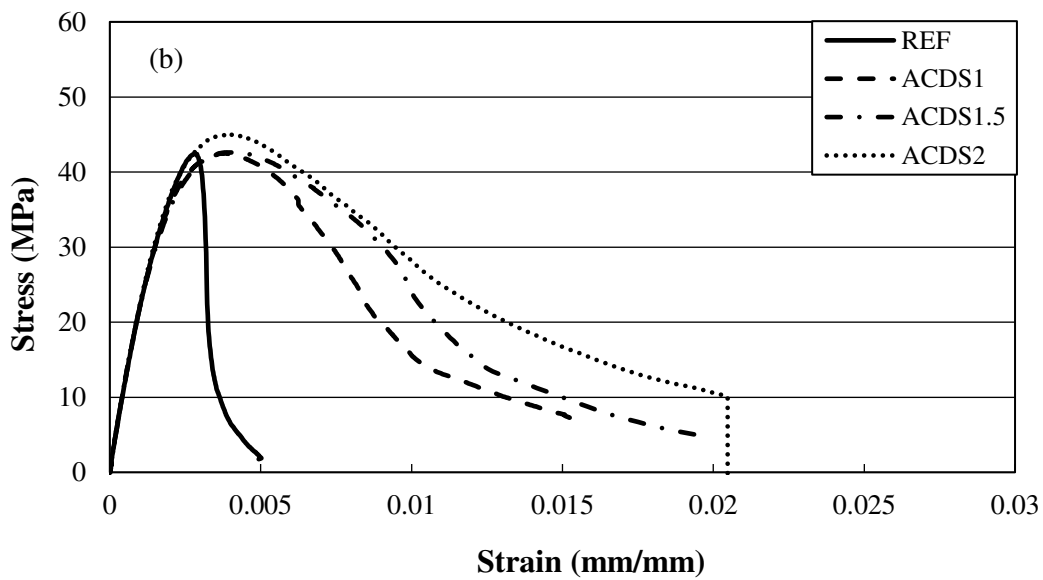
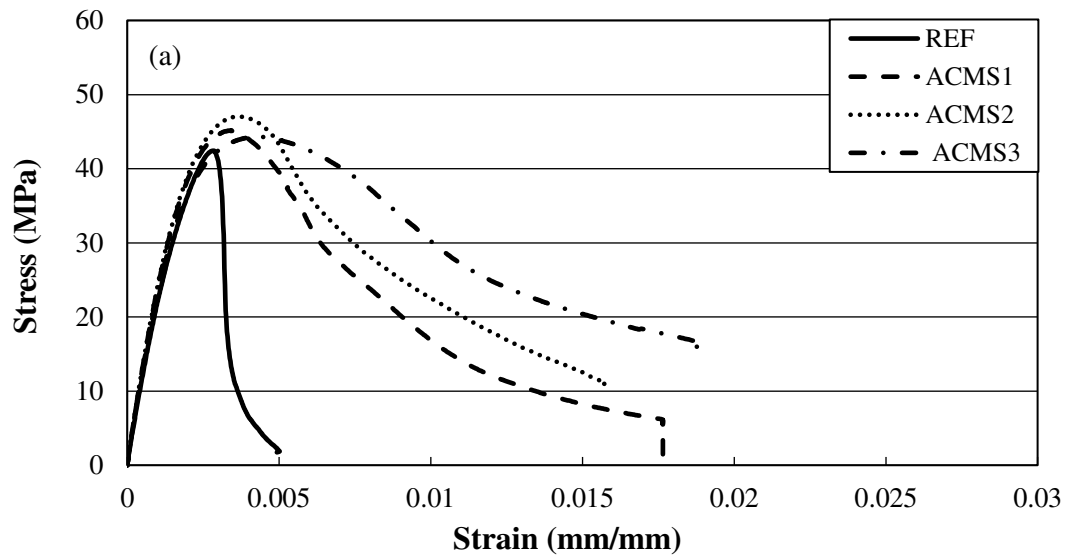


Fig. 11. Typical Stress-strain response of ambient cured alkali-activated slag-fly ash concrete under axial compression: (a) ACMS, (b) ACDS and (c) ACHS