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Investigation of engineering properties of normal and high strength fly ash based geopolymer and alkali-activated slag concrete compared to ordinary Portland cement concrete

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Investigation of engineering properties of normal and high strength fly ash based geopolymer and alkali-activated slag concrete compared to ordinary Portland cement concrete

Abstract

Fly ash-based geopolymer (FAGP) and alkali-activated slag (AAS) concrete are produced by mixing alkaline solutions with aluminosilicate materials. As the FAGP and AAS concrete are free of Portland cement, they have a low carbon footprint and consume low energy during the production process. This paper compares the engineering properties of normal strength and high strength FAGP and AAS concrete with OPC concrete. The engineering properties considered in this study included workability, dry density, ultrasonic pulse velocity (UPV), compressive strength, indirect tensile strength, flexural strength, direct tensile strength, and stress-strain behaviour in compression and direct tension. Microstructural observations using scanning electronic microscopy (SEM) are also presented. It was found that the dry density and UPV of FAGP and AAS concrete were lower than those of OPC concrete of similar compressive strength. The tensile strength of FAGP and AAS concrete was comparable to the tensile strength of OPC concrete when the compressive strength of the concrete was about 35 MPa (normal strength concrete). However, the tensile strength of FAGP and AAS concrete was higher than the tensile strength of OPC concrete when the compressive strength of concrete was about 65 MPa (high strength concrete). The modulus of elasticity of FAGP and AAS concrete in compression and direct tension was lower than the modulus of elasticity of OPC concrete of similar compressive strength. The SEM results indicated that the microstructures of FAGP and AAS concrete were more compact and homogeneous than the microstructures of OPC concrete at 7 days, but less compact and homogeneous than the microstructures of OPC concrete at 28 days for the concrete of similar compressive strength.

Keywords

normal, properties, engineering, investigation, ordinary, compared, concrete, cement, slag, portland, alkali-activated, geopolymer, ash, fly, strength, high

Disciplines

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1 **Investigation of Engineering Properties of Normal and High Strength Fly**
2 **Ash Based Geopolymer and Alkali-Activated Slag Concrete Compared to**
3 **Ordinary Portland Cement Concrete**

4
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29 **Abstract**

30 Fly ash-based geopolymer (FAGP) and alkali-activated slag (AAS) concrete are produced by
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32 free of Portland cement, they have a low carbon footprint and consume low energy during the
33 production process. This paper compares the engineering properties of normal strength and
34 high strength FAGP and AAS concrete with OPC concrete. The engineering properties
35 considered in this study included workability, dry density, ultrasonic pulse velocity (UPV),
36 compressive strength, indirect tensile strength, flexural strength, direct tensile strength, and
37 stress-strain behaviour in compression and direct tension. Microstructural observations using
38 scanning electronic microscopy (SEM) are also presented. It was found that the dry density and
39 UPV of FAGP and AAS concrete were lower than those of OPC concrete of similar
40 compressive strength. The tensile strength of FAGP and AAS concrete was comparable to the
41 tensile strength of OPC concrete when the compressive strength of the concrete was about 35
42 MPa (normal strength concrete). However, the tensile strength of FAGP and AAS concrete was
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44 was about 65 MPa (high strength concrete). The modulus of elasticity of FAGP and AAS
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47 of FAGP and AAS concrete were more compact and homogeneous than the microstructures of
48 OPC concrete at 7 days, but less compact and homogeneous than the microstructures of OPC
49 concrete at 28 days for the concrete of similar compressive strength.

50

51 **Keywords:** Fly ash-based geopolymer concrete; Alkali-activated slag concrete; Engineering
52 properties; High strength; Normal strength

53

54 **1. Introduction**

55 Cement is the main material used in the production of concrete. The production process of
56 cement is associated with the consumption of high energy and natural resources. The
57 production of cement is associated with the emission of greenhouse gases including methane,
58 nitrous oxide and carbon dioxide into the atmosphere. Indeed, it is estimated that the production
59 of one tonne of cement requires about 1.5 tonnes of raw materials and releases nearly one tonne
60 of carbon dioxide into the atmosphere [1-4]. Thus, the use of aluminosilicate materials as an
61 alternative to the cement has become necessary, especially to reduce the carbon dioxide
62 emissions into the atmosphere. Many research studies were carried out to develop new and
63 greener materials as alternatives to cement such as geopolymer and alkali activated binder. Fly
64 ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) are the most common
65 aluminosilicate materials used in the production of fly ash based geopolymer (FAGP) and
66 alkali-activated slag (AAS) concrete. The FAGP and AAS concrete are green concrete without
67 Portland cement. The FAGP and AAS concrete can be produced by blending an alkaline
68 solution with aluminosilicate materials such as FA and GGBS. The FAGP and AAS concrete
69 are proven to have comparable mechanical properties to the OPC concrete but with reduced
70 greenhouse gas emissions. The use of FAGP or AAS concrete can reduce CO₂ emissions into
71 atmosphere associated with the production of concrete by 60-80 % [5-7].

72

73 Fernandez-Jimenez et al. [8] studied the engineering properties of heat cured FAGP concrete
74 and compared with the engineering properties of OPC concrete. The test results showed that
75 the indirect tensile and flexural strengths of FAGP concrete were higher than those of OPC

76 concrete. However, the modulus of elasticity of FAGP concrete was lower than the modulus
77 of elasticity of OPC concrete. Hardjito and Rangan [9] showed that FAGP concrete achieved
78 similar compressive strength, higher indirect tensile and flexural strengths and lower modulus
79 of elasticity than OPC concrete. Neupane et al. [10] studied the engineering properties of heat
80 cured FAGP concrete and compared with the engineering properties of OPC concrete. It was
81 found that the indirect tensile and flexural strengths of FAGP concrete were higher than those
82 of OPC concrete, whereas the modulus of elasticity of FAGP concrete was similar to the
83 modulus of elasticity of OPC concrete. Diaz-Loya et al. [11] investigated the engineering
84 properties of heat cured FAGP concrete. The engineering properties of heat cured FAGP
85 concrete were found to be similar to those of OPC concrete. The test results also showed that
86 the equations in the existing design standards for OPC concrete could be used for FAGP
87 concrete to determine the indirect tensile strength, flexural strength, and the modulus of
88 elasticity.

89

90 Several studies investigated the engineering properties of AAS concrete and compared with
91 the engineering properties of OPC concrete. Bernal et al. [12] studied the engineering
92 properties of AAS concrete produced in the laboratory at an ambient condition and compared
93 with the engineering properties of OPC concrete. The compressive strength of AAS concrete
94 was found to be comparable to the compressive strength of OPC concrete, but the indirect
95 tensile and flexural strengths were slightly higher than those of OPC concrete. Lee et al. [13]
96 studied the engineering properties of AAS concrete produced in the laboratory at an ambient
97 condition and showed that the indirect tensile strength and modulus of elasticity of AAS
98 concrete were slightly lower than those of OPC concrete. Chi [14] investigated the mechanical
99 and durability performance of AAS concrete and compared with the mechanical and durability
100 performance of OPC concrete. The test results showed that AAS concrete could be produced

101 with superior engineering properties (compressive strength, splitting tensile strength, drying
102 shrinkage, sulphate attack resistance, and high-temperature resistance) and the durability to
103 those of OPC concrete.

104

105 Most of the previous studies focused either on the engineering properties of FAGP concrete or
106 the engineering properties of AAS concrete and compared with the engineering properties of
107 OPC concrete. The engineering properties of FAGP and AAS concrete compared to the OPC
108 concrete have not been adequately investigated in the available literature. Very limited
109 information is currently available for the engineering properties of FAGP and AAS concrete
110 compared to the OPC concrete. An extensive review of literature revealed, none of the research
111 studies investigated the engineering properties of normal strength and high strength FAGP and
112 AAS concrete compared with the engineering properties of OPC concrete. A complete
113 understanding of the engineering properties of FAGP and AAS concrete is important for the
114 design and field implementation of eco-friendly concrete structures. This paper compares the
115 engineering properties of normal strength and high strength FAGP and AAS concrete with the
116 engineering properties of normal strength and high strength OPC concrete. Microstructural
117 investigations using scanning electronic microscopy (SEM) are also carried out. The equations
118 in the existing standards for OPC concrete were used to calculate indirect tensile strength,
119 flexural strength and modulus of elasticity of FAGP and AAS concrete and compared with the
120 experimental results. **It is noted that the development of mathematical models for the
121 engineering properties of FAGP and AAS concrete is considered beyond the scope of this
122 paper.**

123

124

125

126 2. Experimental investigation

127 2.1 Materials used

128 The materials used in this study were FA, GGBS and General-purpose cement. The FA
129 supplied by Gladstone Power Station, Australia was used as the source material for FAGP
130 concrete. The GGBS supplied by the Australian Slag Association was used as the source
131 material for AAS concrete. General purpose cement was used as the binder for OPC concrete.
132 The chemical composition of FA and GGBS was determined by X-Ray Fluorescent (XRF) and
133 is shown in Table 1. Chemical analyses of FA and GGBS were carried out in the School of
134 Earth and Environmental Sciences at the University of Wollongong, Australia. Table 1 shows
135 that FA contains less than 5% calcium oxide (CaO). The sum of Al₂O₃, SiO₂ and Fe₂O₃ contents
136 was higher than 70% of the FA components. The CaO content was less than 8% of the FA
137 components. Hence, the FA used in this study can be classified as Type 'F' according to ASTM
138 C618-08 [15]. The chemical compositions of the OPC provided by cement Australia are shown
139 in Table 2.

140

141 Crushed coarse aggregate with 10 mm maximum aggregate size in the saturated surface dry
142 condition and locally available river sand (fine aggregate) were used to prepare all the test
143 specimens. The alkaline activator was a mixture of sodium hydroxide (NaOH) and sodium
144 silicate (Na₂SiO₃) solution. Sodium hydroxide (NaOH) pellets were dissolved in potable water
145 to prepare the sodium hydroxide (NaOH) solution with different concentrations. Sodium
146 silicate solution (Na₂SiO₃) with a specific gravity of 1.53 and an activator modulus (Ms) of 2.0
147 (Ms = SiO₂/Na₂O; SiO₂ = 29.4% and Na₂O = 14.7%) was supplied by PQ Australia. To obtain
148 fresh concrete with high workability, commercially available high range water reducer
149 (Glenium 8700) supplied by BASF, Australia was used in this study.

150

151 **2.2 Preparation of concrete mixes**

152 Three types of concrete were used in this study: FAGP, AAS and OPC concrete. The design
153 compressive strengths of the concrete at 28 days were 35 MPa (normal strength concrete, NSC)
154 and 65 MPa (high strength concrete, HSC). The total amount of aggregate in the FAGP and
155 AAS concrete was between 60-80% of the mass of the concrete. The amount of aggregate
156 varied depending on the amount of binder (FA and GGBS) and alkaline activator. The
157 concentration of NaOH used to prepare the normal strength and high strength FAGP concrete
158 was 12 moles/litre (M) and 14 moles/litre (M), respectively. The ratio of sodium silicate
159 (Na_2SiO_3) to sodium hydroxide (NaOH) was fixed at 2. The concentration of NaOH used to
160 prepare the normal strength and high strength AAS concrete was 12 M and 14 M, respectively.
161 The ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) was fixed at 2.5. Extra
162 water and high range water reducer were added into the concrete mixes to obtain consistent
163 workability during the casting of concrete.

164

165 For the normal strength OPC concrete, the mix proportions by weight of cement, fine
166 aggregate, and coarse aggregate were 1:2.2:3.3 with a maximum aggregate size of 10 mm and
167 water to cement ratio of 0.52. For the high strength OPC concrete, the mix proportions by
168 weight of cement, fine aggregate, and coarse aggregate were 1:1.3:2.3 with a maximum
169 aggregate size of 10 mm and water to cement ratio of 0.30. Table 3 shows the mix proportions
170 of FAGP, AAS and OPC concrete mixes.

171

172 The concrete was mixed in an electrical pan mixer with a capacity of 0.1 m³ in the High Bay
173 Laboratory at the University of Wollongong, Australia. To produce FAGP and AAS concrete,
174 the dry materials including FA or GGBS, fine aggregates and coarse aggregates were mixed
175 for about four minutes. Afterwards, alkaline activator, water and the high range water reducer

176 were added to the dry mix, which was then mixed for another five minutes for a uniform
177 consistency of concrete. These fresh mixes were then poured into Polyvinyl chloride (PVC)
178 moulds to prepare specimens to test the dry density, ultrasonic pulse velocity (UPV),
179 compressive strength, indirect tensile strength and stress-strain behaviour under compression.
180 Also, the fresh concrete was poured into plywood moulds to prepare the specimen for the
181 flexural and direct tensile strength tests. These mixes were then vibrated on a vibration table
182 for 1 minute to remove air bubbles and to ensure that the concrete was adequately compacted.
183 In total, 24 cylinder specimens with 100 mm diameter and 200 mm height were cast to test the
184 dry density, ultrasonic pulse velocity (UPV) and compressive strength of FAGP and AAS
185 concrete. In addition, 48 cylinder specimens with 150 mm diameter and 300 mm height were
186 cast to test the indirect tensile strength and stress-strain behaviour. Moreover, 48 prism
187 specimens with a cross-section of 100 mm × 100 mm and a length of 500 mm were cast for the
188 flexural and direct tensile strength tests. After casting, the FAGP and AAS concrete specimens
189 were kept in the moulds and left in the laboratory at the ambient condition (temperature of 23
190 ± 3° C) for 24 hours. The FAGP concrete specimens were heat cured at 80° C for 24 hours.
191 Then the specimens were removed from the moulds and left in the laboratory until the time of
192 testing. The AAS concrete specimens were removed from the moulds after 24 hours of casting
193 and were left in the laboratory at the ambient condition until the time of testing.

194

195 The dry material (cement, fine and coarse aggregates) for OPC concrete were mixed for about
196 four minutes and water and high range water reducer were slowly added. The mixing continued
197 for another five minutes for a uniform consistency of concrete. The fresh mix was then poured
198 into the steel moulds and vibrated for 1 minute on a vibration table to remove any air bubbles
199 and ensure that the concrete was aduaqatly compacted. Twelve cylinder specimens of 100 mm
200 diameter and 200 mm height were cast with OPC concrete to test dry density, ultrasonic pulse

201 velocity (UPV) and compressive strength. In addition, 24-cylinder specimens of 150 mm
202 diameter and 300 mm height were cast to test the indirect tensile strength and stress-strain
203 behaviour under compression. Twenty-four prism specimens with a cross-section of 100 mm
204 \times 100 mm and a length of 500 mm were cast for the flexural and direct tensile strength tests.
205 After casting, the OPC concrete specimens were kept in the moulds and left in the laboratory
206 at the ambient condition (temperatures of $23 \pm 3^\circ$ C) for 24 hours. Afterwards, the specimens
207 were removed from the moulds and cured in water until the time of testing. **The preparation of**
208 **FAGP and AAS concrete specimens are shown in Fig. 1.**

209

210 **3. Test methods**

211 ***3.1 Microstructural analysis***

212 The microstructure of primary materials (i.e. FA, GGBS and OPC) and the microstructure of
213 FAGP, AAS and OPC concrete specimens were assessed using a Scanning Electron
214 Microscope (SEM). The SEM analysis were carried out using JEOL-JSM 6490LV at the
215 Electron Micro Centre (EMC), University of Wollongong, Australia. The samples for SEM
216 investigation of FAGP, AAS and OPC concrete specimens were taken from the broken
217 particles of the specimens which were tested under compressive strength. The samples were
218 cut for 20 mm in diameter and 10 mm high. The samples were left in the laboratory at the
219 ambient condition for 7 days before testing to ensure that the samples were adequately dried
220 and then coated with gold for SEM imaging.

221

222 ***3.2 Tests for fresh concrete***

223 Slump tests were carried out according to AS 1012.3.1-1998 [16] to determine the consistency
224 of the mixes. The workability of fresh concrete was determined by the slump test using a steel

225 cone with a top diameter of 100 mm and a bottom diameter of 200 mm and a height of 300
226 mm.

227

228 ***3.3 Tests for hardened concrete***

229 To evaluate the engineering properties of hardened FAGP and AAS concrete and compare with
230 the engineering properties of OPC concrete, dry density, ultrasonic pulse velocity, compressive
231 strength, indirect tensile strength, flexural strength, direct tensile strength and stress-strain
232 behaviour tests were carried out. The density of the hardened concrete was measured according
233 to AS 1012.12.2-1998 [17]. The density test was carried out on three specimens of 100 mm in
234 diameter and 200 mm in height for each mix and the average density was recorded. Ultrasonic
235 Pulse Velocity (UPV) tests were carried out in accordance with ASTM C597-2009 [18]. The
236 UPV test was carried out on three specimens of 100 mm in diameter and 200 mm in height for
237 each mix and the average UPV was recorded. Three specimens were tested and the average
238 result has been reported to evaluate the compressive strength and quality of the concrete based
239 on the speed of a stress wave passing through a solid medium. The speed of the stress wave is
240 related to the density of the concrete. The UPV test was carried out with a Portable Ultrasonic
241 Non-destructive Digital Indicating Test set up.

242

243 The compressive strength tests were carried out with the Avery compression testing machine
244 of 1800 kN capacity according to AS 1012.9-1999 [19]. Before testing, the specimens were
245 capped with high strength plaster to ensure a uniform loading surface. Three specimens from
246 each mix were tested and the average compressive strength was recorded. Indirect tensile
247 strength tests were carried out to determine the tensile strength of concrete according to AS
248 1012.10-2000 [20]. The specimens were tested with the Avery compression testing machine at
249 a loading rate of 106 kN/min until the specimen failed. Three specimens from each mix were

250 tested and the average indirect tensile strength was recorded as the tensile strength of concrete.
251 The four-point bending tests were carried out according to AS 1012.11-2000 [21] using an
252 Avery 50 tonne testing machine at a loading rate of 2 kN/sec. The specimens were tested until
253 failure. The average measurement of three specimens was recorded as the flexural strength of
254 concrete.

255

256 The direct tensile strength of the specimens was determined according to the test setup
257 proposed by Alhussainy et al. [22]. The direct tensile test was carried out with a 500 kN
258 Universal Instron testing machine at 0.1 mm/min. To ensure that the specimens fractured in the
259 middle, the cross-sectional area in the middle was reduced by 20% using two wooden triangular
260 prisms. Three specimens were tested for each mix and the average direct tensile strengths have
261 been reported.

262

263 The stress-strain behaviour of specimens (150 mm diameter by 300 mm high) under
264 compression was determined according to AS 1012.17-2014 [23] with a 5000 kN Denison
265 compression testing machine at a loading rate of 0.3 mm/min. Three linear variable differential
266 transducers (LVDT) were used to record the axial deformation of the specimens. The
267 specimens were capped before testing with high strength plaster to ensure uniform loading
268 surfaces.

269

270 **4. Results and Discussion**

271 ***4.1 Microstructural Development***

272 The microscopic characteristics of primary materials (i.e., FA, GGBS and OPC) used in the
273 production of FAGP, AAS and OPC concrete are shown in Fig. 2. Figure 2 (a) shows that the
274 FA consists mainly of glassy, spherical particles. The surfaces of the particles appear to be

275 dense and smooth. The OPC and GGBS particles consist mainly of clear edges and angular
276 shapes (Fig. 2 b and c).

277

278 The microstructural development of normal strength and high strength FAGP, AAS and OPC
279 concrete are shown in Figs. (3-5). The microstructure of normal strength and high strength
280 FAGP concrete showed an abundance of unreacted spherical shaped particles of fly ash and a
281 loose amorphous structure with visible micro-cavities in the FAGP concrete specimens at 7
282 days (Fig. 3). These visible micro-cavities at 7 days are due to the evaporation of water from
283 FAGP concrete specimens during the heat curing stage. The microstructure of FAGP concrete
284 at 28 days showed less unreacted particles of fly ash. The structures of the geopolymer mixes
285 look denser and more compact due to some additional geopolymerisation and the formation of
286 aluminosilicate gel in the FAGP concrete specimens. The aluminosilicate gel diffused through
287 the micro-cavities to fill the interior voids in the FAGP concrete specimens and increase
288 adhesion with particles of geopolymer matrices, which resulted in a highly compacted and
289 homogeneous structure [24].

290

291 The microstructural development of normal strength and high strength AAS concrete displayed
292 heterogeneous gel matrices at 7 days (Fig. 4). Figure 4 shows that most of the GGBS particles
293 were partially dissolved by the alkaline activator to form C-S-H gel. Small microcracks were
294 formed on the surface of the AAS microstructure due to a rapid reaction between the alkaline
295 activator and GGBS particles in the initial period [12, 25]. After 28 days, the microstructural
296 development of AAS concrete showed more C-S-H gel due to the dissolution of the remaining
297 unreacted GGBS particles. **It is noted that, as the reaction continued, the small microcracks on
298 the surface of the AAS microstructure were filled with C-S-H gel. This helped to bridge the
299 microcracks on the surface of AAS microstructure. Hence, the density and uniformity of AAS**

300 microstructure increased and a more compacted and homogeneous structure was formed
301 between 7 and 28 days. The findings demonstrated in this study are consistent with those
302 reported in few previous studies [25, 26].

303

304 The microstructure of normal strength and high strength OPC concrete was less compact and
305 homogeneous than FAGP and AAS concrete at 7 days (Fig. 5). However, the microstructural
306 development of OPC concrete at 28 days achieved denser microstructures and was more
307 homogeneous than FAGP and AAS concrete at 28 days. Less unreacted OPC particles and no
308 cracks were observed in the OPC matrices at 28 days.

309

310 ***4.2 Workability***

311 The workability of fresh FAGP, AAS and OPC concrete was measured using slump test. The
312 workability of fresh FAGP, AAS and OPC concrete was determined immediately after mixing
313 the ingredients of the concrete. For the normal strength concrete (NSC), the fresh FAGP, AAS
314 and OPC concrete were handled, placed, compacted and finished easily. It was observed that
315 FAGP concrete exhibited the highest workability compared to AAS and OPC concrete. During
316 the slump tests, it was observed that the FAGP concrete collapsed during the slump test as soon
317 as the slump cone was lifted. This was attributed to the spherical shaped particles of fly ash,
318 which increased the followability of the mixes (Fig. 2a). In addition, the sodium silicate
319 solution and the added water contributed further to the high flowability [27, 28].

320

321 For the high strength concrete (HSC), the workability of FAGP, AAS and OPC concrete
322 decreased with the decrease in the liquid/binder and increase in the binder content. The
323 decrease in the workability was more significant for AAS and OPC concrete. This can be
324 attributed to the angular shape of the GGBS and OPC particles, which increased the internal

325 shear friction of the mixture [29]. It was also observed that, with the increase in the NaOH
326 concentration, the viscosity of the alkaline activator solution was increased, which made the
327 mix very sticky. As a result, the workability of the FAGP and AAS concrete decreased.

328

329 **4.3 Dry density**

330 The dry density of FAGP, AAS and OPC concrete at 7 and 28 days are presented in Table 4.
331 For the NSC, the average dry density of FAGP, AAS and OPC concrete at 7 days was 2373
332 kg/m³, 2389 kg/m³ and 2368 kg/m³, respectively. The dry density of FAGP, AAS and OPC
333 concrete increased as the age of the concrete increased. The average density of FAGP concrete
334 increased from 2373 kg/m³ at 7 days to 2378 kg/m³ at 28 days with an overall increase of 0.21%.
335 The average density of AAS concrete increased from 2389 kg/m³ at 7 days to 2403 kg/m³ at 28
336 days with an overall increase of 0.58%. The average density of OPC concrete increased from
337 2368 kg/m³ at 7 days to 2415 kg/m³ at 28 days with an overall increase of 1.98%. The OPC
338 concrete achieved the highest dry density compared to the dry density of FAGP and AAS
339 concrete at 28 days.

340

341 For the HSC, the average dry density of FAGP, AAS and OPC concrete at 7 days were 2381
342 kg/m³, 2420 kg/m³ and 2401 kg/m³, respectively. The dry density of FAGP, AAS and OPC
343 concrete increased as the concrete age increased. The average density of FAGP concrete
344 increased from 2381 kg/m³ at 7 days to 2384 kg/m³ at 28 days, while the average density of
345 AAS concrete increased from 2420 kg/m³ at 7 days to 2432 kg/m³ at 28 days. This increase in
346 density was about 0.13% and 0.50% for FAGP and AAS concrete, respectively. The average
347 density of OPC concrete increased from 2401 kg/m³ at 7 days to 2443 kg/m³ at 28 days with an
348 overall increase of 1.75%. These results indicated that there were slight increases in the density
349 of normal strength and high strength FAGP, AAS and OPC concrete over time. Whereas, the

350 average density of FAGP and AAS concrete was less than the average density of OPC concrete
351 with similar compressive strengths. These findings were confirmed by SEM analyses. The
352 SEM images showed that FAGP and AAS concrete were less dense, less compacted, and had
353 less homogeneous microstructures than OPC at 28 days (Figs. 3-5).

354

355 ***4.4 Ultrasonic Pulse Velocity***

356 The ultrasonic pulse velocity (UPV) test is used to evaluate the strength and quality of concrete.
357 The pulse velocity depends mostly on the density and properties of concrete. The pulse velocity
358 of FAGP, AAS and OPC concrete at 7 and 28 days are shown in Table 4. Table 4 indicates that
359 the pulse velocity of FAGP, AAS and OPC concrete increased as the concrete age increased.
360 For the NSC, the average pulse velocity of FAGP concrete increased from 3.14 km/s at 7 days
361 to 3.20 km/s at 28 days, while for AAS concrete the average pulse velocity increased from 3.18
362 km/s at 7 days to 3.31 km/s at 28 days. The increase in the pulse velocity of FAGP and AAS
363 concrete was about 1.91% and 4.1%, respectively. The average pulse velocity of OPC concrete
364 increased from 3.30 km/s at 7 days to 3.52 km/s at 28 days with an overall increase of 6.67%.
365 The ultrasonic pulse velocity test results indicated that the quality of the concrete improved
366 over time. The quality of the concrete can be evaluated according to the International Atomic
367 Energy Agency [30], as shown in Table 5. Based on the IAEA, OPC concrete can be classified
368 as "medium" quality at 7 days, because the pulse velocity was 3.30 km/s. As the pulse velocity
369 increased to 3.52 km/s at 28 days, the concrete can be classified as "good" quality. The average
370 pulse velocity of FAGP and AAS concrete is less than the average pulse velocity of OPC
371 concrete, which was between 3-3.5 km/s at 7 and 28 days. Hence, the FAGP and AAS concrete
372 are classified as "medium" quality concrete [30].

373

374 For the HSC, the average pulse velocity of FAGP concrete increased from 3.82 km/s at 7 days
375 to 3.93 km/s at 28 days with an increase of 2.88%. The average pulse velocity of AAS concrete
376 increased from 3.78 km/s at 7 days to 3.98 km/s at 28 days with an increase of 5.29%. The
377 average pulse velocity of OPC concrete increased from 3.87 km/s at 7 days to 4.15 km/s at 28
378 days with an increase of 7.23%. **The pulse velocity of FAGP concrete was lower than the pulse**
379 **velocity of OPC concrete at 7 and 28 days. Similarly, the pulse velocity of AAS concrete was**
380 **lower than the pulse velocity of OPC concrete at 7 and 28 days.** Since the pulse velocity of
381 FAGP, AAS and OPC concrete at 7 and 28 days ranged between 3.5-4.5 km/s, they can be
382 classified as “good” quality concrete [30].

383

384 ***4.5 Compressive strength***

385 The average compressive strength of FAGP, AAS and OPC concrete at 7 and 28 days are
386 shown in Table 4. The compressive strength of AAS and FAGP concrete is comparable to the
387 OPC concrete at 28 days (Table 4). For the NSC with the design compressive strength of 35
388 MPa, the average compressive strength of FAGP, AAS and OPC concrete at 7 days was 33.90
389 MPa, 29.03 MPa and 26.51 MPa, respectively. The FAGP concrete achieved the highest initial
390 compressive strength at 7 days, which was 94.44% of the compressive strength at 28 days.
391 However, AAS and OPC concrete obtained a lower initial compressive strength than FAGP
392 concrete at 7 days, which were 79.66% and 74.01% of the compressive strength at 28 days.
393 The compressive strength of FAGP, AAS and OPC concrete increased with time (Table 4), the
394 average compressive strength of FAGP, AAS and OPC concrete at 28 days was 35.91, 36.44
395 MPa and 35.82 MPa, respectively.

396

397 For the HSC with the design compressive strength of 65 MPa, the average compressive strength
398 of FAGP, AAS and OPC concrete at 7 days was 61.71 MPa, 53.68 MPa and 50.73 MPa,

399 respectively. The FAGP concrete achieved the highest initial compressive strength at 7 days,
400 which was 94.53% of the compressive strength at 28 days. The compressive strength of AAS
401 and OPC concrete at 7 days were 81.20% and 76.06%, respectively, of the compressive
402 strength at 28 days. The compressive strengths of FAGP, AAS and OPC concrete increased
403 with time. The average compressive strengths of FAGP, AAS and OPC concrete at 28 days
404 were 65.28, 66.12 MPa, and 66.69 MPa, respectively. For the NSC and HSC, FAGP concrete
405 developed most of its compressive strength at 7 days although there was a slight increase in the
406 compressive strength at 28 days (Table 4) due to heat curing, which accelerated the
407 geopolymerisation (dissolution mechanism) reaction and increased the compressive strength.
408 The findings of this study agree with Adam [28], in which it was shown that FAGP concrete
409 developed most of its compressive strength at 7 days and there was a marginal increase in the
410 compressive strength at 28 days [28].

411

412 ***4.6 Indirect tensile strength***

413 The indirect tensile strength of FAGP, AAS and OPC concrete was determined at 7 and 28
414 days, and the results are reported in Table 4. For the NSC, the average indirect tensile strength
415 of FAGP, AAS and OPC concrete at 7 days was 3.37 MPa, 2.93 MPa and 2.66 MPa,
416 respectively. The FAGP concrete achieved the highest indirect tensile strength at 7 days. The
417 indirect tensile strength of FAGP, AAS and OPC concrete increased as the concrete age
418 increased. The average indirect tensile strength of FAGP, AAS and OPC concrete at 28 days
419 was 3.58 MPa, 3.55 MPa and 3.51 MPa, respectively. The indirect tensile strength of FAGP,
420 AAS and OPC concrete increased by 6.23%, 21.16% and 31.95% at 28 days, respectively,
421 compared to the indirect tensile strengths at 7 days. When compared with the OPC concrete,
422 the FAGP and AAS concrete achieved very similar indirect tensile strength at 28 days (Table
423 4).

424

425 For the HSC, the average indirect tensile strength of FAGP, AAS and OPC concrete at 7 days
426 was 5.32 MPa, 4.49 MPa and 3.78 MPa, respectively. The FAGP concrete achieved the highest
427 indirect tensile strength at 7 days. The indirect tensile strength of FAGP, AAS and OPC
428 concrete increased with age. The average indirect tensile strength of FAGP, AAS and OPC
429 concrete at 28 days was 5.73 MPa, 5.23 MPa and 4.94 MPa, respectively. The indirect tensile
430 strength of FAGP, AAS and OPC concrete increased by 7.71%, 16.48% and 30.68% at 28 days,
431 respectively. From the test results, it can be observed that the FAGP and AAS concrete
432 achieved about 15.99% and 5.87%, respectively, higher indirect tensile strength at 28 days than
433 OPC concrete of similar compressive strength. These results are consistent with previous
434 studies carried out on FAGP and AAS concrete. Ryu et al. [5] examined the indirect tensile
435 strength of fly ash based geopolymer concrete and found that the indirect tensile strength of
436 geopolymer concrete was higher than the indirect tensile strength of OPC concrete. Bernal et
437 al. [31] reported that AAS concrete achieved a higher indirect tensile strength than OPC
438 concrete at 28 days.

439

440 ***4.7 Flexural strength***

441 The flexural strength is generally higher than the indirect tensile strength as specified in the
442 ACI 318-14 [32] and AS 3600-2009 [33]. The average flexural strengths of FAGP, AAS and
443 OPC concrete at 7 and 28 days are shown in Table 4. For the NSC, the average flexural strength
444 of FAGP, AAS and OPC concrete at 7 days was 3.57 MPa, 3.21 MPa and 3.06 MPa,
445 respectively. The FAGP concrete achieved the highest flexural strength at 7 days. The flexural
446 strength of FAGP, AAS and OPC concrete increased with age. The average flexural strength
447 of FAGP, AAS and OPC concrete at 28 days was found to be 3.81 MPa, 3.79 MPa and 3.78
448 MPa, respectively. The flexural strength of FAGP, AAS and OPC concrete increased by 6.72%,

449 18.07% and 23.53%, respectively, at 28 days compared to the flexural strengths at 7 days. From
450 the test results, it can be seen that a significant development in the flexural strength of FAGP
451 concrete at 7 days (3.57 MPa), which was 93.70% of its flexural strength at 28 days. The
452 flexural strength of FAGP and AAS concrete was very similar to the OPC concrete at 28 days,
453 as shown in Table 4.

454

455 For the HSC, the average flexural strength of FAGP, AAS and OPC concrete at 7 days was
456 6.07 MPa, 5.40 MPa and 4.57 MPa, respectively. The FAGP concrete achieved the highest
457 flexural strength at 7 days. The flexural strengths of FAGP, AAS and OPC concrete increased
458 with the increase in the age of concrete. The average flexural strength of FAGP, AAS and OPC
459 concrete at 28 days was 6.42 MPa, 6.31 MPa and 5.81 MPa, respectively. The flexural strength
460 of FAGP, AAS and OPC concrete increased by 5.76%, 16.85% and 27.13%, respectively, at
461 28 days compared to the flexural strengths at 7 days. The FAGP concrete achieved the highest
462 flexural strength at 7 days (6.07 MPa), which was 94.54% of its flexural strength at 28 days.
463 The flexural strength of FAGP and AAS concrete was 10.5% and 8.6%, respectively, higher
464 than the flexural strengths of OPC concrete at 28 days (Table 4). These findings agree with
465 previous studies which reported that FAGP concrete achieved higher flexural strength than
466 OPC concrete for heat cured [34] and ambient cured geopolymer concrete of similar
467 compressive strengths [8, 11, 35, 36]. Sarker et al. [37] also reported that AAS concrete had
468 higher flexural strengths than OPC concrete of similar compressive strengths.

469

470 ***4.8 Stress-strain behaviour under uniaxial tension***

471 The stress-strain behaviour under uniaxial tension of normal strength and high strength FAGP,
472 AAS and OPC concrete are shown in Figs. (6-7). It can be observed that the ascending branches
473 of the stress-strain curves of FAGP, AAS and OPC concrete exhibited similar behaviours up

474 to the peak stress. After reaching peak stress, the FAGP, AAS and OPC concrete showed a
475 brittle failure as soon as they reached the peak stress. The reduction of the cross-sectional area
476 in the middle increased the stresses in the middle of the specimens and induced uniform failure
477 in the middle of the specimens.

478

479 ***4.8.1 Direct tensile strength***

480 The direct tensile strength of normal strength FAGP, AAS and OPC concrete are presented in
481 Table 4. The average direct tensile strengths of FAGP, AAS and OPC concrete at 7 days was
482 2.33 MPa, 2.02 MPa and 1.91 MPa, respectively. The average direct tensile strength of FAGP,
483 AAS and OPC concrete at 28 days was 2.43 MPa, 2.42 MPa and 2.41 MPa, respectively. The
484 direct tensile strength of FAGP, AAS and OPC concrete increased by 4.29%, 19.80% and
485 26.18% at 28 days, respectively, compared to the direct tensile strength at 7 days.

486

487 The high strength FAGP, AAS and OPC concrete specimens achieved average direct tensile
488 strengths at 7 days of 3.36 MPa, 2.93 MPa and 2.79 MPa, respectively (Table 4). The direct
489 tensile strength of FAGP, AAS and OPC concrete increased with the increase in the concrete
490 age. The average direct tensile strength of FAGP, AAS and OPC concrete at 28 days was 3.52
491 MPa, 3.52 MPa and 3.51 MPa, respectively (Table 4). The direct tensile strength of FAGP,
492 AAS and OPC concrete increased by 4.76%, 20.14% and 25.81%, respectively, at 28 days
493 compared to the direct tensile strength at 7 days.

494

495 It was observed that the average direct tensile strength of FAGP, AAS and OPC concrete was
496 less than the average indirect tensile and flexural strength of FAGP, AAS and OPC concrete,
497 respectively. The lower direct tensile strength compared to the indirect tensile and flexural
498 strengths was similar to the observation reported in Swaddiwudhipong et al. [38] for normal

499 strength OPC concrete. The average direct tensile strength of normal strength FAGP, AAS and
500 OPC concrete was found to be 32%, 30% and 31% less than the average indirect tensile strength
501 of FAGP, AAS and OPC concrete at 28 days, respectively. Also, the average direct tensile
502 strength of FAGP, AAS and OPC concrete was found to be 37%, 33% and 36% less than the
503 average flexural strength of FAGP, AAS and OPC concrete at 28 days, respectively. For the
504 HSC, the average direct tensile strength of FAGP, AAS and OPC concrete was found to be
505 38%, 32% and 29% less than the average indirect tensile strength of FAGP, AAS and OPC
506 concrete at 28 days, respectively. Also, the average direct tensile strength of FAGP, AAS and
507 OPC concrete was found to be 45%, 44% and 40% less than the average flexural strength of
508 FAGP, AAS and OPC concrete at 28 days, respectively.

509

510 ***4.8.2. Peak stress and corresponding strain***

511 The peak stress and strain at peak stress of normal strength FAGP, AAS and OPC concrete are
512 presented in Table 6. It can be observed that the FAGP, AAS and OPC concrete specimens
513 achieved peak stresses at 7 days of 2.33 MPa, 2.02 MPa and 1.91 MPa, respectively. The FAGP
514 concrete achieved higher peak stress than OPC and AAS at 7 days. However, the peak stress
515 of FAGP, AAS and OPC concrete specimens was similar at 28 days. The specimens of FAGP,
516 AAS and OPC concrete achieved peak stresses at 28 days of 2.43 MPa, 2.42 MPa and 2.41
517 MPa, respectively. The peak stresses of FAGP, AAS and OPC concrete increased by 4.29%,
518 19.80% and 26.18% at 28 days, respectively. Also, the strain corresponding peak stress of
519 FAGP, AAS and OPC concrete increased by 7.14%, 16.67% and 8.34%, respectively, at 28
520 days compared to the strain at peak stresses at 7 days.

521

522 For the HSC, the peak stress of FAGP, AAS and OPC concrete at 7 days was 3.36 MPa, 2.93
523 MPa and 2.79 MPa, respectively. The peak stress of FAGP, AAS and OPC concrete increased

524 with time. The FAGP, AAS and OPC concrete achieved peak stresses of 3.52 MPa, 3.52 MPa
525 and 3.51 MPa at 28 days (Table 6). The peak stresses of FAGP, AAS and OPC concrete
526 increased by 4.76%, 20.14% and 25.81%, respectively, at 28 days compared to the peak
527 stresses at 7 days. Also, the strain corresponding peak stress of FAGP, AAS and OPC concrete
528 increased by 17.64%, 12.5% and 13.34%, respectively, at 28 days compared to the strain at
529 peak stresses at 7 days (Table 6).

530

531 **4.8.3. Modulus of elasticity**

532 The modulus of elasticity of FAGP, AAS and OPC concrete was calculated using the slope of
533 ascending branches of tensile stress-strain curves. The modulus of elasticity of normal strength
534 and high strength FAGP, AAS and OPC concrete are presented in Table 6. For NSC, the
535 modulus of elasticity at 7 days was 16.59 GPa, 16.20 GPa and 16.23 GPa for the FAGP, AAS
536 and OPC concrete specimens, respectively (Table 6). The modulus of elasticity at 28 days was
537 16.63 GPa, 16.59 GPa and 17.98 GPa for the FAGP, AAS and OPC concrete specimens,
538 respectively. The modulus of elasticity of FAGP, AAS and OPC concrete increased by 0.24%,
539 2.41% and 10.78 % at 28 days, respectively, compared to the modulus of elasticity at 7 days.
540 The OPC concrete achieved 8.12% and 8.38% higher modulus of elasticity than FAGP and
541 AAS concrete at 28 days, respectively. The modulus of elasticity of high strength FAGP, AAS
542 and OPC concrete was 19.22 GPa, 18.38 GPa and 18.66 GPa at 7 days, respectively (Table 6).
543 The modulus of elasticity of FAGP, AAS and OPC concrete at 28 days was found to be 19.46
544 GPa, 19.36 GPa and 20.95 GPa, respectively. The modulus of elasticity of FAGP, AAS and
545 OPC concrete increased by 1.25%, 5.33% and 12.27% at 28 days, respectively; compared to
546 the modulus of elasticity at 7 days. The OPC specimens achieved 7.65% and 8.21% higher
547 modulus of elasticity than FAGP and AAS concrete at 28 days, respectively.

548

549 ***4.9 Stress-strain behaviour in compression***

550 For the NSC, the experimental stress-strain behaviour in compression of the specimens of
551 FAGP, AAS and OPC concrete at 7 and 28 days are shown in Fig. 8. It was observed that the
552 ascending branch of the stress-strain curves of FAGP, AAS and OPC concrete was almost
553 linear until the peak stress (Fig. 8). After reaching peak stress, the FAGP and AAS concrete
554 showed a more rapid decline in the descending branch of the stress-strain curves and failed in
555 a brittle manner immediately after the peak stress. However, OPC concrete showed a softening
556 decline in the descending branch of the stress-strain curves. The increase in the brittleness of
557 FAGP and AAS concrete was also reported by Atiş et al. [39] and can be attributed to the high
558 micro-cracking in FAGP and AAS concrete [13]. For the HSC, the experimental stress-strain
559 behaviour of specimens of FAGP, AAS and OPC concrete at 7 and 28 days are shown in Fig.
560 9. As the compressive strength increased, the slope of the ascending and descending branches
561 of the stress-strain curves became steeper (Fig. 9). In addition, the failure was more sudden and
562 explosive rather than continual softening.

563

564 ***4.9.1. Peak stress and corresponding strain***

565 The peak stress and strain at peak stress obtained from the stress-strain curve are shown in
566 Table 7. For the NSC, the peak stress of FAGP, AAS and OPC concrete at 7 days was 32.40
567 MPa, 26.88 MPa and 24.81 MPa, respectively (Table 7). The FAGP concrete achieved higher
568 peak stress than AAS and OPC concrete at 7 days. The peak stress for FAGP concrete increased
569 slightly with time, whereas the peak stress of AAS and OPC concrete increased significantly
570 with time. The peak stress of FAGP, AAS and OPC concrete at 28 days was 33.39 MPa, 34.08
571 MPa and 33.06 MPa, respectively. The peak stress of FAGP, AAS and OPC concrete increased
572 by 3.05%, 26.78% and 33.25 %, respectively, at 28 days compared to the peak stresses at 7
573 days. While, the strain corresponding peak stress of FAGP, AAS and OPC concrete increased

574 by 1.83%, 5.42% and 2.46%, respectively, at 28 days compared to the strain at peak stress at 7
575 days (Table 7).

576

577 For the HSC, the peak stress of FAGP, AAS and OPC concrete at 7 days was 59.36 MPa, 52.18
578 MPa and 48.56 MPa, respectively. The peak stress of FAGP concrete was higher than AAS
579 and OPC concrete at 7 days. The peak stress of FAGP concrete slightly increased with time,
580 whereas the peak stress of AAS and OPC concrete increased significantly with time. The peak
581 stress of FAGP, AAS and OPC concrete at 28 days was 63.07 MPa, 64.26 MPa and 63.34 MPa
582 respectively. The peak stress of FAGP, AAS and OPC concrete increased by 6.25%, 23.15%
583 and 30.44%, respectively, at 28 days compared to the peak stresses at 7 days. The strain
584 corresponding to the peak stress of FAGP, AAS and OPC concrete increased by 3.65%, 2.55%
585 and 12.96%, respectively, at 28 days compared to the strain at peak stresses at 7 days (Table
586 7).

587

588 ***4.9.2. Modulus of elasticity***

589 The modulus of elasticity was calculated according to ACI 318-11 [40] as the slope of the
590 tangent of a stress-strain curve drawn from the origin to the stress equals 45% of the peak stress.
591 The slope of the tangent represents the modulus of elasticity of FAGP, AAS and OPC concrete.
592 The modulus of elasticity of normal strength FAGP, AAS and OPC concrete are presented in
593 Table 7. The modulus of elasticity of FAGP, AAS and OPC concrete at 7 days was 17.34 GPa,
594 16.82 GPa and 18.78 GPa, respectively. The modulus of elasticity increased as the concrete
595 age increased. The modulus of elasticity of FAGP, AAS and OPC concrete at 28 days was
596 18.05 GPa, 17.95 GPa and 20.20 GPa, respectively. The modulus of elasticity of FAGP, AAS
597 and OPC concrete increased by 4.09%, 6.72% and 7.56%, respectively, at 28 days compared
598 to the modulus of elasticity at 7 days.

599

600 The modulus of elasticity of high strength FAGP, AAS and OPC concrete was 21.35 GPa,
601 20.21 GPa and 22.10 GPa, respectively, at 7 days (Table 7). The modulus of elasticity increased
602 as the concrete age increased. The modulus of elasticity of FAGP, AAS and OPC concrete at
603 28 days was found to be 24.47 GPa, 23.30 GPa and 27.63 GPa, respectively. The modulus of
604 elasticity of FAGP, AAS and OPC concrete increased by 14.61%, 15.29% and 25.02%,
605 respectively, at 28 days compared to the modulus of elasticity at 7 days. As such, the FAGP
606 and AAS concrete had a lower modulus of elasticity than OPC concrete with similar
607 compressive strength. The experimental results indicated that FAGP concrete had about 12-
608 13% less modulus of elasticity than OPC concrete at 28 days. The AAS concrete had about 13-
609 19% less modulus of elasticity than OPC concrete at 28 days. A similar observation was
610 reported by Olivia and Nikraz [41] for heat cured fly ash based geopolymer concrete which
611 exhibited a modulus of elasticity of 14.9-28.8% less than OPC concrete with similar
612 compressive strengths. Hardjito et al. [42] reported that the modulus of elasticity of heat cured
613 fly ash based geopolymer was about 10% lower than OPC concrete with similar compressive
614 strengths. Yang et al. [25] and Douglas et al. [43] also reported that alkali-activated concrete
615 generally had a lower modulus of elasticity than OPC concrete with similar compressive
616 strengths.

617

618 **5. Comparison between calculated and experimental results**

619 The design standards specified equations to calculate indirect tensile strength, flexural strength
620 and modulus of elasticity from compressive strength of OPC concrete. The equations specified
621 in the ACI 318-14 [32] and AS 3600-2009 [33] for OPC concrete and the equations proposed
622 in the previous studies [11, 42, 44, 45, 46] for geopolymer concrete were used to calculate

623 indirect tensile strength, flexural strength and modulus of elasticity of FAGP and AAS concrete
624 and compared with the experimental results.

625

626 **5.1. Indirect tensile strengths**

627 The ACI 318-14 [32] specified Eq. (1) as the approximate relationship between the indirect
628 tensile strength and the compressive strength.

$$629 \quad f_{ct.sp} = 0.56 \sqrt{f_{c'}} \quad (\text{MPa}) \quad (1)$$

630 where $f_{ct.sp}$ is indirect tensile strength (MPa) and $f_{c'}$ is the specified compressive strength
631 (MPa) at 28 days.

632 The AS 3600-2009 [33] specified Eq. (2) as the relationship between the indirect tensile
633 strength and compressive strength.

$$634 \quad f_{ct.sp} = 0.36 \sqrt{f_c'} \quad (\text{MPa}) \quad (2)$$

635 Sofi et al. [44] proposed Eq. (3) for the relationship between indirect tensile strength and
636 compressive strength of fly ash based geopolymer concrete.

$$637 \quad f_{ct.sp} = 0.48 \sqrt{f_{c'}} \quad (\text{MPa}) \quad (3)$$

638 **Gunasekera et al. [45] proposed Eq. (4) for the relationship between indirect tensile strength
639 and compressive strength of concrete.**

$$640 \quad f_{ct.sp} = 0.45 \sqrt{f_{c'}} \quad (\text{MPa}) \quad (4)$$

641 The relationship between indirect tensile strength and compressive strength of the experimental
642 and calculated values are shown in Fig. 10. It can be seen that the experimental indirect tensile
643 strength of normal strength FAGP and AAS concrete are close to the calculated indirect tensile
644 strength using ACI 318-14 [32] and mostly higher than those calculated using AS 3600-2009

645 [33], Sofi et al. [44] and Gunasekera et al. [45]. However, the experimental indirect tensile
646 strength for high strength FAGP and AAS concrete were higher than the indirect tensile
647 strength calculated using ACI 318-14 [32], AS 3600-2009 [33], Sofi et al. [44] and Gunasekera
648 et al. [45] (Fig. 10). The results obtained using ACI 318-14 [37] for OPC concrete provided a
649 conservative estimate of normal strength FAGP and AAS concrete. However, the ACI 318-14
650 [32] for OPC concrete did not provide a conservative estimate of high strength FAGP and AAS
651 concrete.

652

653 **5.2. Flexural Strengths**

654 The equations in the ACI 318-14 [32] and AS 3600-2009 [33] for OPC concrete and proposed
655 in previous studies [11, 44, 46] for geopolymer concrete were used to calculate the flexural
656 strength of FAGP and AAS concrete and compared with the experimental results.

657 The ACI 318-14 [32] recommended Eq. (5) for the relationship between the flexural strength
658 and compressive strength of concrete.

$$659 \quad f_{ct,f} = 0.62 \sqrt{f_{c'}} \text{ (MPa)} \quad (5)$$

660 where $f_{ct,f}$ is the flexural strength (MPa) and $f_{c'}$ is the specified compressive strength (MPa)
661 at 28 days.

662 The AS 3600-2009 [33] recommended Eq. (6) for the relationship between the flexural strength
663 and compressive strength of concrete.

$$664 \quad f_{ct,f} = 0.6 \sqrt{f_{c'}} \text{ (MPa)} \quad (6)$$

665 Diaz-Loya et al. [11] suggested Eq. (7) for the relationship between the flexural and
666 compressive strength of geopolymer concrete.

$$667 \quad f_{ct,f} = 0.69 \sqrt{f_{c'}} \text{ (MPa)} \quad (7)$$

668 Nath and Sarker [46] proposed Eq. (8) for the relationship between the flexural strength and
669 compressive strength of concrete.

$$670 \quad f_{ct.f} = 0.93\sqrt{f_{c'}} \text{ (MPa)} \quad (8)$$

671 The relationship between flexural strength and compressive strength of the experimental and
672 calculated values are drawn in Fig. 11. Figure 11 indicates that the experimental flexural
673 strength of normal strength FAGP and AAS concrete are comparable to those calculated using
674 ACI 318-14 [32] and AS 3600-2009 [33]. However, the experimental flexural strength of
675 normal strength FAGP and AAS concrete are lower than those calculated using Diaz-Loya et
676 al. [11] and Nath and Sarker [46] for geopolymer concrete. The experimental flexural strength
677 of high strength FAGP and AAS concrete are higher than those calculated using ACI 318-14
678 [32], AS 3600-2009 [33] and Diaz-Loya et al. [11] and lower than those calculated using Nath
679 and Sarker [46]. This means that ACI 318-14 [32] and AS 3600-2009 [33] for OPC provided
680 a conservative estimate of normal strength FAGP and AAS concrete in terms of flexural
681 strength. However, the ACI 318-14 [32] and AS 3600-2009 [33] for OPC concrete did not
682 provide a conservative estimate of high strength FAGP and AAS concrete.

683

684 **5.3. Modulus of elasticity**

685 The equations specified in the ACI 318-14 [32] and AS 3600-2009 [33] for OPC concrete were
686 used to calculate modulus of elasticity of FAGP and AAS concrete and compared with the
687 experimental results. Also, the equations proposed in Hardjito et al. [42] and Diaz-Loya et al.
688 [11] for geopolymer concrete were used to calculate the modulus of elasticity of FAGP and
689 AAS concrete and compared with the experimental results.

690

691 The ACI 318-14 [32] specified Eq. (9) for the modulus of elasticity of OPC concrete.

692 $E_c = (\rho^{1.5}) \times (0.043\sqrt{f_{c'}})$ (9)

693 where E_c is the modulus of elasticity, ρ is the density of concrete (kg/m^3) and $f_{c'}$ is
694 compressive strength at 28 days.

695 The AS 3600-2009 [33] specified Eq. (10) for the modulus of elasticity of OPC concrete.

696 $E_c = (\rho^{1.5}) \times (0.024\sqrt{f_{c'}+0.12})$ when $f_{c'} > 40$ MPa (10)

697 According to AS 3600-2009 [33], the modulus of elasticity can be calculated using a similar
698 equation proposed in the ACI 318-14 [32] for OPC concrete of compressive strength less than
699 40 MPa.

700 Hardjito et al. [42] proposed Eq. (11) for the modulus of elasticity of geopolymer concrete.

701 $E_c = 2707\sqrt{f_{c'}} + 5300$ (11)

702 Diaz-Loya et al. [11] proposed Eq. (12) for the modulus of elasticity of geopolymer concrete

703 $E_c = 0.037 \times \rho^{1.5} \times \sqrt{f_{c'}}$ (12)

704 The calculated and experimental results of the modulus of elasticity of FAGP and AAS
705 concrete are shown in Fig. 12. The results obtained from the ACI 318-14 [32], AS 3600-2009
706 [33] and Diaz-Loya et al. [11] overestimated the experimental results of normal strength and
707 high strength FAGP and AAS concrete (Fig. 12). Similar observations were reported in the
708 previous studies conducted on the comparison between calculated and experimental modulus
709 of elasticity. Yost et al. [47] reported that the modulus of elasticity of FAGP concrete was 11-
710 16% less than the calculated modulus of elasticity using ACI 318-14 [32]. Yang et al. [25]
711 found that modulus of elasticity of AAS concrete was 12-15% lower than the values calculated
712 using ACI 318-14 [32]. The calculated modulus of elasticity using ACI 318-14 [32] and AS
713 3600-2009 [33] for OPC concrete did not provide a conservative estimate of normal and high
714 strength FAGP and AAS concrete in terms of modulus of elasticity. However, the results

715 obtained using Hardjito et al. [42] was very close to those obtained from experimental results.
716 Therefore, the modulus of elasticity for normal strength and high strength FAGP and AAS
717 concrete can be reasonably estimated using the equation proposed by Hardjito et al. [42].

718

719 **6. Conclusions**

720 This paper compares the engineering properties of normal strength and high strength FAGP
721 and AAS concrete with OPC concrete. The following conclusions are drawn from the test
722 results.

723 1. The average dry density and ultrasonic pulse velocity of FAGP and AAS concrete were
724 lower than those of OPC concrete. This finding was confirmed by SEM analyses. The SEM
725 images showed that at 28 days, FAGP and AAS concrete were less dense and less compacted
726 with less homogeneous microstructures compared to OPC concrete.

727 2. The normal strength FAGP, AAS and OPC concrete have comparable indirect tensile,
728 flexural and direct tensile strengths. However, the indirect tensile, flexural strength and direct
729 tensile strength of high strength (compressive strength of about 65 MPa) FAGP and AAS
730 concrete were higher than those of high strength OPC concrete.

731 3. The equations recommended in ACI 318-14 [32] for OPC concrete can be used for the
732 conservative prediction of the indirect tensile strength of normal strength (compressive strength
733 of about 35 MPa) FAGP and AAS concrete. However, the current ACI 318-14 [32] for OPC
734 concrete does not provide a conservative estimate of the indirect tensile strength of high
735 strength (compressive strength of about 65 MPa) FAGP and AAS concrete. The equations
736 recommended in ACI 318-14 [32] and AS 3600-2009 [33] can be used for conservative
737 prediction of the flexural strength of normal strength concrete (compressive strength of about
738 35 MPa) FAGP and AAS concrete. However, the equations recommended in ACI 318-14 [32]

739 and AS 3600-2009 [33] does not provide a conservative estimate of the flexural strength of
740 high strength (compressive strength of about 65 MPa) FAGP and AAS concrete.

741 4. The modulus of elasticity of normal strength and high strength FAGP and AAS concrete
742 under uniaxial tension was about 7-8% and 8-9% less than the modulus of elasticity of OPC
743 with the similar compressive strengths at 28 days. The modulus of elasticity of normal strength
744 and high strength FAGP and AAS concrete under compression was about 12-13% and 13-19%
745 less than the modulus of elasticity of OPC with a similar compressive strength at 28 days.

746 5. The modulus of elasticity of normal strength and high strength FAGP and AAS concrete
747 calculated using ACI 318-14 [32], AS 3600-2009 [33] and Diaz-Loya et al. [11] was higher
748 than the experimental modulus of elasticity. However, the modulus of elasticity of normal
749 strength and high strength FAGP and AAS concrete can be closely estimated reasonably using
750 equation recommended in Hardjito et al. [42].

751

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754 Laboratories of the University of Wollongong in carrying out the experimental work. The
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757 scholarship.

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913 concrete.

914 **Fig. 12.** Modulus of elasticity versus compressive strength: (a) FAGP concrete and (b) AAS
915 concrete.

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918 **Table 1**

919 The chemical composition FA and GGBS.

Composition (mass)	Mass content (%)	
	FA	GGBS
SiO ₂	62.2	32.4
Al ₂ O ₃	27.5	14.96
Fe ₂ O ₃	3.92	0.83
CaO	2.27	40.70
MgO	1.05	5.99
K ₂ O	1.24	0.29
Na ₂ O	0.52	0.42
TiO ₂	0.16	0.84
P ₂ O ₅	0.30	0.38
Mn ₂ O ₃	0.09	0.40
SO ₃	0.08	2.74
Loss on ignition	0.89	NA

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932 **Table 2**

933 Chemical composition of cement.

Composition (mass)	Mass content (%)
Portland Cement Clinker	<97
Gypsum (CaSO ₄ 2H ₂ O)	2-5
Limestone (CaCO ₃)	0-7.5
Calcium Oxide (CaO)	0-3
Hexavalent Chromium Cr (VI)	<20 ppm
Crystalline Silica (Quartz)	<1

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951 **Table 3**

952 Mix proportion of FAGP, AAS and OPC concrete.

Concrete mix	Normal strength concrete (NSC)			High strength concrete (HSC)		
	FAGP	AAS	OPC	FAGP	AAS	OPC
Cement (kg/m ³)	-	-	350	-	-	461
GGBS (kg/m ³)	-	400	-	-	450	-
FA (kg/m ³)	410	-	-	480	-	29
Alkaline activator/Binder	0.45	0.45	-	0.35	0.35	-
Fine aggregate (kg/m ³)	627	636	760	606	625	650
Coarse aggregate (kg/m ³)	1164	1169	1138	1140	1154	1150
Na ₂ SiO ₃ /NaOH	2	2.5	-	2	2.5	-
Na ₂ SiO ₃ (kg/m ³)	123	128	-	112	106	-
NaOH (kg/m ³)	61.5	52	-	56	53	-
NaOH (moles/liter)	12	12	-	14	14	-
Water (kg/m ³)	45	48	182	35	40	148
Superplasticizer (kg/m ³)	22.5	20	8	17.5	12.5	6.5

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956 **Table 4**

957 Engineering properties of FAGP, AAS and OPC concrete at 7 and 28 days.

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Concrete Mix	Design compressive strength (MPa) at 28 days	Dry density (kg/m ³)		Ultrasonic pulse velocity (km/s)		Compressive strength (MPa)		Indirect tensile strength (MPa)		Flexural strength (MPa)		Direct tensile strength (MPa)	
		7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
FAGP-35	35	2373	2378	3.14	3.20	33.90	35.91	3.37	3.58	3.57	3.81	2.33	2.43
AAS-35		2389	2403	3.18	3.31	29.03	36.44	2.93	3.55	3.21	3.79	2.02	2.42
OPC-35		2368	2415	3.30	3.52	26.51	35.82	2.66	3.51	3.06	3.78	1.91	2.41
FAGP-65	65	2381	2384	3.82	3.93	61.71	65.28	5.32	5.73	6.07	6.42	3.36	3.52
AAS-65		2420	2432	3.78	3.98	53.68	66.12	4.49	5.23	5.40	6.31	2.93	3.52
OPC-65		2401	2443	3.87	4.15	50.73	66.69	3.78	4.94	4.57	5.81	2.79	3.51

959 **Table 5**

960 Classification of the quality of concrete based on ultrasonic pulse velocity.

Longitudinal pulse velocity (km/s)	Quality of concrete
>4.5	Excellent
3.5-4.5	good
3.0-3.5	medium
2.0-3.0	Poor
<2.0	Very poor

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978 **Table 6**

979 Experimental results of the peak stress, strain at peak stress, and modulus of elasticity of the
 980 tested specimens under uniaxial tension.

Concrete Mix	Average peak stress (MPa)		Average strain at peak stress * 10 ⁻³		Average modulus of elasticity (GPa)	
	7 days	28 days	7 days	28 days	7 days	28 days
FAGP-35	2.33	2.43	0.14	0.15	16.59	16.63
AAS-35	2.02	2.42	0.12	0.14	16.20	16.59
OPC-35	1.91	2.41	0.12	0.13	16.23	17.98
FAGP-65	3.36	3.52	0.17	0.20	19.22	19.46
AAS-65	2.93	3.52	0.16	0.18	18.38	19.36
OPC-65	2.79	3.51	0.15	0.17	18.66	20.95

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997 **Table 7**

998 Experimental results of peak stress, strain at peak stress, and the modulus of elasticity of
 999 specimens tested under compression.

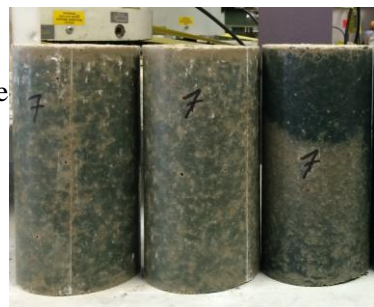
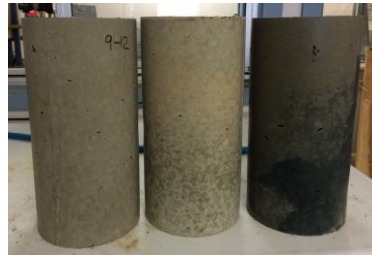
Concrete Mix	Average peak stress		Average strain at peak stress		Average modulus of elasticity (GPa)	
	7 days	28 days	7 days	28 days	7 days	28 days
FAGP-35	32.40	33.39	0.00219	0.00223	17.34	18.05
AAS-35	26.88	34.08	0.00203	0.00214	16.82	17.95
OPC-35	24.81	33.06	0.00203	0.00208	18.78	20.20
FAGP-65	59.36	63.07	0.00301	0.00312	21.35	24.47
AAS-65	52.18	64.26	0.00275	0.00282	20.21	23.30
OPC-65	48.56	63.34	0.00216	0.00244	22.10	27.63

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Fresh concrete



Compressive strength specimens



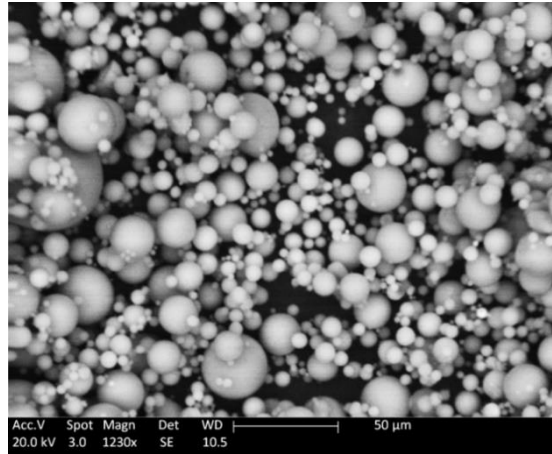
Failure mode

(b) FAGP

(a) AAS

Fig.1. Preparation and failure for: (a) FAGP concrete and (b) AAS concrete.

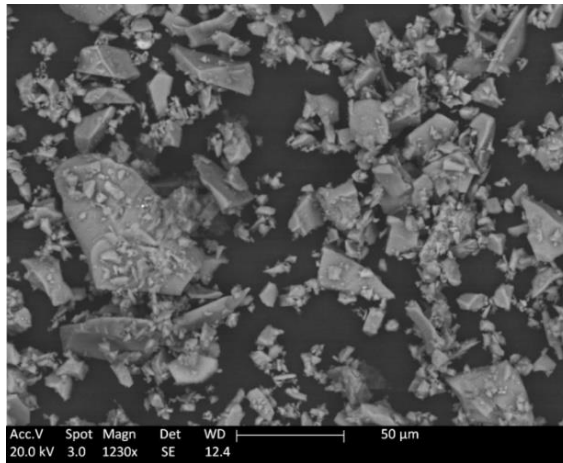
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(a) FA

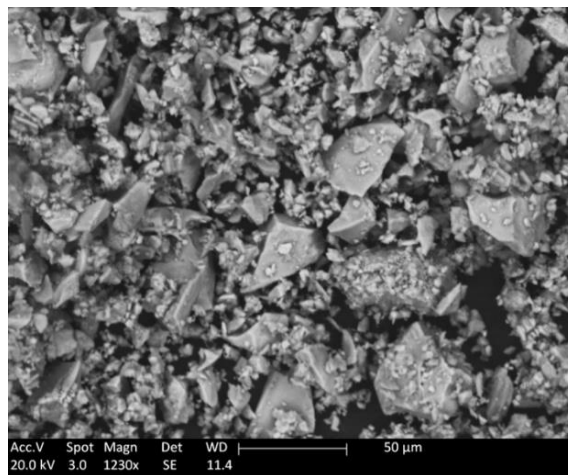
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(b) GGBS

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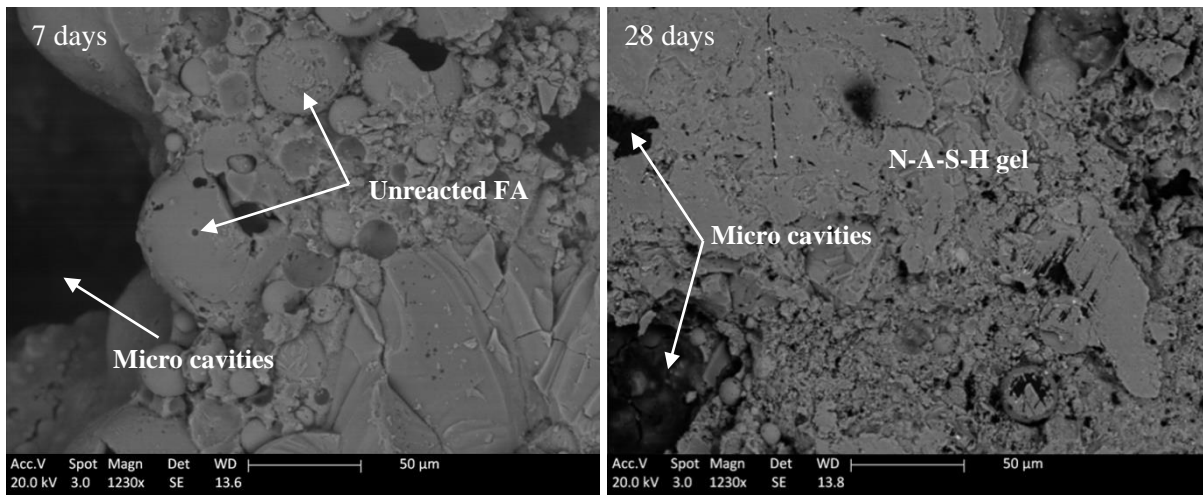


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(c) OPC

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Fig. 2. SEM images for (a) FA, (b) GGBS and (c) OPC binder.

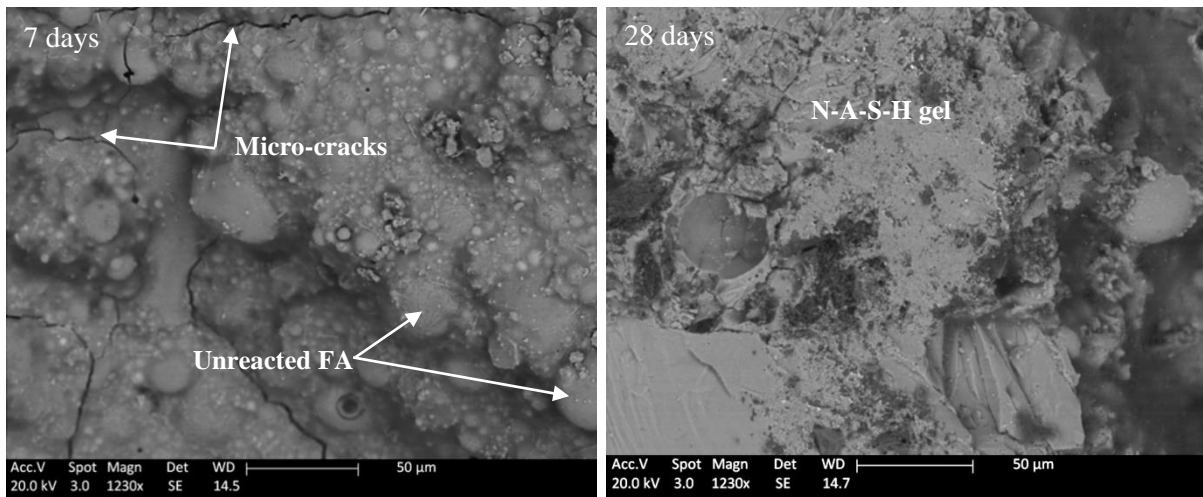


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1047 **Fig. 3.** SEM images of FAGP concrete: (a) Normal strength concrete and (b) High strength

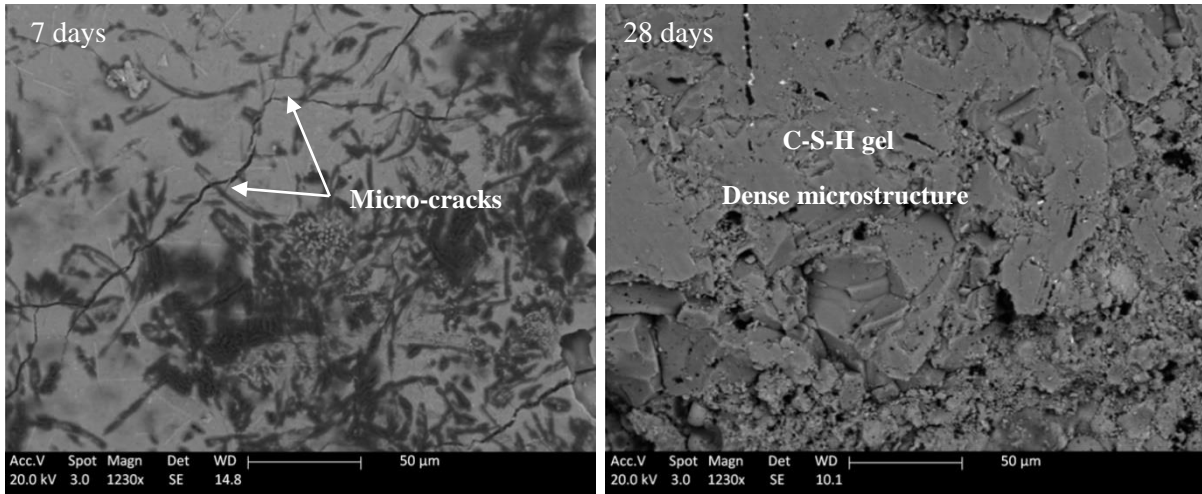
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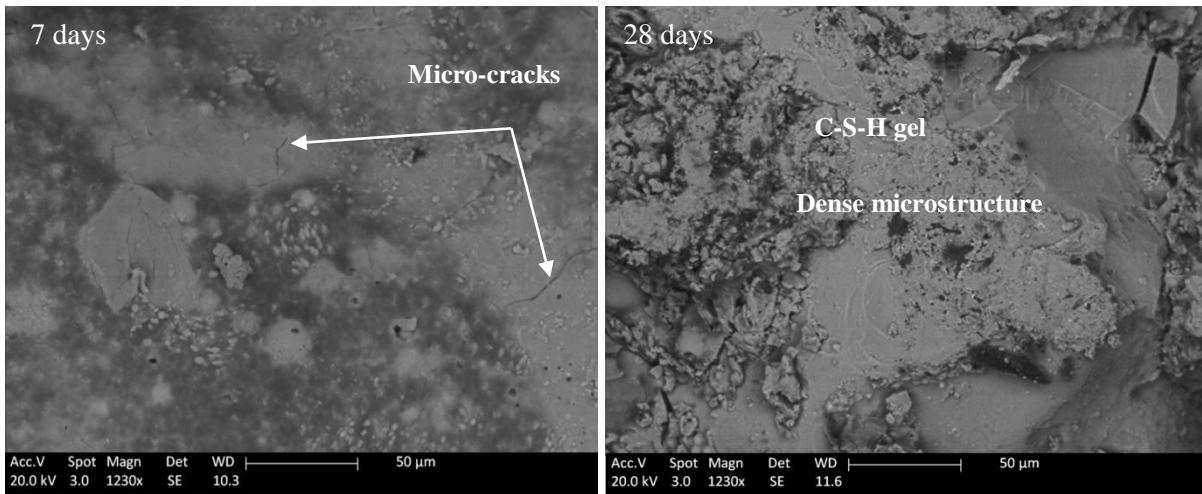


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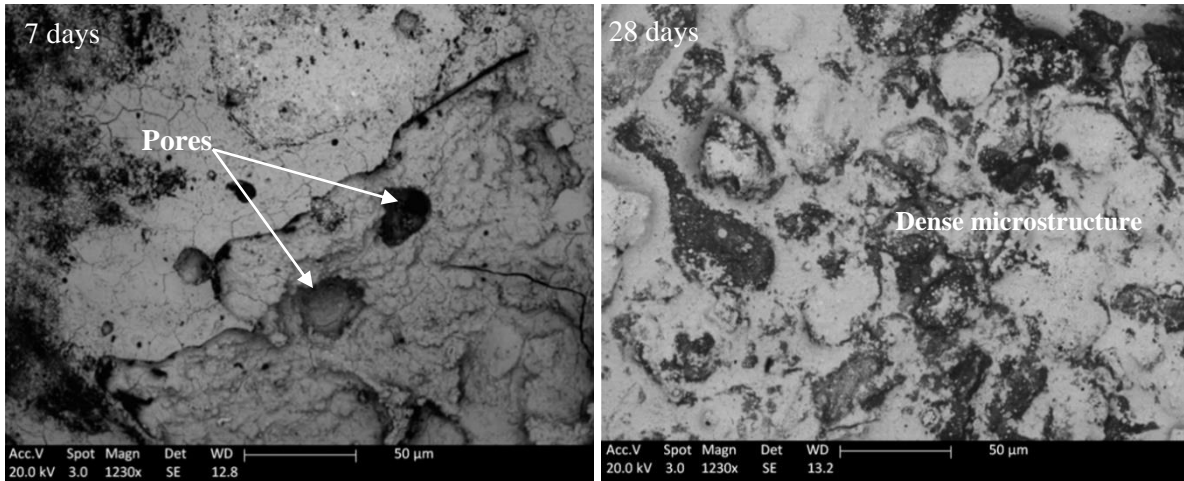
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Fig. 4. SEM images of AAS concrete: (a) Normal strength concrete and (b) High strength concrete.

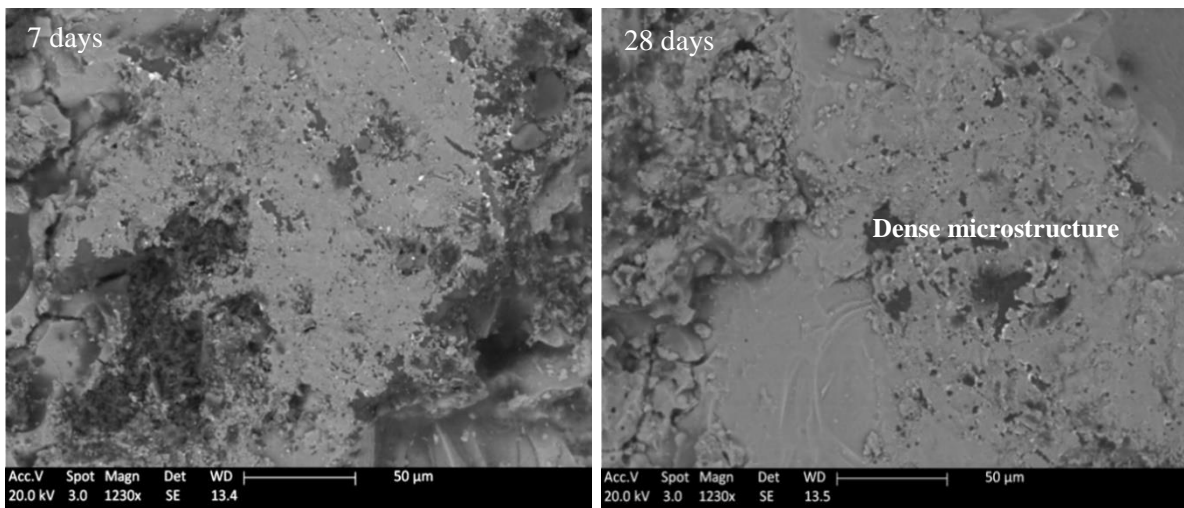


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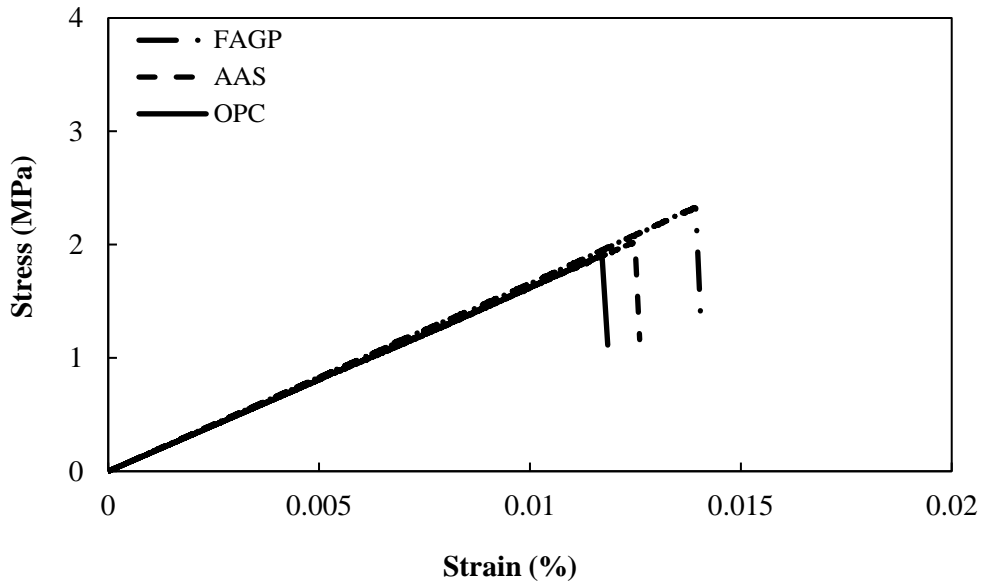
Fig. 5. SEM images of OPC concrete: (a) Normal strength concrete and (b) High strength

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concrete.

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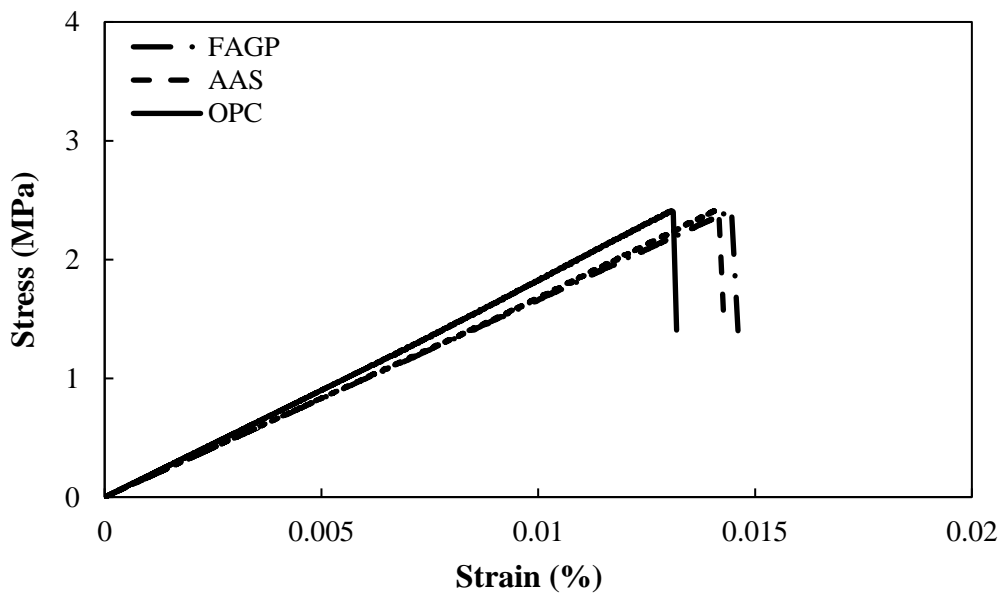
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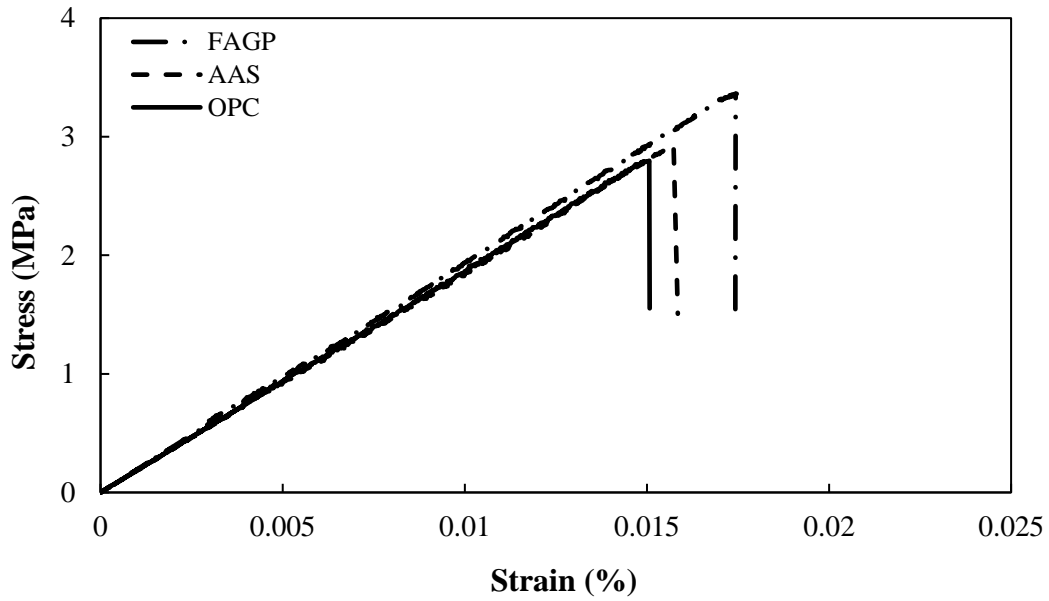
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(b)

Fig. 6. Typical stress-strain behaviour under uniaxial tension for specimens of design compressive strength of 35 MPa: (a) at 7 days and (b) at 28 days.

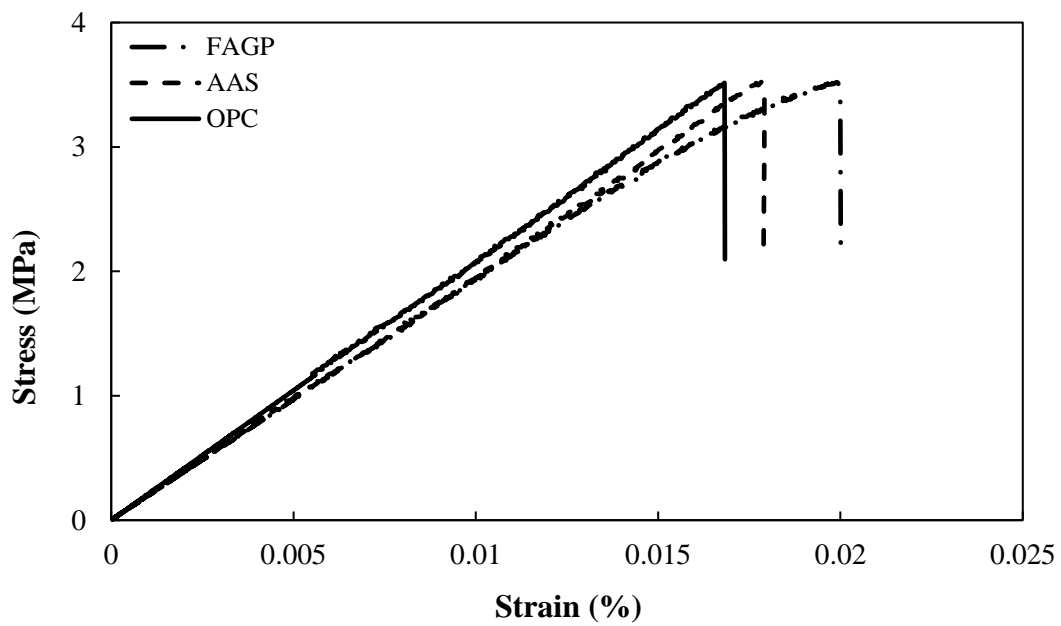
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(a)



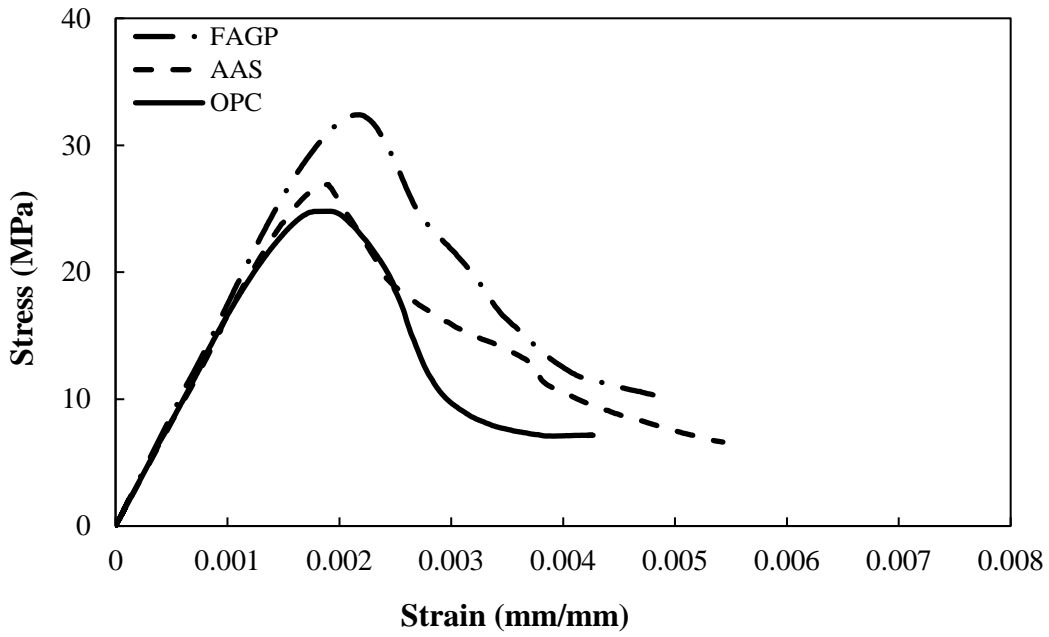
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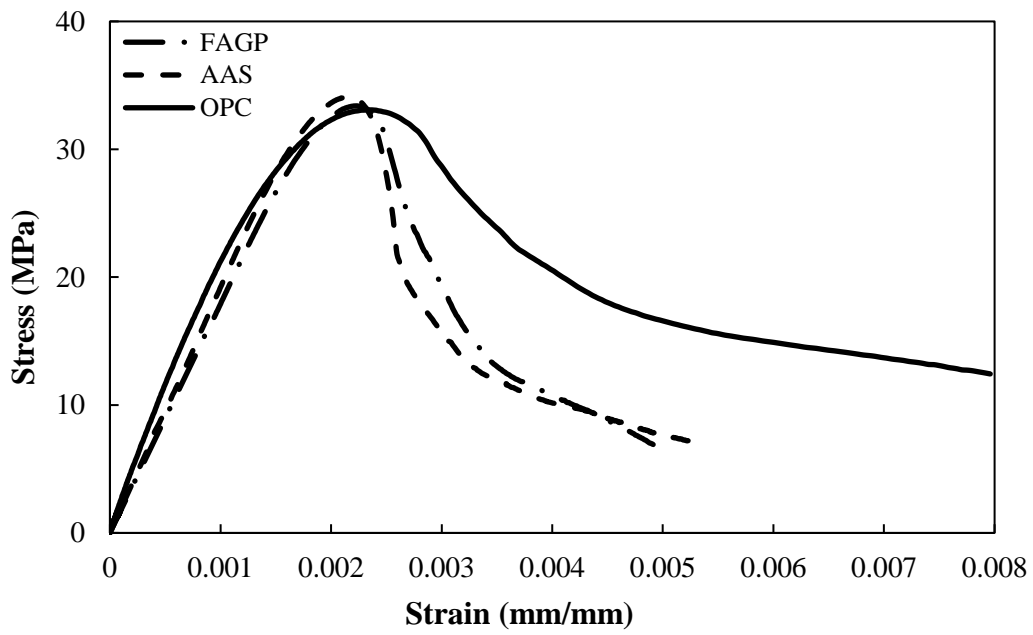
(b)

1083 **Fig. 7.** Typical stress-strain behaviour under uniaxial tension for specimens of design

1084 compressive strength of 65 MPa: (a) at 7 days and (b) at 28 days.

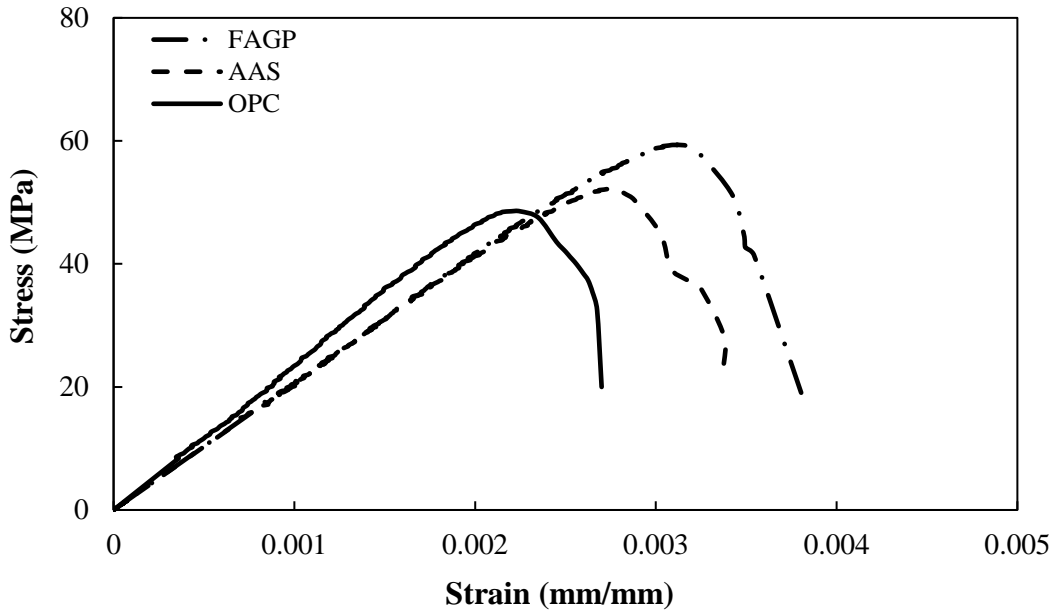


(a)



(b)

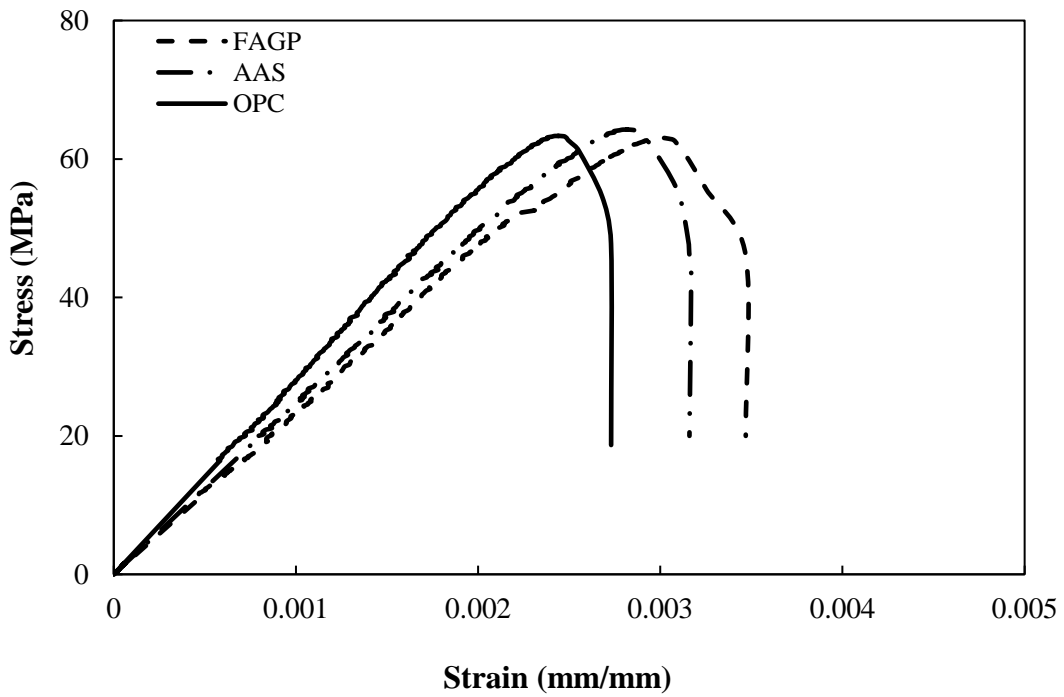
1089 **Fig. 8.** Typical stress-strain behaviour under compression for specimens of design
 1090 compressive strength of 35 MPa: (a) at 7 days and (b) at 28 days.



1091

1092

(a)



1093

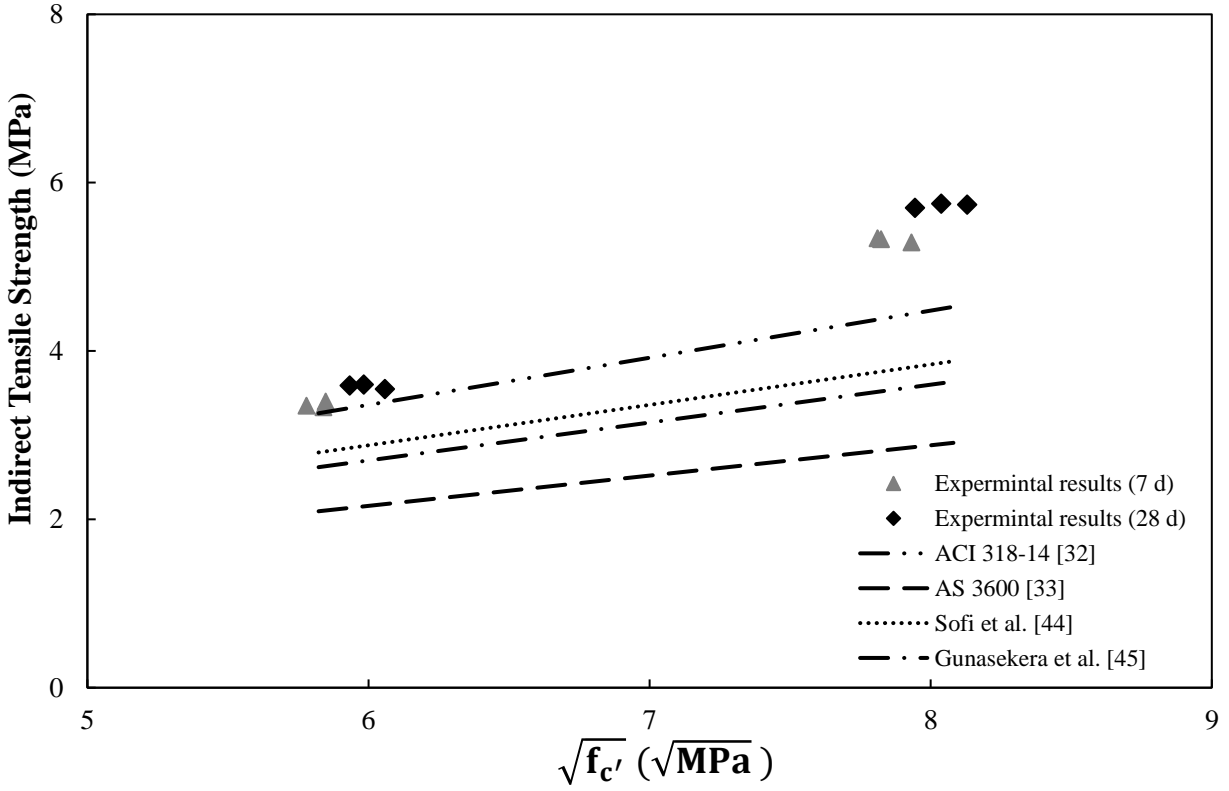
1094

(b)

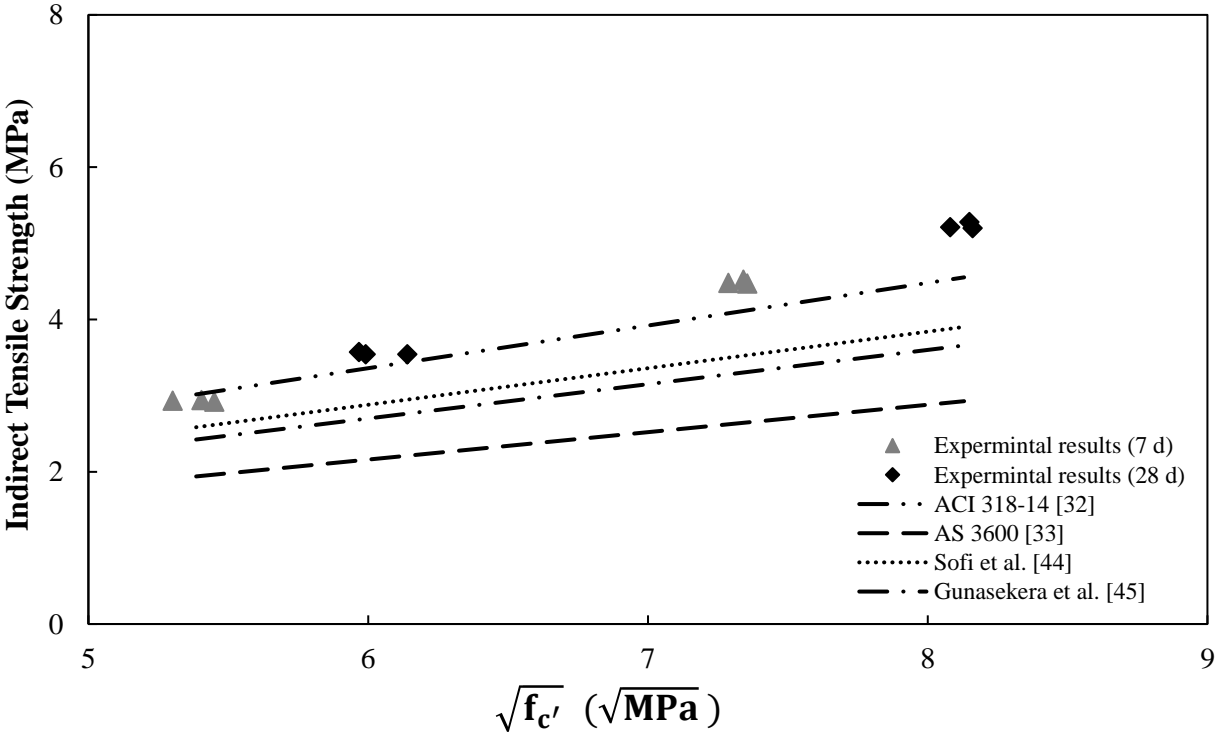
1095 **Fig. 9.** Typical stress-strain behaviour under compression for specimens of design

1096 compressive strength of 65 MPa: (a) at 7 days and (b) at 28 days.

1097

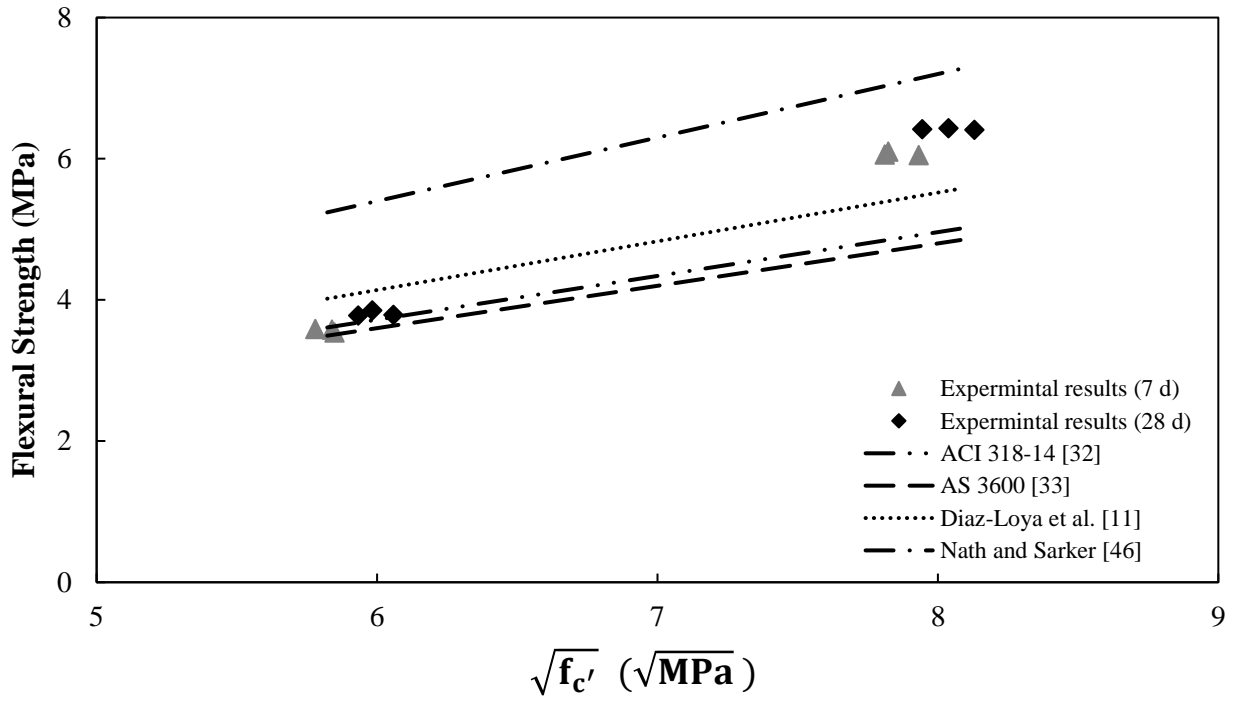


(a)



(b)

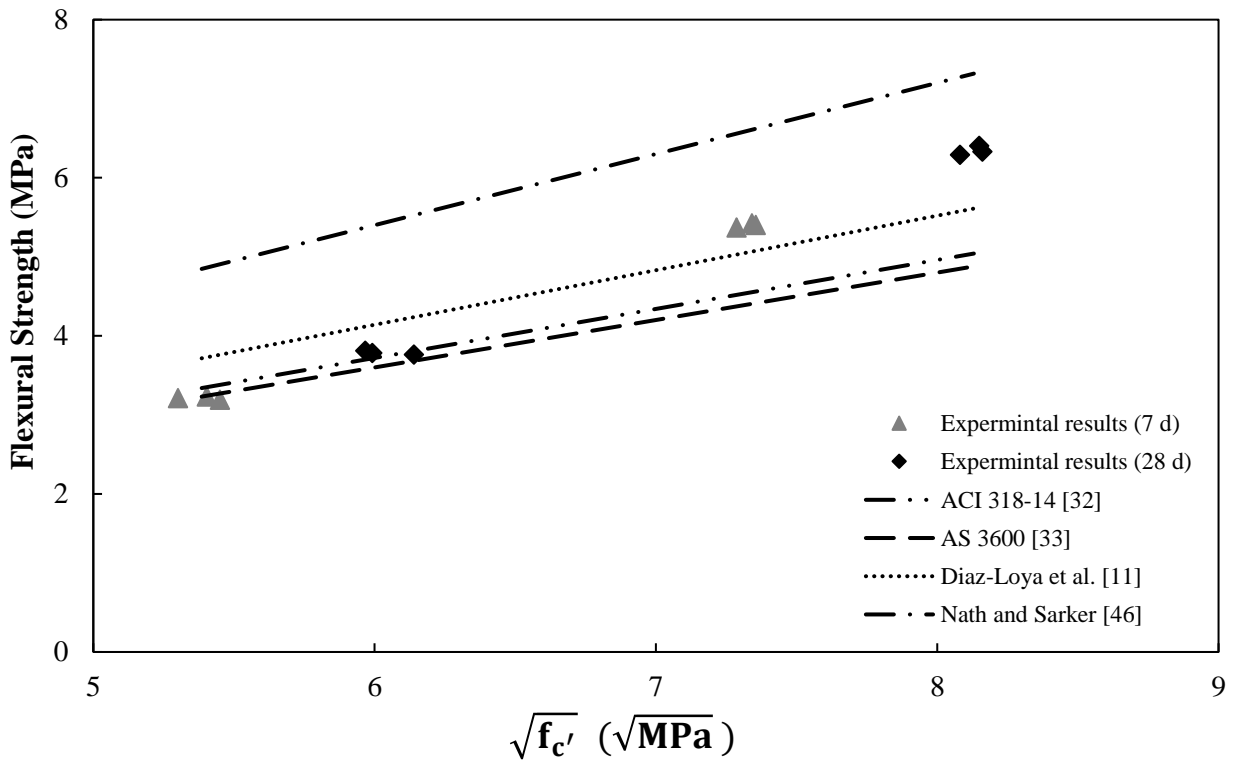
1102 **Fig. 10.** Indirect tensile strength versus compressive strength: (a) FAGP concrete and (b)
 1103 AAS concrete.



1104

1105

(a)



1106

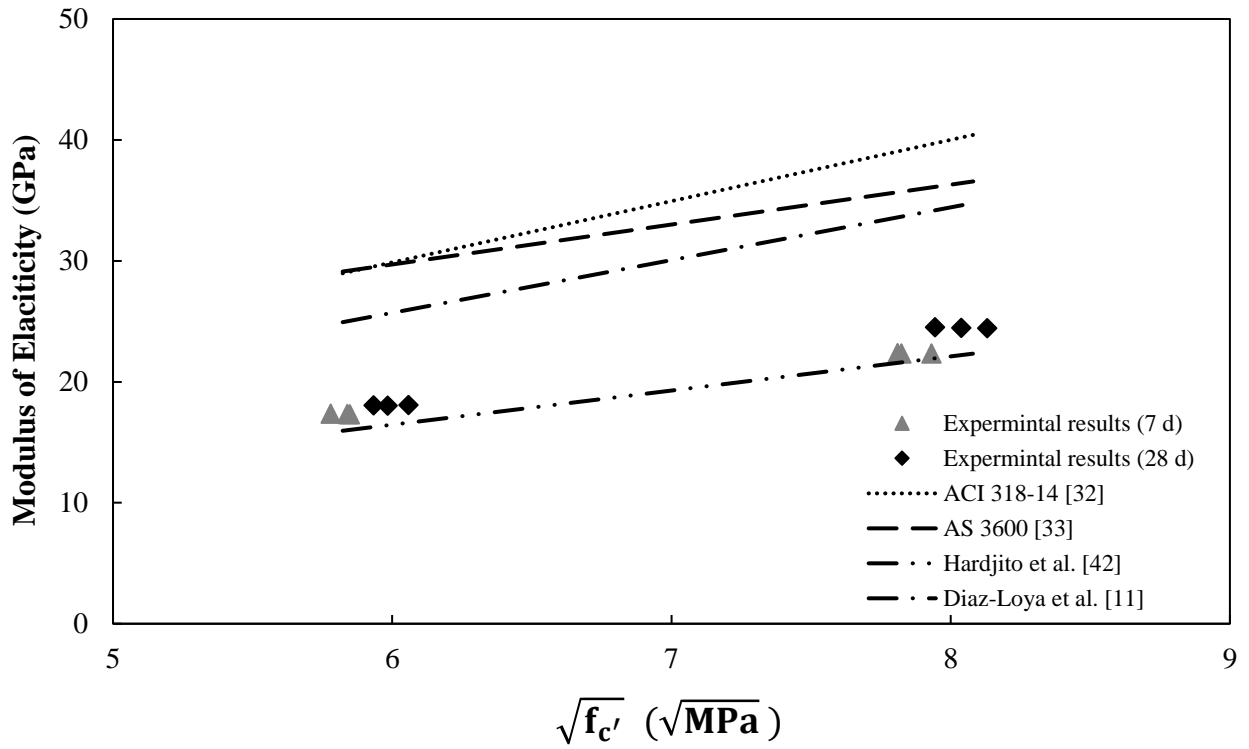
1107

(b)

1108 **Fig. 11.** Flexural strength versus compressive strength: (a) FAGP concrete and (b) AAS

1109

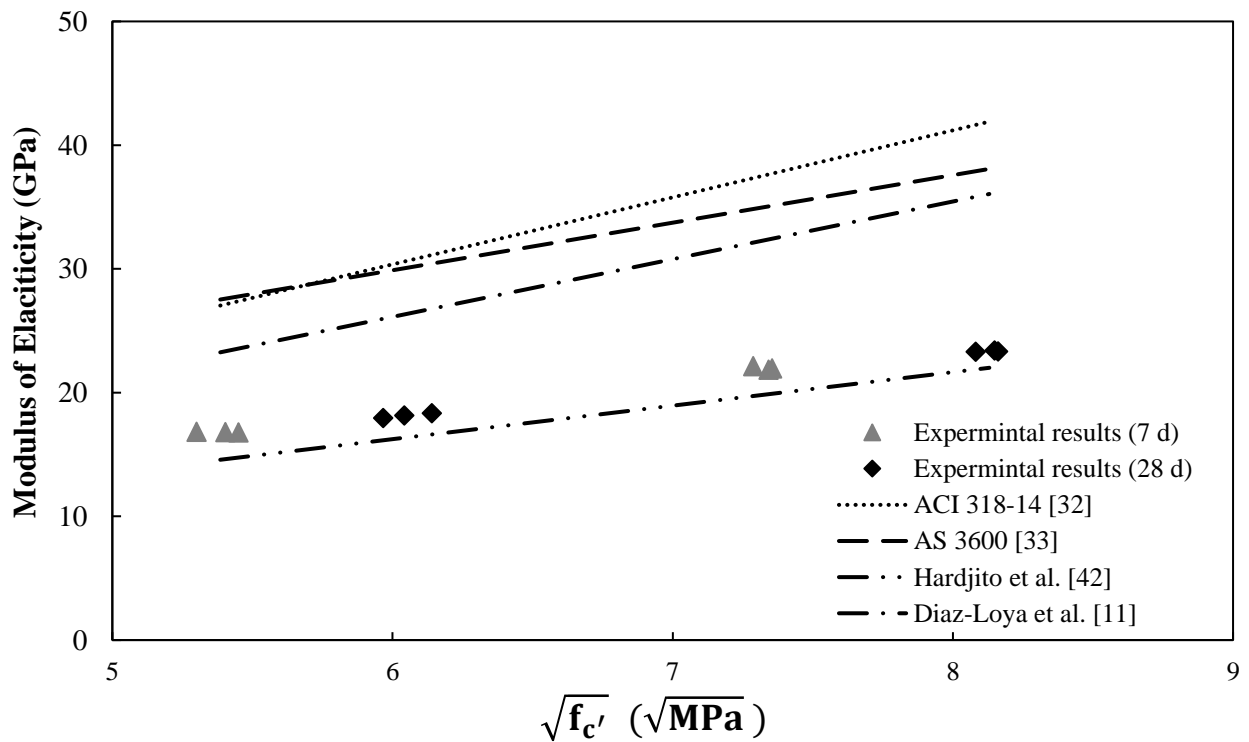
concrete.



1110

1111

(a)



1112

1113

(b)

1114

1115

Fig. 12. Modulus of elasticity versus compressive strength: (a) FAGP concrete and (b) AAS concrete.